Annotated Bibliography of Urban Wet Weather Flow Literature from 1996 through 2002

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Abstract

This paper is a compilation of urban wet weather flow (WWF) literature reviews for the seven years from 1996 through 2002. This subject, urban wet-weather flows, is comprised of three basic subareas – combined-sewer overflows (CSOs), sanitary-sewer overflows (SSOs), and stormwater discharges. The following therefore includes literature citations and reviews for each of these main subareas.

These reviews were originally published in the annual literature review issues of Water Environment Research. Many of these citations have been expanded since the initial publications. Over this seven year period of time, many people were involved in preparing these urban wet weather flow reviews, many associated with the EPA’s Wet-Weather Flow Research Program. See the acknowledgements section for the complete list of contributors. This paper re-organizes and combines these individual reviews into a single document for easier use. Over this seven year period, the field of urban wet weather flow research has expanded dramatically, likely due to increased interest in the US due to the NPDES stormwater permit program, plus increased awareness of the seriousness of urban WWFs throughout the world. About 3350 references are included in this compiled review, indicating the magnitude of interest in this topic. In addition, the number of references for each year has dramatically increased compared to the previous year. Another indication of the increasing interest in urban WWFs is the large number of specialized stormwater conferences that are now scheduled each year, plus the increasing number of nonpoint sessions at large international conferences.


Many of these conferences produced summary papers of what is known and where the knowledge gaps still exist. Heaney (2002b) reported on research needs to quantify the impacts of urbanization on streams. Keyes (2002) presented the EWRI/ASCE perspective on urban watershed needs in the 21st century. Swetnam et al. (2002) reviewed the collation, management and dissemination of urban environmental research in the UK. Urbonas and Jones (2002) summarized the emergent urban stormwater themes that were highlighted at the Engineering Foundation Conference on “Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation.” Walesh (2002) described the threats and opportunities facing the urban water field. The paper urged more diligence in applying the state-of-the-art, guarding against software misuse, adopting a holistic approach to watershed development, and rejecting price-based selection for clients needing consulting services.

Schiff and Bernstein (2002) reported on the stormwater monitoring coalition in Southern California and the stormwater research needs identified by the coalition. The projects identified by the research panel fell into one of three broad categories including developing a stormwater-monitoring infrastructure, understanding fundamental stormwater mechanisms and processes, and assessing receiving water impacts. A further refinement identified seven projects that relate to identifying receiving water impacts. These projects included identifying the causes of impacts in receiving waters, developing bioassessment indicators and protocols, developing improved toxicity testing procedures, developing rapid response indicators for microbial contamination, developing microbial source tracking protocols, evaluating BMP effects on receiving waters, and developing improved indicators of peak flow impacts.

Major proceedings related to WWFs published during 2001 were: (1) ASCE EWRI Conference – Bridging the Gap: Meeting the World’s Water and Environmental Resources Challenges (ASCE, 2001); (2) WEFTEC 2001, 74th Annual Conference and Exposition (WEF, 2001); (3) 5th International Conference: Diffuse/Nonpoint Pollution and Watershed Management (IWA, 2001); (4) Models and Applications to Urban Water Systems, Monograph 9 (CHI, 2001); (5) 2001 A Collection Systems Odyssey: Integrating O&M and Wet Weather Solutions (WEF, 2001); (6) 7th Annual Industrial Wastes Technical and Regulatory Conference (WEF, 2001); and (7) Proceedings of the Third International Conference on Watershed Management (ASCE, 2001).

Major proceedings related to WWFs published during 2000 included: (1) 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management (ASCE, 2000); (2) WEFTEC 2000, 73rd Annual Conference and Exposition (WEF, 2000); (3) Collection Systems Wet Weather Pollution Control: Looking into Public, Private and


For 1996, much of the literature cited came from documents covering noteworthy global conferences (Bathala, 1996; Eng. Foundation, 1996; EPA 1996a; Hallam et al., 1996; Int. Water Res. Assoc., 1996; Maxwell et al., 1996; Sieker and Verworn 1996; Soc. Environ. Toxicol. and Chem., 1996; Water Environ. Fed., 1996a, 1996b, and 1996c.). In addition, the U.S. Environmental Protection Agency (EPA) (EPA, 1996b, 1996c, 1996d, and 1996e) published guidance documents which are discussed in more detail in the subsection entitled “Regulatory Policies and Financial Aspects”. The proceedings of several global conferences on urban stormwater management were also published in 1996. James (1996) edited a book overviewing 18 papers dealing with the modeling aspects of urban stormwater. These papers address a variety of topics including the use of the models themselves, data management including GIS, and the interrelationships between BMPs and water quality. The two-volume proceedings of RIVERTECH96 (Maxwell et al., 1996) provided many papers related to urban-stormwater management. The proceedings from a national conference on SSOs provide an excellent information source on SSO problems generally and infiltration/inflow (I/I) problems in particular (EPA, 1996a). The three-volume proceedings of the 7th International Conference on Urban Storm Drainage, held in Hannover, Germany, provide an excellent source of information regarding new developments throughout the world (Sieker and Verworn, 1996).

Introduction

There has been a dramatic shift in the objectives associated with drainage design over the past decades. Burian, et al. (1999) presented a historical development of WWF management as part of the EPA-sponsored research effort on developing designs for the future (Pitt, et al. 1998a). An extensive annotated bibliography was prepared containing several thousand references tracing the history of drainage design and associated hydraulic and water quality issues. This bibliography (in both text from and in searchable ProCite formats) is available from the student organization AWRA web page at the Department of Civil Engineering, University of Alabama.

An overview of the evolution of urban drainage, illustrating where the concept of a single design objective was replaced by the sustainability concept, was provided by Marsalek (2000a). The advances highlighted by Marsalek included improved (dynamic) control of urban drainage, source controls, integrated modeling, public and political support, innovative university training, sustainable funding, adaptive water management, and investment in research and development (Marsalek 2000b). The paper also highlighted the future challenge of involving the public in the planning of drainage systems and protection of urban waters (Marsalek 2000c). Cigana and Couture (2000) advanced a list of key steps required to achieve a global approach to wet weather issues.

The overall challenges of urban drainage design and monitoring were discussed by both Marsalek and Kok (2000) and by Cigana (2000a). Cigana provided a discussion of the pollution resulting from stormwater runoff and combined sewer overflows (CSOs). The paper also reviewed the technologies available to control this pollution. Marsalek and Kok noted that the effectiveness of stormwater BMPs is not fully understood, and advocated future research into the design, operation and maintenance of these pollution control practices. Field (2000) presented an overview of the U.S. Environmental Protection Agency’s (EPA’s) urban watershed wet-weather flow (WWF) research program. U.S. EPA divided its 1996 research plan into five major areas: characterization and problem assessment, watershed management, toxic substances characterization and control, control technologies, and infrastructure improvement. Since that time, other organizations, notably the Water Environment Research Foundation (WERF), have reviewed WWF research programs and developed associated research needs reports, an effort that EPA endorses.

Sullivan and Field (1999) presented an overview of the Environmental Protection Agency’s (EPA’s) WWF research
program, which was expanded in October 1995 with the establishment of the Urban Watershed Management Branch at Edison, New Jersey. Research priorities for 1999 were presented as well as efforts to collaborate with other government organizations and professional societies. Watershed management research at ORD’s National Risk Management Research Laboratory (NRMRL) addressed the following question: what effective watershed management strategies were available and how do communities select the most appropriate subset from these to match specific watershed needs? (Borst and O’Shea, 1999). Heaney et al. (1999) presented the results of a national assessment of research needs in urban WWF management. Three interrelated categories of urban WWF management were discussed: CSO, SSO, and urban stormwater discharges.

Based on the past 30 years of research on urban WWF water quality, impact, modeling, control, and treatment demonstrated results, Field et al. (1997a) delineated a framework of future research directions for risk management of urban WWF.

**Characterization**

**General**

The paper by Bicknell (2002) reviewed the discussion at the Engineering Foundation Conference on linking stormwater BMP design and performance to receiving water impacts mitigation. The paper described the roles, types and considerations for use of environmental indicators in characterizing receiving water conditions and monitoring stormwater program effectiveness. It also addressed data needs for future application of indicators, incorporating the comments made during the discussion.

Brandt et al. (2002) described two case studies of the development of two systems that will be monitored for land use and ecological change. The purpose of this project will be to collect reliable, quantifiable and independent data for monitoring these effects. The two case studies were the Small Biotype project of Denmark and the Countryside Survey project of Great Britain. These systems illustrated the problems involved in studies at the landscape level and the way satisfactory results can be achieved. Monitoring is considered to be effectively repeated surveillance and needs especially strict protocols to separate real change from the artifacts of sampling.

Morrissey et al. (2002) investigated the factors that affect the distribution of benthic macrofauna in estuaries that have been contaminated by urban runoff. Distributions of benthic invertebrates were significantly related to those of environmental variables, and were ordinated along axes that correlated with both natural environmental variables (nature of the sediment, position in estuary) and contaminants. Differences in faunas between the urban and non-urban estuaries were not, however, clear-cut and nor were relationships between faunal assemblages and environmental variables (including contaminants) consistent between two times of sampling. Papanicolaou et al. (2002) investigated the impacts of watershed changes on the fish population in the Clearwater River, Idaho. The study was a statistical analysis performed at the macroscale (watershed-wide) level. Factor analysis, along with linear regression, was used to develop relationships between fish indicators and fifty man-made disturbances, watershed landscape, water discharge and geometry, channel morphology, river water depth, and temperature. The statistical analysis indicated that some macroscale parameters such as, landscape and water discharge could be strong predictors of Fish Indicators and should be considered in restoration plans in the region.

Patwardhan and Kreutzberger (2002) linked sediment loads to biotic integrity for developing clean sediment TMDLs. The WISE (Watershed Improvements through Statistical Evaluations) Model was designed to link the watershed pollutant loads to narrative standards, i.e., biological indices. Specific biological standards, based on biological indices such as Index of Biological Integrity (IBI), Fish Score, and Invertebrate Community Index (ICI), were used as measurement tools and were linked to various pollutant loads from the watershed.

Fan et al. (2001b) reviewed the transport of toxic pollutants through multiple media and drainage systems in the urban watershed during wet-weather periods. Field studies have identified that a major portion of hazardous waste priority pollutants including benzene, polynuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and heavy metals (e.g., arsenic, cadmium, chromium, copper, lead, mercury, and zinc) contained in urban stormwater runoff are in particulate form or sorbed onto particles. Fatoki and Mathabatha (2001) investigated the distribution of heavy metals (zinc, cadmium, copper, iron, manganese and lead) in seawater and in sediment samples from the East London and Port Elizabeth harbors. The results indicate the contribution of heavy metal pollution from storm drains. Ship repair activities were also suspected to a source of elevated concentrations in the upper reaches of the harbor. Kayhanian
et al. (2001b) analyzed the impact of ‘non-detects’ or ‘NDs’ on stormwater data because dissolved fractions of stormwater constituents often are not detected above laboratory reporting limits. Analysts and stormwater modelers have represented these NDs in stormwater data sets using a variety of methods. In the paper, different methods of data analysis were used to determine constituent mass concentrations from water quality datasets that include ND values. Depending on the number of NDs and the method of data analysis, differences ranging from 1 to 70 percent were in mean values, which would have significant impacts on estimations of constituent mass loading.

For California’s implementation of industrial stormwater discharge control, Shaver and Duke (2000) characterized Los Angeles industrial facilities as to the types of operations and exposures to rainfall that occur on a site. The results of the survey showed that the majority of sites were impervious, conducted more than one regulated activity, and had a wide range of housekeeping practices and intensities of activity that were exposed to rainfall. The authors questioned whether the general permit should be applied equally to all industrials sites or whether resource allocation should be based on sites where pollutant load reduction potential would be greatest.

The known thermal pollution of Oregon’s streams and rivers was reviewed by Bullock and Eimstad (2000), and included a review of sensitive habitats for salmonid species. They presented information on the Oregon Department of Environmental Quality temperature standards for receiving waters, as well as guidance for developing a Temperature Management Plan.

Ball (2000b) reported on the quantities of pollutants that entered the stormwater treatment facility at Centennial Park in Sydney, Australia, and showed that the gross pollutant trap when combined with a wetland or detention pond removed 87% of suspended solids and 50% of the entering phosphorus. Lieb and Carline (2000) investigated the effects of detention pond effluent on a headwater in central Pennsylvania and showed that the macroinvertebrate community immediately downstream of the pond was highly degraded, although recovery was seen farther downstream. Stormwater sediments in Ottawa, Ontario, Canada, were analyzed for their ecoxic risk by vanLoon et al. (2000). The results indicated that the sediments present significant potential risks to the ecosystems that develop around passive stormwater treatment sites. Jones (2000a) reported on the results of using the US EPA’s Rapid Bioassessment Protocol (RBP) in streams affected by stormwater runoff in Fulton County, Georgia. The results of their assessments from 30 stations showed that changes in habitat had a greater effect on the biological communities than did water quality and that control of total suspended solids entering the stream was necessary for habitat protection.

Smullen et al. (1999) compiled stormwater quality data collected from several large sampling programs that have been conducted over the past 20 years. They concluded that it was possible to differentiate stormwater quality based on land use, region of the country, and season. Duke et al. (1999) examined water quality data for separate storm sewer systems during storm event discharges and during dry weather conditions in the San Francisco Bay Area, California. Long-term mean concentrations for many parameters in most streams were higher during storm discharges than during dry-weather flows.

A three-year study on the distributions of concentrations of 14 contaminants in five sources of urban-stormwater-runoff was performed. The log-normal-probability distribution was more accurate in the calculation of pollutant loads than normal-probability distributions (Van Buren et al., 1997).

The runoff on a 95 ha urban catchment in Aalborg, Den. was found to show significant first-flush effects and a strong correlation in concentration between COD and SS and biochemical oxygen demand (BOD) and SS. The study further discussed the most appropriate way to characterize the quality of the outflow comparing average concentration and accumulated event mass methods (Larsen et al., 1997a).

Numerous papers at the 7th International Conference on Urban Storm Drainage held in Hannover, Germany (Sieker and Verworn 1996), presented broad-based stormwater data from throughout the world, including data from Denmark and the Netherlands (Grum et al., 1996), from Poland (Bartkowska and Królikowski, 1996), and from Japan (Uchimura et al., 1996).

Bannerman et al. (1996) conducted a study for the USGS in conjunction with the Wisconsin Department of Natural Resources in which water-quality data from four urban stormwater-monitoring projects conducted between 1989 and 1994 were compiled. Concentrations of many of the constituents including Pb; Zn; Cu; Ag (silver); Cd; nine PAHs (polycyclic aromatic hydrocarbons); bis(2-ethylhexyl) phthalate; DDT; atrazine; alachlor, 2,4-D; SS; chlorides; total
phosphorus (P); BOD₅; and bacteria were high enough to say that stormwater runoff may be contributing to the degradation of the streams.

**Rainfall Monitoring and Urban Hydrology**

Current forecasting systems from meteorological offices have not been well suited for accurate rainfall forecast in urban areas (Aspergren et al., 2001). This project provided a short-term small-scale prediction of rain based on radar images. The extrapolation part of the methodology, based on a sophisticated cross correlation of images, was optimized by a neural network technique. Three different application sites in Europe have been used to validate the system. Burian et al. (2001a) reported on one technique for disaggregating long-term hourly rainfall records into subhourly increments that involved the use of artificial neural networks (ANNs). The research evaluated the influence on performance of several ANN model characteristics and training issues including data standardization, geographic location of training data, quantity of training data, number of training iterations, and the number of hidden neurons in the ANN. Results suggested that data from rainfall-gauging stations within several hundred kilometers of the station to be disaggregated would be adequate for training the ANN rainfall disaggregation model.

Schreider et al. (2000) predicted the impact that global warming due to increased carbon dioxide concentrations would have on flood frequencies in the urban areas near Sydney and Canberra, Australia. Their results showed that storms that currently cause the 1 in 100-year flood become the 1 in 44-year event for one basin, and the 1 in 10-year event for another local basin.

Pitt (1999) reports that different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Most of the urban hydrology methods currently used have been successful for large “design” storms, but were inappropriate for use when evaluating many water quality problems.

**Urban hydrology**

Doll et al. (2002) investigated hydraulic geometry relationships relating bankfull stream channel dimensions to watershed drainage area for the Piedmont of North Carolina. The focus of this study was on the development of an urban curve that showed the bankfull features of streams in urban and suburban watersheds throughout the North Carolina Piedmont. Comparisons were made with regional curves developed previously for the rural Piedmont, and enlargement ratios were produced. These enlargement ratios indicated a substantial increase in the hydraulic geometry for the urban streams in comparison to the rural streams. A comparison of flood frequency indicates a slight decrease in the bankfull discharge return interval for the gaged urban streams as compared to the gaged rural streams.

The impact of long-term land use change on the hydrological regime of the Dyle catchment (Belgium) was reviewed by El Idrissi et al. (2002). The consequences of the land use dynamics on the hydrological cycle were studied by means of a distributed hydrological model, which was coupled to a geographical information system of the land use dynamics. The researchers concluded that the change in the hydrological behavior of the Dyle catchment in terms of the historical land use change was attenuated by the presence of compensating effects within the changing land use patterns. However, if the Sector Development Plan is executed, urbanization will increase by up to 21% of the total area, considerably increasing thereby the flooding risk, even if rainfall events with a small return period occur.

Herricks (2002) presented the observed stream responses to changes in runoff quality. Toxicity was associated with the frequency of exposure to a given concentration or duration of exposure couple. Bioassessments indicated that the urbanization affects the integrity of receiving streams. Pilling and Jones (2002) reviewed the impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye catchment in mid-Wales. Results indicated increased seasonality of flows, with markedly drier summers. Analysis of extreme events suggested significant increases in the frequency of both high-and low-flow events.

Sheeder et al. (2002) investigated the hydrograph responses to dual rural and urban land uses in three small watersheds. Two important conclusions were deduced from this investigation. First, in all cases, the researchers found two distinct peaks in stream discharge, each representing different contributing areas to direct discharge with greatly differing curve numbers and lags representative of urban and rural source regions. Second, the direct discharge represented only a small fraction of the total drainage area with the urban peak becoming increasingly important with respect to the rural peak with the amount of urbanization and as the magnitude of the rain event decreases.

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The L-THIA (Long-Term Hydrologic Impact Assessment) model can be used to assess how land-use changes affect annual average runoff (Bhaduri et al., 2001). Looking at runoff calculations, SWMM was compared with L-THIA. Applications of L-THIA and SWMM to two small watersheds in Chicago showed that L-THIA predicts annual average runoff between 1.1 and 23.7% higher than SWMM, and was easier and quicker to use than SWMM. Results suggested that L-THIA could be an appropriate tool for initially assessing the relative impacts of land-use change scenarios. The runoff coefficient (ratio of total streamflow volume to the total precipitation over a certain area and time) has been shown to play a fundamental role in the planning, design and operation of water resources in a catchment (Kadioglu and Sen, 2001). In this paper, monthly runoff coefficient changes within an annual period were represented through a simple polygon diagram concept obtained from monthly precipitation and runoff data. The application of the polygon method was presented for catchments around Istanbul, Turkey. Kojiri et al. (2001) reviewed the flood management system used for urban rivers in Japan. The system is composed of three subsystems: an on-line data collection subsystem for collecting rainfall and water level data; a flood prediction subsystem based on the previous 3-hour hydrologic data; and a results display subsystem. This system has been used for practical flood prediction. Semadeni-Davies et al. (2001) investigated the radiation balance of urbanized catchments as it relates to snowmelt. Snowpacks experience either enhanced or decreased irradiance depending on snowpack location and condition, and changes to localized irradiance (and melt rates) have implications for urban runoff generation. Net allwave radiation measurements over snow made in Lulea, Sweden during April 1997 and 1998 were presented. The results showed that urban structures significantly alter radiation over snow, and therefore, including snowmelt energetics within design and management techniques is needed.

A model (based on dynamic wave equations) for characterizing overland flow on paved surfaces was evaluated by James et al. (2000) and tested successfully using a laboratory-scale rig. Using chloride tracers, Kirchner et al. (2000) showed that many catchments do not have characteristic flushing times. Travel times in the catchments and streams followed an approximate power-law distribution, where contaminants initially were flushed rapidly, but then low-level contamination was delivered to the streams for a long time after the initial flush.

James and Johnson (1999) examined simplified, nondeterministic theories regarding the link between rainfall at the ground surface and the resulting runoff. They showed that linear unit hydrograph theory overlooks the inherent non-linearity in the time dimension of the process. A modified approach, the initial storage theory (IST), was therefore proposed and tested in the laboratory. They concluded that the IST was an improvement over the basic unit hydrograph method.

Becker et al. (1999) described the results of detailed field studies investigating lateral flow along different pathways, especially along hillslopes at small catchment scales. Grimmond and Oke (1999) directly measured detailed evapotranspiration mechanisms for urban areas and found that evapotranspiration varied for different land uses and land covers. Hakonson (1999) studied the effects of the burrowing of pocket gophers and vegetative covers on water runoff amounts and erosion losses and resulted in large decreases in runoff and erosion, while vegetation alone slightly decreased runoff but also greatly decreased erosion. Nagasaka and Nakamura (1999) examined the influences of landuse changes on the hydrologic response and the riparian environment in a northern Japanese area. Temporal changes in a hydrological system and riparian ecosystem were examined with reference to landuse conversion in order to clarify the linkages between the two. The results indicated that the hydrological system has been altered since the 1970s, with increasing flood peaks of 1.5-2.5 times and shortening the time of peak flow appearances by 7 hours. The ecological systems were closely related to and distinctly altered by the changes that have occurred in the local landuse.

During studies in Scotland, Soulsby et al. (1999) found that $^{18}O$ was a useful tracer to indicate the relative influence of spring snowmelt and summer rainfall on stream waters along with their mean residence times. Preliminary estimates of the various waters’ residence times in the catchments were < 0.5 year for near-surface soil water and storm runoff, 2.5 years for shallow groundwater, and >5 years for deeper groundwaters. The effects of frozen soil on snowmelt runoff in Vermont were studied by Stanley and Chalmers (1999). The depth of the soil frost varied greatly during the 15 years of observation, with annual maximum frost depths varying from 70 to 390 mm. The enhancement of runoff due to soil frost was most evident on small plots and during extreme events, such as when rain occurred on frozen, snow-free ground.

In the On-Cheon Stream watershed in Pusan, Korea, the peak discharge of runoff increased and the mean lag time of the study area decreased due to urbanization over the past two decades (Kang et al., 1998). It was not possible to determine a priori what mechanism dominated storm runoff in suburban and forested basins (Burges et al., 1998). While 12—30% of annual precipitation became runoff in the forest basin, 44—48% became runoff in the suburban basin, emphasizing the
need to consider surface flow from all sources in the catchment when evaluating mitigation measures. An evaluation of precipitation records revealed that the majority of storms at most locations are relatively small and produce less precipitation and runoff than is often used in the design of traditional drainage networks (Urbonas, 1998). These storms need to be targeted when attempting to mitigate the effects of urbanization on the receiving waters.

Rainfall errors and flow forecasting
Kawaguchi et al. (1999) presented a case study of short-term rainfall characteristics that showed considerable changes in rainfall intensity during the past 40 years, where the 20-minute rainfall intensity having a 10-year return period increased by 20 mm/hr. This increase in the design storm characteristics has a profound effect on the performance of urban drainage systems. Fo and Crawford (1999) examined rainfall data having a 2 km x 2 km grid resolution over time intervals of 15, 30, 60, and 120 min. to quantify runoff prediction errors in Oklahoma. They found that the test watershed had an average underestimated rainfall error of about 28% which resulted in significant prediction errors when modeling stream flows in the Dry Creek watershed in north-central Oklahoma. Fo et al. (1999) further described new forecast systems using high-resolution rainfall data-sets from the WSR-88D radar system, the Oklahoma Mesonet, and the Oklahoma Local Analysis and Prediction System (OLAPS). They found that because of the lag time between the peak in precipitation and the peak in stream-flow in Dry Creek, the greatest impact upon the accuracy of hydrologic forecasts resulted from improvements in analyzing the precipitation data.

Krejcik et al. (1999) described rainfall data monitoring needs for urban drainage design in the Czech Republic. They verified the need for a high-density network of rain gauges for sewer system design and evaluations, especially when using single-event simulations. The need for high-resolution data was not as great when conducting long-term simulations and when preparing statistical evaluations of the modeling results. Willems et al. (1999) examined intensity/duration/frequency (IDF) relationships for different types of storms and seasons in Belgium. For every re-occurrence time period between 10 min. and 15 days, they identified two separate distributions, one associated with convective thunderstorms and the other with cyclonic/frontal storms.

Nguyen and Nguyen (1999) presented a scaling approach for estimating the distribution of short duration rainfall extremes (e.g., less than 1 hour) from rainfall data having longer durations (e.g., 1 day), using recently developed “scaling” theory. The scaling concept implies that statistical properties of the extreme rainfall processes for different temporal scales were related to each other by a scale-changing operator involving only the scale ratio. Rainfall monitoring with radar. In spite of the highly positive outlook of the obvious benefits, Einfalt and Maul-Kotter (1999) were concerned about the lack of a standard for the use of radar-based precipitation measurements in conjunction with hydrologic models. They described current efforts by the State Environmental Agency in North Rhine-Westphalia, Germany, to investigate the possibilities of developing a standard for radar data use from the German Weather Service for standard hydrological watershed modeling.

Faure et al. (1999) described some limitations for using radar rainfall data to aid sewage system management. They concluded that weather radar seems an important tool in evaluating the spatial structure of rain and in anticipating very short-term changes in precipitation over an urban area. However, the rainfall variability in space and time restricts the accurate forecasting period. In order to quantify the ability of radar data for forecasting, they examined the forecasting range limits for typical urban catchment areas (1 to 180 km²) in Nancy, France. They found that the limits varied greatly according to the rain conditions, leading them to propose a sewage system management strategy based on predefined management scenarios and real time identification of the type of the rain event. Koishikawa et al. (1999) also examined the application of rainfall radar information for use with operational support systems used for urban drainage facilities. They found that in order to be effective, the radar rainfall data must be collected accurately and with high resolution in both time and space. They demonstrated increases in the accuracies of runoff simulation modeling when adequate radar rainfall data were used. Vivekanandan et al. (1999) studied the influence of terrain on rainfall estimates from radar for a severe storm near Denver, Colorado. Estimates of rain intensities in areas having low or high beam-blockage were compared. They found that specific propagation phase-based quantitative precipitation estimates tend to be less influenced by terrain than reflectivity-based precipitation estimates, as they had hypothesized.

One of the most unappreciated tasks associated with stormwater characterization is an understanding of urban-rainfall patterns and rainfall-monitoring requirements. The Danish Meteorological Institute (Mikkelsen et al., 1996a and 1996b) has established a nationwide- raingauge network for monitoring short- and intense-rain events. This was of special interest in designing stormwater-drainage systems. It was found that a large geographical variation in rainfall cannot be described by typical topographic or other standard factors. Therefore the way that rainfall data are being used by engineers for...
design and analysis is being revised. Arnbjerg-Nielsen and Harremoës (1996) coupled a stochastic time-series model with a model for the geographical variation of extreme point rainfall in order to make inference about extreme rainfalls at ungauged locations. The use of the U.S. NEXRAD-radar system for estimating point rainfalls was discussed by Seliga and Chen (1996). This information should be very useful, especially within an urban environment.

Desa and Niemczynowicz (1996) studied short-term- and long-term-rainfall patterns in Malaysia. These were the first rainfall data having very small-time and -space resolution in the humid tropics region.

The City of Philadelphia’s modernized raingauge network provides the Water Department with a method of preplanning for events based on intensity and duration and the ability to determine publicly owned treatment works (POTW) effects on multiple events (Day and Nicolo, 1996). It provides information, which can be used for calibrating models, to aid in improving general effluent quality and plant operations.

Legg et al. (1996) investigated the rainfall-runoff relationship for 20 residential lawns in Madison, WI using a rainfall simulator, in order to identify the significant factors affecting infiltration in disturbed urban soils. All lawns were characterized as having silt-loam soils. The runoff coefficients for lawns younger than three years were significantly greater than for older lawns. Changes in rain intensity had little effect on runoff volumes, with total rainfall depth having the most significant effect. The effect of antecedent-soil moisture on infiltration was questioned, requiring more study.

Urban Snowmelt
Glenn and Sansalone (2002) reviewed the accretion and partitioning of heavy metals associated with snow exposed to urban traffic and winter highway maintenance activities. Results from partitioning analysis indicate that Pb, Cu, Cd, Zn, Al, Mg, and Fe were all highly particulate bound, while Na and Ca were mainly dissolved for all highway sites. Partition coefficients for most heavy metals in snowmelt ranged from $10^3$ to $10^6$ L/kg.

Taylor et al. (2002) investigated how the isotopic fractionation of snowmelt affects hydrograph separation using the isotopic composition of meltwater samples from four seasonal snowpacks. Despite the very different climate conditions the $d^{18}O$ of meltwater from all four snowpacks increased as melting progressed. The error in the new water fraction depended on: (1) the isotopic difference between the snow core and the old water; (2) the isotopic difference between the snow core and the meltwater; and (3) the new water fraction contributing to the stream flow, during a spring melt event. The error was large when snowmelt contributes a dominant fraction of the stream flow.

Thorolfsson and Brandt (1996) studied urban storm runoff during summer and winter in Norway from 1988 through 1994. It was found that snowmelt runoff is much greater in volume than typically considered in drainage designs, resulting in much more winter flooding and CSOs than during the summer. An urban storm-runoff model that considers snowmelt and rainfall was produced but it was concluded that there is still a notable lack of experience about urban storm runoff during the winter season.

Saxton et al. (1996) reported the results of a study conducted to quantify the pollutant characteristics of snow versus snowmelt runoff at Eielson Air Force Base, AK. The sampling results showed that snow is, in general, more contaminated than snowmelt runoff and that snowmelt runoff appears to be representative of what reaches surface water.

Sansalone (1996) investigated the forms of heavy metals in stormwater and snowmelt. It was found that zinc (Zn), cadmium (Cd), and copper (Cu) were mainly dissolved in stormwater, while only Cd was mainly dissolved in snowmelt. Lead (Pb) was associated with the finer particulate fractions in both stormwater and snowmelt. The dissolved fraction of the metals should be immobilized by sorption, while the particulate bound metals should be immobilized by filtration in a partial exfiltration trench.

Stormwater Quality
Kayhanian et al. (2002) addressed the impacts of non-detects (NDs) on estimation of constituent mass loading in water quality data. In this paper, different methods of data analysis were introduced to determine constituent mean concentrations from water quality datasets that include ND values. Depending on the number of NDs and the method of data analysis, differences ranging from 1 to 70 percent were observed in mean values.

McCorquodale et al. (2002) performed a study looking at the composition of urban rainwater in New Orleans. The samples were analyzed for water quality parameters: pH, total Kjeldahl nitrogen (TKN), nitrate (NO$_3^-$), ammonia (NH$_3^+$)
and total phosphorus (TP). Average concentrations show clear seasonal variations with higher levels in spring and summer and lower levels in winter and fall for NO$_3$-N and TP. The findings suggest that for some species of nutrients such as NH$_4^+$, NO$_3$- and PO$_4^{3-}$, anthropogenic emissions are major sources. A strong inverse relationship generally was found between the observed nutrient concentration and the quantity of rainfall in a particular event; however, the total loading due to rainfall increased with increased amounts of rainfall but at a diminishing rate.

The research by McPherson et al. (2002) compared the pollutant loads in wet and dry weather in the highly urbanized Ballona Creek watershed. Models were used to compare the loading of the following pollutants: total suspended solids, biochemical oxygen demand, total nitrogen, total inorganic nitrogen, total Kjeldahl nitrogen, total phosphorus, copper, lead, arsenic, nickel, cadmium, and chromium. The results indicated that dry-weather flow contributed approximately 10-30% of the total annual flow discharged from Ballona Creek. The relative contribution to the annual pollutant load varied considerably between each pollutant. In general, the dry-weather-flow load was found to be significant, especially in years with lower precipitation totals.

Rose (2002) compared the major ion geochemistry of Piedmont streams in the Atlanta, Georgia region in order to investigate the effects of urbanization. The regression correlation coefficients for the ions that would evolve through mineral weathering (Ca, Mg, Na, and HCO$_3$) were much higher in urban stream flow than in the less urbanized waters. This potentially indicated that stormwaters in the urban basin were more closely derived from a two-end member mixture (groundwater and street runoff) than waters from the less developed area, which represented a more complex mixture.

McPherson et al. (2001) compared the relative contributions of dry weather flow (DWF) and wet weather flow (WWF) from the highly urbanized Ballona Creek watershed (BCW) in Southern California using empirical and deterministic models. DWF contributed approximately 10 – 30% of the total annual flow discharged from Ballona Creek, a significant contribution. Yamada et al. (2001c) compared the pollutant load from runoff that were collected from storm sewer pipes in 7 cities. The contribution of land use, soil, amount of rainfall, rainfall intensity and antecedent dry period was quantified. Choe et al. (2001) analyzed surface runoff from selected residential and industrial zones. The event mean concentrations of COD, SS, TKN, and TP in the residential zone were 313 mg/L, 279 mg/L, 8.45 mg/L, 1.98 mg/L, and those in the industrial zone were 80 mg/L, 106 mg/L, 5.07 mg/L, and 1.93 mg/L, respectively. The degree of first-flushing effect was in the following order: TKN > COD > SS > TP > PO$_4$-P. The pollutant loads of the above constituents was highly correlated with SS. The report titled "The removal of urban litter from stormwater conduits and streams" (by Armitage et al.,) noted that little data was available on the nature and quantity of litter in stormwater drainage systems (Marais et al., 2001). The Council for Scientific and Industrial Research estimated in 1991 that 780 000 tonnes of waste a year entered the drainage systems of South Africa.

Smith (2001) presented a case study of stormwater and sediment analysis in flood control sumps in an urban watershed. The results suggested that: (1) first-flush samples may not reflect outfall concentrations of stormwater to the sump; (2) time-variable concentrations of pollutants in a sump can be related to the hydraulic characteristics of the basin; and, (3) post-event sediment analysis verified pollutant capture in the sumps. HEC-1 software was used to estimate the flow hydrograph for each outfall to a sump as part of the overall flow balance (Smith et al., 2001c). The results suggested that HEC-1 calculation provide a satisfactory estimate of the total runoff and its time-distribution to the sump. The hydraulic model was then used to estimate nonpoint loads of selected heavy metals to the sump and to the river.

EMCs were analyzed by Behera et al. (2000) for areas of Toronto, Canada, that had both separate and combined sewer systems, and noted that the data followed the gamma and exponential probability distributions, in addition to the log-normal probability distribution. Lee and Bang (2000) investigated the relationship between pollutant loadings and runoff flows, especially the first flush in the urban areas of Taehon and Chongju, Korea. They found that the pollutant concentration peak occurred earlier than the flow rate peak in areas smaller than 100 ha where impervious area was more than 80%. However, in areas more than 100 ha with impervious area of less than 50%, the pollutant concentration peak followed the flow rate peak, with this second order occurring more frequently in watersheds with combined sewer systems. Mattson et al. (2000) investigated the event mean concentrations of a range of pollutants in urban stormwater runoff that entered the Severn Sound. In samples from the beach areas, they found E. coli concentrations exceeding 600 organisms/100 mL when rain events were greater than 20 mm. The model of the stormwater entering the Sound estimated a phosphorus loading of 1083 kg/yr.

The impact of experimental watershed acidification on xylem cation chemistry was evaluated in eight species at two sites in West Virginia (Clover Run and Fernow) and one site in Maine, BBWM. Experimental watershed acidification or N
saturation using applications of \((\text{NH}_4)_2\text{SO}_4\) equivalent to twice the normal annual wet plus dry N and S deposition caused base cation mobilization followed by depletion that was detectable in sapwood xylem after about 8 yr. of treatment (Dewalle et al., 1999).

A study of stormwater-runoff quality from two adjacent urban watersheds in Singapore used continuous recording of rainfall and stream flow within the basins and systematic sampling of stormwater runoff during rainfall events. Correlations of EMC and SS and chemical oxygen demand (COD) loads to both antecedent-dry-weather period and rainfall characteristics were conducted (Chui, 1997). Muller et al. (1997) conducted a five-year study of the seasonal input variation and the distribution and residence time of herbicides in three Swiss lakes. The compounds investigated showed a conservative behavior in the water column of the lakes with triazine herbicides and the metabolites occurring in the epilimnion during or right after the application period and the annual input of atrazine depending on the rainfall during the application period. A three-year study (Vanburen et al., 1997) of parking-lot discharges into an on-stream pond concluded that log-normal was the better distribution for parking-lot runoff and creek baseflow while less suitable for creek event flow and pond baseflow. A normal distribution applied for soluble constituents (total dissolved solids [TDS], chlorides, sulphate, COD) and/or event outflow from the pond. Munn and Gruber (1997) studied the relationship between land use and organochlorine compounds in streambed sediment and fish in the Central Columbia Plateau in eastern Washington and Idaho and reported that most organochlorine compounds were still present in the environment.

A sampling program in North Carolina collected the first flush at 20 different sites covering ten different industrial groups (Line et al., 1997). Zn and Cu were the most common metals found while other contaminants included volatile and semivolatile organics, pesticides, and conventional pollutants, especially, nutrients and solids, which had high concentrations when a significant amount of biological waste or exposed soil was present. Muscara et al. (1997) reported typical pollutants, i.e., Fe, Zn, nickel (Ni), nitrate as nitrogen (\(\text{NO}_3^–\)-N), and nitrite as nitrogen (\(\text{NO}_2^–\)-N), leaving a highway construction site near Houston, Tex.

Thomson et al. (1997a) examined the relationships between surrogate parameters (i.e., SS, TDS, total volatile solids, and TOC) and other constituents of interest (e.g., metals, ionic species, and nutrients) by using the Minnesota highway stormwater quality database for regression analysis. The findings indicated that the metal and nutrient constituent relationships were limited to urban sites with similar environmental conditions. Further, statistical model analysis of monitoring results (Thomson et al., 1997b) concluded that approximately 15 — 20 samples are required to provide reasonable estimates of the mean concentrations of runoff events for SS, TDS, TOC, and Zn.

**Litter**

Armitage and Rooseboom (2000a) demonstrated that large quantities of litter are being transported in South Africa in urban stormwater runoff, and that the amount of litter produced was related to land use, vegetation, level of street cleaning and type of rainfall. The benefits of litter reduction were documented using their work in Australia and New Zealand, and design equations for sizing litter traps were proposed (Armitage and Rooseboom 2000b). Newman et al. (2000a) characterized the flotables found in urban stormwater runoff. The results of this study were used to develop transport models of the movement of and controls for these flotables.

The principal source of litter on the Bristol Channel of the United Kingdom was postulated as riverine derived from sanitary-wastewater debris originating from CSO (Williams and Simmons, 1997a). River bank clearances provided valuable information on litter accumulation and movement showing a distinctive correlation between flood events and litter movement. Some litter types have an increased input during flood events, e.g., sanitary-wastewater-derived material from combined sewer outfalls, whereas accumulation of other litter types could be due to their distribution throughout the catchment (Williams and Simmons, 1997b).

**Nutrients**

Groffman et al. (2002) studied the soil nitrogen cycle processes in urban riparian zones, through measurements of stream incision, water table depths, and pools, production (mineralization, nitrification), and consumption (denitrification) of \(\text{NO}_3^–\) in urban soils. The results suggested that urban hydrologic factors could increase the production and reduce the consumption of \(\text{NO}_3^–\) in riparian zones, reducing their ability to function as sinks for \(\text{NO}_3^–\) in the landscape.

Hranova et al. (2002) studied the qualitative, quantitative and environmental aspects of water resources management in the Chivero Basin, Zimbabwe, which is in the advanced stages of eutrophication. Background pollution in the basin varied from 0.1 to 0.3 mg/L and from 0.1 to 0.4 mg/L for nitrates and phosphates (as total P), respectively. At Marimba
River confluence the annual median values recorded were 3.5 and 4.4 mg/L for ammonia and phosphates, respectively, thus exceeding the effluent discharge regulations 7-9 times. The major nutrient sources contributing to this status are associated with operational problems of the treatment facilities and diffuse sources of pollution from pastures irrigated with effluent, as well as from urban storm water.

Owens and Walling (2002) tested the phosphorus content of fluvial sediment in rural and industrialized basins in Yorkshire, UK. The total phosphorus (TP) content of fluvial sediment in the rural basin was generally within the range 500-1500 µg g⁻¹, with little evidence of any major downstream increase in TP content. In contrast, fluvial sediment from the industrialized catchments exhibited both higher levels of TP content and marked downstream increases, with values of TP content ranging from less than or equal 2000 µg g⁻¹ in headwater areas upstream of the main urban and industrial areas, to values > 7000 µg g⁻¹ at downstream sites, due mostly to P inputs from point sources, such as sewage treatment works (STWs) and combined sewer overflows. Based on the sediment samples collected from the study basins, a simple four-fold classification which relates the TP content of suspended sediment to upstream land use has been established. Both the range and the absolute values of TP content tend to increase with an increase in the level of urbanization and industrialization.

Ball and Abustan (2000) investigated the phosphorus export from an urban catchment in Sydney, New South Wales, Australia, and derived a relationship between inorganic suspended solids and particulate phosphorus for this catchment. These results were to be used to predict the performance of detention ponds and/or wetlands for treating this runoff.

Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.

Fluxes of total phosphorus (P), total phosphate, and total organic P from seven small watersheds on the Atlantic Coastal Plain of Maryland for up to 25 years were reported by Correll et al. (1999), indicating cropland watershed’s P flux were much higher than forested watershed and increased significantly with precipitation. The Bear Brook Watershed in Maine (BBWM) was the sight of a paired watershed study in which the West Bear (WB) catchment was being artificially acidified with 1,800 eq ha⁻¹ y⁻¹ of (NH₄)₂SO₄ resulting in changes in the soil and stream chemistry, while the East Bear (EB) serves as the control (Norton et al., 1999). P chemistry in streams was evaluated at the pair watershed study at the BBWM, indicating the export of Al and P was greater from the treated watershed because the induced acidification was translocating more Al from soils to the streams and the export of P was related to acid-soluble Al particulate material (Roy et al., 1999). One hundred and sixty-two rainfall-induced soil erosion tests were conducted to assist in predicting soil loss and subsequent increase in total suspended solids, indicating soil loss was dependent upon rainfall intensity, and the soil’s shear and compressive strength (Liu et al., 1999). After six years of monitoring flow and water quality Jaynes et al. (1999) conclude nitrate appears to be the primary agriculturally related pollutant of concern in Walnut Creek, California thus management practices designed to reduce NO₃ leaching from fields and increase removal within the watershed/stream system should receive primary consideration.

**Microorganisms**

Dwight et al. (2002) investigated the associations between storm events, urban runoff and coastal water quality using a spatial and temporal analysis of 2 years of data in Orange County, California. Bacterial levels rose substantially across all sites during wet months, and river discharge and bacterial levels were all highest during the winter with the most rainfall. Precipitation was significantly associated (Spearman rank bivariate correlation, P less than or equal 0.01) with water discharged from the rivers. River discharge was significantly associated with bacterial levels at 20 out of 22 beaches, with the strongest associations at sites next to rivers. The results indicated that urban river discharge is a primary source of Southern California’s coastal water pollution and, as a result, swimming at beaches near rivers may pose a significant public health risk. Paul et al. (2002) reviewed the Bacterial TMDL for impaired water bodies in Texas. The primary aim of the study was to explore the possibility of clustering the waterbodies into groups having similar watershed characteristics. Studying the watersheds as a group would reduce the number of required TMDLs and thereby will help in reducing effort required for restoring the health of the impaired waterbodies in Texas. The main characteristics being considered for the classification of waterbodies were designated use of the waterbody, sources of pathogens, frequency of water quality violation, location and type of the waterbody, and the size of the watershed.

Jeng et al. (2002) investigated the fate of indicator organisms (fecal coliforms, E. coli, and enterococci) in stormwater runoff when the water enters brackish recreational waters. Results indicated that satisfactory water quality of Lincoln
Beach was observed during dry weather periods. Concentrations of indicator organisms in both water column and sediment, however, significantly increased during and after heavy stormwater runoff, particularly at sites near the Jahncke Canal discharge point. However, the elevated titers of indicator organisms decreased to background levels after 24 to 48 hours. Overall removal rate constants for fecal coliform, E. coli, and enterococci from the water column ranged from 0.112 to 0.124 h⁻¹, 0.106 to 0.170 h⁻¹, and 0.101 to 0.110 h⁻¹, respectively. Attachment of microbial indicators to suspended matter and subsequent sedimentation appeared to be a significant fate mechanism. Results indicated that enterococci may be a more stable indicator than E. coli or fecal coliform and consequently a more conservative indicator under marine water conditions.

Brion et al. (2002) investigated the prevalence of F-specific RNA coliphage serotypes as indicators of fecal contamination in the waters of a small, well-defined watershed. Results from laboratory studies showed that F+RNA differed in their survival in water and that Type IV strains were the least persistent. Type III F+RNA were found to be reliably related to the release of uncontrolled human fecal material in the watershed, but the results of this study suggest that further study is required before utilizing for fecal source identification in natural waters.

As part of a modeling exercise for predicting removal of beach closure restrictions after a storm event, Jin et al. (2000) characterized the movement of indicator organisms (E. coli, enterococci, and fecal coliforms) from stormwater outfalls in Lake Ponchartrain to Lincoln Beach in New Orleans. They found that, as expected, a rapid decrease in organism concentration occurred near the outfall and that two or three days after pumping, indicator organism concentrations at Lincoln Beach were below the health standards for swimming. Their data also showed that E. coli was a better indicator organism for fresh water environments, while enterococci was more suited for use in marine or brackish environments.

Francy et al. (2000) related potential sources of microorganisms (total coliforms, Escheria coli, and Clostridium perfringens) to receiving water quality. In general, fewer organisms were found in the groundwater. Land use was found to have the greatest influence on bacterial indicators in stream water, while presence of septic systems and well depth had the greatest influence on the bacteria concentration in groundwater. Skerrett and Holland (2000) found that Cryptosporidium oocyst occurrence in Dublin, Ireland, area waters increased after a heavy rainfall, likely due to increased the runoff volume into the receiving water. Their results also showed that Cryptosporidium oocysts were widely dispersed in the Dublin-area aquatic environment.

Waters adjacent to the County of Los Angeles, California receive untreated runoff from a series of storm drains year round, in which persons swim there were exposed to these untreated waters. Measures of exposure included distance from the storm drain, selected bacterial indicators (total and fecal coliforms, enterococci, and Escherichia coli), and a direct measure of enteric viruses. It was found higher risks of a broad range of symptoms, including both upper respiratory and gastrointestinal, for subjects swimming (a) closer to storm drains, (b) in water with high levels of single bacterial indicators and a low ratio of total to fecal coliforms, and (c) in water where enteric viruses were detected (Haile et al., 1999). Particulate fluxes of aliphatic and aromatic hydrocarbons were measured with a sediment trap moored at 80 m depth offshore of Monaco (200 m water column) during an 18-month period (Raoux et al., 1999). Timperley (1999) described the concepts of chemical bioavailability and its relevance to urban stormwaters and streams.

Water samples were collected from four locations within the Munnell Run Watershed in Mercer County, Pennsylvania, and analyzed for fecal coliforms by MPN and enteric phages by plaque assay using Salmonella typhimurium WG 49 and Bacteroides fragiles HSP 40 as hosts. The presence of host specific phages indicate the existence of septic discharges in the watershed, but both fecal coliforms and enteric viruses persist in stream systems, especially during the summer months (Brenner et al., 1999).

Ferguson et al. (1998) found 50% of 34 first-flush samples taken from two major watersheds tested positive for giardia cysts and cryptosporidium oocysts. This information will be used to review the current source water monitoring program conducted by the Metropolitan Water District of South Calif. and to assist in the implementation of watershed management strategies to control protozoa in source waters. A literature review (Bagley et al., 1998) revealed that the cysts of giardia lamblia and cryptosporidium species oocysts are commonly detected over a wide range of concentrations in a wide variety of aquatic systems.

In a southern California study, eight of 12 plants were positive for salmonella at the chlorination/dechlorination site and effluents from 11 of 12 plants were positive for salmonella when sampled downstream of the chlorination/dechlorination site before merging with the receiving stream (Kinde et al., 1997). Two of the three control sites, i.e., an urban-
stormwater-runoff and a raw-potable-water reservoir, were also positive for *salmonella*. Fecal coliform (FC) and fecal streptococci densities were detected at 12 sites in the Buffalo River watershed during 1992-1993 with the highest levels of indicator bacteria in the water column coinciding with rainfall events; however three sites closest to the Buffalo River violated New York State water quality standards of FC levels in 79% of all samples. SS were strongly correlated with FC (*r* = 0.86) in the upper watershed during the summer months when flow velocities were greatest and solids may play an important role in transporting bacteria into the Buffalo River (Pettibone and Irvine, 1997). Urban stormwater runoff from various large urban developments in South Africa were investigated to establish the extent of fecal pollution (Jagals, 1997). The level of sanitation ranged from pit and bucket latrines to full-waterborne-sewerage systems. Stormwater runoff from developing urban settlements, as well as developed urban structures, constituted a major source of pollution for a downstream river catchment used as a source of water for human consumption and recreation.

**Toxicity**

Parker et al. (2000) analyzed the sediment found in urban stormwater runoff in the Phoenix, Arizona, metropolitan area. They found that the inorganic content of the sediments was similar to that in soils that were not impacted by urban runoff. The metals concentrations (Cd, Cu, Pb, and Zn) were higher, but below levels that would recommend remediation. Arsenic concentrations were above recommended levels; however, this contribution likely was geologic not anthropogenic. Chlordane, DDT (and DDE and DDD), dieldrin, toxaphene, and PCBs were found in the sediments at all sampling locations. Sediment toxicity was seen, but could not be explained based on their chemical results. Vollertsen and Hvitved-Jacobsen (2000) investigated the resuspension of sewer solids in combined sewers. They found that sewer solids that were undisturbed for up to two weeks were more easily resuspended and their oxygen uptake rate was significantly greater than fresh solids, indicating that the flushing of these solids into receiving waters may cause oxygen depletion problems.

Love and Woolley (1999) found that stormwater was alarmingly more toxic than treated sewage. The Concord project, funded by EPA, examined the possibility of the needed treatment for reuse of residential area stormwater before source area. Runoff from sawmills in British Columbia was monitored for toxicity by Bailey et al. (1999) and found that 42 of the 58 samples were toxic to juvenile rainbow trout. Divalent cations, especially zinc, were the most common source of the toxicity. Tannins and lignins, associated with bulk log handling, were responsible for the remaining toxicity.

A stormwater toxicity study for Santa Monica Bay, Calif. included analysis of surface water and sediment samples following four significantly-sized storms. Toxicity was present in water samples offshore and was proportional to the concentration of runoff in the plume and changes in sediment characteristics, such as grain size and total organic carbon (TOC), were also evident (Bay et al., 1998).

**Heavy metals**

Glenn et al. (2002) investigated the influence of chemistry, hydrology and suspended solids concentration on partitioning of heavy metals to particles and the applicability of this information to design of on-site controls for stormwater quality. Aqueous chemistry and residence time characteristics such as low alkalinity, low hardness and short pavement residence time (less than 30 minutes) could result in a majority of the heavy metal mass remaining in solution at the edge of the pavement with trends in partitioning only approaching equilibrium conditions towards the end of the event as heavy metals partition to entrained solids.

Fatoki et al. (2002) investigated trace metal pollution in the Umtata River. High levels of Al, Cd, Pb, Zn and Cu were observed, which may affect the "health" of the aquatic ecosystem. Generally the sources of the metals in the river appeared to be diffuse, including rural, urban and agricultural runoff sources in the catchment. Tuccillo (2002) analyzed heavy metals in stormwater at six outfalls draining nonindustrial land uses in Monmouth County, New Jersey. Of the heavy metals, only Cu and Zn were found in all samples, mostly in dissolved form. Larger colloids (=0.45 μm) were composed mostly of Fe, Al, and Si. Organic colloids were found mostly in the 0.01-0.45-μm-size range. Wardas et al. (2002) investigated the levels of heavy metals in sediments of the water and wastewater system in Cracow. Estimation of the quantity of metals in samples was done based on sediment samples from "Rudawa", "Dlubnia" and "Raba" drinking water plants and "Plaszow" and "Kujawy" sewage treatment plants.

Buffleben et al. (2002) investigated the concentrations of hazardous metal pollutants associated with the aqueous and suspended solids phases entering Santa Monica Bay from the Ballona Creek watershed during wet weather flow. Other objectives of this study were to evaluate during a storm event the relationship between (1) soluble and sorbed metals, (2) storm flow and pollutant loading, including a determination of a first flush was present, and (3) total mass loading of
pollutants and relative pollution loading from three watershed sub-basins. The results indicated the suspended solids phase primarily transported the mass for five of the six hazardous metals studied: cadmium, chromium, copper, lead, and nickel. Arsenic was found primarily in the aqueous phase.

Ramessur and Ramjeawon (2002) determined the lead, chromium and zinc concentrations in sediments from the St. Louis River in Mauritius. The mean concentration of Cr (105 ± 30 mg kg\(^{-1}\)), Zn (167 ± 30 mg kg\(^{-1}\)) and Pb (14 ± 7 mg kg\(^{-1}\)) in sediments in an urbanized and industrialized were well below the limits of 600, 2500 and 700 mg kg\(^{-1}\) in the draft standards (24% clay and 10% organic matter by weight) from the Netherlands. Industrial contamination appeared to undergo rapid dilution in the estuary as Cr had high levels near point sources from industries, but decreased rapidly in amount in the estuary possibly because of dilution by other sediments. The significant Zn levels from upstream to the estuary suggest that the potential sources could be the adjacent motorway and road runoff. Pb was two folds higher in the sediments in the estuary of St. Louis River compared to upstream and downstream indicating accumulation of Pb in estuarine sediments. The potential sources of sediment Pb were from the adjacent motorway and road runoff.

Robertson et al. (2002) characterized the geochemical and mineral magnetic qualities of urban sediment particulates from both inner and outer city road surfaces in Manchester, UK. High metal concentrations, coupled with the largely ferrimagnetic multi-domain (MD) mineral magnetic composition of the particulates, indicated anthropogenic origin, primarily particulates derived from automobiles. Iron and Pb concentrations showed a clear spatial trend, whereby concentrations were enhanced in the inner city samples. Lead concentrations for inner and outer city samples averaged 354 and 185 µg g\(^{-1}\), respectively. Iron concentrations for inner and outer city samples average 11302 and 6486 µg g\(^{-1}\), respectively. Sequential extraction analysis showed Mn, Fe, Zn and Pb were largely associated with the reducible fraction, whereas Cu was largely associated with the oxidizable fraction. Zinc was the only metal showing significant association with the exchangeable fraction (up to 33%), suggesting that it may be the most susceptible metal to mobilization during runoff.

Gabriel et al. (2002) investigated the availability of atmospherically deposited mercury to runoff and receiving waters. The review illustrated the importance of the relationship between mercury deposition and runoff efficiency for common watershed surfaces. The purpose of the review was to illustrate that the availability of atmospherically deposited mercury is a function of watershed characteristics including: terrestrial sorption properties, surface water chemistry, rainfall intensity, antecedent dry weather periods, and photochemical reactions.

The fate and transport of metallic pollutants through a watershed were related to the characteristics of the solid particles to which they are bound (Magnuson et al., 2001). Because the particles most often associated with metal pollution have nominal diameters of < 50 µm, split-flow thin-cell (SPLITT) fractionation was investigated as a means to study the metal loading as a function of particle settling rate. Sansalone et al. (2001) showed that urban storm water levels of Zn, Cu, Cd, Pb, Cr, and Ni can be significantly above ambient background levels, and for many urban and transportation land uses, often exceed surface water discharge criteria for both dissolved and particulate-bound fractions. The authors advocated a multiple-unit-operation approach to stormwater treatment.

Turer et al. (2001) investigated the accumulation of metals in roadside soils at a site for which extensive runoff data were also available. The results demonstrated that heavy metal contamination in the top 15 cm of the soil was very high compared to local background levels. The maximum measured amount for Pb was 1980 ppm (at 10-15 cm depth) and for Zn was 1430 ppm (at 0-1 cm depth). The correlation to organic C is stronger than the correlation to depth. Cluster analysis of the heavy metal data showed that Pb, Zn and Cu were closely associated to one another, but that Ni and Cr did not show an association with each other or with either organic C or depth. Mass balance calculations for Pb in soil showed that most of the Pb came from exhausts of vehicles when leaded gasoline was in use, with about 40% of the Pb retained in the soil. Zinc and other trace metal (V, Cr, Co, Ni, Cu, Cd, and Pb) concentrations were measured in the Atlanta metropolitan region and in relatively undeveloped watersheds within the Georgia Piedmont and Blue Ridge Provinces (Rose et al., 2001). Zinc concentrations in street runoff [median (Zn) = 905 µg/L] were significantly greater than zinc concentrations in Peachtree Creek storm runoff [median (Zn) = 60 µg/L], which were, in turn, greater than zinc concentrations contaminants within non-storm baseflow in Peachtree Creek [median (Zn) = 14 µg/L]. A two end member mass balance model suggested that a large proportion of the zinc present in the street runoff was adsorbed and transported by the suspended sediment.

Mosley and Peake (2001) characterized urban runoff from a catchment in Dunedin, New Zealand during base flows and storm flows from five rainfall events. Fe and Pb were found to be predominantly particle-associated (>0.4 µm) with
concentrations increasing significantly at the beginning of storm run-off. In contrast, the majority of Cu and Zn was found in the <0.4 µm fraction prior to rain but a significant proportion was present in the > 0.4 µm fraction during the initial period of storm flows. The results indicate that Cu and Zn may be more bioavailable, and more difficult to remove by stormwater treatment, than Pb. The pH level and the concentration of major ions (Ca$^{2+}$, Na$^+$, Mg$^{2+}$, K$^+$), dissolved PO$_4$-P, and NO$_3$ generally decreased during storm flows due to rainwater dilution. Concentrations of total N and P often increased during the initial period of storm run-off, likely because of wash-off of particulate plant material. Significant amounts of non-point source runoff were shown to enter the Santa Monica Bay from the Ballona Creek Watershed during wet weather flow. Buffleben et al. (2001) monitored four storms in the watershed. The watershed is developed mostly with residential, commercial and light industrial land uses. They found that the suspended solids phase primarily transported the mass for five of the six metals studied: cadmium, chromium, copper, lead, and nickel. Arsenic was found primarily in the aqueous phase.

Williamson and Morrisey (2000) modeled the build-up of heavy metals (Pb, Zn, and Cu) in urban estuaries due to stormwater contamination, with the model being based upon the behavior of the metals in runoff and during transport in the estuarine system.

Urban stormwater runoff was targeted by Neto et al. (2000) as a potential source for the elevated metals (Pb, Zn, Ni, Cu and Cr) concentrations found in Jurujuba Sound in Southeast Brazil. Investigation of sediment cores indicated that the increase in sediment metals concentration occurred at approximately the time that rapid urbanization began in the watershed.

Barbosa and Hvitved-Jacobsen (1999) examined heavy metals in highway runoff in Portugal. Concentrations of Cd and Cr were usually lower than the detection limit (1 µg/L), copper levels were between 1 and 54 µg/L, lead from 1 to 200 µg/L, and zinc from 50 to 1460 µg/L. A lowering of the pH value increased the desorption of previously retained Zn, Cu and Pb from the soil lining the infiltration pond used to treat this water.

Barry et al. (1999) identified salinity effects on the partitioning of heavy metals in the stormwater canals entering Port Jackson (Sydney), Australia. Cu, Pb, and Zn was found increasingly in dissolved phases as the salinity increased in the lower sections of the canals. During high flows, most of the metals seemed to be rapidly exported from the estuary as a discrete surface layer, while low flows contributed most of the metals to the estuary. Birch (1999) also studied the Port Jackson estuary sediments. Historical industrial activity was responsible for much of the contaminated sediments, but atmospheric contributions were also likely important. Stormwater from small catchments, along with sewer overflows, had no observable effects on the distribution of heavy metals in surficial sediments.

Grout et al. (1999) studied the colloidal phases in urban stormwater runoff entering Brays Bayou (Houston, Texas). Colloids in the filtrate after 0.45 µm filtering and further separation by ultracentrifuging, accounted for 79% of the Al, 85% of the Fe, 52% of the Cr, 43% of the Mn, and 29% of the Zn present in the filtrates. Changes in the colloidal composition were caused by changes in colloidal morphologies, varying from organic aggregates to diffuse gel-like structures rich in Si, Al, and Fe. Colloids were mostly composed of silica during periods of dry weather flow and at the maximum of the stormwater flow, while carbon dominated the colloidal fraction at the beginning and declining stages of the storm events. Garnaud et al. (1999) examined the geochemical speciation of particulate metals using sequential extraction procedures for different runoff sources in Paris, France. They found that most metals were bound to acid soluble particulates in the runoff but that copper was almost entirely bound to oxidizable and residual fractions.

Datta and Subramanian (1998) report that despite a very dense population in its watershed, the lower Ganges-Brahmaputra-Meghna drainage basin remains relatively-unperturbed alluvial basin with regards to heavy metal pollution, due in part to a very high rate of sediment deposition.

A study by Sansalone and Buchberger (1997) analyzed stormwater runoff at five sites on a heavily traveled roadway in Cincinnati, Ohio. They found that the the event-mean concentrations (EMC) of Zn, cadmium (Cd), and copper (Cu) exceeded surface-water-quality-discharge standards. Further, it was noted that Zn, Cd, and Cu are mainly in the dissolved form while other metals, i.e., lead (Pb), Fe, and aluminum (Al) are mainly bound to particles.

Analytical techniques were used to determine the speciation of Cu and Ni in point and non-point source (NPS) discharges and found that the existence of a strong metal-complexing ligand in wastewater effluent, and to a lesser degree, surface runoff must be accounted for when evaluating metal treatability (Sedlak et al., 1997).
**Organic toxicants**

Borden et al. (2002) evaluated the presence and concentration of MTBE and aromatic hydrocarbons in North Carolina stormwater runoff. m-, p-Xylene and toluene were detected in over half of all samples analyzed, followed by MTBE; o-xylene; 1,3,5-trimethylbenzene; ethylbenzene; and 1,2,4-trimethylbenzene. Benzene, DIPE, TAME and 1,2,3-trimethylbenzene were detected in less than or equal 10% of the samples analyzed. Median contaminant concentrations (when detected) varied from 0.07 µg/l for ethylbenzene to 0.11 µg/l for toluene. All of the locations with significantly higher contaminant concentrations were associated with direct runoff from a gas station or discharge of contaminated groundwater from a former leaking underground storage tank.

Moilleron et al. (2002) sampled runoff from different types of urban surfaces (11 roofs representing four different covering materials, two courtyards and six streets) and from drainage outlets in the ‘Le Marais’ experimental catchment in the center of Paris. The total aliphatic hydrocarbon concentration medians ranged from 345 to 827, from 297 to 790, and from 393 to 1359 µg L\(^{-1}\) in the roof, courtyard and street samples, respectively. The levels found at the catchment outlet during dry and wet weather periods were of the same order of magnitude, i.e. 700 µg L\(^{-1}\). The particulate phase represented 85% of the total aliphatic hydrocarbon content whatever the sample.

The concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans in the sediments from the River Po (Italy) were studied by Fattore et al. (2002). The sum of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) concentrations, and the toxic equivalent content, ranged from 121 to 814 and from 1.3 to 13 ng/kg dry weight sediment, respectively. These levels of contamination seemed lower than in the sediments of rivers draining highly industrialized areas. Principal component analysis suggested that widespread sources, such as urban runoff and domestic wastewaters, were probably the main cause of these levels of PCDDs and PCDFs.

Mai et al. (2002) investigated the spatial distribution of chlorinated hydrocarbons and PAHs in riverine and estuarine sediments from the Pearl River Delta, China. Concentrations of chlorinated pesticides in the riverine sediment samples ranged from 12 to 158 ng/g, dry weight, while those of PCBs range from 11 to 486 ng/g, and estuarine sediments ranged from 6-1658 ng/g for chlorinated pesticides, while concentrations of PCBs are in the range 10-339 ng/g. Total PAH concentration ranged from 1168 to 21,329 ng/g in the riverine sediment samples, whereas the PAH concentration ranged from 323 to 14,812 ng/g in the sediment samples of the Estuary. Possible factors affecting the distribution patterns were discussed based on the usage history of the chemicals, hydrologic condition, and land erosion due to urbanization processes.

Furumai et al. (2002a) performed a runoff monitoring study of a highway drainage system in Switzerland. The runoff samples with higher SS concentration had higher heavy metals and PAH concentrations. The particle-bound Zn, Cu, Pb, and PAH concentrations were 155-524 µg/L, 29-69 µg/L, 13-46 µg/L, and 1.3-3.3 µg/L. Particle size distribution analysis revealed that the runoff samples with higher SS concentrations contained coarser size fractions. The contents of heavy metals (Zn, Cu, and Pb) were about ten times higher in the runoff samples than in the three size-fractionated dusts (less than or equal 50, 50-125, 125-250 µm fractions). The PAH content was higher in the dusts than the runoff samples, although the contents were both in the same range of 10-50 µg/g. The PAH profiles in the fine size fractions (less than or equal 50, 50-125, and 125-250 µm) of the dusts looked similar except for higher percentage of B(a)An in the less than or equal 50 µm fraction.

Heberer (2002) tracked persistent pharmaceutical residues from municipal sewage to drinking water through the natural water system in Berlin (Germany). The results from several monitoring studies between 1996 and 2000, pharmaceutically-active compounds (PhACs) such as clofibric acid, diclofenac, ibuprofen, propyphenazone, primidone and carbamazepine were detected at individual concentrations up to the µg/l-level in influent and effluent samples from sewage treatment plants (STP) and in all surface water samples collected downstream from the STPs. Under recharge conditions, several compounds were also found at individual concentrations up to 7.3 µg/l in samples collected from groundwater aquifers near to contaminated water courses. Holthaus et al. (2002) investigated the potential for estradiol and ethinylestradiol to sorb to suspended solids and sediments in British rivers. The purpose of determining this potential was because the endocrine-disrupting impact of steroid estrogens on fish will be strongly influenced by their distribution between sediment and water. Using anaerobic conditions to inhibit biodegradation, it was found that 80 to 90% of binding to bed sediments was complete within 1 d, but that an equilibrium had not been reached after 2 d. The K\(_d\) values for suspended solids suggested less than 1% removal of the steroid estrogens from the aqueous phase.
Kolpin et al. (2002) performed a nationwide survey of pharmaceuticals, hormones and other organic wastewater constituents in U.S. streams in 1999 and 2000. Organic wastewater constituents (OWCs) were prevalent during this study, being found in 80% of the streams sampled. The compounds detected represent a wide range of residential, industrial, and agricultural origins and uses with 82 of the 95 OWCs being found during this study. The most frequently detected compounds were coprostanol (fecal steroid), cholesterol (plant and animal steroid), N,N-diethyltoluamide (insect repellant), caffeine (stimulant), triclosan (antimicrobial disinfectant), tri(2-chloroethyl)phosphate (fire retardant), and 4-nonylphenol (nonionic detergent metabolite). Measured concentrations for this study were generally low and rarely exceeded drinking-water guidelines, drinking-water health advisories, or aquatic-life criteria.

Sherrard et al. (2002) investigated the comparative toxicity of chlorothalonil and chlorpyrifos to Ceriodaphnia dubia and Pimephales promelas. In the experiments P. promelas was more sensitive to chlorothalonil, and C. dubia was more sensitive to chlorpyrifos. The results of this study illustrated differences in species' sensitivities to chlorothalonil and chlorpyrifos as well as differences in the duration of the exposure necessary to illustrate effects that might be elicited from pesticide exposures.

Atmospheric deposition of particulate matter, organic carbon and PAHs was measured at two stations in an urban area (Ozaki et al., 2001). The deposition fluxes of particulate matter and organic carbon were nearly constant over the sampling periods, while PAHs had seasonal variability. The first flush phenomenon was clearly observed during all the rainy periods. Although the PAHs in runoff agreed with that of atmospheric deposition, their fluxes were several times larger. Loading of dissolved organic carbon (DOC) from parking lot storm runoff was found to be a significant, yet relatively neglected, source of elevated DOC concentration in urban streams (Lee and Schwartz, 2001). This study investigated DOC transport and loading from an paved parking lot during rainstorm events in order to elucidate impacts of the stormwater runoff on the chemistry of an urban stream. DOC measurements from the parking lot showed that the interval between storms and the precipitation intensity controlled the maximum DOC concentration and the time required to reach the maximum DOC concentration, respectively.

In the central Paris district of “Le Marais,” Gonzalez et al. (2000) found PAHs primarily in the particulate phase in all catchments, with the median concentration in combined sewer overflows of 204 ng/L. Phenanthrene, anthracene, fluoranthene and pyrene were the most observed compounds. The results indicated that atmospheric deposition was an important source of PAHs in urban stormwater runoff. Ngabe et al. (2000) analyzed urban stormwater runoff in coastal South Carolina for PAH content. The authors found the highest concentrations (5590 ng/L) of PAHs in runoff from Columbia, a major metropolitan area, and lower concentrations (282 ng/L) from the small town of Murrells Inlet. The PAH profiles in the runoff from the two urban areas were similar to those found in atmospheric deposition and unlike those in used crankcase oil. However, the aliphatic fraction of the organics in Columbia’s runoff were more similar to used crankcase oil than to urban aerosols.

Shinya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Phenanthrene, fluoranthene, and pyrene comprised about 50% of the quantified PAH constituents in each sample. Smith et al. (2000a) analyzed for PAHs in stormwater runoff from four locations in an urban area: a gas station, a highway off-ramp, and a low- and a high-traffic volume parking lot. The gas station site produced the highest total PAH loading (2.24 g/yr/m²), followed by the high-traffic-volume parking lot (0.0556 g/yr/m²), the highway off-ramp (0.052 g/yr/m²), and the low-traffic-volume parking lot (0.0323 g/yr/m²). PAH concentrations were usually highest during the ‘first flush’ of storm-water runoff and tapered off rapidly as time progressed. The concentrations and characteristics of organic carbon (as DOC) in surface waters in Arizona were studied by Westerhoff and Anning (2000). Fluorescence measurements indicated that DOC in desert streams was from autochthonous sources; however, DOC in unregulated upland rivers and desert streams shifted from autochthonous to allochthonous sources during runoff events. The urban water system affected temporal variability in DOC concentration and composition.

Analysis of patterns in pesticide use revealed that concentrations of herbicides and insecticides in agricultural streams, and in most rivers in agricultural regions, were highest in those areas of the nation with the greatest agricultural use. More than 95% of the samples collected from streams and almost 50% of samples collected from wells contained at least one pesticide (Gilliom et al., 1999).

Fisher et al. (1999) found trace concentrations of dioxins and furans in urban runoff entering Santa Monica Bay,
fractions behaved similarly; however, the pollutant loadings were different with the coarse fraction needing a more
behavior of two separate fractions (fine – less than 45 um; coarse – greater than 45 um). They found that the two
Hijioka et al. (2000) investigated the behavior of suspended solids in runoff from a 67-ha urban watershed by looking at
was explained by the different washoff behavior of fine (less than or equal 20 µm) and coarser particles. Based on the PSD results, a stepwise wash-off phenomenon of TSS under varying runoff rate conditions
of particle size distribution (PSD) analysis of runoff samples indicate that high TSS concentration samples contain
loads than soluble fractions. Their content decreased with increasing total SS concentration in runoff samples. The results
recent highway runoff research. Particle-bound heavy metals (Zn, Pb, and Cu) accounted for more significant pollutant
sources of PCB in CSO and to the Buffalo River.

Seasonal changes of the herbicides (diuron and simazine) in urban runoff were examined by Revitt et al. (1999). The herbicide concentrations were higher in storm events, with maximum levels of diuron at 238 µg/L and simazine at 2.2 µg/L recorded. The very high diuron level was during a storm event, which closely followed application of the herbicide. During this event, more than 45% of the applied diuron was lost to runoff. Qian and Anderson (1999) examined five commonly used herbicides and three pesticides in small streams in the Willamette River Basin, Oregon. Of the variables examined, landuse was the most important for all but one (simazine) of the eight pesticides studied, followed by geographic location, intensity of agriculture activities in the watershed, and the size of the watershed. There were significant differences in the variabilities of the stream concentrations for the urban and agriculture sites. While all 16 nonurban watersheds had significantly higher variations than the urban sites, the same was not necessarily true for the mean concentrations.

Several stormwater-runoff samples were accurately evaluated for oil and grease with an alternative analysis method using octadecyl siloxane (18C) solid-phase-extraction columns. The amount of the solvent was reduced and more reproducible results were obtained using this alternative method (Lau and Stenstrom, 1997).

Crunkilton and Devita (1997) investigated the concentrations of freely dissolved polycyclic aromatic hydrocarbons (PAH) in an urban stream at high flow and baseflow by an equilibrium partitioning model (EPM) and by use of lipid-filled semipermeable membrane devices (SPMD). The results, compared to direct measurements made on bulk (unfiltered) water samples, indicated that concentrations of freely dissolved PAH and total PAH at high flow are about 20 times greater than at baseflow. In another study, Kucklick et al. (1997) investigated the contamination of PAH in surface sediment of Winyah Bay, Charleston Harbor and the North Edisto River estuary in South Carolina. Concentrations of total PAH (i.e., analyzed for 24 PAH, two to six rings), were extremely variable; however, this observed variability was not explained by total organic carbon (TOC) or grain size, indicating that other factors were more important. Loganathan et al. (1997) evaluated sources of polychlorinated biphenols (PCB) in CSO to the Buffalo River, N.Y. by analyzing combined and sanitary wastewater, atmospheric wet and dry deposition, and street dust samples from the Babcock Street sewer district. PCB congener composition suggested that the local contaminated street dusts are one of the potential sources of PCB in CSO and to the Buffalo River.

Particle size/settling
Furumai et al. (2002b) studied the dynamic behavior of suspended pollutants and particle size distribution in highway runoff. Except for Pb, the concentrations of TSS and heavy metals in runoff were within the range of the EMC reported in recent highway runoff research. Particle-bound heavy metals (Zn, Pb, and Cu) accounted for more significant pollutant loads than soluble fractions. Their content decreased with increasing total SS concentration in runoff samples. The results of particle size distribution (PSD) analysis of runoff samples indicate that high TSS concentration samples contained coarser particles. Based on the PSD results, a stepwise wash-off phenomenon of TSS under varying runoff rate conditions was explained by the different washoff behavior of fine (less than or equal 20 µm) and coarser particles.

Hijioka et al. (2000) investigated the behavior of suspended solids in runoff from a 67-ha urban watershed by looking at the behavior of two separate fractions (fine – less than 45 um; coarse – greater than 45 um). They found that the two fractions behaved similarly; however, the pollutant loadings were different with the coarse fraction needing a more
intense storm to generate runoff containing that fraction.

The composition and morphology of colloidal materials entering an urban waterway (Brays Bayou, Houston, Texas) during a storm event was investigated. Analyses of organic carbon, Si, Al, Fe, Cr, Cu, Mn, Zn, Ca, Mg, and Ca were performed on the fraction of materials passing through a 0.45 µm filter. This fraction, traditionally defined as "dissolved", was further fractionated by ultra-centrifugation into colloidal and dissolved fractions (Grout et al., 1999).

Lloyd and Wond (1999) presented examples of particulate size fraction distributions for road and highway runoff collected in Australia and compared the information with United States and European samples. They found that the particle size distribution of suspended solids in stormwater runoff from roads and highways in Australia were relatively finely graded. Sansalone and Hird (1999), in contrast, found that the particle sizes of stormwater particulates investigated at a freeway site in Cincinnati, Ohio were much larger than typically found elsewhere. In their samples, particles several hundred µm in size were common. They stressed the need to carefully collect stormwater samples for particle size analyses considering the difficulty of representing large particles in samples collected with automatic samplers. Pitt et al. (1999), during pilot-scale testing of a critical-source-area-treatment device, monitored particle size characteristics both in the influent and effluent. The parking lot stormwater had median particle sizes ranging from 3 to 15 µm. They also monitored particle sizes from 75 source areas in the Birmingham, Alabama, area as part of treatability tests during an earlier phase of this research and found similar small-sized particles. Corsi et al. (1999) measured stormwater particle sizes as part of a treatment system evaluation at a public works yard in Milwaukee, Wisconsin, and found median particle sizes in the influent of about 18 µm.

Andral et al. (1999) analyzed particle sizes and particle settling velocities in stormwater samples collected from eight storm events from the A9 motorway in the Kerault Region of France. They concluded that to effectively treat runoff, particles smaller than 50 µm in diameter (which represented approximately three-quarters of the particulates analyzed, by weight) must be captured. The median particle size for their samples averaged about 15 µm. Settling velocities of these particulates were also studied. The median settling velocities of the particulates smaller than 50 µm ranged from 2.5 to 3.3 m/h, while the larger particles between 50 to 100 µm in diameter had median settling velocities ranging from 5.7 to 13 m/h. Krishnappan et al. (1999) examined particle size distributions of suspended solids in a wet detention pond. They used a submersible laser particle size analyzer that enabled them to examine the particulate characteristics without disturbance by sampling. They found that the suspended solids were mostly composed of flocs, with maximum sizes ranging from 30 (winter) to 212 µm (summer). They concluded that flocs in the size range from 5 to 15 µm would settle faster than both smaller primary particles of higher density, and somewhat larger flocs of lower density. The larger flocs were also found to be susceptible to break up by turbulence.

Organic matter in sediments from pipes and silt traps in combined sewers was divided into fractions with different settling velocities. The largest fraction of organic material was found in the faster settling material, however the faster settling material had a slower biodegradability than the slower settling fraction (Vollersten et al., 1998). The efficiencies estimated using particle size distribution and settling velocities as suggested in the Ministry of the Environment and Energy Stormwater Management Practices Planning and Design Manual of Ont., Can., which is used to design best management practices (BMP), were less than those estimated using the observed particle distribution and settling velocities estimated from these sites. Suspended solid removal estimation based on the manual would result in removal efficiencies more conservative than observed (Liang et al., 1998).

Jones and Washburn (1998) mapped the three-dimensional distribution of dissolved and particulate components associated with stormwater runoff in Santa Monica Bay, Calif. The three major particles types in the bay were particles associated with the stormwater runoff, phytoplankton in the water column, and resuspended sediments.

Water quality and particle-size distribution were characterized from urban-stormwater runoff from two storms that indicated potential relationships between zinc (Zn)/organic carbon and iron (Fe)/macromolecule (0.45 µm — 20 µm) pairs. Results also indicated that concentrations of particle ion number, organic carbon, suspended solids (SS), Fe, and Zn increased during storms but showed no evidence of the “first flush” (Characklis and Wiesner, 1997).

Solids-settling characteristics are very important for designing many CSO- and stormwater-sedimentation-control facilities. Pisano (1996) summarized more than 15 years of settling data obtained in the United States, separated by wastewater types.
**CSOs and SSOs**

A case study to establish measures against damages caused by heavy storms was presented by Kinoshita et al. (2002). Manhole covers were blown away due to the sudden rise in the water level in the sewer, resulting in the submergence of sewerage facilities due to the increased sewage flow coming in from the open manholes. Joannis et al. (2002) reviewed a method for validating dry-weather data a posteriori. The method relies on flow-rate forecasts, a combination of standard daily wastewater flow profiles and an estimation of infiltration flows, and then the measurement results are then compared with the forecast and an appropriate series of statistical tests are run to detect all major anomalies. The diagnostic rules are then applied to derive an initial interpretation of these anomalies and, in particular, to identify the influence of rainfall events.

The paper by Agbodo and Rowe (2002) evaluated available approaches to selecting the appropriate design storm criteria for sizing SSO relief facilities and assessed techniques for establishing peak flows in sanitary sewer systems. Agbodo et al. (2002b) introduced the use of gage-adjusted radar data to estimate precipitation volumes for wastewater and water resources planning studies for either sanitary or combined sewer systems; the methods to estimate the optimum number of rain gages for precipitation-volume measurement; the advantages and disadvantages of alternative measurement approaches; and the use of radar precipitation data for enhancing collection systems planning, development, and operations and maintenance. The paper reviewed the data collected in South Florida and contained a cost comparison of gage-adjusted radar and rain gage methods for precipitation measurement. Mau et al. (2002) evaluated the spatial and temporal variability of storm events and the application of this to CSO facility design. The data from 6 Spokane-area rain gages was correlated with the measurements at the airport and these regressions were used to predict CSO design storm events for the individual CSO watersheds. The results showed that CSO facilities designed with basin-specific storm events were overdesigned by up to 70%, while using airport data directly caused an underdesign of approximately 35%. The paper by Dent et al. (2002) described methods available (including advantages and disadvantages) for determining the size of the design storm for sizing collection systems and treatment plants. The paper also offered approaches to develop wet weather design events for the system and the plant, including examples from several municipal master-planning studies to illustrate how the results can vary from one approach to another.

Hannan et al. (2001) reviewed the ASCE study that developed a guidance manual for identifying Sanitary Sewer Overflows (SSOs). The project surveyed twelve medium-to-large utilities for their SSO-identification protocols, with protocols organized into three major categories: Hydraulic, Maintenance and Inspection, and Structural. King County (Washington) has been assessing inflow and infiltration (I/I) in the county’s service area (Swarner et al., 2001a). The program included rainfall and flow monitoring, computer modeling, economic analyses, field investigations and pilot projects. The results will be used to determine the cost effectiveness of removing I/I from the system. This project has developed detailed information about the location of I/I sources and potential cost-effective improvements to remove or reduce critical sources of I/I. Inflow/infiltration values were estimated in the South Beaches regional wastewater collection system (Brevard County, FL) through re-examining pump flow data (Fernandez 2001). Operating station data was used in a custom-designed hydraulic model. Pump operating points were deduced through an interactive process of balancing flows from tributary pump stations.

Ahyerre et al. (2001b) investigated the solids composition of dry weather flow in the “Le Marais” combined sewer network in Paris after it was noted that there was an increase in the solids concentration in the lower part of the sewer’s flow. The study results showed that the accumulation rate of the organic solids layer was 215 g/(m²·day) with the particles heavily loaded with pollutants (VSS to TSS = 66 – 75%). Flushing experiments showed that this organic layer is easily eroded by small storm events. A second publication by Ahyerre et al. (2001b), as part of the same sewer investigation, reported that the erosion does not occur only locally but along the entire length of the section even at low shear stresses (0.5 N/m²). Cigana et al. (2001) investigated the impacts of underflow baffles on the retention of floatables in a combined sewer system. The study showed that a critical horizontal velocity can develop in overflow chambers and when this critical velocity is exceeded, floatables that would normally rise to the surface and be skimmed off are kept in the flow and therefore are not intercepted.

Gromaire et al. (2001) documented the sources of pollutants (SS, VSS, COD, BOD₅, Cd, Cu, Pb, and Zn) in the Paris combined sewer area called the “Marais” catchment. The erosion of in-sewer pollutants was the main source of particles and organic matter in wet weather flows, whereas heavy metal loads mainly originated from runoff due to the corrosion of metallic roofs. A change of the chemical form of heavy metals was noted during sewer transport. It was hypothesized that a fraction of the dissolved metals from the runoff adsorbed onto sewer sediments. Griffin et al. (2001) reported on the CSO Control System Evaluation report for the City of Atlanta, Georgia. Based on the testing, the main pollutants of
concern for meeting water quality standards were copper (Cu), zinc (Zn) and bacteria (fecal coliform). The two metals exceeded the baseline dissolved criteria frequently enough for remedial measures to be needed. Supplemental stormwater runoff sampling from parking lots and parks demonstrated high levels of metals (Cu and Zn) and bacteria. The frequency of exceedences for the stormwater runoff were similar to that of CSOs; thus, similar water quality compliance issues would remain even if the sewers were fully separated.

Sacramento County, California has completed a two-year project on the impact of grease accumulation in selected areas of the collection system (Hassey and Joyce 2001). Current grease handling policies of CSD-1 and local food producing facility wastewater flows result in heavy localized grease accumulation in the collection system that account for approximately seven percent of the annual grease related sewage overflows, and 36 percent of the flooded structure mitigation costs related to the overflows.

Servais et al. (1999) studied suspended solids, COD, and BOD in CSO affecting the River Seine (France). These basic measurements were compared with values of the biodegradable and refractory fractions of particulate and dissolved organic carbon. They found very similar numeric ratios between these parameters, even in areas having highly different conditions, making it possible for reasonable predictions of the biodegradable and refractory fractions of dissolved and particulate organic matter and of the bacterial biomass in combined sewage. CSO and source area runoff was investigated in Paris (France) by Chebbo et al. (1999). Resuspended material from the sewers contributed a larger fraction of the pollutants (suspended solids, organic matter, copper, and total hydrocarbons) than from the runoff during a runoff event. The results were quite different for lead, zinc, and cadmium whose main source was roof runoff due to corroding roofing materials.

Kerbs et al. (1999) found that the wave front that formed when a significant increase in flow occurred in a combined sewer was composed of the sewage that was present in the sewer before the flow rate increased and not the stormwater component that comprised most of the flow volume. By means of measurements and numerical simulations, they showed that this effect may cause the significant increase of dissolved constituents found in the first flush during CSO events. The vertical (rise) velocity of CSO floatable material, in addition to other basic measurements, was investigated by Cigana et al. (1999) in Montreal (Canada). They found that 80% of the floatables had a vertical velocity greater than 0.07 m/s.

Solids transport in sewers

McIlhatton et al. (2002) reviewed the influence of solids eroded from the bed of the combined sewer on receiving waters and treatment plants using data obtained from field studies carried out in the main Dundee interceptor sewer in Scotland. In addition, the paper described some of the methods used to investigate the pollutant characteristics associated with the solids erosion in combined sewers. Sakrabani et al. (2002) described the efforts using an endoscope that allowed visualization of combined sewer deposits (Near-Bed Solids) in a non-destructive way. Based on this work, several models have been proposed to estimate near-bed solids and predict the pollutant loads of consequence from CSOs. Pollert and Stansky (2002) reported on the use of computational techniques (a 1-D MOUSE model and the 3-D FLUENT model) to evaluate the separation efficiency of suspended solids in a CSO system. A combination of the two models was used to describe the CSO behavior.

Modeling the transport of sediment and other debris in sewers was investigated by Babaeyan-Koopaei et al. (1999). Using correct velocity distributions were found to be critical in order to obtain accurate predictions of sediment transport. A sensitivity analysis investigated the influence of some important parameters involved in the model, especially the drag coefficient, the lift coefficient, solid density, and pipe roughness. Arthur et al. (1999) proposed a new design approach to minimize sedimentation in sewers. They also compared the results of laboratory investigations with real sewer conditions. Johnstone et al. (1999) described on-going research concerning the disposal of large sanitary solids in combined sewers, assessing the relative sustainability of conventional disposal methods using an integrated, holistic approach, incorporating economics, sociology, life cycle data, and a risk assessment. They also described a project designed to study the behavior of the sanitary solids in the sewerage system through laboratory, field, and modeling studies. Skipworth et al. (1999) sampled and analyzed combined sewer sediment deposits and found coarse, loose, granular, predominantly mineral material that was overlain by a mobile, fine-grained cohesive-like sediment deposit in the invert of pipes. The erosion of this more mobile fraction was identified as the major source of the first flush of pollutants associated with CSO events. They presented a new approach to model the erosion and subsequent transport of these mobile sediments.

Rushforth et al. (1999) examined the relationships between the erosion of in-sewer organic deposits and the sediment composition. They found that sewer sediments consist of mixtures of organic and inorganic material and exhibit a much
wider range of particle sizes and densities than typically assumed. Specifically, the characteristics of the fine organic sediment found in combined sewer deposits fall outside the applicable range of grain size and density for typically used sediment transport models. Their laboratory experiments showed that the addition of granular material in sewer deposits significantly increases the amount of organic material eroded, compared to a deposit composed entirely of organic material.

**In-sewer processes**

Hass and Herrmann (1999) examined the problems associated with gas transfer in sewer systems through laboratory and field reaeration studies using volatile tracers and conservative dye tracers. They found that traditional empirical models for reaeration in open channels worked well, with modifications to account for the sewage matrix used instead of clean water. During the field studies in sewer systems having low gas transport rates, concentrations close to the Henry’s law equilibrium near the wastewater surface were found to minimize the transfer of the volatile gases from the wastewater to the sewer gas. Huisman et al. (1999) studied oxygen mass transfer and the biofilm respiration rate in sewers. Oxygen transfer mass fluxes were found to be responsible for the major changes to wastewater as it flows to the wastewater treatment plant. They concluded that about 20% of the dissolved COD could be degraded in the investigated sewer system during the wastewater transport process.

Hvitved-Jacobsen and Vollertsen (1999) also developed a conceptual model for wastewater quality changes during transport in sewers. The model includes reaeration and major aerobic and anaerobic microbial processes in the water phase and in the sewer biofilm. Emphasis was placed on microbial transformations of the heterotrophic biomass and of the soluble and particulate fractions of the organic substrate. Vollertsen et al. (1999) measured the effects of temperature and dissolved oxygen (DO) on the kinetics of microbial transformation processes of the suspended sewer sediment particles, suspended wastewater particles, and wastewater. The average Arrhenius constants found for sewer sediment particles and wastewater particles were found to differ significantly from the average Arrhenius constant found for the wastewater. However, no differences for the oxygen saturation coefficients were found between sewer sediment particles, wastewater particles, and wastewater. The anaerobic transformations of wastewater organic solids in sewers were studied by Tanaka and Hvitved-Jacobsen (1999), leading to a aerobic/anaerobic wastewater process model. During 19-25 hours of anaerobic conditions, a net production of readily biodegradable substrate, originating from hydrolyzable substrate, was observed. A small amount of methane production was also observed. Suguira et al. (1999) found that sewage stagnation at the downstream side of a separating tidal weir at a CSO discharge location caused an extraordinary generation of hydrogen sulfide, and associated nuisance odors.

**Pollution Sources**

**General Sources**

Malmqvist and Rundle (2002) discussed the threats to the world’s running water ecosystems. The main ultimate factors forcing change in running waters (ecosystem destruction, physical habitat and water chemistry alteration, and the direct addition or removal of species) stem from proximate influences from urbanization, industry, land-use change and watercourse alterations. Concentrations of chemical pollutants such as toxins and nutrients have increased in rivers in developed countries over the past century, with recent reductions for some pollutants (e.g. metals, organic toxicants, acidification), and continued increases in others (e.g. nutrients); there are no long-term chemical data for developing countries. The overriding pressure on running water ecosystems up to 2025 will stem from the predicted increase in the human population, with concomitant increases in urban development, industry, agricultural activities and water abstraction, diversion and damming. Future degradation could be substantial and rapid (c. 10 years) and will be concentrated in those areas of the world where resources for conservation are most limited and knowledge of lotic ecosystems most incomplete; damage will center on lowland rivers, which are also relatively poorly studied.

Cosgrove (2002) described the approach used in New Jersey to characterize the relative contribution of point and nonpoint sources of pollutants in the Raritan River Basin. The “screening level” methodology uses only existing data and does not require advanced modeling techniques. Maimone (2002) presented the overall approach that was used to screen and evaluate the thousands of potential sources within the Schuylkill River watershed as part of the Schuylkill River Source Water Assessment Partnership. EVAMIX is the decision support software used for the assessments. The greatest benefit of EVAMIX, compared to other software, is that it allows mixed criteria evaluation – qualitative and quantitative – to be considered concurrently. The assessment included both point sources and run-off, and evaluations were performed for an overall priority of potential sources, as well as for priority lists for ten different contaminant categories of concern in drinking water treatment. Kim et al. (2002) investigated the impacts of land-use changes on runoff in the Indian River
Lagoonal ecosystems. The study demonstrated that land-use change could have a dramatic impact on runoff volume (increase of nearly 113% between 1920 and 1990).

Jia et al. (2002) coupled simulations of water and energy budgets for complex land covers to determine the impact of urbanization on land surfaces/canopies, soil moisture content, land surface temperature, groundwater level and river water stage. Wotling and Bouvier (2002) performed an initial characterization of pollution associated with stormwater runoff in Tahiti. Organic pollution appeared to be related closely to sediment, thus TSS could be used as a global indicator. Next, regression models between an event's TSS load and its hydrological characteristics were used to obtain annual load estimates. Great interannual variability was found to be strongly influenced by the few major floods that occur during the rainy season. The results also emphasized the importance of the impact of urbanization on solid catchment exportation: from 60 TSS t/km²/year in a natural forested catchment, fluxes reached more than 700 TSS t/km²/year during preparatory urbanization earthworks before stabilizing at 140 TSS t/km²/year in a consolidated urbanized area.

The pollutant export from various land uses (single-family residential, golf course, industrial, dairy cow pasture, construction site and wooded site) was investigated for at least 20 storm events in the upper Neuse River Basin by Line et al. (2002). Annual total nitrogen export was greatest for the construction land use during the house-building phase, followed closely by the residential and golf course land uses. Total phosphorus export was greatest for the golf course site followed by the pasture and residential land uses. Sediment export was greatest for the construction site during the rough grading phase, which averaged more than 10 times more sediment export than any of the other sites. To estimate export from a multiuse urban watershed, total nitrogen, phosphorus, and sediment export from the residential, golf course, and construction sites were averaged. The average total nitrogen, phosphorus, and sediment export from the three land uses (average of residential, golf course and construction site) was, respectively, 269, 302, and 256% greater than the corresponding exports from the wooded site, which was considered similar to the predevelopment land use. Lee et al. (2002) analyzed the first flush of urban stormwater runoff. The magnitude of the first flush phenomenon was found to be greater for some pollutants (e.g. suspended solids from residential areas) and less for others (e.g. chemical oxygen demand from industrial areas). No correlation was observed between the first flush phenomenon and the antecedent dry weather period, however, the first flush phenomenon was greater for smaller watershed areas.

The movement of water and particulate matter through a simulated coal pile using a rainfall-coal-pile simulator was investigated by Curran et al. (2002). Results demonstrated the need to determine the optimal coal-pile slope that minimizes water contact time, but at the same time minimizes the potential for mass wasting and rill erosion. Promotion of a compacted surface is beneficial for the minimization of solids loss.

Pritts et al. (2002) reviewed the EPA’s assessment methodology for measuring the potential benefits of effluent guidelines, including reductions in pollutant loadings, habitat/biological impacts, and impacts on floodplain size. This was related to an environmental assessment of construction and land development. Stiles (2002) discussed incorporating hydrology into determining TMDL endpoints and allocations. The endpoints to be achieved by TMDLs utilizing analysis of hydrology would be a more accurate assessment of the level of water quality to be attained upon implementation of the load allocations. The implications to point sources would reflect a more direct linkage of their impacts to the stream and the desired goals of the TMDLs under flow conditions which are a subset of the total flow regime occurring on the river.

Richards (2002) reviewed the EPA’s study of the water quality impacts of alternative development patterns and locations. Preliminary results indicate that low-density, dispersed development located in metropolitan edge areas transforms a large area that was previously undeveloped, resulting in far more runoff. Conversely, redeveloping a centrally located brownfield site with compact, mixed uses converts a relatively small area of one form of developed land into another form of developed land, resulting in far less impact to runoff quantity and quality. The runoff characteristics when looking at post-development pollutant loads such as sediments and nutrients were far more impacted at the greenfield site than at the brownfield site.

Gippel et al. (2002) described four key aspects of the process being undertaken to meet the flow and water quality objectives, and to design the flow options to meet the objectives, for the River Murray: establishing an appropriate technical, advisory and administrative framework; establishing clear evidence for regulation impacts; undergoing an assessment of environmental flow needs; and filling the knowledge gaps. The paper described two important investigations: how to enhance flows to wetlands of national and international significance, and how to physically alter or change the operation of structures (including a dam, weir, lock, regulator, barrage or causeway), to provide significant environmental benefits.
Hale et al. (2000) investigated the occurrence of nonylphenols (an endocrine disruptor often from laundry products) from a variety of outfalls, and found that the highest concentrations in the sediment (14,100 ug/kg) was detected near a federal facility’s stormwater outfall. Sediment samples taken below an out-of-service sewage treatment plant indicated that nonylphenol persisted in the sediment. Hartmann et al. (2000) investigated the application of linear alkylbenzenes (LABs) as a molecular marker in marine sediments in Narragansett Bay. In the urban rivers at the head of the bay, the Providence River, Seekonk River, and Taunton River concentrations were locally high with a few values exceeding 2000 ng/g total LABs. The I/E (internal/external C-12 isomers) ratio, a measure of the degree of degradation, indicated that treated sources (i.e. sewage effluents) and local fresh sources (e.g. combined sewer overflows and boat cleaning detergents) were major contributors of LABs to the rivers. The observed decrease in LAB concentration with distance downbay suggested that most of the LABs were deposited within a few kilometers of their source.

Storm runoff from the log handling area at the Port of Tauranga, North Island, N.Z., showed that the runoff may contain significant concentrations of resin acids, e.g., dehydroabietic acid (Tian et al., 1998). Seabed sediment samples were collected adjacent to the log handling area and analyzed to determine the extent of the resin acid deposition. The concentrations of conventional parameters, i.e., biochemical oxygen demand (BOD), chemical oxygen demand (COD) and SS, and 123 priority pollutants of stormwater runoff samples from a log storage and handling facility in La. were determined and no significant levels of priority pollutants were found. Only about 1—13% of COD was biodegradable and similar to SS concentrations, suggesting that effective control of SS will control COD as well (De Hoop et al., 1998b).

Hydrologists have known for some time that runoff can occur as the result of both saturation and infiltration excesses in soil containing nonpoint source (NPS) contaminants. Watershed areas that generated NPS polluted runoff needed to be identified prior to the design of basin-wide water quality projects (Endreny and Wood, 1999).

Hydrologic runoff was one of the main processes in which radionuclides deposited in the surface environment migrate widely in both particulate and dissolved forms. Amano et al. (1999) concentrated on the transfer capability of long lived Chernobyl radionuclides from surface soil to river water in dissolved forms.

Zaman (1999) found that the catchments with high intensities of development in close proximity to stormwater systems were found to be transporting more pollutants to receiving waters than other catchments. Dry-weather water quality monitoring was used to identify the most polluted areas of the catchment. Nirel and Revaclier (1999) used the ratio of dissolved Rb to Sr to identify and quantify the impact of sewage effluents on river quality in Geneva, Switzerland. Rubidium was present in larger quantities than strontium in feces and urine, making the ratio of these two elements represents an effective tracer. This was especially true in regions where the natural Rb/Sr ratio was low (calcareous regions).

Gromaire-Mertz et al. (1999) collected stormwater runoff from 4 roofs, 3 courtyards and 6 streets on an experimental catchment in central Paris, France, and analyzed the samples for SS, VSS, COD, BOD$_5$, hydrocarbons, and heavy metals both in dissolved and particulate fractions. The street runoff showed large SS, COD and hydrocarbon loads, but the roof runoff had high concentrations of heavy metals. Wiese and Scmitt (1999) described urban stormwater contributions into large river systems. Their purpose was to develop a mass balance model for many stormwater pollutants, stressing nitrogen and phosphorus, the oxygen depleting substances and some heavy metals.

Iatrou et al. (1996) described the results of stormwater samples collected from the New Orleans drainage system. The sampling locations chosen represented residential, commercial, and industrial areas. Sakai et al. (1996) measured characteristics of storm runoff from road and roof surfaces and found the ratio of COD$_{AN}$:T-N to be in the range of 3:1 for roof-storm runoff and in the range of 7:1 for road-surface-storm runoff. They found the ratio of COD$_{AN}$:T-P to be 160:1. Most of the organic components and T-P in road-surface-storm runoff are insoluble, and road-surface-storm runoff contained soluble nitrogen (N), which could have been contributed from air pollutants.

Nowakowska-Blaszczzyk et al. (1996) studied the sources of wet-weather pollutants in Poland. It was found that storm runoff from parking areas and streets had the greatest concentrations of suspended solids (SS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD$_5$), and Pb, while phosphorus was mostly contributed from landscaped-area storm runoff. Storm runoff from roofs covered with roofing paper was also a significant contributor of many pollutants.
**Atmospheric**

Yunker et al. (2002) investigated the sources of PAHs in the Fraser River Basin (British Columbia). PAH ratios and total concentration data revealed a basin lightly impacted by a variety of sources in its remote regions, especially near roads, but heavily impacted in urban areas, particularly near Vancouver. Contamination sources shift from biomass (e.g. wood and grass) burning to vehicle emissions between remote and urban locations. Stormwater and wastewater discharges appeared to collect PAH from urban areas and release them as point sources. In all cases the examination of a variety of PAH indicator ratios that encompass a range of masses is necessary for a robust interpretation.

Ahn and James (2001) report that atmospheric deposition is a substantial source of phosphorus to the Florida Everglades. Phosphorus has been measured on a weekly basis since 1974, but the results were highly variable: the average mean and standard deviation of the calculated P deposition rates for 13 sites were 41±33 mg P m⁻² yr⁻¹. They found that the atmospheric P deposition load showed high spatial and temporal variability, with no consistent long-term trend. Because of the random nature of P deposition, the estimated P deposition loads have a significant amount of uncertainty, no matter what type of collection instrument is used, and replicate sampling is highly recommended. Atasi et al. (2001b) conducted source monitoring using specialized sampling equipment and ultra-clean analytical methodology to quantify the concentrations and fluxes of mercury, cadmium, and polychlorinated biphenyl in ambient air, precipitation, runoff, sanitary sewer, and wastewater treatment plant influent. The relationships between the atmospheric deposition and runoff on controlled surfaces were also examined. Atmospheric deposition was found to be the primary source of these pollutants in runoff. They concluded that wet weather flows, not atmospheric deposition, contributed the main portion of these pollutants to the Detroit Wastewater Treatment Plant. Atasi et al. (2001a) also pointed out that most water resources regulations (especially TMDL procedures) do not normally account for atmospheric deposition sources. Tsai et al. (2001) described their pilot study, conducted from August 1999 through August 2000, that estimated the loading of heavy metals from the atmosphere to San Francisco Bay. Dry deposition flux of copper, nickel, cadmium, and chromium was approximately 1100 +/- 73, 600 +/- 35, 22 +/- 15, and 1300 +/- 90 µg/m²/year, respectively. The volume-weighted average concentrations of these trace metals in the rain water were 1.2, 0.4, 0.1, and 0.2 µg/L, respectively. Direct atmospheric deposition onto Bay waters, from both dry deposition and rainfall, contributed approximately 1900, 930, 93 and 1600 kg/yr of copper, nickel, cadmium and chromium, respectively. Stormwater runoff contributed approximately twice as much as the loading from direct atmospheric deposition. Direct atmospheric deposition was therefore found to be a minor contributor to the total load of these pollutants to the Bay.

In a study on the influence of atmospheric deposition on the concentrations of mercury, cadmium and PCBs in urban runoff, Atasi et al. (2000) found that atmospheric deposition was the primary source of these compounds in runoff from controlled surfaces. The authors argued that the contribution of atmospheric deposition must be accounted for both in modeling of pollutant sources, but also in planning for pollution prevention.

Atmospheric deposition, often contaminated to varying degrees, can be a significant source of phosphorus to South Florida’s aquatic system. Outliers were detected by field notes, derived from visual inspection of the samples, and statistics, based on simple linear regression used for additional screening. Based on detected outliers in the data from 115 monitoring sites, a lumped cutoff value, used for further quality control, of 130 Fg/L was determined (Ahn, 1999).

Garnaud et al. (1999) studied heavy metal concentrations in dry and wet atmospheric deposits in Paris, France, for comparison with urban runoff. Samples were continuously collected for 2 to 13 months at each of four test sites. Comparisons of median values of metal concentrations showed that rainwater contamination with heavy metals was only slightly higher in the center of Paris than at Fontainebleau (48 km SE of the city) which illustrates the medium range transport of atmospheric contamination.

Atasi et al. (1999) used specialized sampling equipment and ultra-clean analytical methodology to quantify the concentrations or fluxes of mercury, cadmium, and polychlorinated biphenyl in ambient air, precipitation, runoff, sanitary sewage, and treated sewage in Detroit, Michigan. Atmospheric deposition was found to be the primary source of the mass of Cd, Hg, and PCB, in runoff from the controlled surfaces. Shiba et al. (1999) also investigated the role of atmospheric deposition as a source of urban runoff contaminants. They found that the chemical substances in rainwater were an important pollution source.

Detailed characterization of 71 individual polychlorinated biphenyl (PCB) congeners in the waste streams at the 26 New York City (NYC) and N. J. water pollution control plants (WPCP) showed that of the estimated 88 kg of PCB released
annually by the WPCP, roughly 3% was contributed by CSO due to heavy precipitation (Durell and Lizotte, 1998). Atasi et al. (1998) analyzed atmospheric and runoff samples to determine wet and dry deposition and the relative contribution of deposition to runoff pollutant mass. Ahn (1998) recorded the total phosphorus (P) concentrations in south Fla. rainfall at weekly intervals with a detection limit of 3.5 µg/L. Air deposition was found to be the primary source of Cd, Hg, and PCB mass in runoff at the controlled sites in the study. Phenols were present at high concentrations in urban rainwater and ambient air (Allen and Allen, 1997).

Results from ten watersheds indicated organic P and carbon (C) correlated with the concentration of suspended particles, which differed among the watersheds. Recent estimates also suggest that 40% of the nitrogen (N) loading to the Chesapeake Bay watershed comes from atmospheric deposition, 33% from livestock waste, and 27% from fertilizer (Jordan et al., 1997).

Pankow et al. (1997) proposed that frequent observations of the fuel additive methyl-tert-butyl ether (MTBE) in shallow urban groundwater may be due to atmospheric deposition accumulated during precipitation events and subsequent infiltration of stormwater. A one-dimensional mathematical model simulated five scenarios with varying conditions of precipitation, transport, source concentrations, and evapotranspiration and indicated that significant contributions of the compound may be coming from the atmosphere.

**Roof Runoff**

Polkowska et al. (2002) presented the results of testing roof runoff waters from buildings in Gdansk, Poland. More than half of the samples (25) were found to be toxic, with inhibition exceeding 20%. The toxicity was weakly correlated to the levels of organonitrogen and organophosphorus pesticides in runoff waters. It was established that at least in some cases the roofing material affected the levels of the pollutants found in the samples. Heijerick et al. (2002) investigated the bioavailability of zinc in runoff from roofing materials in Stockholm, Sweden. Chemical speciation modeling revealed that most zinc (94.3-99.9%) was present as the free Zn ion, the most bioavailable speciation form. These findings were confirmed by the results of the biosensor test (Biomer(TM)), which indicated that all zinc was indeed bioavailable. Analysis of the ecotoxicity data also suggested that the observed toxic effects were due to the presence of Zn^{2+} ions. Gromaire et al. (2002) investigated the impact of zinc roofing on urban pollutant loads in Paris. On an annual basis, runoff from Parisian zinc roofs would produce around 34 to 64 metric tons of zinc and 15 to 25 kg of cadmium, which is approximately half the load generated by runoff from all of Paris.

Karlen et al. (2002) investigated runoff rates, chemical speciation and bioavailability of copper released from naturally patinated copper roofs in Stockholm, Sweden. The results show annual runoff rates between 1.0 and 1.5 g/m² year for naturally patinated copper of varying age with rates increasing slightly with patina age. The total copper concentration in investigated runoff samplings ranged from 0.9 to 9.7 mg/l. The majority (60 – 100%) of the released copper was present as the free hydrated cupric ion, Cu(H_{2}O)_{6}^{2+}, the most bioavailable copper species. The copper-containing runoff water, sampled directly after release from the roof, caused significant reduction in growth rate of the green alga. Wallinder et al. (2002) studied the atmospheric corrosion of naturally and pre-patinated copper roofs in Singapore and Stockholm. Measured annual runoff rates from fresh and brown prepatinated were 1.1–1.6 g/m² and 5.5-5.7 g/m², in Stockholm and Singapore, respectively. Naturally aged copper sheet (130 years old) and green pre-patinated copper sheet showed slightly higher (1.6-2.3 g/m²), but comparable runoff rates in Stockholm. In Singapore, runoff rates from green pre-patinated copper sheet were 8.4-8.8 g/m². Comparable runoff rates between fresh and brown-patinated copper sheet and between green naturally patinated and green pre-patinated copper sheet at each site were related to similarities in patina morphology and composition.

Wallinder and Laygraf (2001) studied the seasonal variations in the corrosion and runoff rates from copper roofs. Their experiments lasted for two years, at one urban and one rural location. Seasonal variations in corrosion rates were observed at the rural site, likely associated with variations in humidity, while no seasonal variations were observed at the urban site. The corrosion rates continually decreased with time. The yearly copper runoff rates ranged from 1.1 to 1.7 g m⁻² y⁻¹ for the urban site, and from 0.6 to 1.0 g m⁻² y⁻¹ for the rural site. The runoff rates were significantly lower than the measured corrosion rates as long as the adhering copper patina was increasing with exposure time. From 70 to 90% of the copper in the runoff (collected immediately after leaving the surface) was present in the most bioavailable form, the hydrated cupric ion, Cu(H_{2}O)_{6}^{2+}.

Zobrist et al. (2000) examined the potential effects of roof runoff on urban stormwater drainage from three different types of roofs: an inclined tile roof, an inclined polyester roof and a flat gravel roof. Runoff from the two inclined roofs showed
initially high ("first flush") concentrations of the pollutants with a rapid decline to lower levels. The flat gravel roof showed lower concentrations of most of the pollutants because of the ponding of the water on the roof surface acting like a detention pond. Pollutant loadings was similar to atmospheric deposition, with the exception of copper from drain corrosion (rate about 5 g/m²/yr).

Tobiason and Logan (2000) used the whole effluent toxicity (WET) to characterize stormwater runoff samples from four outfalls at Sea-Tac International Airport. Three of the four outfalls met standards; the source of the toxicity at the fourth outfall was found to be zinc-galvanized metal rooftops. Typically, more than 50% of the total zinc in the runoff was in dissolved form and likely bioavailable.

Foerster (1999) and Foerster et al. (1999) reported on studies investigating roof runoff as stormwater pollutant sources. Runoff samples were taken from an experimental roof system containing five different roofing materials and from house roofs at five different locations in Bayreuth, Germany. It was found that local sources (e.g. PAH from heating systems), dissolution of the roof systems’ metal components, and background air pollution were the main sources of the roof-runoff pollution. They found that the first flush from the roofs often was heavily polluted and should be specially treated. They concluded that roofs having metal surfaces should not be connected to infiltration facilities as concentrations of copper and zinc far exceed various toxicity threshold values. They also examined a green (vegetated) roof for comparison. These roofs were found to act as a source of heavy metals which were found to be in complexes with dissolved organic material. Leaching from unprotected zinc sheet surfaces on the green roofs resulted in extremely high zinc concentrations in the runoff. In contrast, the green roofs were a trap for PAH.

Sakakibara (1996) investigated roof-runoff quality in Ibaraki prefecture, Japan, in order to determine the feasibility of using roof runoff in urban areas for various beneficial uses. Eighty three samples were collected during one year and analyzed for pH (averaged 6.1), BOD₅ (averaged 1.6 mg/L), COD (averaged 3.2 mg/L), and SS (averaged 12 mg/L). It was concluded that roof-runoff could be used for toilet flushing and landscaping watering with minimal treatment or problems. Heavy metals and major ions in roof-runoff were investigated by Förster (1996) in Bayreuth, Germany. It was found that the major ions were from the rain, while very high Cu and Zn concentrations were from metal flashings used on the roofs. It was concluded that the best option would be to abandon the use of exposed metal surfaces on roofs and walls of buildings.

**Highway and other Roadway Runoff**

Zakaria et al. (2002) reviewed the distribution of PAHs in rivers and estuaries in Malaysia. Total PAHs concentrations in the sediment ranged from 4 to 924 ng/g. Alkylated homologues were abundant for all sediment samples. The ratio of the sum of methylphenanthrenes to phenanthrene (MP/P), an index of petrogenic PAHs contribution, was more than unity for 26 sediment samples and more than 3 for seven samples for urban rivers covering a broad range of locations. PAHs and hopanes fingerprints indicated that used crankcase oil is one of the major contributors of the sedimentary PAHs. Two major routes of inputs to aquatic environments have been identified: (1) spillage and dumping of waste crankcase oil and (2) leakage of crankcase oils from vehicles onto road surfaces, with the subsequent washout by street runoff. N-Cyclohexyl-2-benzothiazolamine (NCBA), a molecular marker of street dust, was detected in the polluted sediments.

Neary et al. (2002) studied the pollutant washoff and loadings from parking lots in Cookeville, Tennessee. The monitoring results indicated that the washoff response from small parking lot catchments was also affected by other factors that included antecedent dry conditions and rainfall intensity. Ma et al. (2002) investigated the first-flush phenomenon for highways. Most pollutants showed median mass first flushes where 30 percent of the mass is released in the first 20% of the runoff. Pollutants representing organic contaminants had the highest first flush ratios.

Rood and Lackey (2002) investigated the impacts of new highway construction on the Ocmulgee Old Fields Reserve near Macon, Georgia, by studying the impacts of the earlier interstate (I-16) construction in the same area. A general survey indicated that the minimal bridging on I-16 prevents surface waters from their natural flow toward the river. The crossing of the I-16 roadbed with a pre-existing railroad bed has impounded waters on the southeastern border of the Ocmulgee National Monument. Impoundment has transformed this zone from a forested wetland plant community with rich organic soils to an open aquatic wetland with emergent and floating vegetation. The findings indicated that between the highway and the river that any random or non-random event that removed forest canopy had a more significant impact on wetland community structure and function than did proximity to the highway.

Lau et al. (2002b) studied whether a first flush of organics (COD, oil and grease, and PAHs) would be seen in highway
runoff. The three highway sites exhibited a first flush in most cases for most parameters. The mass first flush ratio (the ratio of the normalized transported mass of pollutant to the normalized runoff volume) generally was above 1.8 for the first 25% of the runoff volume, and in some cases as high as 2.8.

Glenn et al. (2001a and 2001b) described their research at highway test sites in Cincinnati, Ohio investigating the effects of traffic activities and winter maintenance on the behavior of particulates in the runoff. They found that urban snow has a much greater capacity to accumulate traffic-related pollutants, as compared to stormwater, due to longer residence times before melting, and the snow’s porous matrix. Parameters such as residence time, solids loadings, alkalinity, hardness and pH influence the heavy metal partitioning in the snow. They found that Pb, Cu, Cd, Zn, Al, Mg, and Fe were mostly particulate bound, while Na and Ca were mostly dissolved. Partition coefficients for most heavy metals in snowmelt water ranged from 103 to 106 L/kg. Stenstrom et al. (2001) studied freeway runoff from three sites in the west Los Angeles area. Each site was sampled for 14 storms during the 1999-2000 rainy season. Samples were collected very early in the storm in order to compare water quality from the first runoff to water quality from the middle of the storm. A large range of water quality parameters and metals were analyzed. The data showed large first flushes in concentration and moderate first flushes in mass emission rates. Zhou et al. (2001) studied accumulations of heavy metals in roadside soils. Heavy metal accretion in the surficial soils was a function of depth, surface drainage patterns, distance from the pavement edge and soil indices. Rapid decreases in heavy metal accumulations were found as the distance from the pavement increased. Plasticity and organic matter content were important soil characteristics affecting the observed heavy metal concentrations.

Fifteen highway construction sites were monitored by the California Department of Transportation (Caltrans) to assess the runoff quality from the sites (Kayhanian et al., 2001a). The results indicated the following: (a) construction-site runoff constituent concentrations were less than typical Caltrans and non-Caltrans highway runoff constituent concentrations, with the exception of total chromium, total nickel, total phosphorus, total suspended solids (TSS), and turbidity. (b) The concentrations of TSS and turbidity likely resulted from soil disturbance. (c) The origins of the total chromium, total nickel, and total phosphorus concentrations are unknown. (d) A correlation was observed between TSS and particulate runoff concentrations of chromium, copper, and zinc, indicating that solids removal may reduce total metals concentrations. The Solids Transport and Deposition Study (STDS) characterized the rates and patterns of solids transfer to, and the collection within, storm water drain inlets located along Caltrans highway facilities (Quasebarth et al., 2001). The primary objective was to determine if certain distinguishable site characteristics controlled the transport and deposition of sediment, metals, vegetation, litter, and petroleum hydrocarbons to highway drain inlets. The ANOVA results indicated that the four primary factors (erosion control/sediment loading [vegetation factor], litter management [litter factor], toxic pollutant generation potential [adjacent land use factor], and roadway design [design factor]) likely had little overall control on solids accumulation or metals mass accumulation, although roadway design and litter management were possibly important in some cases.

Since urban roads are typically directly connected to the drainage system and therefore respond quickly to storm events, the quality of urban road runoff in the Sydney, Australia, region was investigated by Ball (2000a). This paper also proposed guidelines for estimating the transportable trace-metal loading from road surfaces. Ball et al. (2000) showed that the quality of the runoff resulting from the construction of a new highway intersection in Australia could be improved by using treatment devices such as detention ponds and sand filters. Hirsch (2000) reported on the development of a TMDL for Straight Creek in Colorado due to the sediment and pollutant loads contributed to the stream by Interstate 70 runoff. The interstate construction increased erosion in the stream due to the significant cut-and-fill, as did the snowy winter road conditions which required extensive sand applications. An investigation by Drapper et al. (2000) showed that the pollutants concentrations (heavy metals, hydrocarbons, pesticides, and physical characteristics) in ‘first flush’ road runoff in Brisbane in southeast Queensland, Australia was within the ranges reported internationally for highways. Traffic volumes were the best indicator of road runoff pollutant concentrations, with interevent duration also being statistically significant factor. Exit-lane sites were found to have higher concentrations of acid-extractable copper and zinc, likely due to brake pad and tire wear caused by rapid deceleration, and laser particle sizing showed that a significant proportion of the sediment in runoff was less than 100 um. Krein and Schorer (2000) investigated heavy metals and PAHs in road runoff and found that, as expected, an inverse relationship existed between particle size and particle-bound heavy metals concentration existed. However, particulate-bound PAHs were found to be bimodally distributed. Three-ring PAHs were mostly find in the fine sand fraction, while six-ring PAHs were mostly concentrated in the fine silt fraction. Sutherland et al. (2000) investigated the potential for road-deposited sediments in Oahu, Hawaii, to bind contaminants, and thus transporting these bound contaminants to the receiving water as part of the runoff. In the sediment fractions less than 2 mm in diameter, the origins of the aluminum, cobalt, iron, manganese and nickel were determined to be geologic. Three
of the metals concentrations, copper, lead and zinc, were found to be enhanced by anthropogenic activities. Sequential extraction of the sediment determined the associations of the metals with the following fractions: acid extractable, reducible, oxidizable, and residual).

An overview of the National Cooperative Highway Research Program (NCHRP) upcoming work was presented by Stein et al. (2000). This presentation included an evaluation of past work on stormwater runoff from transportation facilities and a prioritization of future research in this area.

Walker et al. (2000a) reviewed the on-going water quality assessment program implemented by the San Diego region of the California Department of Transportation (Caltrans). Constituents of concerns were being targeted for monitoring and potential remediation. The thermal enhancement of stormwater runoff by paved surfaces was investigated by Van Buren et al. (2000a and 2000b). The results from the test-plot studies were used to help develop, calibrate and verify the wet-weather model TRMPAVE, a mathematical model that uses an energy balance to predict the temperature of the runoff. Glenn et al. (2000) found that the snow residuals along highways had high levels of particulate and solid matter, likely from nearby vehicular traffic. Snow also accumulated traffic-based pollutants to a greater degree.

In the Kerault Region of France, the effects of pollution were studied using solid matter from a section of the A9 motorway. This study analyzed both settled sediments from collecting basin and characteristics of sediments in the water column during and after eight storm events between October 12, 1993, and February 6, 1994. Settled sediments were used to measure particle sizes, mineral content, and related characteristics, whereas water samples were used to document total suspended solids, mineral content, and heavy metals (Andral et al., 1999).

Runoff from highways contains significant loads of heavy metals and hydrocarbons, according to German regulations it should be infiltrated over embankments to support groundwater recharge. To investigate the decontaminating effect of greened embankments, soil-monoliths from highways with high traffic densities were taken. Soils were analyzed to characterize the contamination in relation to distance and depth for lead, zinc, copper, cadmium, PAH and MOTH (Dierkes and Geiger, 1999).

The quality of highway runoff monitored in the Austin, Tex. area at three locations on the MoPac Expressway were similar in constituent concentration to median values compiled in a nationwide study of highway runoff quality (Barrett et al., 1998a). A grassy swale at one site which had a lower runoff coefficient due to infiltration reduced concentrations of most constituents in runoff. The pollutants available for transport during storm events of a suburban road in the eastern suburbs of Sydney, Aust. were significantly different from published data for North Am. (Ball et al., 1998). Both rain and wind events lowered the available pollutant constituent mass on the road surface. Fourteen composite samples of Marinette, Wis. stormwater, as well as baseflow samples, were analyzed to determine requirements for a National Pollutant Discharge Elimination System (NPDES) permit and the results indicated similarity to stormwater found in other communities (Scholl and Lauffer, 1998). Measurements of conductivity and turbidity taken in a study of the Crum Creek which runs through the suburbs of Philadelphia, Pa. indicated two stages during the first three hours of wet weather runoff: a dissolved solids flush followed by a suspended solids (SS) flush (Downing and McGarity, 1998).

In San Francisco, Calif., vehicle emissions of both ultrafine (< 0.12 µm) and accumulation mode (0.12 — 2 µm) particulate polycyclic aromatic hydrocarbons (PAH) are derived from diesel vehicles while gasoline vehicles emit higher molecular weight PAH primarily in the ultrafine mode. Heavy duty diesel vehicles were found to be important sources of fine black carbon particles (Miguel et al., 1998). In a European study, 90% of the particles from a contaminated highway runoff catchment were smaller than 100 µm. The constituents of the contaminants smaller than 50 µm were further analyzed by X-ray diffraction, thermogravimetry and specific mass and contained 56% clay, 15% quartz, 12% chalk, 9% organic matter, 5% feldspars, and 2% dolomite (Roger et al., 1998).

Several researchers investigated roadway storm runoff as a nonpoint pollution source and reported their results at the 7th International Conference on Urban Storm Drainage in Hannover (Sieker and Verworn, 1996). Wada and Miura (1996) examined storm runoff from a heavily traveled highway in Osaka, Japan. A significant “first-flush” for COD was found and the amount of small rubber pieces from tire wear in the highway storm runoff was more than 20 times greater than for an “ordinary” road. The primary factors affecting storm runoff concentrations were the amount of traffic (and related exhaust emissions and tire wear) and the fraction of the total traffic that was comprised of trucks and buses. Montrejaud-Vignoles et al. (1996) collected storm runoff from a heavily used six-lane motorway in the Mediterranean area of France. The very irregular rainfall in this area and associated very-long dry periods can result in storm runoff that is much more
polluted than elsewhere in France. As an example, during the one-year study, a single rain of only 10 mm but having an antecedent-dry period of 35 days, produced more than 12% of the annual COD discharges. Ball et al. (1996) examined roadway pollutant accumulations in a suburb of Sydney, Australia. It was concluded that the local heavy winds have a significant effect on pollutant accumulations that commonly available stormwater models do not consider, and that historical United States’ data on roadway-pollutant accumulations are much greater than found in their area. Sansalone and Buchberger (1996) studied metal distributions in stormwater and snowmelt from a major highway in Cincinnati, OH. Zn and Cd were mostly in filterable (dissolved solids) forms in the storm runoff, while lead was mostly associated with particulates.

**Deicing Discharges**

Deicing salt (NaCl) fate was determined from retention and loss in snow cover adjacent to a 14 km section of the highway in southern Ontario during the 1994-1995 winter. Almost all applied NaCl reached the soil surface via direct runoff and infiltration of saline water from the road into the shoulder and right-of-way, and transfer of salt to snow cover adjacent to the highway and release during snow melt (Buttle and Labadia, 1999).

Paschka et al. (1999) studied the water-quality effects associated with the extensive use of water-soluble iron cyanide compounds used as anticaking agents in road salt. Although available information did not indicate a widespread problem, it was also clear that the water-quality effects of cyanide in road salt had not been adequately examined.

During the winter of 1995-1996, deicing chemicals (approximately 3x10^6 L of ethylene glycol, 0.5x10^6 kg of urea, and 23x10^3 kg of potassium acetate) were spread on the Pittsburgh (Pa.) International Airport and presumably drained into Montour Run, a nearby stream. The metabolism of glycols and urea exerted a strong BOD in receiving water and elevated concentrations of ammonia (NH₃) (Koryak et al., 1998).

Complex ferrocyanide compounds, which can break down into free, toxic, cyanide compounds, are added to salt to prevent caking (Novotny et al., 1998a). Salt also decreased partitioning between adsorbed and dissolved metals which increased dissolved metals in snowmelt. A dynamic model was developed and calibrated to calculate daily loads and concentrations from snowpiles of three northern cities using salt for deicing (Novotny et al., 1998b). Snowmelt runoff from an urban watershed can produce density current intrusions in a lake (Ellis et al., 1997). Snowmelt runoff entering Ryan Lake in Minneapolis, Minn. increased electrical conductivity, salinity and density with salt spread on urban streets as the source of the salinity.

**Treated Wood**

Treated wood has periodically been identified as a potential source of toxicants in stormwater but few studies have specifically examined its role. Weis and Weis (1996) examined the leaching potential of Cu-Cr-As (arsenic) mixture (CCA) treated wood in Chesapeake Bay. Sediment and benthos samples were analyzed for Cu, Cr, and As at varying distances from treated-wood bulkheads at test and control sites. In general, sediment metal concentrations decreased with distance from the treated-wood bulkheads but not at the control stations. The species diversity and the number of individual species were also less at the treated-wood site at the poorly flushed location but not at the control area having similar flushing conditions.

**Wastewater, CSOs, and Sanitary Sewer Overflow Sources**

Heijs et al. (2002) reviewed Project CARE in North Shore City (New Zealand), which is a program that planned improvements to wastewater and stormwater systems in order to protect the streams and beaches. Hydrological and hydraulic models were both constructed to represent the sanitary and storm sewer systems and were coupled with a receiving water model to simulate the impact on beaches. Ferreira et al. (2002) investigated the performance of partially separate sewer systems in Oeiras, Portugal, and their impact on receiving waters. The volume and characteristics (COD loads) were estimated and used to evaluate the potential contamination of swimming/beach areas by bacterial loads, especially due to first-flush effects.

The Massachusetts Water Resources Authority (MWRA) completed its Long-Term Control Plan for CSO control in 1997. The plan used a watershed approach to assess the impacts of CSOs in relation to other sources of pollution in the watershed, including stormwater and upstream flows. The EPA and the Massachusetts Department of Environmental Protection agreed to revise the water quality standards for certain waters within Boston Harbor. For the Charles River, a two-year water quality variance was granted to allow further study of the impacts of non-CSO sources of pollution, as well as for additional CSO control alternatives. Important current activities described by Walker et al. (2001) include an
assessment of additional CSO storage; performance evaluations of the MWRA’s Cottage Farm CSO facility; development of a more detailed stormwater runoff model for areas tributary to the Charles River; and upgrading the receiving water model for the Charles River.

Lessard and Michels (2000) examined the effects of CSO basin discharge on the water quality in the Menominee River in 1997. Based on the data collected, the overflow from the CSO retention basin does meet the Michigan Water Quality Standards during the overflow discharge events, with the basin providing the equivalent of primary treatment plus disinfection. The loadings of most of the pollutants, including nutrients, metals and suspended solids, were insignificant compared to background. The CSO basin effluent also did not appear to impact the dissolved oxygen in the river to the point where the DO fell below standards.

CSO and urban streams receiving CSO in the Pittsburgh, Pa. area were tested for cryptosporidium and giardia. Data suggested CSO are a significant source in small streams (Stadterman et al., 1998).

The EPA (1996f) conducted case studies to examine the effects of CSOs on the biological integrity of some example streams in Ohio and New York using rapid-bioassessment protocols. Results were compared with historical assessments of the same streams. Drinnan et al. (1996) presented data that showed the application of rating systems developed to identify discharges that have public-health or environmental concerns and provide a protocol for initiating mitigative measures in Victoria, BC, Canada. The number of discharges designated as high priority because of their effects on public health has decreased steadily between 1992 and 1995 and the number of bathing beaches posted with a health advisory has decreased from 28 in 1969 to none in 1995. Water Environ. & Technol. (1996b) reported that the fecal coliform counts decreased from about 500/100 mL to about 150/100 mL in the Mississippi River after the sewer-separation program in the Minneapolis and St. Paul, MN area. Combined sewers in 8,500 ha were separated during this 10-year, $332 million program.

Results from sediment samples collected adjacent to each of four CSO along the lower Passaic River of New Jersey indicated that sediments proximate to the CSO outfalls were contaminated with a range of chemicals including toxic metals, PAH, PCB, pesticides, and other organic chemicals. The spatial distribution of these contaminants strongly suggested that the CSO were the primary source of contamination in sediments near these outfalls (Iannuzzi et al., 1997).

**Inappropriate Discharges**

The techniques, experiences, and lessons learned by the Village of Romeo (outside Detroit, Michigan) in eliminating illicit discharges into the storm sewer system were reported by McLaughlin et al. (2002). This work was performed in response to local health department reports of high bacteria levels and sanitary debris in East Pond Creek.

McGee et al. (2000) investigated the potential sources of indicator bacteria that closed a portion of Huntington State Beach in Orange County, California. The approach used was termed a “risk-based sanitary survey,” and the investigation used both state-of-the-art technologies (radar, sonar, and infrared imaging) and conventional techniques (geo-probes, television inspection of the sewers, and monitoring wells). White et al. (2000) investigated the effects of land use change and resulting bacterial concentrations on shellfish closures in Jump Run Creek in North Carolina. The results of this project showed that the likely sources of the elevated bacterial concentrations (high during wet weather, moderate during dry weather) was the area draining an older, medium density residential neighborhood (single family homes, trailerpark with two malfunctioning septic tanks and more than 100 pets, plus wildlife). Dye studies in the area indicated that flow through area was too small for bacterial mortality to occur.

The combined use of sterol biomarkers and bacterial indicators showed that during wet weather, all sites sampled in the storm drainage system of Geelong, Victoria, Aust. were subject to human fecal contamination. Ratios of coprostanol to bacterial indicators were similar to those for samples collected from nearby sewer mains (Leeming et al., 1998).

Sangal et al. (1996) conducted a feasibility study for the Rouge River National Wet Weather Demonstration Project to evaluate the applicability of the stable-isotope approach to identify illicit connections in three mini-watersheds in or near Wayne County, MI. The results indicated that the isotopic technique is extremely cost-effective and robust for distinguishing between local groundwater and water derived from domestic and industrial or commercial sources.

Baltimore, MD as part of their NPDES permit, examined their storm-drainage system for sources of illicit entries (Stack and Belt, 1996). About one third of the 344 small subwatersheds in the city have been targeted as potential sources of
toxicants from illicit entries, based on analyses of surfactants, phenols, ammonia, Cu, Pb, Zn, and total petroleum hydrocarbons, with eight sources specifically identified.

**Industrial Sources**

Choe et al. (2002) characterized the surface runoff in urban (residential and industrial zones) areas. The event mean concentrations (EMCs) of COD, SS, TKN and TP in the residential zone were 313 mg/L, 279 mg/L, 8.45 mg/L, and 1.98 mg/L, and those in the industrial zone were 80 mg/L, 106 mg/L, 5.07 mg/L, and 1.93 mg/L, respectively. No general relationship between the cumulative load and runoff could be established. The degree of first-flushing effect by constituents was in the following order: TKN > COD > SS > HEM > TP > PO₄-P. Based on the correlation of constituents with SS, high treatment efficiency of SS, heavy metals, organic matter, and TP was expected. The unit pollutant loading rates of COD, SS, TKN, TP, Cr and Pb in the residential zone were 2.392, 2, 130, 64.6, 15.1, 0.31, and 1.83 kg/ha/yr, and those in the industrial zone were 612, 812, 38.7, 14.8, 0.51 and 0.82 kg/ha/yr, respectively.

Chang and Duke (2001b) summarized their research that examined stormwater quality from eight auto dismantling facilities in Los Angeles, CA, over a three year period. The majority of the samples had constituents exceeding stormwater discharge guidelines, but were highly variable. Talbot (2001) discussed some of the stormwater management challenges and solutions for power generation facilities.

Stormwater from a modern waste disposal site was characterized by Marques and Hogland (2001). They examined 22 different constituents and found that suspended solids, COD, BOD, total nitrogen and total phosphorus, exceeded discharge standards. Some of the runoff constituents were greater than found in the leachate from covered landfill sites. Copper, zinc and nickel were the most commonly detected heavy metals, being found in every sample. Surprisingly, the concentrations of zinc, nickel, cobalt, iron and cadmium found in runoff from composting areas were greater than the metal concentrations found in the runoff from areas having stored and exposed scrap metal. They concluded the presence of large amounts of organic compounds, plus site specific drainage pathways, were responsible for these findings.

Akan et al. (2000) noted that a significant pollutant loading to the adjacent receiving water can occur due to runoff from marine drydocks. The authors modeled the quantity and quality of marine drydock runoff by combining the two-dimensional kinematic wave and convective transport equations with an empirical formula for washoff. Lewis et al. (2000) reviewed stormwater-runoff monitoring data from industrial facilities discharging into the upper San Gabriel watershed in the Los Angeles region. The results of this review showed that while industrial facilities occupy less than 1% of the watershed area, they contribute between 10% and 70% of the total copper and between 15% and 60% of the total zinc loads. Moreno-Grau et al. (2000) investigated the heavy metal content of atmospheric aerosols and suspended particulate matter from industrial areas in Cartegena. The industries contributing to the atmospheric metals contamination included power plants, oil refineries, non-ferrous metals, fertilizer plants and a shipyard.

Samples of stormwater runoff from three sawmills on Vancouver Island, British Columbia, Canada, were tested for acute toxicity with juvenile rainbow trout. Causes of toxicity were investigated using toxicity identification evaluation techniques; specifically, treatment with the chelating agent EDTA (Bailey et al., 1999a). Samples of stormwater runoff from nine sawmills in British Columbia, Canada, were also tested for acute toxicity with juvenile rainbow trout over a 23-month period. Toxicity was attributed to divalent cations, particularly zinc, in 32 of the samples. Toxicity in the remaining samples was largely attributed to tannins and lignins and was associated with areas of bulk log handling (Bailey et al., 1999b).

The EPA has released NPDES stormwater-monitoring data from industries using agricultural products (Amick, 1996). Data from facilities representing the food, tobacco, textile mill, apparel, and other industries and appropriate best management practices for reducing or eliminating the pollutants are presented. Su and Christensen (1996) developed a chemical-mass-balance model to identify sources of polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF) in a sediment core from the Baltic Sea that spanned the time period from 1882-1985. The results indicate that coal-fired-power plants, municipal incinerators, and pentachlorophenol-containing matter contribute significantly to the measured PCDD and PCDF.

Hall (1996) collected samples from two estuarine wetlands in highly urbanized areas to determine if chromite ore processing residue surrounding one site contributes to significantly higher chromium (Cr) concentrations in biotic and abiotic media relative to those at a reference site. Although concentrations of Cr, Cu, and Pb were significantly higher in sediment samples from the study site compared to the reference site, no pattern of higher metals concentrations in biotic
samples from the study site was found.

*Line et al.* (1996) examined stormwater from ten industrial sites in North Carolina for a broad list of conventional- and metal- and organic-toxic-substance-pollutant parameters. Automobile-salvage-yard runoff had the highest metal concentrations except for the wood-preserving sites which had the highest chromium concentrations. Other pollutants did not vary significantly between different types of industrial operations.

**Specific Pollutant Sources**

**Litter**

*Williams and Simmons* (1999) investigated the sources of litter in and along the river Taff, South Wales, UK. The greatest inputs of sewage-derived solids were introduced to the river by malfunctioning CSO. While sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (illegally dumped rubbish in public places).

**Sediment**

*Paul et al.* (2002) evaluated the quantitative relationships that had been previously developed between landscape metrics and sediment contamination in 75 small estuarine systems across the mid-Atlantic and southern New England regions of the U.S. The landscape metrics important for explaining the variation in sediment metals levels ($R^2 = 0.72$) were the percent area of nonforested wetlands (negative contribution), percent area of urban land, and point source effluent volume and metals input (positive contributions). The metrics important for sediment organics levels ($R^2 = 0.5$) and total PAHs ($R^2 = 0.46$) were percent area of urban land (positive contribution) and percent area of nonforested wetlands (negative contribution).

*Nelson and Booth* (2002) reported on sediment sources in the Issaquah Creek watershed, an urbanizing, mixed-land use watershed. Human activity in the watershed, particularly urban development, has caused an increase of nearly 50% in the annual sediment yield, now estimated to be 44 tons km$^{-2}$ yr$^{-1}$. The main sources of sediment in the watershed are landslides (50%), channel-bank erosion (20%), and road-surface erosion (15%).

*Benoit et al.* (1999a) studied sources of sediment entering Jordan Cove, Connecticut. Recent sediment accumulation rates were found to be decreasing (from 0.84 cm/yr to 0.40 cm/yr) but were slightly faster than relative sea-level rise at this site (0.3 cm/yr). Long Island Sound was found to be an important source of sediment to the cove; a minor part of total sediment was supplied from the local watershed. *Benoit et al.* (1999b) also studied sources and the history of heavy metal contamination and sediment deposition in Tivoli South Bay, Hudson River, New York. The measured sedimentation rate ranged from 0.59 to 2.9 cm/yr suggesting that rapid accumulation occurred during the time period represented by the length of the cores (approximately the past 50 yrs). The sources of this material were expected to be upland streams, or the Hudson River, during storm events. Concentrations of Pb, Cu and Zn correlated with each other within individual cores at five of the six sites tested, suggesting a common proximate source. *Nelson* (1999) described the sediment budget of Issaquah Creek, a 144 km$^2$ mixed-use, urbanizing watershed near Seattle, WA. The water quality of Lake Sammamish, located at the outlet of the basin, was degrading with time, and fine sediment entering the lake from the watershed was a likely source of phosphorus during periods of lake anoxia. Another potential in-channel concern was the effect of fine sediment on spawning gravel for the salmon species that occupy Issaquah Creek. The sediment balance was being used to identify the major sources of sediment, and thus guide the most effective remedial measures.

**Nutrients**

*Nhapi et al.* (2002) performed an assessment of the major water and nutrient flows in the Chivero catchment area, Zimbabwe. The results showed that urban water demand would exceed available treatment capacity by the year 2003. Sewage effluent presently is the major source of nutrients in the rivers. It was concluded that the current situation is not sustainable.

The research conducted by *Sonoda et al.* (2000) investigated the impact of land use on streamwater nutrient concentrations in an urbanizing watershed in Oregon. During the dry season, soluble reactive phosphorus (SRP) was correlated with light industry land use, while during the wet season, SRP was correlated with light industry, single family residential and mixed residential land uses. During the dry season, nitrate-plus-nitrite was correlated with rural, and heavy and light industry land uses, while during the wet season, NO$_3$ + NO$_2$-N was correlated with rural and heavy industry land uses.
Basnyat et al. (1999) described a methodology to assess the relationships between landuse and nitrate and sediment concentrations in streams in the Fish River, Alabama watershed. Residential and other developed urban areas were identified as the largest contributors of nitrate in the area, while active agriculture was identified as the second largest contributor.

Waschbusch et al. (1999) investigated sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin. They collected numerous sheetflow runoff samples from throughout the test watersheds and used SLAMM, an urban stormwater quality model, to quantify the significance of the different phosphorus sources. Lawns and streets were found to be the most significant sources of phosphorus in the test basins, contributing about 80% of the total annual loading. Peters and Donohue (1999) examined nutrient concentrations and fluxes in tributaries to the Swan-Canning estuary, Western Australia. In addition to the rapid mobility of nutrients in stream water from agricultural areas during the wet season, urban area storm drains typically had high nutrient concentrations, and were also an important source of nutrients to the estuary. Sonoda et al. (1999) described correlations between land use and nutrient inputs to an urbanizing Oregon stream. In the urbanizing areas, possible nutrient sources included fertilizer applied to yards, in addition to roof runoff, various household chemicals, and street runoff.

Manure or compost from beef cattle feed lots can be an excellent source of nutrients and organic matter when added to soils, but they can also pollute runoff. Eghball and Gilley (1999) determined the effects of simulated rainfall on runoff losses of P and N, and EC and pH following application of manure and compost to a Sharpsburg silty clay loam (fine smectitic, mesic Typic Argiudoll) soil having grain sorghum [Sorghum bicolor (L.) Moench] and winter wheat (Triticum aestivum L.) residues.

A study has been conducted on a 4% slope during 1991 to 1993 at Belie Mina, Alabama, on a Decatur silty clay (clayey, kaolinitic, thermic Rhode Paleudult) to determine effects of broiler litter CBL on seasonal transport losses of nutrients and heavy metals in surface water (Wood et al., 1999). Rainfall, slopewash (the erosion of soil particles), surface runoff and fine-litter transport at humid-tropical steepland sites in the Luquillo Experimental Forest, Puerto Rico (18 degrees 20' N, 65 degrees 45' W) were measured from 1991 to 1995 (Larsen et al., 1999). To identify critical sources of P, Sharpley et al. (1999) investigated chemical and hydrologic factors controlling P export from a mixed land use (30% wooded, 40% cultivated, 30% pasture) 39.5 ha watershed in east-central Pennsylvania.

Sauer et al. (1999) reported that grazing animal excretions were not as significant a source of nutrients to runoff water as was poultry litter; such treatments receiving poultry litter had significantly higher losses of nutrients, including those most commonly associated with surface water indices.

Mass balance calculations for a treated and untreated watershed at the BBWM in Maine showed that annual and cumulative retention of experimental N amendments has leveled off at about 80% after nine years of treatment. The annual retention of treatment S has declined to less than 34% after nine years, with the cumulative retention below 60% over the course of the experiment (Kahl et al., 1999). Soils that contained high P levels could become a primary source of dissolved reactive P (DRP) in runoff, and thus contribute to acceleration eutrophication of surface waters. Because results might differ on other soils, runoff studies were conducted on three additional Ultisols to identify the most consistent STP method for predicting runoff DRP levels, and determine effects of site hydrology on correlations between STP and runoff DRP concentrations (Pote et al., 1999).

An investigation of nonpoint sources (NPS) of P loads to Lake Champlain (Vt./N.Y.) revealed that 18% of the P load came from urban sources which only represented 3% of the contributing Lake Champlain Basin (Meals and Budd, 1998). Other sources included agricultural (66%) making up 28% of the basin, and forest (16%) making up 62% of the basin. An analysis of the Middle Huron River Watershed concluded that the highest concentration of P in runoff came from urban residential areas (Brenner and Rentschler,1998). A watershed for a small lake in suburban Boston, Mass., supplied over 90% of the P in the lake during a year with normal precipitation and only 15% of the P during a dry year. The P not supplied by the watershed was supplied by a large population of Canada Geese directly to the lake (Moore et al., 1998a).

Choi and Blood (1999) reported the increase of urban growth along coastal states, resulting in the growth of urban non-point source nitrogen runoff to be a major contributor to coastal and estuarine enrichment.

Sediments in the rivers and basins around Washington, D.C. have high concentrations of phosphorus (P) and based on geographic distributions are largely derived from urban stormwater runoff and municipal wastewater (Huanxin et al.,
of bacteria indicators. They found that first flush discharges contained high levels of pathogens, originating from stormwater drainage canals, for at least two to three days following a storm event. The study period was characterized by unusually low rainfall and lower than typical fecal coliform observations. They suspected that the lower bacteria concentrations may have been due to the drought conditions, rather than from decreased contamination. Brion et al. (2001) addressed sources of bacteria indicators. They found that first flush discharges contained high levels of pathogens, originating from stormwater drainage canals. Fecal coliform concentrations was found to be wet weather-dependant at all stations, except for one. They found that the water is generally unsuitable for primary contact recreation, especially close to urban channel and as much as eighty percent of the time along its banks; 7) the greatest benefit to water quality from CSO reductions occurred for “average” storm events; 8) Even with 100 percent control of bacteria loads from CSOs, contact recreation criteria would be exceeded on occasion. 9) a survey of Giardia and Cryptosporidium identified both pathogens present sporadically for two airport outfalls and two stream locations, but occurred in small numbers relative to animal sources.

Griesel and Jagals (2002) investigated the impact of a variety of urban discharges from Bloemfontain on the numbers of microbiological fecal indicator organisms in the water of the Renoster Spruit subcatchment. The results indicated that the facally polluted urban runoff, combined with inadequately treated wastewater effluent, exceeded the assimilation capacity of the Renoster Spruit in the immediate vicinity of the city to the extent that it posed a possible risk of infection to potential water users for a considerable distances downstream from the urban area. The high levels of fecal indicators in the Renoster Spruit diminished downstream sufficiently that the receiving Modder River, directly downstream from the confluence with the Renoster Spruit, posed an infection risk for domestic users only but not for recreational users of the water.

Heath et al. (2002b) investigated the impacts and control of wet weather pollutant sources on the Ohio River. Key findings of the study included: 1) bacteria were the only pollutant of concern; 2) the project framework could be successfully transferred to other projects; 3) Ohio River bacteria levels exceeded criteria for contact recreation; 4) Ohio River bacteria criteria violations significantly increased during and after wet weather events (typically two-plus days); 5) CSOs collectively accounted for approximately 75 percent of the total annual fecal coliform load; 6) modeling results showed the Ohio River exceeded contact recreation criteria approximately fifteen percent of the time along the center channel and as much as eighty percent of the time along its banks; 7) the greatest benefit to water quality from CSO reductions occurred for “average” storm events; 8) Even with 100 percent control of bacteria loads from CSOs, contact recreation criteria would be exceeded on occasion. 9) a survey of Giardia and Cryptosporidium identified both pathogens in the Ohio River – no consistent relationship with the occurrence of wet weather was identified.

Rifai et al. (2002) reviewed the development of the urban indicator bacteria TMDL for Buffalo and Whiteoak Bayous in Houston, Texas. The paper presented the results of efforts aimed at quantifying the relative contribution of these sources to the observed fecal levels in the bayous. The paper also presented modeling results aimed at developing TMDLs and load allocation scenarios for the two watersheds. Results from summer 2001 monitoring for two storm events showed a direct correlation between in-stream bayou flow and Escherichia coli concentrations. In-situ studies conducted to assess the rates of bacterial regrowth in chlorinated wastewater effluent, sediment resupply and die-off as influenced by light intensity, sediment concentrations, organic strength and isolation from sediment indicated that sediment resupply may be a significant reservoir and source of bacteria to bayou waters.

The suspected source of the bacterial contamination that has affected Lake Pontchartrain, New Orleans, LA, is urban stormwater that is collected and pumped to the lake. Barbe’ et al (2001) concluded that the stormwater may be contaminated by sanitary sewage. Five monitoring stations were selected for study that had varying distances to stormwater drainage canals. Fecal coliform concentrations was found to be wet weather-dependent at all stations, except for one. They found that the water is generally unsuitable for primary contact recreation, especially close to urban drainage canals, for at least two to three days following a storm event. The study period was characterized by unusually low rainfall and lower than typical fecal coliform observations. They suspected that the lower bacteria concentrations may have been due to the drought conditions, rather than from decreased contamination. Brion et al. (2001) addressed sources of bacteria indicators. They found that first flush discharges contained high levels of pathogens, originating from stormwater.
De Luca-Abbott et al. (2000) used enterococci to trace the spatial and temporal impacts of stormwater discharges from an outfall in northeastern New Zealand. Both seasonal and temporal trends in enterococci concentrations were noted, with the maximum contamination being found with the high winter rainfalls and near the outfalls. The occurrence and possible sources of Giardia and Cryptosporidium in Paris rivers were investigated by Rouquet et al. (2000). The results showed that non-source points likely influenced parasite concentrations in the rivers. Parasite sedimentation was high, as was the potential for resuspension by urban runoff. Ramirez Toro et al. (2000) presented the study design for investigating water quality in La Parguera in relation to onshore development, stormwater outfalls, and mangroves and sewage treatment plants in the vicinity. Samples were analyzed for the following constituents: bacteriological indicators (total and fecal coliforms, Escherichia coli, enterococcus), total suspended solids, chlorophyll, light attenuation (light reaching the bottom compared to surface) and nutrients (NH$_4^+$, NO$_3^-$, NO$_2^-$ and PO$_4^{3-}$).

Young and Thackston (1999) studied fecal bacteria in urban tributaries in Nashville, Tennessee. The urban streams (unaffected by sewage discharges) were much higher in sewered basins than in nonsewered basins and the fecal bacteria densities were related to the density of housing, population, development, percent impervious area, and apparent domestic animal density. Preliminary fecal bacteria data collected for surface runoff samples in these urban neighborhoods indicated that a relationship existed between various urban land uses and bacterial loading.

Rainfall increased levels of both giardia cysts and cryptosporidium oocysts in the Delaware River through its influence on turbidity, flow volume, and possibly other unidentified factors (Atherholt et al., 1998). The sources included river bottom sediments, stormwater runoff, direct inputs from domestic or wild animals and possibly WPCP. Samples of point and nonpoint discharges in a creek in Nashville, Tenn. were analyzed for fecal coliforms during four wet-weather events. Modeling showed that bacterial contamination originated minimally (14%) from SSO and mostly from other sources including urban runoff, and upstream agricultural, wildlife and septic tank sources (Goffinet et al., 1998). Duke and Kihara (1998) report that available information supports an improved regulatory approach to nonstorm discharges to storm drains. Some discharge types, including condensate from machinery and firefighting equipment discharges, are believed to represent minimal threats to receiving-water quality while runoff from landscape irrigation is an unregulated discharge that may represent a threat to receiving-water quality and is fairly widespread. During an investigation to identify major sources of bacteria that were keeping the town of Greenwich, Conn. beaches closed, the primary identified WWF sources were an outdoor sewage sludge composting facility and a regional municipal solid waste transfer station (Audet, 1998).

Gibson et al. (1996) reported an overall increase in fecal coliform densities during wet-weather compared with dry weather for the Ohio River and the physical parameters (temperature, pH, and conductivity) do not correspond to CSO discharges into this large river. Lyons et al. (1996) reported that the intensive monitoring conducted could not support the hypothesis that depressed levels of dissolved oxygen found during the low-flow, summer months are associated with discharges from CSOs in the Cincinnati, OH area. Van Der Tak et al. (1996) presented the results of New Jersey’s Tri-City Sewerage Authority’s monitoring program of CSOs for Hg, SS, BOD$_5$, and fecal coliform. Clean-sampling techniques were used in order to detect mercury at extremely low levels.

Toxicants

Mumley and Abu-Saba (2002) investigated the sources of mercury in San Francisco Bay as part of the TMDL development for mercury. Half of the contemporary excess mercury concentration in Bay sediments is accounted for by background processes, including shifts in the mineralogy of watershed source sediments and atmospheric deposition of global air sources. The other half of the excess mercury in Bay sediments is mostly attributed to mining legacy sources, with lesser fractions attributed to wastewater discharge (1-3%) and urban runoff (3-10%). Water column mercury concentrations in the turbid Bay waters are directly proportional to mercury concentrations of suspended sediments.

An investigation of natural and anthropogenic sources of SO$_4^{2-}$ in the Arno River catchment, northern Tuscany, Italy was conducted by Cortecci et al. (2002). The river solutes consisted mainly of Ca$^{2+}$ and HCO$_3^-$, but the proportions of Na$^+$, Cl$^-$ and SO$_4^{2-}$ increase downstream, in keeping with the basically anthropogenic origin of the latter. The d$^{34}$S(SO$_4^{2-}$) signature also increases downstream toward the urban areas.

Toxicity testing was performed by de Vlaming et al. (2000) in order to identify chemical causes and sources of contamination. Urban runoff was found to be toxic to Selenastrum. The overall results indicated that the whole-effluent contamination.
toxicity (WET) tests, when combined with traditional chemical analyses, were beneficial in locating sources of toxicity within a watershed.

Pitt et al. (1999) investigated typical toxicant concentrations in stormwater, the origins of these toxicants, and storm and landuse factors that influenced these toxicant concentrations. Nine percent of the 87 stormwater source area samples analyzed were considered extremely toxic (using the Microtox® toxicity screening procedure). Thirty-two percent of the samples exhibited moderate toxicity, while fifty-nine percent of the samples had no evidence of toxicity. Vehicle service and parking area runoff samples had many of the highest observed concentrations of organic toxicants. All metallic toxicants analyzed were found in the analyzed samples. Marsalek and Rochfort (1999) also investigated the toxicity of urban stormwater and CSO. Acute toxicity, chronic toxicity and genotoxicity of stormwater and CSO were studied at 19 urban sampling sites in Ontario, Canada, using a battery of seven bioassays. Most frequent responses of severe toxicity were found in stormwater samples (in 14% of all samples), particularly those collected on freeways during the winter months. Compared to stormwater, CSO displayed lower acute toxicity (7% of the samples were moderately toxic, and none of the samples was severely toxic).

Huber and Quigley (1999) studied highway construction and repair materials (e.g. deck sealers, wood preservatives, waste-amended pavement, etc.) for their chemical and toxicological properties and leaching characteristics. *Daphnia magna* (a water flea) and the algae *Selenastrum capricornutum* were used for the toxicity tests. Leaching was evaluated as a function of time using batch tests, flat plate tests and column tests, as appropriate for the end-use of the highway material.

Malmquist et al. (1999) investigated the sources of pollutants discharging to Lake Trekanten, Stockholm, which receives stormwater from residential and traffic areas. Lead, cadmium, copper, zinc, phosphorus, and PAH in the stormwater from the catchment area were quantified by a source model. It was concluded that building materials were the dominant sources for copper and important sources for zinc. Source control measures, including covering copper-plated roofs, decreasing traffic, and changes of vehicle materials, were expected to reduce discharges of copper to less than a third of current levels.

Potential contributions of urban runoff pollutants to surface sediments of the Passaic River in New Jersey were investigated by Walker et al. (1999). Mass loading calculations demonstrated that urban runoff was a significant source of the metals observed in the sediments, and that PAH and DDT sediment loadings could, in some cases, be accounted for by urban runoff. Observed sediment loads for PCB, however, were significantly higher than were estimated from urban runoff.

**Heavy metals**

Sorme and Lagerkvist (2002) investigated the sources of heavy metals in urban wastewater in Stockholm, Sweden. Results showed that it was possible to track the sources of heavy metals for some metals such as Cu and Zn (110 and 100% found, respectively) as well as Ni and Hg (70% found). Other metals sources are still poorly understood or underestimated (Cd 60%, Pb 50%, Cr 20% known). The largest sources of Cu were tap water and roofs. For Zn the largest sources were galvanized material and car washes. For Pb, Cr and Cd, where sources were more poorly understood, the largest contributors for all were car washes. Vink and Behrendt (2002) investigated the heavy metal emissions, loads and transport in the Rhine and Elbe river basins. In most cases the measured heavy metal loads at monitoring stations were lower than the sum of the heavy metal emissions. This behavior in large river systems could largely be explained by retention processes (e.g. sedimentation) and was dependent on the specific runoff of a catchment. Between 51% (for Hg) and 74% (for Pb) of the total transport in the Elbe basin was supplied by inputs from diffuse sources. In the Rhine basin diffuse source inputs dominated the total transport and deliver more than 70% of the total transport. The diffuse hydrological pathways with the highest share were erosion and urban areas. Boller and Steiner (2002) investigated the emission and control of copper from roofs and roads in urban surface runoff. A large copper façade was used to investigate the concentrations of copper emitted. The concentrations ranged from 1 – 10 mg/L.

Notgrass (2002) performed an analysis of the effect of precipitation on metals loading in Boulder Creek (Arizona). The sources of pollutants (arsenic, beryllium, copper, lead, manganese and zinc) are three tailings piles, the upper, middle, and lower tailings piles, and an adit discharge from the abandoned Hillside Mine. The critical condition of Boulder Creek occurs during low flow (0.75 cfs). Flow ranges from spatially interrupted, independent pools in the summer to raging floods in response to large winter storms. The winter storms have a larger areal extent, contribute higher overall flows to Boulder Creek, but bring rain mainly to the higher elevations of the headwaters. Metals flushed into the system during
these types of precipitation events are diluted due to the high flows in the creek. The monsoon storm driven flows are highly variable, dependent upon location and storm intensity. Monsoon storms also have a dramatic effect on metals loading in Boulder Creek. By providing brief, but intense, precipitation, monsoon storms flush large amounts of metals into the creek without greatly increasing the overall flow.

De Vos et al. (2002) performed a survey of the distribution and origin of platinum group elements in contemporary fluvial sediments in the Kentish Stour, England. The main factor responsible for the dispersion of these elements is their extensive anthropogenic use, and significant quantities enter fluvial systems via road runoff, storm drains, and wastewater and sewage treatment systems. The highest element abundances occur in the motorway-runoff sediments (maximum total PGE content of 55 ng/g), whilst the lowest values were recorded in the sedimentary rocks, where some samples contain PGE at concentrations below the limit of detection. The total PGE content of the river sediments ranged from 0.4 to 10.8 ng/g. The distribution and variation in concentrations and ratios of the PGE in the contemporary fluvial sediments correspond strongly with land-use changes (urban versus rural) and with points of discharge from sewage works. In-stream metal loadings in the Tijuana River watershed were characterized by Gersberg et al. (2002). In general, metal-loading trends could be ascertained from the shape of the storm hydrographs. Elevated metal concentrations existed in base and storm flow conditions.

Nonpoint sources of heavy metals (Hg, Cd, Cu, Zn, Pb, Ni) in the Rhine River watershed were investigated by Mohaupt et al. (2001). They found that urban stormwater was the most important source for these metals in the Dutch portion of the watershed. Erosion was of lesser importance, while atmospheric deposition onto open water was a much less important source. Anthropogenic nonpoint sources accounted for 40 to 80% of the total sources for some metals. They recommended further studies of urban nonpoint sources of heavy metals and on ways to improve urban stormwater management. A mass balance of all known sources and sinks for heavy metals (Ag, Cd, Cu, and Pb) in New Haven Harbor, CT, was conducted by Rozan and Benoit (2001). Sources included direct atmospheric deposition, rivers, treated sewage effluent, combined sewer overflows, and permitted industrial discharges. All of the fluxes were directly measured, and the uncertainties were quantified. River inputs accounted for most of the total yearly metal discharges, while the salt marshes removed about 20 to 30% of the metals from the rivers before reaching the harbor. Atmospheric deposition is of minor importance, and is comparable to sewage effluent discharges. Davis et al. (2001a) presented loading estimates of lead, copper, cadmium, and zinc in stormwater from different sources. They reviewed available data from the literature, and conducted controlled experiments and other sampling. Specific sources that they examined included building siding and roofs; automobile brakes, tires, and oil leakage; and wet and dry atmospheric deposition. The most important sources they identified were building siding for all four metals, vehicle brake emissions for copper, and tire wear for zinc. Atmospheric deposition was an important source for cadmium, copper, and lead.

A study of heavy metal concentrations in sediments from Australian estuaries and the continental shelf by Birch (2000) showed that the concentration of metals was significantly higher in the estuaries than along the continental shelf. Also, the estuaries were found to have sediment metals concentrations that were related to the degree of urbanization/industrialization in the watershed. High metals concentrations, including Pb and Zn in Port Jackson (Sydney, New South Wales) which were at levels expected to have adverse environmental/biological effects, were found in the fluvial sediments, indicating that metals are still being added to the estuaries, potentially through stormwater runoff (including land reclamation leachate). Webster et al. (2000) analyzed the sources and transport of trace metals in the Hatea River catchment and estuary in New Zealand. They found that the recently deposited estuarine sediment has elevated levels of Cu, Pb, and Zn from the more densely-populated areas, city stormwater drains and the Cu-containing antifoulants used in the marina. All metals were transported in both dissolved and particulate form in the tributaries, with lead being shown to bind most effectively to the sediment. Levesque and De Boer (2000) investigated the impact of a large urban center on the trace metal chemistry of a surficial fine-grained sediment in the South Saskatchewan River, Canada. No effect from the urban center on the metals content of the sediment was seen - with the exception of uranium, whose concentration was measurably greater below the urban center. Smith and Swanger (2000) investigated the impact of leaching of lead-free solders in construction waste and found that alloys containing antimony had leachate concentrations above regulatory limits. Alloys containing silver also potentially could impact the environment if entrained in stormwater runoff.

Birch et al (1999) investigated the sources of heavy metals in stormwater draining into Port Jackson, Sydney, Australia. Road dust from streets with different traffic densities in the catchment were highly enriched with Cu, Pb, and Zn. Soils also contained high concentrations of these metals over extensive areas of the catchment. Preliminary data suggests that roads and soils were probably important in supplying heavy metals to the estuary but the contributions of atmospheric
deposition and contaminated sites had not yet been evaluated.

Land applications of organic soil amendments can increase runoff concentrations of metals such as Fe and Zn, metalloids such as B and As, and non-metals such as P and S that have the potential for causing adverse environmental impacts. Aluminum sulfate, or alum (Al₂(SO₄)₃·14H₂O), can reduce concentrations of some materials in runoff from sites treated with organic amendments (Edwards et al., 1999).

Sanudo-Wilhelmy and Gill (1999) examined dissolved (< 0.45 µm) trace metals and phosphate concentrations in surface waters collected along the Hudson River estuary, New York, between 1995 and 1997 and compared them with samples collected in the mid-1970s. They concluded that the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary.

Concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd) and nickel (Ni) measured in the headwaters of the Hawkesbury-Nepean River, Aust. were amongst the lowest reported in the literature for freshwater systems, and will be used as a benchmark for assessing the effects of increasing urbanization in the catchment (Markich and Brown, 1998). Davis et al. (1998a) studied the levels of chloride and bromide and the ratio between them in the groundwater of Yucca Mountain, Nev. Atmospheric precipitation generally has a mass ratio between 50 and 150 and summer runoff in urban streets, between 10 and 100. Samples of mercury (Hg) and methyl-mercury (MMHg) were collected during baseflow and storm flow from the Anacostia River, an urban, impacted river of greater Washington, D.C. (Mason and Sullivan, 1998). Total concentrations of Hg during the storm flow measured 3—5 times that of the baseflow indicating storm flow is the major vector for Hg in the Anacostia.

Birch et al. (1997) reported that point sources (waste dumps, sewage overflows, and discharge from a polluted river) were responsible for elevating sediment heavy-metal concentrations up to 50 times above background while NPS contributed in raising baseline levels to four times background. High trace-element concentrations in the Piedmont province streambed sediments were related to land use (O’Brien, 1997).

Solo-Gabriele and Perkins (1997) quantified metal transport (i.e. Fe, Cu, chromium [Cr] and arsenic [As]) for the Aberjona-River watershed and proposed storm-sewer overflows and direct urban stormwater runoff as mechanisms of metal transport. The runoff from roofs and streets contributed 50% — 80% of heavy metals, i.e., Cd, Cu, Pb and Zn, to the total mass flow in domestic wastewater (Boller 1997).

Schueler (1996b) summarized the effort to characterize metal and organic toxicants in stormwater discharges in the 700 mi² Santa Clara Valley, CA watershed. The highest Zn, Cd, Ni (nickel), Pb, and Cu concentrations were associated with industrial-land uses and all of the heavy industrial-area samples were found to be extremely toxic; probably from the dissolved metal fractions. Pesticides and other nonpolar hydrocarbons were probably responsible for the moderate to toxic samples obtained from the mixed-land-use areas.

Cadmium van Geen and Luoma (1999) conducted a five-year study of dissolved Cd in San Francisco Bay, California and adjacent coastal waters. They showed that the composition of surface waters towards the mouth of the estuary was determined largely by the effect of coastal upwelling. However, surface samples collected throughout San Francisco Bay confirmed an internal Cd source unrelated to river discharge. The Cd content of a benthic foraminifer (Elphidiella hannai) in a dated sediment core from San Francisco Bay was measured to determine if the water column Cd enrichments in San Francisco Bay could be related to the rapid development of the watershed.

Copper. Copper mine spoil from Touro, A Coruna, Sp. was used in the construction of rural roads and tracks in the surrounding area. Roadside soils, sediment in drainage ditches, and water from first-order streams were analyzed to determine both total Cu content and the Cu fraction susceptible to uptake by plants. Despite some high soil concentrations of total Cu, Cu fraction susceptible to uptake was low in most samples, and no water samples were found to exceed European Community legislation thresholds for drinking water and for supporting fish (Arias et al., 1998).

Lead. Davis and Burns (1999) examined lead concentrations in runoff from painted surfaces. In many tests, high lead concentrations were found (using 100 mL of wash water over 1600 cm² of surface). Lead concentrations from 169 different structures followed the following order (median concentrations in the wash water): wood (49 µg/L) > brick (16 µg/L) > block (8.0 µg/L). Lead concentration depended strongly on paint age and condition, with the lead levels from washes of older paints being much higher than from freshly painted surfaces. Lead from surface washes were found to be
70%, or greater, in particulate lead form, suggesting the release of lead pigments from the weathered paints.

**Mercury.** Bonzongo et al. (1999) studied the impacts of land use and physicochemical settings on methyl mercury levels in the Mobile-Alabama River system. In the Coastal Plain portion of the state, Hg concentrations above the FDA’s safe limit have been found in tissues of some fish species in both Fish River and Mobile Bay, Alabama. These rivers/streams receive most of their Hg from NPS (e.g. atmospheric deposition and inputs related to land use within the watersheds). They reported results of detailed investigations aimed to study the biogeochemistry of Hg and other trace metals, specifically the impact of different land-use types within the watersheds on Hg speciation. Glass and Sorensen (1999) examined a six-year trend (1990-1995) of wet mercury deposition in the Upper Midwest of the United States. The annual wet mercury deposition averaged 7.4 μg Hg/m²-yr and showed significant variations between sites and illustrated significant increasing trends over the monitoring period. Warm (rain) season wet mercury deposition was found to average 77% of total annual wet deposition.

**Platinum.** Schaefer et al. (1999) studied the increasing concentrations of Pt, Rh, and Pd in urban areas associated with increased use of catalytic converters on automobiles. At a typical urban site, the daily deposition rate of Pt in airborne dust was up to 23 ng/m².

**Organic toxicants**
Watcher and Herrmann (2002) measured the concentrations of PAHs, polynuclear aromatic sulfur heterocycles (PASH) and polynuclear aromatic ketones (PAK) in stormwater runoff from roofs and roads in Dresden, Germany. The selected classes of trace organic pollutants are mainly released during incomplete combustion and are emitted by traffic, industry and residential-heating. The pollutographs of the particle-bound fraction showed a "first-flush" effect. Rain contributed about half of the load of pollutants in the runoff of roof sites. Its contribution to the load at the street sites was far less important. Specific concentrations of pollutants sorbed on to particles as well as the concentrations in the aqueous phase were smaller in street runoff than in roof runoff. Grynkiewicz et al. (2002) traced 16 selected compounds from the PAH group at 10 precipitation and 5 runoff sampling sites located across the “Threecity” (Gdansk-Sopot-Gdynia). Naphthalene, phenanthrene+anthracene, fluoranthene and pyrene were found most frequently and at top concentrations (from few ng L⁻¹ up to several hundred ng L⁻¹), while dibenzo(a,h)anthracene, indeno(1,2,3-c,d)pyrene, benzo(a)pyrene, and benzo(g,h,i)perylene were present at concentrations close to the detection limit only. Correlations of PAH concentration with the percentage of coal stoves in the area gave coefficient of correlation (R²) equal to 0.85 and 0.78, for rainwater and runoff, respectively, while PAHs concentration vs. traffic intensity correlation yielded the respective values of 0.40 and 0.54.

Muller et al. (2002) studied the point and nonpoint sources of pesticides in surface waters and their transport pathways. The contribution by the WWTPs to the pesticide load was defined as point-source pollution (PSP). The load was dominated by PSP with at least 77% of the total pollution. No significant interdependencies between intrinsic properties of the pesticides, hydrometeorological factors, and the loads occurring in the stream could be found. Kay (2002) studied organophosphate pesticides and metals in the Chollas Creek watershed from 1999 to 2001. The first four storm events monitored from 2000-2001 resulted in no definitive linkage between diazinon and toxicity. There were no observed relationships between dissolved metals and toxicity to either Ceriodaphnia dubia or Hyalella azteca. Further, there was no specific area or watershed reach that definitively demonstrated greater contaminant contribution during storm events. Only after analyzing the data resulting from the first flush event was a correlation between diazinon and bioassay organism toxicity evident, but no specific area or watershed reach demonstrated greater concentrations of contaminants.

Ellis and Chatfield (2001) reported that nonpoint discharges of oil and hydrocarbons to urban receiving waters constitutes a major pollution source, being responsible for up to 30% of all reported water pollution incidents in the UK. Commercial and industrial areas, along with heavily used highways, are the major sources of these pollutants, with about 20,000 to 24,000 tonnes of oil per year being discharged to urban receiving waters from these sources. Blanchard et al. (2001) investigated PAHs and PCBs in the combined urban flows to the Acheres wastewater treatment plant in Paris, France, under different meteorological conditions. The PAH concentrations were found to increase much more than the PCB concentrations during wet weather. They concluded that atmospheric wet deposition was the most important source for the PCBs, while urban stormwater was the most important source for the PAHs.

Ashley and Baker (1999) developed inventories and identified sources for hydrophobic organic contaminants (HOC) in the surficial sediments of Baltimore Harbor, Maryland. There was enormous spatial variability in the concentrations of HOC at the 80 sampling sites which was not well correlated to grain size or organic carbon content, suggesting that
nonequilibrium partitioning and/or proximity to sources were important factors. High concentrations of HOC were localized around major urban stormwater outfalls. Lower molecular weight PAH, having lower affinity for particles, may travel further from the sources. Ollivon et al. (1999) studied the PAH fluctuations in rivers near Paris (France). During storm events, the atmospheric contributions of PAH were negligible, compared to stormwater discharges. During heavy rains affecting the river Seine, high first flush PAH concentrations were observed, and about 25% of the PAH came from the rain and about 75% came from the stormwater. During light rains, atmospheric contributions only accounted for about 2% of the total PAH to the river.

Air-water exchange fluxes of 13 polycyclic aromatic hydrocarbons (PAH) were determined along a transect in the Patapsco River from the Inner Harbor of Baltimore, Maryland, to the mainstream of the northern Chesapeake Bay. The direction and magnitude of the daily fluxes of individual PAH were strongly influenced by the wind speed and direction, by the air temperature, and by the highly variable PAH concentrations in the gas and dissolved phases. The largest PAH volatilization fluxes occurred adjacent to the stormwater discharges, driven by elevated dissolved PAH concentrations in surface waters (Bamford, 1999).

Urban runoff samples were collected in a 1-year period in the Santa Monica Bay Watershed during both dry and storm periods and analyzed for polychlorinated dioxins, polychlorinated furans, and polychlorinated naphthalenes (Fisher et al., 1999).

A study of methyl tert-butyl ether (MTBE) in an alpine lake in the Sierra Nevada, Calif. suggested that neither highway runoff nor snowmelt runoff is a significant source of MTBE to the lake. Most MTBE is introduced to the lake from motorized watercraft operating on the lake during the summer (Reuter et al., 1998). Hydrocarbon pollution in lake core sediments, streambed sediments, stormwater and street surface sediments were investigated in the Brunette River watershed in Burnaby, British Columbia, Can. Hydrocarbon concentrations in streambed sediments corresponded to the land use indices of impermeable area and traffic density and road washoff of nonparticulate oil appeared to be an important source of hydrocarbons to stormwater solids, and ultimately streambed and lake core sediments (Larkin and Hall 1998). A thorough review of previous studies analyzing the contribution of highway runoff and urban stormwater to source loadings of semivolatile organic compounds (SVOC) and volatile organic compounds (VOC) showed that SVOC, primarily PAH, have been extensively studied, and are correlated with SS concentration. VOC have been studied to a lesser extent, and result primarily from urban land surfaces, but also from atmospheric washout (Lopes and Dionne, 1998). PCB found in street dust in Buffalo, N.Y. were redistributed by natural and vehicle-generated wind. More frequent street cleaning was suggested to reduce CSO and stormwater contamination of the Buffalo River (Irvine and Loganathan, 1998).

While spills may not be important in terms of the average annual loading of petroleum hydrocarbons in a watershed, large and medium size spills pose a significant risk to the aquatic resources in urban areas (Zandbergen and Hall, 1998).

Particle scavenging was the dominant contributor of PCB and PAH to falling snow in Minn., but less important in rain (Franz and Eisenreich, 1998). Gas scavenging was important only for low molecular weight PCB congeners and PAH which exceeded levels as predicted by Henry's Law constants for both snow and rain.

The concentration levels of phenol found in Terre Haute, Indiana were high enough to cause eye irritation and skin disorders in humans according to the U.S. Environmental Protection Agency (U.S. EPA) standards. The Environment Protection Department of Hong Kong identified stormwater as one of the likely sources of pollutants to Victoria Harbor, Hong Kong. Chlorohydrocarbons; PCB (as Aroclor 1254); total 2,2-bis (p-chlorphenyl)-1,1,1-trichloroethane (DDT); and total hexachlorocyclohexane (HCH) pose a significant risk, and probably have caused damage to the marine ecosystem as well as posing a hazard to seafood consumers (Connell et al., 1998). Enhanced concentrations of dissolved methane (CH$_4$) and nitrous oxide (N$_2$O) were observed only in the western Oder Estuary of the Baltic Sea near the mouth of the Peene River. The distributions of CH$_4$ and N$_2$O in the investigated Bodden waters are, directly or indirectly, linked to the Peene River runoff (Bange et al., 1998).

A receptor-source model was used to apportion source contributions for PAH in street and creek sediments. The model showed that vehicles along with the coke ovens, are the major contributors to PAH in street sediments (Sharma et al., 1997). The spatial distribution and fingerprint patterns of PCB and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) strongly indicated that CSO was a source of contamination in sediments near these outfalls. Evaluation of the industries operating within the CSO districts provides a link between tile facilities that discharge wastes to the combined
sewer system (CSS) and PCB and PCDD/F found in the sediments (Huntley et al., 1997). Concentrations of 18 hydrophobic chlorinated-organic compounds in streambed sediments from 100 sites throughout New Jersey were examined (Stackleberg, 1997). The highest median normal concentrations were found in samples from the most heavily urbanized and populated areas, with the lowest concentrations in the least developed, most heavily forested areas.

Trihalomethane (THM) formation potential at different stations of the Kurose River and the contribution from point and NPS within the river basin were determined. THM precursors in the river could be attributed mainly to industrial effluents, domestic wastewater, and agricultural drains with stormwater runoff contributing significant amounts of THM precursors to the river during storm events (Galapate et al., 1997).

The source and fate of benzothiazoles leached from crumb rubber material (CRM) and asphalt containing 1% — 3% CRM were investigated (Reddy and Quinn, 1997). The environmental chemistry suggests that benzothiazoles from CRM should not be harmful. Measurements of aliphatic hydrocarbons in the Point Loma Wastewater Treatment Plant (PLWTP) effluents were mainly petroleum derived and were generally consistent with those of PAH. (Tran et al., 1997). The PLWTP discharged approximately 3.85 metric tons of n-alkanes (C-10 — C-35) in 1994, well below the level (136 metric tons) estimated in 1979.

Steuer et al. (1996) reported on a two-year study that monitored stormwater from eight cities in the Lake Superior basin. Four to five storms were sampled at each station, for a broad list of conventional and toxic-substance-pollutant parameters, with fluoranthene and pyrene having the highest concentrations for any of the organic toxicants (site-median concentrations were about 5 µg/L).

Results reported by Shepp (1996) suggested that storm-runoff concentrations of petroleum hydrocarbons from automotive-intensive land uses typically range from 0.7-6.6 mg/L. Evaluation of these observations and their respective catchments suggested that the degree of automotive exposure (a combination of duration of exposure and volume of exposure) is the primary factor in the generation of petroleum hydrocarbons in storm runoff from automotive-intensive land uses. Delzer et al., (1996) reported that in the most comprehensive evaluation of stormwater volatile organic compounds (VOCs) ever conducted, the USGS analyzed 592 stormwater samples collected from 16 United States cities for 62 VOC compounds, including methyl tert-butyl ether (MTBE). Stormwater was thought to be a potential source of MTBE in urban groundwaters. Four of the VOCs were detected in more than 10% of the samples (toluene, xylene, chloroform, and trimethylbenzene); MTBE was found in about 7% of the samples at a median concentration of 1.5 µg/L.

Revitt et al. (1996) identified the sources of hydrocarbons in urban storm runoff through an extensive monitoring program and the use of principal component statistical analyses. It was found that anthropogenic organics were invariably associated with the greatest concentrations of hydrocarbons in aquatic organism tissue. Automobile-exhaust-related hydrocarbons (especially fluoranthene and pyrene) and lubricating oil components (methylated homologues), along with biogenic hydrocarbons (high-molecular-weight odd-numbered carbon-chain alkanes, with >C25) were most closely related to bioassay-mortality rates.

Using site-specific nonpoint and point source PAH-concentration data from waterborne sources, PAH loadings in the near-shore regions of Massachusetts Bay were estimated to be 1.4 x 10^4 kg/yr (Cura and Studer, 1996). The greatest loadings of low-molecular-weight and total-PAH compounds were from POTW while the greatest sources of high-molecular-weight and carcinogenic compounds were nonpoint sources including rivers. Urban stormwaters and CSOs were found to have the highest PAH concentrations of the various source types.

**Pesticides and herbicides.** Lee et al. (2000) found that stormwater runoff in San Diego Creek was toxic to Ceriodaphnia and Mysidopsis. About half of this toxicity was found to be attributable to the use of the organophosphate pesticides diazinon and chlorpyrifos used in the urban areas for structural termite and ant control and for lawn and garden pest control. Lutes et al. (2000) investigated an eleven-acre lake on a golf course at NAS Jacksonville in terms of potential ecological and health risks posed by sediments and fish in the lake. The identified contaminants of interest at the site; PCBs in fish, metals in sediments, pesticides in sediments, and PAHs in sediments, are most likely attributable to storm water impacts. The identified exposure pathways to the contaminants are through recreational fishing and the use of the lake by wildlife.

Temporal trends of three phenoxyacid herbicides: 2, 4-D, dichlorprop and MCPA and the phenolic herbicide (bromoxynil), were determined in ambient air and precipitation over a 4-yr period within a well-defined watershed in
southern Manitoba. Elevated levels of these herbicides in creek water samples were observed during period of high concentration in both atmospheric compartments, despite the lack of surface runoff events within the watershed over that period (Rawn et al., 1999).

Farrugia et al. (1999) studied household herbicide use. They found that typical urban uses of herbicides exceeded agricultural uses, and the transfer coefficients (amount of the herbicide in the runoff compared to the amount applied) was also higher in urban areas. The highest measured diuron concentration was 20 µg/L, while the average was 5 µg/L. Compared to EEC standards for drinking water protection (0.1 µg/L), they concluded that suburban uses of herbicides may severely endanger drinking water supplies.

A study that examined surface waters adjacent to golf courses in N.C. showed that levels of pesticides and nutrients were generally below U.S. EPA health advisory levels in water bodies on the course, and always below detection levels at the outflows from the courses (Ryals et al., 1998). An analysis of water samples from 64 rivers and streams in New York showed that pesticide concentrations were dependent on upstream land use and pesticide application patterns (Phillips et al., 1998). Specific pesticides are correlated with each land use type.

Pesticides present in rainwater do not pose a greater groundwater contamination problem during artificial roof runoff infiltration (a practice in Switz. to reduce runoff) than does the direct application in agriculture (Bucheli et al., 1998a); however, the herbicide (R,S)-mecoprop, a root protection agent in Preventol B 2 commonly applied to roofs, is of the same order of magnitude as loads from agricultural applications (Bucheli et al., 1998b).

**Monitoring and Sampling**

Davenport et al. (2002) reviewed the EPA National Nonpoint Source Monitoring Program (NMP), whose purposes are to provide credible documentation of the feasibility of controlling nonpoint sources and to improve the technical understanding of nonpoint source pollution and the effectiveness of controlling nonpoint source control technologies and approaches. Maglione et al. (2002) reviewed the data collection plan for non-point and point source determination for the Upper Ashley River system. This new data collection was needed because the TMDL was based on data that was almost 10 years old and significant changes had occurred in the watershed within the past decade. Wilson (2002) reviewed Pennsylvania’s community-based water monitoring. The paper explored the makeup of these groups as well as the rationale behind their formation and sustained activity. The role of community based water monitoring in state assessments also was explored.

Leecaster et al. (2002) assessed sampling designs for urban stormwater monitoring for their efficiency. Flow and TSS information was collected every 15 minutes in the Santa Ana River in 1998. The data was used to calculate the "true load" and then three within-storm sampling designs (flow-interval, time-interval, and simple random) and five among-storm sampling designs (stratified by size, stratified by season, simple random, simple random of medium and large storms, and the first m storms of the season) were simulated. The evaluation included estimating three estimators for storm mass emissions (mean, volume-weighted, and ratio) and three estimators for annual mass emissions (median, ratio, and regular). Single storms were most efficiently characterized (small bias and standard error) by taking 12 samples following a flow-interval schedule and using a volume-weighted estimator of mass emissions. Sampling seven storms is the most efficient method for attaining small confidence interval width for annual concentration. Sampling three storms per year allows a 20% trend to be detected in mass emissions or concentration over five years. These results are decreased by 10% by sampling seven storms per year.

De Ridder et al. (2002) presented an overview of the influence of analytical method, data summarization method, and particle size on the total suspended solids removal. Based upon the data from three source studies, each of these variables were isolated, evaluated, and found to demonstrate the potential to influence the summary of TSS removal efficiency by a minimum of 7 to 10 percentage units. Compounding of these differences resulting from combinations of these variables could lead to a considerable range of possible results. It was found that a consistent analytical method, data summarization method, and particle size must be applied to systems under review in order to produce accurate, comparable data.

Pitt and Burton (2002) reviewed methods available for the assessment of urban wet-weather flow impacts. The data from the past decade has shown, during numerous receiving water assessment studies that no one single approach (e.g., chemical-specific criteria, benthic microorganisms, or habitat surveys) can routinely be used to accurately determine or
predict ecosystem health and beneficial use impairment. Each assessment approach or component has associated strengths and weaknesses. The selection of specific assessment tools and goals would be highly dependent on local conditions and objectives.

Ruby and Brosseau (2002) reviewed the comprehensive long-term monitoring and assessment plan for the San Francisquito Creek watershed. The objectives were placed into the following general categories: Physical – activities related to the physical habitat of the watershed (erosion, sedimentation, barriers, etc.) and land use impacts Hydrological – flooding potential, surface/groundwater interactions, low flow conditions (re: aquatic habitat), etc. Chemical – sources, distribution and impact of known and potential (suspected) chemical pollutants Biological – biological habitat and processes, as well as biodiversity and special status species Social – community interests and concerns (aesthetics, uses, property and water rights), social aspects and resources (demographics, complementary facilities, access), and direct impacts of human activities (litter, recreation, etc.).

The Patrick Center for Environmental Research of The Academy of Natural Sciences in conjunction with the University of Delaware developed a method to assess streams based on geomorphic, habitat and riparian features (Cianfrani et al., 2001). An overall Stream Quality Index (SQI) was developed that could classify streams into four major categories: severely impaired, impaired, moderately impaired, and slightly or non-impaired. The SQI rating was used with other natural-resource inventory data in restoration planning and overall management of the Fairmount Park system.

Dwyer and Wissing (2000) described Waterwatch Australia, a national monitoring and environmental education program. The program has involved over 2000 groups monitoring approximately 5400 sites in 246 catchments, with most work done by volunteers and community groups.

Buried mineral soil-bags and natural solutions, studied as indicators of forest response to elevated N and S inputs at the BBWM, were reported by Fernandez et al. (1999) having continued utility in environmental monitoring and assessment research. In the Mediterranean region, climatological factors make CSO a major urban pollution problem that should be monitored and controlled. In comparing rainfall estimates from weather radar pictures to a rain-gauge network in terms of the ability to predict sewer flow in the urban basin in Barcelona, Spain, the results showed that the use of radar data enabled the combined sewer system model to improve the reproduction of the observed flows. Also indicating the spatial description of rainfall was a key problem in modeling the events giving rise to CSO (Sempre-Torres et al., 1999).

A receiving water quality monitoring program was developed to measure beneficial use impacts resulting from toxicity in stormwater runoff. The goals of the water quality monitoring program were to determine the persistence, fate and significance of the aquatic toxicity in the receiving water (Taylor, 1999).

Gracie (1999) presents a monitoring protocol and evaluates performance of several projects which have had varying degrees of success. Clar et al. (1999) described the current approach adopted by Baltimore County, Maryland to integrate stream stability assessment and water quality modeling for a comprehensive study of the Patapsco River Watershed in south-western Baltimore County.

The 1996 handbook *Environmental Indicators to Assess Stormwater Control Programs and Practices* described the use of 26 indicators within 6 general categories B water quality, physical/hydrological, biological, social, programmatic and site-specific B to measure the success of stormwater programs. The handbook also suggests a methodology for using the indicators to identify problems within local watersheds and for assessing, re-evaluating and improving stormwater management programs. With grant assistance from the Water Environment Research Foundation, the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) was demonstrating this methodology at a watershed scale (Coyote Creek watershed, Santa Clara County, California) and at a smaller, more defined scale, that of a 28-acre industrial catchment in the City of Santa Clara, California (Cloak and Bicknell, 1999).

A new settling testing method was compared to a traditional test in a laboratory side-by-side evaluation. The comparison attempted to determine whether these tests can capture the rapidly settling particles in wet-weather flow. A summary of the performance, as measured by predicted percent removal of the columns for 15 laboratory bench-scale tests, and the limitations and advantages of each approach were presented and compared (O’Connor et al., 1999). Kuo et al. (1999) presented results of field tests of pollutant removal efficiencies of grassed swales conducted in Taiwan and Virginia. The Virginia experiments tested a highway median swale, while the Taiwan experiments were conducted on an agricultural test farm.
The specific goals of the Small Business Innovation Research (SBIR) project, sponsored by the Federal Highway Administration (FHWA), was to develop a small, inexpensive, simple, effective sheetflow sampler to aid transportation officials in meeting their regulatory requirements. The field testing program includes the installation of approximately 18 samplers throughout varying highway environments in Virginia, Maryland, and California. Stormwater samples will be collected and analyzed for various highway pollutants over a period of 9 months (Graziano et al., 1999).

According to Klove and Bengtsson (1999) the hydrology of a cutover fen was studied from May to October in 1995 and 1996. Rainfall equivalent depths were measured every 15 min and stream runoff was continuously monitored. Storm runoff was separated into different components; rain falling directly into channels and rapid groundwater response based on a contributing area method and on different electrical conductivities of rain-, ground- and stream-water. The Ohio Environmental Protection Agency employed biological, chemical, and physical monitoring and assessment techniques to assess how effectively they were achieving their goals of the Clean Water Act, namely the maintenance and restoration of biological integrity and the basic intent of water quality standards (Yonder et al., 1999). Strecker (1999) described some of the problems with typical BMP monitoring and effectiveness reporting; and suggested the utilization of consistent stormwater monitoring techniques.

A method for quick, simple, and inexpensive analysis of CSO used a statistical approach for rainfall analysis and considered the preceding dry period, which has a significant affect on the pollutant loading of the overflow (Udale and Osborne, 1997). The Greater Houston Wastewater Program devised an innovative flow-remonitoring effort that allowed engineers to eliminate the construction of overflow-control facilities. The initiative integrated temporary- and permanent-meter-flow data that allowed for modifications in design to save 77-million dollars (Bagstad, 1997). MacDonald and Phillips (1997) discussed applications and configurations for multiple-path ultrasonic transit-time flowmeters under various hydraulic regimes commonly encountered in wastewater collection systems. A station was established to perform continuous high quality time-series flow, wastewater, and stormwater-runoff characteristics monitoring. Time-series research will be carried out in order to establish knowledge of dry-weather characteristics and rainfall-runoff relationships including the variability of relevant stormwater pollutants (Schaarup-Jensen et al., 1997). An experimental urban catchment was created in the center of Paris for the purpose of obtaining a description of the pollution of urban WWF. Results revealed that a significant portion of pollution originates from inside the combined sewer and it is suspected that the pollution is probably due to resuspension of sewer sediments (Gromaire-Mertz et al., 1997). Baloch (1997) observed large seasonal differences in river-mercury (Hg) concentrations and loadings showing dramatic increases in response to spring snowmelt and precipitation events. Results revealed total Hg concentrations were highly correlated with SS.

Dowling and Mar (1996) developed and tested a low-cost “culvert composite sampler” for obtaining flow-weighted stormwater samples. This sampler should enable much more cost-effective stormwater sampling for many purposes, including NPDES monitoring. Initial testing was performed for a sheetflow sampler to collect highway runoff using an acrylic prototype (Stein et al., 1998).

Lee and Jones-Lee (1996) stressed the need to focus receiving-water stormwater-monitoring activities on those pollutants causing the specific problems identified, instead of using very broad (and expensive) monitoring approaches. Highly focused site-specific studies are needed for each type of use impairment. The focus of the monitoring program should be devoted towards the suspected use impairments, such as, aquatic-life toxicity and bioaccumulation, closure of beaches and shellfish harvesting due to high bacteria concentrations, etc. When specific impairments are identified, then detailed chemical analyses may be justified in order to identify the specific compounds causing the observed problems.

Fuchs et al. (1996) investigated the use of biofilm samplers (six glass plates inside a 30 cm PVC pipe, initially coated with stearic acid and exposed for 14 days) to indicate heavy-metal variations in an urban area. The biofilm samplers were found to be very representative of more difficult to conduct sampling efforts, and are probably more representative of conditions affecting aquatic life.

**Rainfall and Flow Measurement**

Grottker et al. (2002) discussed limited flow reduction as a measure for reducing hydraulic stress from urban storm flows into rivers and creeks. Bowns et al. (2002) reviewed the use of a multiphase data collection and analysis program (inspection of plant headworks, system metering and pump stations; collection system flow metering with rainfall recording; groundwater level identification; structure inspections; flow isolation; and smoke test and CCTV inspections)
in Sandy Hook, Kentucky to create digital aerial maps of the city’s sewer system and to guide an upgrade of both the treatment plant and collection system. Cowger et al. (2002) reviewed the problems experienced by the Sanitary District of Decatur (Illinois) with its existing infrastructure telemetry system. An evaluation of alternatives demonstrated that Cellular Digital Packet Data (CDPD) provided for a more reliable system and one that could be polled for data more frequently.

Carlson (2002) reviewed the coupling of land surface classification and impervious surface cover derived from Landsat™ imagery with an urban growth model. The results have been used to predict future changes in surface runoff resulting from urbanization. An illustration was presented.

The Tropical Rainfall Measuring Mission (TRMM) is a United States-Japan joint project to measure rainfall from space (Ohsaki 2001). In this paper, rain/no-rain discrimination for the TRMM was validated through simulation and theory for the no-rain condition and by comparison with the ground-based radar data for rain conditions. The precipitation radar (PR) aboard the TRMM demonstrated the feasibility of measuring rainfall from space (Sadowy et al., 2001). The Second Generation Precipitation Radar (PR-2) has been developed. The PR-2 will improve capabilities and substantially reduce system mass compared to the TRMM PR. This paper surveyed the technologies for the PR-2.

A combined Microwave/Infrared Rain Rate Algorithm (MIRRA) was presented by Miller et al. (2001). MIRRA combined the strengths of these two broad approaches to rain rate measurement from space. The algorithm was tested using data from the TOGA-COARE campaign, with shipboard radar rain rate estimates used as truth. Results indicate enhanced performance in bias, correlation, and rms error for MIRRA. Calibrated radar rainfall systems, often called ‘virtual rain gauges,’ have become popular due to the advantages they offer over conventional precipitation monitoring networks (Orie et al., 2001). The 3 Rivers (Allegheny County, Pennsylvania) Wet Weather Demonstration Program made virtual rain gauges available to the public by integrating the calibrated rainfall system with the Internet. A methodology was developed that matched coincident space-based radar (PR) and ground-based volume scanning weather radar observations in a parallel three-dimensional Cartesian grid (Anagnostou et al., 2001). The data matching was performed to minimize uncertainties associated with the type of weather seen by the radars, grid resolution, and differences in radar sensitivities, sampling volumes, viewing angles, and radar frequencies. The authors compared reflectivity observations from the PR and several U.S. weather surveillance Doppler radars (WSR-88D) as well as research radars from the TRMM field campaigns in Kwajalein Atoll and the Large Biosphere Atmospheric (LBA) Experiment. Correlation values above 0.8 were seen between PR and ground radar.

A daily rainfall disaggregation method that yields regional hourly rainfall estimates was presented in terms of application to continuous-simulation watershed models (Socolofsky et al., 2001). When compared with hourly data, the method reproduced well the variance, lag-1 autocovariance, and probability of zero rainfall. Application of the method in the upper Charles River watershed in eastern Massachusetts demonstrated that the method greatly improved the river flow simulation capability of the hydrologic model over alternate simulations using hourly rainfall from outside the watershed. An overview of weather radar-related developments in South Africa, as related to hydrological research and operations, was given by Terblanche et al. (2001). This program developed the necessary infrastructure, expertise and related hardware and software to collect and archive high-quality radar data. Shortcomings of weather radar data for hydrological applications were described and the ongoing research efforts to address these shortcomings were highlighted. Valeo and Tang (2001) developed a model for the second order process of rainfall in an area of southern Ontario. Hourly rainfall data collected from 17 gages over a period of five years were used to develop a correlation function for rainfall, with an exponential model for the correlation function being selected over a spherical and Gaussian model. A regional, index storm approach based on L-moments was applied to estimate short duration (less than or equal 24 h) design rainfalls in South Africa (Smithers and Schulze 2001). The regionalization was performed using only site characteristics (latitude, longitude, altitude, concentration of precipitation, mean annual precipitation (MAP), rainfall seasonality and distance from sea). The index storm used was the mean of the annual maximum series and a relationship was derived between the index storm and MAP.

Rainfall simulation experiments were carried out on more than 40 1-m² plots to measure infiltration point-processes (Perrin et al., 2001b). The high density of measurement devices allowed identification of the origin and nature of the various contributions to runoff for the different physiographic units of the watershed: urban area, farmland, pasture, forested land, and paramo. Variations in the runoff coefficients were related first to the baseflow and second to the amount of rainfall in the previous 24 h. In the paper by Morin et al. (2001), high-resolution meteorological radar data are used for the determination of a characteristic temporal scale for the hydrological response of the basin – the ‘response time scale’ (T-s*). The identification of the response time scale was carried out by analysis of observations only and
without assuming a specific rainfall-runoff model. For all analyzed basins a stable response time scale was identified with relatively short time scales found for the urban and arid basins (15-30 min) and longer time scales for the rural basins (90-180 min). Habib and Krajewski (2001) reported on the application of a computational fluid dynamics-based method to improve the aerodynamic design of rainfall measurement devices, including a two-dimensional video disdrometer that provides information about raindrop size distribution. The distorted wind field around and inside the instrument's body was simulated using a three-dimensional numerical model. Raindrop trajectories were simulated to investigate the wind effect on the catchment efficiency of the instrument.

The study by Kurz and Qualls (2001) evaluated the EPA’s PCS (Permit Compliance Study) database and determined the various parameters that may be useful in developing I/I control and sewer rehabilitation strategies on a state and regional level. The study summarized DMRs (monthly NPDES Discharge Monitoring Reports) for 1999 from 790 systems in Region 4 categorized as “major.” Maheepala et al. (2001) described the issues that need to be considered when conducting a successful and cost-effective hydrologic data monitoring program. It was found that that tipping bucket resolutions up to 0.5 mm would give reasonably accurate results in urban stormwater modeling, and two-minute data logging intervals were suitable for flow data monitoring. The results also suggested that combining low cost simple flow measurements and limited high cost sophisticated measurements could reduce the data acquisition cost without compromising the accuracy of flow hydrographs measured in stormwater conduits. Remote sensing was used as a source of data to address the spatial variability of hydrologic processes such as storm runoff (Melesse et al., 2001). Remote sensing provided quantitative land cover information of suitable spatial resolution for model inputs. The study area was the S-65A sub-basin of the Kissimmee River basin in south Florida, and results showed that the temporal and spatial variability of runoff volume resulting from changes in land cover could be determined from Landsat images.

The WERF research described by Schultz et al. (2001b) will assist municipal agencies to quantify and simulate rainfall-derived infiltration and inflow (RDII) that affects their sewer systems. Eight major categories of RDII analysis methods were tested in several diverse sewersheds and metrics suitable for objective comparison of the RDII analyses were identified. An accurate dye dilution testing protocol using Rhodamine WT was used to quantify flow meter accuracy in the Greater Detroit Regional Sewer System (Stonehouse et al., 2001). The seven technologies assessed were electromagnetic induction meters (magneters); full-conduit, multiple-path, transit-time meters; full-conduit, open-channel, ultrasonic meters; flumes; and weirs. It was concluded that (i) there were observable accuracy differences between flow meter technologies, (ii) objective standards like dye dilution testing were critical, (iii) verifying installed accuracy was important, and (iv) the simplest technology that can be used often was the best. Swarner et al. (2001b) reported on the effort by King County determine the wet weather performance and geographic distribution of I/I through its entire service area; conduct several pilot rehabilitation projects to evaluation rehabilitation effectiveness; develop and calibrate an accurate hydraulic model of the system; and implement a Regional I/I Control Program. The paper discussed the political and administrative actions to achieve consensus among the local agencies and analyzed the I/I results as a function of basin size.

Chao and Hegwald (2000) documented procedures for deploying flow meters and for data evaluation to ensure that a flow-monitoring program would be successful. Stonehouse et al. (2000) reported on the work of the Flow Metering Task Force (FMTF) in Detroit, whose purpose was to evaluate and improve the current flow metering occurring in the Detroit sewer system. The guidelines developed by this group included procedures for meter evaluation, data collection and review, and information sharing. This group also developed a dye dilution testing protocol that provided more accurate results than prior protocols. A specialized probe using time-domain reflectometry (TDR) was developed, calibrated and field tested for continuously measuring soil-water content and surface runoff during studies of water erosion and sediment transport (Thomsen et al., 2000). The laboratory investigation of this TDR probe showed that water levels could be measured with a standard deviation of less than 2 mm. Zandbergen and Schreier (2000) investigated the current methodologies used to assess the impervious cover in a watershed. These included ground surveys, stereophotogrammetry, air photo interpretation, and satellite image analysis. The following factors were found to influence the accuracy of imperviousness measurements (in order of decreasing importance): selection of imperviousness factors; accuracy and scale of land use mapping; consideration of land cover in addition to land use; and watershed delineation.

Burrows et al. (1999) evaluated a flow stick with inclination transducer. The data from the flow stick, when combined with a depth measure, provided an accurate measure of the instantaneous flow rate in a storm, sanitary or combined sewer. Goyen and O’Loughlin (1999) described their project in which they used intra-catchment gauging stations in Canberra, Australia to collect data regarding rainfall and runoff. They determined that the spatial and temporal variability of rainfall and runoff even over a single catchment were great enough to ensure the single-parameter models cannot
perform well consistently and so, they proposed a runoff simulation model that incorporates the intra-catchment elements needed to determine runoff from a larger watershed. Tilley et al. (1999) demonstrated the inadequacy of current stream-gauge height-measurement-averaging techniques combined with a rating curve to estimate flow at a site during flash flooding in urban areas. They recommended that the monitored gauge height be used for each subarea for each time increment in order to calculate the volume of flow during a flash flood. Steiner et al. (1999) demonstrated the necessity for having good quality rain gauge data if it will be used to adjust for biases in radar rainfall estimates of precipitation. They concluded that the differences resulting from radar data processing scenarios were small compared to the effects of rainfall data adjustment based on rain gauge information. Maheepala and Perera (1999) described the quality assurance checks program used during the collection of urban drainage hydrologic information for a flood-prediction model for Victoria, Australia. They discussed not on the quality of the data but also the occupational safety and health aspects of collecting it. Guiterrez (1999) reported on the development of regional regression equations for predicting flows at ungaged urban catchments in Mexico.

Riotte and Chabaux (1999) found that the ratio of U-234/U-238 could be used to investigate hydrological processes such as flooding events. Weiler et al. (1999) used natural tracers/isotopes with mass balance calculations to determine the fraction of surface flow and subsurface flow in the receiving water prior to a rain event. The isotopes were also used to demonstrate the importance of infiltration water to the quantity of subsurface runoff due to preferential flow. McDonnell et al. (1999) combined tracer studies (using 18O) with measures of rainfall and runoff in four nested catchments on South Island, New Zealand. The results showed that water contributions from various source areas in a catchment was a complex function of the mixing of these contributions and of the contact time in the groundwater and drainage system. Mehlhorn and Liebundut (1999) determined that the modeling approaches for tracer hydrology and rainfall-runoff modeling were mathematically equivalent and therefore, tracer time parameters could be used to calibrate baseflow runoff models. Coupling the water age and turnover time of the mobile groundwater led to a more accurate determination of the baseflow in the stream.

Post et al. (1999) used hand-held radiometers to evaluate the ground cover of semiarid rangelands and to correlate the data collected with the hydrologic characteristics of the area. The results showed that vegetative cover and percent runoff were highly correlated with spectral reflectance, while soil-rock cover and eroded sediment were poorly correlated with the reflectance.

A method to adjust the daily precipitation measured by the U.S. National Weather Service (NWS) 20.3 cm (8 in.) standard gauge for wind-induced undercatch, wetting loss, and trace amount of precipitation was tested at ten climate stations in Alaska during 1982-83. Results showed that daily adjustment increased the gauge-measured annual precipitation by up to 800 mm for the two years (Yang et al., 1998). An accuracy test conducted in the Stephen F. Austin Experimental Forest, Tex. revealed that a U.S. standard gauge, weighing-type recording gauge, a standard gauge fitted with an Alter windshield, and a pit gauge showed each gauge to have an average deficiency greater than 10% when compared to a recording anemometer (Chang and Flannery, 1998). Correction for wind effect on angle of raindrop reduced the deficiency from 11% to 6% leaving the remaining error to wind effects, nonrandom errors and other unknown sources. The procedures were presented for the collection and quality control of rain data from a network of tipping bucket rain gauges in Den. carried out by the Danish Meteorological Institute as input to software packages such as MOUSE and SAMBA for designing sewers and storage basins, and simulating overflows and flooding. Although it is possible to improve the efficiency of the quality control, long term corrections will always be necessary (Jorgensen et al., 1998).

Spatial and temporal variability in rainfall concentrations of several contaminants were monitored at seven locations in or near the Conodoguinet Creek watershed of south-central Pa. and compared precipitation quality in forested, agricultural and urban areas. The major ion concentrations were related more to regional influences than local while herbicides in precipitation may have had more local influences (Shertzer et al., 1998). Quality checks also indicated that trained volunteers were reliable in collecting data in a timely manner. The Residential Stormwater Monitoring Project, initiated by the Boston Water and Sewer Commission in March of 1997, characterized the seasonal variation in the quality of stormwater discharged from a low density residential area (Schofield and Eggleston, 1998). The project included precipitation monitoring, stormwater quality sampling and quantification of flows at a single manhole location for up to five storms per season for a period of one year, surface stormwater quality sampling at five gutter locations, and inspection and sampling of dry weather flows in storm drains.

Short-term flow monitoring programs such as those employed for SSO and CSO should focus on the anticipated use of
collected data (Hollenbeck, 1998). Monitoring should start approximately two weeks prior to initiation of the normal “storm season” and a minimum of 90 days (ideally 120) of short-term monitoring are necessary to determine a reliable relationship between rainfall intensity and stormwater inflow. Flow monitoring devices at or upstream of sewer overflow structures for recurrent CSO and SSO in the Pittsburgh, Pa. were installed to determine the quantity of sewage which pass through selected regions. The monitors collected data until the selected study points stayed within specified limits for eight consecutive months (Patsey, 1998). In a Boston, Mass. sewer separation project, several flow meters recorded depths which differed significantly from wet and dry weather manual measurements. Analysis determined that the meters were most likely reading a constant fraction of the actual change in depth (DePasquale and Caulfield, 1998).

The U.S National Weather Service radar images have produced significantly greater resolution in the spatial distribution of rainfall in comparison to raingauges alone which can contribute to the accuracy of CSO modeling (Burgess et al., 1997).

Toxicity Testing
Palachek et al. (2002) reviewed recommended assessment protocols for use with ambient toxicity tests in the 305(b) and 303(d) listing process. Assessments were conducted in Texas based on 6 stream segments for sediment toxicity and 4 stream segments for water toxicity in order to provide a means to address observed impairments. The paper presented supporting evidence that the above criteria are reasonable, considering that toxicity test results are used to make regulatory “yes or no” decisions concerning ambient 303(d) listing. The supporting evidence included a summary of the controversy concerning ambient toxicity test variability and Type I errors.

Heijerick et al. (2002) correlated chemical speciation results for zinc from roofing materials with the biosensor test Biomet™. The regression analysis showed that, for this type of runoff samples, the rapid screening biosensor was capable of predicting (a) the total amount of zinc present in the runoff samples (R² of 0.93-0.98; p less than or equal 0.05) and (b) the observed 72 h-EbC₅₀’s (R² of 0.69-0.97; p less than or equal 0.05).

Hall and Lockwood (2002) reviewed methods for identifying fish pathogens in industrial effluents. The study resulted in a very functional “weight of evidence” approach that provides three levels of certainty (symptomatic, preliminary identification, confirmation) regarding the causative role of fish pathogens. This would allow a cost-effective, phased approach in resolving WET permit compliance issues.

Schiff et al. (2002) discussed using Toxicity Identification Evaluations (TIE) to assist in developing the TMDL for aquatic toxicity in the Chollas Creek and San Diego Bay, California. The primary objective of this study was to identify the toxicants and determine the areal extent of impairment in the waterbody of concern. The stormwater plume emanating from Chollas Creek was dynamic, covering areas up to 2.25 km². Approximately half of the plume was estimated to be toxic to marine life, based upon results of purple sea urchin (Strongylocentrotus purpuratus) fertilization tests. The area nearest the creek mouth was the most toxic (No Effect Concentration, NOEC = 3 to 12% plume sample), and the toxicity decreased with distance from the creek mouth.

Warren-Hicks et al. (2002) discussed the need to account for toxicity test variability when evaluating TIE test results. This research was designed to address the precision of WET test procedures, and to develop methods for incorporating variance estimators into EPA decision-making frameworks. In addition, a national data base of reference toxicity tests, a national data base of WET compliance test results, and a series of case studies were developed in support of the statistical analyses.

Bdour et al. (2001) examined the relationships between Index of Fish Density (IFD) and man-made disturbances, watershed parameters, habitat parameters, water quality parameter, and climate parameters for the 61 HUCs (Hydrological Unit Code) for the South Fork Clearwater River basin in Idaho and 15-20 reaches for Red River and Newsome Creek within the South Fork Clearwater River Basin. The results showed that incorporating both fine and coarse scale parameters in any assessment model will improve the correlations. Biomonitoring using juvenile giant clams (Tridacna maxima) was conducted in conjunction with sediment and stormwater sampling at U.S. Army Kwajalein Atoll. Elevated levels of metals, PAHs, pesticides, and PCBs were detected in clams from the sampling locations. Trends in clam tissue, sediment and stormwater data suggested that both sediment and stormwater are significant sources of the pollutants detected in clams.

Baker et al. (2000) reviewed a project undertaken as part of Mecklenberg County’s Surface Water Improvement and
Management (SWIM) program, and which included restoration in the highly-urbanized Edwards Branch watershed. The project emphasized the importance of using a variety of monitoring techniques - EPA stream habitat assessment protocol, ambient water quality monitoring, fish and benthic macroinvertebrate surveys, and channel cross-section monitoring - to investigate the effectiveness of the installed BMPs and other restoration techniques. The bioassessment approach used in the Camp Creek Watershed in Fulton County, Georgia was reviewed by Jones (2000a). By linking the biological results with the water quality monitoring data, management goals were set and improvements were focused on critical management areas. The paper by Rochfort et al. (2000) encouraged the use of benthic assessment techniques, in conjunction with toxicity testing and sediment and water chemistry analyses, to determine the impacts of stormwater and combined sewer overflows (CSOs) on receiving water and the biota. The results from all three analysis techniques showed that the sediment chemistry could not be correlated to either the toxicity testing or the benthic community impacts, and that a combination of techniques was necessary to show a complete picture of stream health.

Chappie and Burton (2000) described the application of in-situ aquatic sediment toxicity testing for stormwater runoff assessment. Burton et al. (2000) described the problems associated with using traditional toxicity testing methods for assessing the biological impacts of stormwater runoff. The problems noted included the inability to produce reliable conclusions when this technique was used to detect the adverse effects of fluctuating stressor exposures, nutrients, suspended solids, temperature, UV light, flow, mutagenicity, carcinogenicity, teratogenicity, endocrine disruption, or other important subcellular responses. In watersheds receiving multiple sources of stressors, accurate assessments should use a range of laboratory (such as whole effluent toxicity [WET] tests) and novel in situ toxicity and bioaccumulation assays, and should include a simultaneous characterization of physicochemical conditions and indigenous communities. de Vlaming et al. (2000) used USEPA protocols for freshwater toxicity testing to evaluate ambient water quality in California. Testing since 1986 showed that the three WET tests, when performed along with toxicity identification evaluations (TIEs) and chemical analyses, were useful in identifying pollutant sources and identifying potential benefits of alternate land uses or best management practices. Tobiason and Logan (2000) reported on the benefits of using WET testing of stormwater at outfalls to trace sources of pollution at Sea-Tac International Airport. WET testing was found to be very effective in helping to identify a zinc-galvanized metal rooftop as the source of zinc contamination and therefore the source of the toxicity of the stormwater runoff. Ellis (2000a) reviewed using in-situ biomarker techniques to evaluate the effects of transient pollution events, such as the inflow of stormwater runoff, in urban receiving waters. This paper also discussed the limitations of more traditional toxicity tests such as the Direct Toxicity Assessment (DTA) procedures for assessing transient events that leave sub-lethal stresses on the biota.

Several field and laboratory assays were employed below an urban storm sewer outfall to define the relationship between stormwater runoff and contaminant effects. Specifically, two bioassays that measure feeding rate as a toxicological endpoint were employed in the field and in the laboratory, along with bioassays measuring survival and growth of test organisms. The results of the study suggest significant toxicity at this site was due to accumulation of contaminants in the sediment and the mobilization of these contaminants during a storm event (Hatch and Burton, 1999).

Doherty et al. (1999) compared Ceriodaphnia dubia and the Microtox® inhibition tests with Vibrio fischeri on industrial and municipal wastewaters. For samples that were not toxic, the Microtox® method correlated well with the results with the C. dubia results. However, for samples that were toxic to C. dubia after 24 hours, the Microtox® detected toxicity in only two. For five other samples that the Microtox® found to the toxic, the C. dubia required a minimum of 48 hours of exposure before toxicity could be detected. Kosmala et al. (1999) used C. dubia in laboratory toxicity tests in combined with field analysis of the Hydropsychid life cycle to assess the impact of both the wastewater treatment plant effluent and the stormwater overflow on the receiving water. They found that the results seen in the laboratory toxicity tests and in the in-situ biological measurements were due to nutrient and micropollutant loadings. Marsalek et al. (1999) used several different toxicity tests to assess the various types of toxicity in typical urban runoff and in runoff from a multi-lane highway. The tests included traditional toxicity analysis using Daphnia magna, the Microtox® toxicity test, sub-mitochondrial particles and the SOS Chromotest for genotoxicity. Tucker and Burton (1999) compared in-situ versus laboratory conditions for toxicity testing of nonpoint-source runoff. They found that NPS runoff from urban areas was more toxic to the organisms in the laboratory while the agricultural runoff was more toxic to the organisms exposed in situ. The differences seen between the two types of toxicity tests demonstrated the importance of in-situ assays in assessing the effects of NPS runoff.

Brent and Herricks (1999) proposed a testing protocol for the toxicity assessment of wet weather events that includes an event-focused toxicity test method, a corresponding test metric that more accurately represents the toxicity of brief exposures, and an event-based index that described the acute toxicity of wet weather events. This testing protocol was
designed to quantify toxic response produced by brief contaminant exposures (< 24 h), as well as time-varying contaminant exposures, which were typical of wet weather events. The protocol described the use of an event-focused toxicity test to determine a PELET50 (post-exposure lethal exposure time for 50% of the population) metric for individual event samples.

When considering urban runoff toxicity, it was necessary to carefully consider magnitude, duration, and frequency in any toxicity analysis. First, to measure this toxicity it was necessary to apply a new paradigm, the time-scale toxicity paradigm. The time-scale toxicity paradigm was reviewed, and data from storm events was provided to illustrate paradigm utility in assessing the toxicity of urban runoff and the related impact of urban runoff on receiving systems (Herricks, 1999).

Researchers in King County, Wash. used transplanted and wild mussels to monitor Cu, tributyltin and PCB. In the wet season, concentrations of Cu increased in wild mussels near CSO although the source of Cu was unclear (Munger et al., 1998b). Seidl et al. (1998a) found that CSO contributed toxicity to the River Seine, Fr. even after settleable solids were removed and effluent was diluted five-fold. The results of this study suggest that Zn may contribute significantly to phytoplankton toxicity of CSO effluent. A further CSO study in the Seine comparing biodegradable to residual dissolved organic carbon (BDOC to RDOC) showed that an additional source of carbon was contributing to the oxygen budget, possibly phytoplankton or degraded particulate organic matter (Seidl et al., 1998b). In Paris, Fr. further CSO studies showed a higher proportion of refractory organic carbon during rain events than during dry weather with a possible contribution of the in-sewer sediments to the bacterial wet weather flux (Seidl et al., 1998c). A multi-parameter continuous water quality monitor was examined for evaluating in-situ photosynthesis/respiration rates of microbes (Easton et al., 1998). The city of Indianapolis, Indiana completed a large in-stream sampling program directed at characterizing ambient bacteria levels in the White River and its tributaries. Analysis showed less wet weather influence on bacteria in the White River than in the tributaries (Burgess et al., 1998). Søballe (1998) illustrated the difficulties inherent in monitoring an ecosystem. Monitoring programs provide unbiased evaluation only for those phenomena whose temporal and spatial characteristics match those of the monitoring program.

Two years of sampling in San Francisco, Calif. revealed that only certain individual dioxins/furans and PAH were commonly detected in the city’s collection system, and may be indicative of specific sources. PAH were also detected more frequently in catchbasin influent than effluent implying that particle deposition in catchbasins may be an effective removal mechanism for PAH (Moore et al., 1998b).

**Testing for Chemical Pollution and Pollution Tracers**

Barraud et al. (2002) discussed the implementation of a monitoring system to measure the impact of stormwater runoff infiltration. The main difficulty in monitoring is due to the complexity of the system and the need for multidisciplinary approaches. A second difficulty is that the measurements must be carried out in situ, in an uncontrolled environment. The paper presented an experimental site, the project objectives and the way the monitoring has been built according to the various disciplines involved (biology, ecology, hydrology, chemistry and soil sciences) and to the will of assessing all the uncertainties in the measurement process.

Gruning and Orth (2002) investigated the dynamic behavior of the composition of combined sewage using on-line sensors – sensors for dissolved solids using UV absorption and sensors for particulates using scattered light measurement. A statistical relationship between these two parameters and the chemical oxygen demand was established. The analyzing methods permitted the real-time control of sewer systems on the basis of the pollution carried in the combined sewage. Hack and Lorenz (2002) presented the use of an on-line wastewater organic load measurement in a combined sewer system as a technique to improve and integrate wastewater transportation and treatment. The paper reviewed the use of the spectral absorption coefficient at $\lambda = 254$ nm (SAC), defined in DIN 38402 by the German Institute for Standardisation. As a purely physical parameter, the SAC shows a good correlation to organic sum parameters like COD and TOC, especially if municipal wastewater is considered.

Polls and Lanyon (2002) introduced the methodology used in a case study in Chicago for determining DO impairment. The methodology was the use of real-time, continuous water quality monitors (monitors). Beginning in August of 1998, DO was measured hourly at 20 stations on the deep-draft waterways using remote in-situ monitors. The paper reviewed the continuous DO monitoring approach used in urban deep-draft waterways in Chicago. Included were (1) the criteria used for selecting monitoring stations; (2) the features of the continuous monitors; (3) a description of the housing enclosures used to protect the monitors in the field; (4) the field and laboratory DO monitoring programs; (5) the quality
control program and the data management system; and (6) examples of the continuous DO monitoring data showing the causes and sources of DO impairment in Chicago urban waterways.

O’Neill et al. (2002) investigated the determination of the method detection limit for methyl tert-butyl ether (MTBE) in water and discussed the application of a convenient headspace analysis method for MTBE. The MDL of the headspace method was calculated at 2.0 µg L\(^{-1}\) by the EPA single-concentration design method\(^1\) and 1.2 µg L\(^{-1}\) by a calibration method developed by Hubaux and Vos (1970). The static headspace method was applied to analysis of a tap water sample and a monitoring well sample from a gasoline service station, a river sample, and aqueous extracts from soil excavated during removal of a leaking underground storage tank (LUST). The water samples examined in this study had MTBE concentrations ranging from 6 to 19 µg L\(^{-1}\). Aqueous extracts of a soil sample taken from the LUST site had 8 µg L\(^{-1}\) MTBE.

Cristina et al. (2002) reviewed the use of a granulometry-based selection methodology for the separation of traffic-generated particles in urban highway snowmelt runoff by testing snow melt particles from 10 highway shoulder sites in Cincinnati. Each site was exposed to traffic and maintenance activities (plowing and de-icing salts only). Model results supported previous experimental data indicating the predominance of surface area and heavy metal mass was associated with the coarser fraction of particles. The methodology was in the form of a process selection diagram to evaluate mechanisms of particle separation.

Automated samplers were used to collect urban runoff in Pecan Creek, Denton, Texas (Appel and Hudak 2001). The results showed that concentrations of some heavy metals (cadmium and arsenic), as well as pesticides (atrazine and diazinon), were within ranges typical for urban runoff and first flush samples were more concentrated than composite samples for most of the constituents. Automated samplers were seen to be an effective way to sample urban runoff in Pecan Creek. Ruban et al. (2001) studied the SS and COD concentrations in combined sewers using in-line ultraviolet and visible absorbances. The optical measurement of SS and COD could then be used to determine average or long term pollution loads, for example the yearly impact of urban stormwater discharges. Continuous and on-line measurements would allow agencies to react with short delay to unexpected phenomena. A portable, field rugged, sampling and analysis system was developed for the rapid screening of aqueous samples during scoping and remediation studies (Beals et al., 2001). The equipment uses ion selective solid phase extraction (SPE) disks and counted for the radionuclide of interest in the field using portable detectors. The Savannah River Site H-area tank farm storm water runoff system was analyzed for Sr-90 and Cs-137.

The investigation by Moustafa and Havens (2001) determined the effect of sampling frequency and sampling type on estimates of monthly nutrient loads and flow-weighted nutrient concentrations in a constructed wetland. The results showed that bi-weekly composite sampling could be used to monitor nutrient concentrations and loads discharged from larger-scale Everglades Stormwater Treatment Areas (STAs) now under construction. Compounds including coprostanol, epicoprostanol, cholesterol and dihydrocholesterol were quantified in CSO waters and their relative ratios calculated to investigate their potential application as source tracers (Marvin et al., 2001). A mean coprostanol:epicoprostanol ratio of approximately 70 was calculated for CSOs. When combined with physical measurements (e.g., current velocities) and meteorological data, these ratios may assist in determining the influence of shore-based activities, including sewage treatment and livestock operations, on aquatic systems. Indicators for assessing pathogen contamination and for distinguishing human origin and animal origin were investigated (Sankararamakrishnan and Guo (2001) with samples being taken from storm sewer outfalls to a coastal lake during wet weather as well as from the lake during the dry weather. The FC-to-FS ratio indicated the contribution of both human and animal wastes, with the presence of human wastes confirmed by increased concentrations of caffeine, fluorescence whitening agent, fluoride and anionic surfactant during wet weather.

Hartmann et al. (2000) investigated the usefulness of linear alkylbenzenes (LABs), a byproduct of LAS detergents, as a marker of sewage in the marine environment. Their usefulness was confirmed in Narragansett Bay where LABs were found in higher concentrations near the urban outfalls and in the upper layers of the sediment. Standley et al. (2000) investigated the potential for using molecular tracers of organic matter, such as fecal steroids, caffeine, consumer product fragrance materials, and petroleum and combustion byproducts to trace sources of organic matter in a watershed. The authors showed that molecular tracer content could be correlated with watershed-scale land uses and that wastewater treatment plant effluents were associated with caffeine and fragrance materials while urban runoff was associated with the PAHs. Allison et al. (2000) described two years of monitoring and characterization (litter material larger than 5 mm) of freeway runoff in California.
Maldonado et al. (1999) evaluated the use of trialkylamines and coprostanol as chemical tracers of pollution in the western Mediterranean and the northwestern Black Sea from urban areas. Trialkylamines were found to be the better marker of urban pollution in the water because they had higher concentrations in the water and were not as likely to associate with the particulate phases. Sidle and Lee (1999) used the deuterium isotope to determine the origin of the stormwater runoff from an urban watershed. Deuterium isotope concentrations were significantly different in the vadose and saturated zones between an area affected by a storm sewer leak and an area where a stream contributes to the groundwater. The measurements were useful in modeling leaks and seepages and in improving mass balances in urban watersheds.

Soerens et al. (1999) reported on the development of a sampling scheme to find the minimum required sampling interval during a storm that would be necessary to obtain realistic pollutant loadings for TMDLs. They found that the optimum sampling interval was dependent on the parameter measured and the stream order. Persson et al. (1999) developed and demonstrated a passive in-situ sampler for metals in stormwater runoff. The results indicated that the metals concentration in the passive sampler corresponded to the bioavailable fraction of the metals in the runoff. They also found that in-situ deployment of the passive sampler with direct analysis of the water by laser ablation-ICP/MS provided better accuracy than traditional bottle sampling, either a grab or a composite sample.

Instream water quality monitoring assessed CSO in the Rouge River, Mich. (Hufnagel et al., 1998). The primary CSO impacts on the river were bacteria and oxygen demand while solids and nutrients were not identified as a limitation of river viability.

A field program sampled conventional parameters, i.e., bacteria, trace metals and organic compounds, in the water column, sediments, CSO discharges and fish and invertebrate tissues in the Duwamish River and Elliott Bay, Seattle, Wash. (Mickelson, et al., 1998). Because concentrations were too low for conventional sampling methods, semi-permeable membrane devices were used to assess water column organic concentrations and low level mercury sampling techniques were used to estimate mercury concentrations. In order to optimize the design and management of sewer networks and settling tanks, there is a need to determine the settling velocity characteristics of sewage and stormwater solids (Lucas-Aiguier et al., 1998). Several methods to determine the settling velocity characteristics of sewage and stormwater solids were selected and compared and results indicated that there is a need to develop an international test procedure in order to be able to compare the results uniformly.

Chemical transfer from soil to surface runoff was simulated using a gypsum tracer under dry, wet, and water-table conditions. During the dry testing, no tracer was found in the stormwater runoff and tracer concentrations were found to decrease exponentially with time under wet and water-table conditions (Zhang, 1997). Observations of rainstorm and sprinkling experiments were conducted to demonstrate stormwater runoff generation in colluvial soils is through near-surface bedrock (Montgomery et al., 1997).

Biological and Microbiological Testing
Rangarajan et al. (2002) reviewed a methodology for pathogen TMDL development for water bodies closed to shellfish harvesting in New York State. The study objectives included: • identification of water quality target(s) for pathogens based on the designated use of shellfish harvesting; • assessment of point and non-point sources of pollution that contribute pathogen load to the waterbody; • establishment of linkage between water quality target(s) and sources, thereby, the baseline scenario of pollution loading from point and non-point sources, and; • development of load allocations and implementation plans to achieve water quality target(s).

Ibekwe et al. (2002) used multiplex fluorogenic real-time PCR for detecting and quantifying Escherichia coli O157:H7. A direct correlation was determined between the fluorescence threshold cycle (C_T) and the starting quantity of E. coli O157:H7 DNA. A similar correlation was observed between the C_T and number of CFU per milliliter used in the PCR assay. These results indicate that the developed PCR assay is suitable for quantitative determination of E. coli O157:H7 in environmental samples and represents a considerable advancement in pathogen quantification in different ecosystems.

Chang and Hsieh (2002) compared the Colitag™ Method and the Standard Methods for the detection of fecal coliforms and Escherichia coli in urban creeks in Berkeley, California. The Colitag™ method was found to be as sensitive as the Standard Methods for detecting fecal coliforms; statistical analysis of parallel test results showed a strong linear correlation of 0.87 between the two methods, a relationship that held up well at both high and low fecal coliform counts.
In addition, the Colitag™ method gave rapid and specific enumeration of E. coli and takes only 24 hours compared to up to 96 hours for the Standard Methods. Saving three days means that monitoring agencies could respond faster to sudden increases in E. coli and could therefore take immediate corrective action to ensure public safety.

Elevated bacteria levels indicated significant impairment to water quality in many urban areas within the Great Lakes watershed (Murray et al., 2001a). CSO outfalls were assumed to be the major source of bacteria to streams in many of these urban areas, including the Rouge River of southeastern Michigan. The data depicted a strong influence of upstream water and rural runoff on the water quality of the Rouge River, and FC to FS ratios suggested the primary source of bacteria throughout the watershed was from domesticated animals and wildlife and not from CSOs. Sources of the indicator bacteria total coliform, fecal coliform, and enterococcus were investigated in stormwater flows discharging to Mission Bay in San Diego, California (Schiff and Kinney 2001). Stormwater flows were targeted because long-term monitoring had indicated that wet weather discharges were the predominant source of bacterial contamination. Upstream tracking during multiple storm events on two watersheds showed that bacterial sources were diffuse and widespread. Two case studies were used to demonstrate how WERF’s ecological risk assessment methods, Aquatic Ecological Risk Assessment: A Multi-Tiered Approach, could be used to improve the ecological- and cost-effectiveness of water quality management (WERF 2001b). The two cases (Salado Creek in the City of San Antonio, Texas, and the Jordan River in Utah) were explored in detail, including direct and indirect effects of changes in flow on fish and invertebrate aquatic life.

Quintero-Betancourt and Rose (2000) investigated the potential use of stormwater and/or reclaimed water to rehydrate wetlands in St. Petersburg, Florida. The adequacy of using these waters was assessed through microbial water quality testing using bacterial indicators, coliphages, Cryptosporidium and Giardia. Long et al. (2000) evaluated the potential of using three alternative (compared to traditional coliform testing) source-specific indicator organisms for determining the human health risks associated with a water source and for determining if the source of the bacterial contamination was human or grazing animal. These alternative organisms were sorbitol-fermenting Bifidobacteria, Rhodococcus coprophilus, and serogroups of F+ coliphages), and they were found to correlate well with predictions of land use contributions to a receiving water. Rex (2000) reported on the impacts of changing from coliforms to enterococcus as the indicator organism of water quality. The paper advocated that more studies need to be done to improve the understanding of enterococcus behavior during treatment so that its use can provide information about the quality of CSO control. Brion and Mao (2000) researched the use of atypical colonies found in the total coliform test as a part of watershed monitoring. The ratio of atypical colonies to coliphage concentrations correlated well with the degree of known fecal pollution. Meek et al. (2000) advocated the use of shellfish as indicators of bacterial pollution of water. When compared to coliforms, the shellfish gave a better representation of the pollution levels and the changes over time of bacterial concentrations in the water. An evaluation of the naturally-forming algal community in stormwater detention ponds by Olding (2000) showed that this algal community could be used to demonstrate the effectiveness of the detention pond as a treatment device. The taxonomic breakdown of the community also indirectly showed the pond influent water quality.

Myrmel et al. (1999) presented their work on using adsorptive filtration and PCR to detect small round-structured viruses in water and wastewater. The method detected virus concentrations of 0.5 – 5 virus particles per milliliter in a 500-mL sample. Abbaszadegan et al. (1999) compared PCR to cell culture testing for the detection of viruses in groundwater. They found that, with the improved sample-processing technique and large-volume amplification protocol, the PCR test was a rapid and effective tool for screening water for enteroviruses, hepatitis A virus, and rotavirus. Betts (1999) reported on the evaluation of “DNA chip” technology for the rapid, sensitive and inexpensive testing of water for bacteria, parasites and viruses. Zisette et al. (1999) used a genetic fingerprinting technique to assist in identifying source of microbial contamination to Drayton Harbor Watershed, Washington. The results from the bacterial tests were then to be used to determine which sources (municipal sewage discharge, failing septic systems, animal management practices, seafood processor discharges, and people who live aboard houseboats at the marina) were causing the shutdown of the oyster and shellfish harvest areas. Clancy and Hansen (1999) discussed the lack of use of protozoan monitoring data in public health decision-making. They found in their survey that the primary reason cited by water companies was unreliable data. However, the protozoan data has been used successfully in conjunction with other water quality results to assess treatment efficiency and support investment planning.

Matlock et al. (1999) used the Matlock Periphytometer to measure nutrient limitations and trophic status in situ in the Bosque River Watershed in Texas. The data was used to develop a lotic ecosystem trophic status index (LETSI), and through the use of LETSI, differences in nutrient limitations in tested streams were detected, including two streams which were co-limited by nitrogen and phosphorus. Toetz et al. (1999) related annual phosphorus loadings from eight subbasins in the Illinois River impacted by NPS runoff to the alkaline phosphatase activity (APA) in the water. The correlation
between APA and soluble reactive phosphorus and between APA and the annual predicted phosphorus loading by the SIMPLE model allowed the researchers to demonstrate which of the eight subbasins did not require pollution abatement and were not in jeopardy of becoming eutrophied.

Fry (1999) measured the concentration of stable C and N isotopes in the clam Potamocorbula amurensis in San Francisco Bay. He determined that the carbon isotope concentrations in the clam correlated to the amount of riverine, freshwater, input into the Bay while the nitrogen isotope concentrations could be correlated to the watershed nutrient loadings due to human activity.

The cost and efficiency of different techniques for processing rapid-assessment samples of macroinvertebrates were evaluated by comparing the ability of data generated by each technique to discriminate between unpolluted reference sites and sites with mild to severe pollution from municipal effluent and urban stormwater runoff (Grown et al., 1997). Of three metrics tested, SIGNAL had the most highly significant differences between reference and polluted sites and was the most robust to variations in processing method.

Surface-Water Impacts
The impact of three demographic and cultural trends - global urbanization, “quality of life” emphasis, and a move towards flexible management - on technology and the regulatory system was discussed by Ruta (2000), especially given the fact that many thousands of U.S. waterbodies still do not meet water quality standards. One example of the watershed-view of impacts was the Urban Pollution Management (UPM) procedure described by Artina and Maglioni (2000). This procedure was developed in England to evaluate the impact on receiving waters of pollutants discharged from sewer overflows during rainfall events. Garland and Pfeffer (2000) proposed using a watershed-based approach to evaluate the impacts of runoff from contaminated sites at the Oak Ridge DOE Reservation and for determining the optimum location and type of pollution control measures. They documented that pollutants released from the contaminated sites typically are transported to the Clinch River through subsurface shallow flow to surface waters where, if they bind well to sediments, they accumulate in aquatic sediments. Otherwise, they are transported off-site via the Cinch River.

Bertrand-Krajewski et al. (2000) reviewed their Experimental Observatory for Urban Hydrology project that demonstrated the need for improved knowledge about the interactions between urbanization, pollutant discharges, impacts on the natural environment, and socio-economics. The aim of the project will be to improve methodologies for investigating the sustainability of urban water systems. Collins et al. (2000) reviewed the USEPA’s Clean Water Compliance Watch (CW2) Environmental Monitoring for Public Access and Community Tracking (EMPACT) project. EMPACT projects use state-of-the-art technology to track environmental conditions and to provide easy public access to information in easily-understood language.

Fernando et al. (2000) presented the development of effectiveness indicators (“a measurable feature that provides managerially and scientifically useful evidence of stormwater and ecosystem quality or reliable evidence of trends in stormwater quality and program effectiveness”) for stormwater and watershed management programs and the development of a regional monitoring program for the Hampton Roads Planning District Commission (Virginia). As reported by Schaad and Kam (2000), the City of Kelowna completed a State of the Environment Report which examined air, land and water quality. Thirteen of the twenty-two indicators directly addressed watershed health. These indicators were designed to show current watershed health and future trends. Cloak (2000) described the implementation of twenty of the Center for Watershed Protection’s Environmental Indicators to Assess Stormwater Programs and Practice, and showed that the indicators were most useful when organized into a framework that could be used to inform stakeholders and the public. The investigation (Cloak et al. 2000) separated the indicators into two groups: The first group, the programmatic indicators targeted at measuring specific program activities, was useful for documenting and understanding pollution-prevention efforts. The second group of indicators (application of physical, water-quality, and biological measurements at a watershed scale) were useful for an overall assessment of stream function and an understanding of the natural and anthropogenic factors influencing those functions.

Albert and Limbeck (2000) reported on the effects of urbanization on storm water quality in five New Jersey watersheds. The report reviewed the water quality, instream habitat, benthic macroinvertebrates, and stream channel changes due to urban runoff. The work also examined various assessment methods to determine which of these methods could be used to develop non-point source or stormwater related goals and objectives.
McMahon and Cuffney (1999) described the U.S. Geological Survey’s National Water Quality Assessment (NAWQA) Program which was intended to study the relationship between varying levels of urban landuse development in drainage basins and in-stream water quality, as measured by physical, chemical, and biological indicators. These studies were being conducted near Boston (Massachusetts), Salt Lake City (Utah), and Birmingham (Alabama), where rapid urbanization was occurring.

David et al. (1999) performed a study to determine the response of stream water dissolved organic carbon (DOC) and organic acidity to increased inputs of ammonium sulfate to a whole catchment. Several mechanisms exist, including evaporative concentration, vapor-liquid phase partitioning, lowered washout volumes of atmospheric deposition water, and dry deposition, which may lead to elevated concentrations of trifluoroacetic acid (TFA) in atmosphere and surface waters above levels expected from usual rainfall washout (Wujik et al., 1999). Correll et al. (1999) reported on a study to determine the relationships between precipitation at the seasonal and annual scale and water discharge per surface area for seven contiguous first and second-order tributaries of the Rhode River, a small tidal tributary to the Chesapeake Bay, Maryland.

Consistently, N and P concentrations increased as the proportion of land area used for dairy waste application fields. The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased; stormwater runoff of nutrients from dairy waste application fields was indicated as the predominant source of NPS nutrients impacting water quality in the upper North Bosque River (UNBR) watershed (McFarland et al., 1999). Mason et al. (1999a) reported that the chemistry of a first-order stream in Amherst, Maine with a catchment area of 103 ha has been strongly altered as a result of road salt application at a rate of approximately 4 t of NaCl per year in the lower 15% of the catchment.

Pesticide compounds, relative to the landuse composition of the basin, were detected in all 50 water samples collected from streams in New Jersey and Long Island, New York, during June 9-18, 1997. Physical and chemical properties as well as application rates of the pesticides studied affect their detection frequencies. Although all pesticide concentrations were within both EPA and State maximum contaminant levels (MCL) and health advisory levels (HAL), these criteria apply only to individual compounds, and more than one compound was detected in 49 of the 50 samples collected (Reiser and O’Brien, 1999). Watershed properties such as peatland area have considerable promise as predictors for estimating total mercury (THg) transport in streams draining forested watersheds in the Great Lakes States (Kolka et al., 1999). Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.

Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Outflows may occur that can deposit water with varying concentrations of the components of sewage onto public areas, potentially resulting in a range of adverse health effects (Colford et al., 1999). Seasonal and event variations in stream channel area and the contributions of channel precipitation to stream flow were studied on a 106-ha forested headwater catchment in central Pennsylvania. Variations in stream velocity, flowing stream surface width and widths of near-stream saturated areas were periodically monitored at 61 channel transects over a two-year period (Crayosky et al., 1999). Johnson et al. (1999) presented information that suggest non-stormwater source, such as on-site sewage systems and illicit discharges, were major contributors to the contamination of the Rouge River in Wayne County, Michigan.

Weber (1998) reviewed the improvements of water quality of the Greater Cleveland, Ohio area over the past century to the present. In a study of the Ho Chi Minh City of Viet Nam (Phuong et al., 1998) found that the aquatic urban ecosystem is strongly influenced by long-term discharge of untreated domestic and industrial wastewaters, stormwater runoff, accidental spills and direct solid waste dumping.

A study of 22 streams in the Puget Sound Lowland ecoregion in Wash. demonstrated that the physical, chemical and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion (May, 1998). Urbanization history and flood frequencies of four low-order stream basins that underwent significant urbanization and two other control basins that did not were monitored in the Puget Lowlands between the 1940/50s and 1980/90s. Flood frequencies increased in the urbanized basins and salmon populations decreased while similar results were not documented in the control basins (Moscrip and Montgomery, 1997).
Booth and Jackson (1997) concluded that established methods of mitigating the downstream impacts of urban development may have limited effectiveness. Using continuous hydrologic modeling, detention ponds designed by conventional event methodologies were evaluated and deficiencies in actual pond performance were demonstrated when compared to their design goals. Novotny and Witte (1997) presented a methodology to calculate risk of wet-weather discharges to aquatic ecology (aquatic life). It can be used for ranking pollutants in wet-weather discharges as well for ranking the discharges themselves. The U.S. Environmental Protection Agency (U.S. EPA) (1997a) examined the published literature which revealed that hydrologic impacts on streams were caused by increased impervious areas in urban developments.

Water Environ. & Technol. (1996a) reported that the latest National Water Quality Inventory released by the EPA only showed a slight improvement in the attainment of beneficial uses in the nation’s waters. Urban storm runoff was cited as the leading source of problems in estuaries, with nutrients and bacteria being the major problems. Problems in rivers and lakes were mostly caused by agricultural runoff, with urban storm runoff the third ranked source for lakes, and the fourth ranked source for rivers. Bacteria, siltation, and nutrients were the leading problems in the nation’s rivers and lakes. Borchardt and Sperling (1996) stressed that many conditions may affect receiving waters from stormwater, specifically physical factors (such as shear stress) and chemical factors (such as oxygen depletion and/or nonionized ammonia).

**Temperature and Dissolved Oxygen**

Picksley and Deletic (1999) studied the thermal behavior of storm runoff from paved surfaces at two different urban catchments. The thermal trends were explained by equilibrium of thermal influences, based on the physical interaction of runoff and paved surfaces.

The impact to receiving water dissolved oxygen (DO) concentration of intermittent CSO and overflows from a treatment plant were investigated. Data from the River Maun, U.K. showed that an immediate, transient oxygen demand exists downstream of an outfall followed by a separate, delayed oxygen demand (Jubb et al., 1998). The NYC Department of Environmental Protection (DEP) analyzed the feasibility of supplemental aeration in conjunction with a proposed CSO pollution control facility at the Paerdegat Basin, Brooklyn, N.Y. (Gaffoglio et al., 1998a). Aeration as a supplement to conventional CSO controls would address DO concerns, however, the continued discharge of solids during WWF would result in an increased sediment oxygen demand of the basin.

The Harrestrup river in Copenhagen, Den was subject to intensive online investigation of oxygen during both dry and wet weather (Harremoes et al., 1997). An evaluation of oxygen fluctuations demonstrated noncompliance of oxygen standards both during dry and wet weather.

**Erosion, Channel Stability, and Sediment**

Rose and Peters (2001) reported an investigation that examined streamflow characteristics that changed during the period from 1958 to 1996, in a highly urbanized watershed (Peachtree Creek) compared to less-urbanized watersheds and non-urbanized watersheds, in the vicinity of Atlanta, GA. Data were obtained from seven US Geological Survey stream gauges, 17 National Weather Service rain gauges, and five USGS monitoring wells. The fraction of the rainfall occurring as runoff in the urban watershed was not significantly greater than for the less-urbanized watersheds, but this ratio did decrease from the higher elevation and higher relief watersheds to the lower elevation and lower relief watersheds. For the 25 largest stormflows, the peak flows for the urban creek were 30% to 100% greater than the peak flows in the streams located in the less developed areas. The streamflow also decreased more rapidly after storms in the urban stream than for the other streams. The low flow in the urban creek was from 25 to 35% less than for the less developed streams, likely caused by decreased infiltration due to the more efficient routing of stormwater and the paving of groundwater recharge areas.

Weng (2001) describes how GIS was used in conjunction with distributed hydrological modeling. GIS was able to document the changing spatial patterns of urban growth in the Zhujiang Delta of southern China. Extensive urban growth over the past two decades has created severe problems in water resources management, indicated by an increase in annual runoff depth during the 1989-1997 period. The urbanization lowered potential maximum storage, and increased runoff.

An emerging concept in channel design uses sediment transport as the basis for quantifying channel stability. Byars and Kelly (2001) examined channel stability in the Austin, TX, area. They concluded that a channel that is not undergoing excessive erosion or sedimentation has a function and form similar to a natural stream and should be the goal of good channel design. This approach, however, requires a more comprehensive understanding of the local climate, geology,
Hunt and Grow (2001) describe a field study conducted to determine the qualitative and quantitative impact to a stream from a poorly controlled construction site. They used fish electroshocking, Qualitative Habitat Evaluation Index, and zigzag pebble count studies. The 33 acre construction site consisted of severely eroded silt and clay loam subsoil and was located within the Turkey Creek drainage, Scioto County, OH. The number of fish species declined (26 to 19) and the number of fish found (525 to 230) decreased significantly when comparing upstream unimpacted reaches to areas below the heavily eroding site. The Index of Biotic Integrity and the Modified Index of Well-Being, common fisheries indexes for stream quality, were therefore reduced from 46 to 32 and 8.3 to 6.3, respectively. Upstream of the area of impact, Turkey Creek had the highest water quality designation available (Exceptional Warm Water Habitat); but fell to the lowest water quality designation (Limited Resource Water) in the area of the construction activity. Water quality chemical analyses conducted on samples from upstream and downstream sites verified that these impacts were not from chemical affects alone.

Morrisey et al. (2000) described the sampling program used to confirm a predictive model of metal contaminant build-up (Cu, Pb, and Zn) in the sediments of sheltered urban estuaries in Auckland, New Zealand that have been subjected to urban runoff inflows. The results of their testing showed good general agreement between the model predictions and the observed concentrations of metals in the sediments. The paper by Butcher et al. (2000) described the problems encountered when developing mercury TMDLs for the Arivaca and Pena Blanca Lakes in Arizona. These two lakes lacked point-source discharges of mercury; however, the concentrations of mercury in fish bodies were sufficiently high to trigger TMDL development. The resultant TMDL addressed the problems inherent with controlling pollutants entering the lake when the lake sediment was found to be a primary source of the pollutant. Rate et al. (2000) investigated the concentration of heavy metals in sediments of the Swan River estuary in Perth, Australia. They found that the concentration of lead was elevated near stormwater drain outfalls when compared to areas away from the outfalls, likely due to vehicular material; no similar effect was seen for copper or cadmium. They also noted that since the vast majority of all heavy metals were bound to iron oxides or organic sediments, most of the metals are not bioavailable. The results of the study performed by Rochfort et al. (2000) on the effects of stormwater and CSO discharges on the benthic community showed that the levels of metals and PAHs in sediments below these discharges were high. However, biological effects were not seen - neither the toxicity endpoints nor the benthic community descriptors could be related to the sediment contaminant levels.

Ghani et al. (1999) found that the thickness of a sediment deposit on the bottom of a rigid rectangular channel greatly affects its erodibility of the deposits. They developed channel erosion equations that included terms for the deposit’s thickness. Keshavarzy and Ball (1999) studied the entrainment of sediment particles in water and found that the number of entrained particles per unit time per unit area was found to be related to the instantaneous shear stress at the bed. These results were used to modify the Shields diagram. Ashley et al. (1999) investigated the integration of sewer solids’ biodegradability into the existing UK waterway protection standards for solids erosion in sewers. This integrated standard would then be used to define the DO criteria in streams and to determine the allowable solids discharge. Rhoads and Cahill (1999) studied the elevated concentrations of chromium, copper, lead, nickel and zinc that were found in sediments near storm sewer outfalls. They noted that copper and zinc concentrations were greater in the bedload compared to the bed material and therefore were more likely to be mobilized during runoff events.

Anecdotal information regarding the impacts of changes in flow on receiving streams were collected, however, not all of it provided conclusive evidence as to the relationship between urbanization and flow-related stream impairment (Frederick and Corrigan, 1998).

Stormwater impacts to streams are not limited to the relatively short duration of runoff events. As an example, sediments can dominate the aquatic physiochemical and biological processing of nutrients; sediment contaminated by stormwater pollutants has a detrimental effect on the receiving-water-biological community. The EPA and other regulatory agencies are attempting to develop sediment quality criteria to determine where excessive concentrations of chemical constituents are present in sediments at sufficient concentrations and in chemical forms to be significantly adverse to the designated beneficial uses of the associated water body. Lee and Jones-Lee (1996a) presented the issues that need to be considered in evaluating the results of a sediment quality assessment procedure to determine whether the toxicity or excessive concentration found is a potentially significant cause of real water quality deterioration in the water body of concern. Maurer et al. (1996) analyzed sediment samples collected from five stations in the Newport Submarine Canyon, CA and six nominal 60-m shelf stations to test the following two hypotheses: (1) there is no increase in sediment contaminant...
concentration with water depth in the Canyon; and (2) there is no difference in contaminant concentration between the canyon and adjacent shelf. The data collected supported hypothesis one and rejected hypothesis two.

**Biological Impacts**

For 20 years, King County, WA, has progressively implemented more demanding structural and nonstructural strategies in an attempt to protect aquatic resources and declining salmon populations from the cumulative effects of urbanization (Booth, et al., 2002). They found that costly structural retrofits of urbanized watersheds can mitigate certain problems, such as flooding or erosion, but they cannot restore the predevelopment flow regime or habitat conditions. They concluded that the preservation of aquatic resources in developing areas will require integrated mitigation which must include impervious-surface limits, forest-retention policies, stormwater detention, riparian-buffer maintenance, and protection of wetlands and unstable slopes. However, the same management goals cannot be achieved in both developed and undeveloped watersheds.

Burleson (2002) reports that coastal counties in southern South Carolina have experienced rapid growth. During this time, a number of shellfish areas have been closed permanently, or on a conditional basis, due to exceedences of the fecal coliform water quality standard for shellfish waters (14 FC/100ml). Proposed developments that will discharge to receiving waters on the 303(d) list are now required to demonstrate that discharges from their site will meet numerical limits. Existing retention/detention options were not able to meet these limits. Spreadsheet evaluations and monitoring at two developments are investigating the application of different stormwater controls to meet the fecal coliform standard. Preliminary results indicate that it will be very difficult to meet this bacteria standard.

Horwitz et al. (2001) examined the different fish communities in paired reaches of streams having forested vs. unforested riparian zones. The streams traversed land uses ranging from rural to highly urban. Their preliminary results found that the type of buffer had little effect on the fish communities in the rural reaches. However, the fish community patterns were much more variable in the urban reaches, being affected by the effects of urbanization on channel morphology, habitat, hydrology, and water quality. Sonneman et al. (2001) studied the effects of urbanization on the benthic diatom communities in streams near Melbourne, Australia. The subcatchments had imperviousness levels ranging from 0 to 51%. They found that the differences observed were best explained by variations in nutrient concentrations (phosphorus, ammonia, and total nitrogen). The level of urbanization, along with the presence of small sewage treatment plants at a few sites, influenced the nutrient concentrations found. They observed that diatoms were better indicators of nutrient enrichment, while macroinvertebrates were better indicators of catchment disturbance. Walsh et al. (2001) reported the effects of macroinvertebrates at the same Melbourne area locations as reported by Sonneman et al., (2001). Responses were more obvious in the eastern areas (having a wide range of development) and were associated with conductivity, while the western areas (having little development) had little observed variations. The metropolitan areas were all severely degraded, having high abundances of a few tolerant taxa. Extensive development of urban drainage systems, even in areas having low urban densities, increased the observed degradation.

Fifty et al. (2001) investigated the impact of wastewater and stormwater discharges on the coastal receiving waters on a coral atoll in the middle of the Pacific Ocean (Kwajalein Atoll), a pristine marine environment. They used *Tridacna maxima*, a giant clam species, as an indicator organism. Juvenile clams were deployed for a 3-month period in the vicinity of pollutant sources and reference sites, and then analyzed for metals, PAHs, pesticides, and PCBs. The clams were a successful bioindicator, with tissue samples from sites near pollutant sources (contaminated sediment and stormwater) containing higher concentrations of chemicals than at the reference sites.

Grant et al. (2001) reported frequent elevated levels of enterococci bacteria in the surf zone at Huntington Beach in southern California. They studied the sources of these indicators and found high levels in urban runoff, bird feces, marsh sediments, and on marine vegetation. They concluded that urban runoff had relatively little impact on these elevated surf zone bacteria levels because of the long travel time needed for the urban runoff to travel from the source areas to the ocean. They found that marsh sources were more likely responsible for the high surf zone bacteria levels. Jiang et al. (2001) used a nested-PCR analytical method to detect viruses in coastal waters at 12 beach locations in Southern California. The sampling locations were all impacted by urban runoff sources. The sampling locations were all located at the mouths of major rivers and creeks. Human adenoviruses were detected in 4 of the 12 samples (880 to 7,500 per L), coliphages were found in all 12 samples (5.3 to 3330 PFU/L), and F-specific coliphages were found in 5 of the 12 samples (5.5 to 300 PFU/L). The bacterial indicator levels (total coliforms, fecal coliforms, and enterococci) all exceeded the California recreational water quality limits, but the bacteria levels found did not correlate well with the observed human adenovirus levels. They concluded that the standards that rely on bacteria observations to indicate viral quality of
recreational waters be re-evaluated, and that more routine monitoring of human viruses be conducted on a regular basis.

Mahin (2001) reviewed recently completed epidemiological studies conducted after the publication of the 1986 EPA bacteria guidance. The Massachusetts Dept. of Environmental Protection were concerned about the risk level that is associated with stormwater runoff to recreational waters, and if enterococci or E. coli can adequately predict the range of possible illnesses that may affect swimmers in contaminated marine waters. Crowther et al. (2001) examined the relationships between microbial water quality and environmental conditions in coastal recreational waters along the Fylde coast, UK. Eight designated bathing beaches continued to exhibit unreliable compliance with the Imperative standards for total coliforms and fecal coliforms, despite significant reductions in geometric mean concentrations following major improvements in the sewerage infrastructure. Fecal streptococci concentrations have remained high. Before the improvements, higher bacterial concentrations were strongly associated with rainfall; and sewage sources were important for TC and FC, but less important for FS. Since the improvements, catchment sources seem to be of greater importance. Pendleton (2001) reported that despite posted warnings and educational campaigns warning about the health risks associated with storm water pollution, swimmers continue to swim in Southern CA coastal areas polluted by stormwater. Passive means of preventing exposure to marine pollution (e.g., posted signs) were found to be more effective if combined with the active management of other beach amenities. Pendleton et al. (2001) further found that despite documented successes in the battle to clean up the coastal waters of Southern California, Los Angeles County residents continue to view the ocean more as a place of pollution than a healthy place for bathing and swimming. Survey results suggest that perceptions of coastal water quality may be influenced less by “current coastal education campaigns” and more by the media and other factors.

One impact of stream habitat degradation that could not be accounted for through chemical and biological monitoring would be the effect of elevated flows on habitat availability. A study by Finkenbine et al. (2000) indicated that restoration of stream health in an urban area was best accomplished by the establishment of a healthy buffer zone and the introduction of large woody debris (LWD) into the stream. They found that, after a stream has reached its equilibrium with the flow, detention pond retrofits had few hydrological benefits.

Bailey et al. (1999) investigated the potential toxicity of stormwater runoff from sawmills in British Columbia to juvenile rainbow trout, and found that the toxicity was related to the divalent cation concentration, especially for zinc. They also determined that the zinc toxicity was directly related to the low hardness in the stream, with the range of LC50 of 72 – 272 µg/L associated with hardnesses of 9 – 100 mg/L. Ambrose and Meffert (1999) investigated the fish assemblages in Malibu Lagoon, a small estuary in California, and found that the species diversity and richness were small compared to large estuaries, but were comparable to other small estuaries with less anthropogenic impacts. Hatch and Burton (1999), using field and laboratory bioassays, demonstrated the impact of the urban stormwater runoff on Hyalella azteca, Daphnia magna, and Pimephales promelas survival after 48 hours of exposure. The significant toxicity seen at the outfall site was attributed to the contaminant accumulation in the sediments and the mobilization of the top layers of sediment during storm events. A comparison of highway runoff toxicity with typical urban runoff toxicity was performed by Marsalek et al. (1999). Their study found that approximately 20% of the samples collected at the edge of a multi-lane divided highway (>100,000 vehicles/day) were severely toxic, while only 1% of the typical urban runoff was severely toxic. Skinner et al. (1999) showed that stormwater runoff produced significant toxicity in the early life stages of medaka (Oryzias latipes) and inland silverside (Menidia beryllina). Developmental problems and toxicity were strongly correlated with the total metal content of the runoff and corresponded with exceedances of water quality criteria of Cd, Cu, W, and Zn.

Ecotoxicological experiments were used by Delbec and Mouchel (1999) to develop a wet-weather quality potential (F) that can be used to evaluate oxygen depletions during WWF. The quality potential was used to demonstrate the impact of seasonal hydrological conditions on the occurrence of damaging situations in the River Seine. Pess and Bilby (1999) identified Coho salmon (Oncorhynchus kisutch) distribution and abundance in Puget Sound rivers and explained the distribution by using both stream-reach and watershed-scale habitat characteristics, including the influence of urban areas on the habitat. Tree swallows were used by Secord et al. (1999) to determine the impact of contamination of a watershed and waterway with PCB. The elevated PCB concentrations in the swallows and in the sediments indicate that PCBs in the sediments can be passed up the aquatic food web of the Hudson River ecosystem to the terrestrial and avian wildlife that depend on the River for food. Mallin et al. (1999) documented the effects of Hurricanes Bertha and Fran on the biological community in the Cape Fear area of North Carolina. The natural hurricane effect of swamp water flooding into river basins was reduced DO levels that resulted in fish kills. However, this damage, such as the length of the low DO levels, was considerably increased by anthropogenic practices, including sewage diversions into the rivers and flooding and
discharge from swine waste lagoons sited adjacent to the river. The relationship between benthic chlorophyta (Ulothrix zonata) and urban stream water quality was demonstrated by Shigemitsu and Hiratsuka (1999).

While exact cause-and-effect relationships have not yet been determined between toxic blooms and algae, dinoflagellates, and similar organisms, evidence suggested that nutrients from agricultural runoff or sewage may stimulate the growth of harmful organisms such as *Pfiesteria* spp (Pelley 1998). High P loading to Como Lake, a shallow lake in Minn., from the surrounding urbanized watershed caused eutrophic conditions. Despite efforts to manipulate fish and macrophyte populations, and DO levels in the lake, maintenance of healthy populations of fish, macrophytes, and plankton in the lake will require control of the large P inputs (Noonan, 1998). Heinzmann (1998) described efforts in Berlin, Ger. to reduce P loading to surface water bodies. The response of algae to suspended clay and P loading in an urban lake in N.C. showed that clay tended to reduce algae production, while P tended to increase algae production in this study. However, high P loadings produced nuisance algal blooms and mitigated the adverse effects of high clay loading on algal production (Burkholder et al., 1998).

DNA strand breakage, growth rate, condition index and percentage tissue water were measured in freshwater Asiatic clams (Corbicula fluminea) exposed in‐situ to a stream that received urban and industrial stormwater runoff versus a non-impacted reference stream. After four weeks, DNA strand lengths of the exposed clams were significantly shorter than from reference clams which suggested a reduction in DNA integrity in the exposed clams, possibly indicating exposure to genotoxic chemicals, while no significant differences were observed in the growth rates (Black and Belin, 1998). Loumbourdis and Wray (1998) detected high concentrations of Cu, chromium, molybdenum, Zn, manganese, and aluminum, in the tissues of frogs living in a small river in Macedonia, north. Greece, corresponding to highly polluted areas. The main sources of the river pollution seem to be fertilizers containing heavy metals as trace elements, pesticides with heavy metals in their formula, urban runoff, and various light industries along the river. The bioaccumulation and toxicity of Zn in Spirogyra Fluvialitlis Hilse (chlorophyta), from two populations in the River Seyhan, Adana, Turkey, showed little difference in Zn bioaccumulation between Spirogyra from a site showing mild organic pollution or that from a site subjected to considerable inputs from urban and motorway runoff. Cellular damage was evident in Spirogyra subjected to 0.5 mg/L Zn, and increased with increasing Zn concentration (Saygideger 1998).

Wernick et al. (1998) compared land-use indicators to streamwater nitrate-N levels in the Salmon River watershed near Vancouver, British Columbia, Can. and found that urbanized areas, as indicated by septic tank density, contribute to elevated nitrate-N levels in an urban-rural fringe environment. In the main tributary of the Salmon River, nitrate-N levels correlated with urban land use, but not with agricultural land use as indicated by animal unit density, indicating that urban land use is the primary source of nitrate-N in that basin.

Winter and Duthie (1998) documented the adverse effects of urbanization on periphyton and macroinvertebrate community structure in Laurel Creek, a rapidly urbanizing subwatershed of the Grand River in southern Ont., Can. Pesacreta (1997) monitored the benthic life of the urban Morgan Creek of Carrboro and Chapel Hill, N.C. The macroinvertebrate *Pteronarcy dorsiata*, which is intolerant to pollution was observed as a sub-lethal toxicity indicator. Schultz (1998) presented a brief overview of how urban streams got into their current predominantly degraded conditions and the activities and results of several recent programs aimed at rehabilitation of urban streams.

A correlation between runoff events and poor water quality in Lake Michigan established that runoff events have had significant impact on the drinking-water quality in Milwaukee, Wis. where 400,000 people were infected with *cryptosporidiosis* in 1993 (Christensen et al., 1997). *Giardia* and *Cryptosporidium* were monitored monthly for two years to determine their occurrence in the Allegheny and Youghiogheny Rivers of Pennsylvania, their source, and the efficiency of their removal by the Pittsburgh Drinking Water Treatment Plant. Sources investigated included a dairy farm stream, wastewater treatment plant (WWTP) effluent, and several samples from CSO (States et al., 1997).

Macrobenthic communities were surveyed in 1987-88 as part of a comprehensive study of fish kills and water quality in the upper Trinity River of Texas (Davis, 1997). While some impact was evident in certain reaches from pesticides, dissolved metals, and WWTP effluents, the overall impacts were relatively slight on a long-term basis and a high aquatic life use was attained at most sites. The Bloomington and Normal Water Reclamation District of McLean County, Ill. began an ongoing biological survey of Sugar Creek in 1983 (Callahan 1997). Improvement in the fish community was linked to the discontinuation of effluent chlorination through an annual exemption in 1991, while the addition of nitrification, construction of CSO controls, and tertiary filter failure did not demonstrate immediate and directly attributable affects. In many southern California salt marshes, increased freshwater inflows have promoted the
establishment of exotic plant species. Kuhn and Zedler (1997) proposed that salt applications may be a practical method for controlling exotic plant invasions in areas receiving urban stormwater runoff or other unwanted freshwater inflows.

Hellou et al. (1997) exposed rainbow trout to waste crankcase oil, a recognized source of PAH contamination in urban stormwater runoff. The accumulation of compounds in muscle tissue, the elimination of bile metabolites, the activity of 7-ethoxyresorufin O-deethylase (EROD) in liver, and morphometric variables were compared at different concentrations and times of sampling. Jennings et al. (1997) extracted ten pollutant phenols from an oil-refinery discharge, urban stormwater, and WWTP effluent with the highest concentration found in the WWTP effluent. Bioaccumulation experiments were conducted using the mussel, Mytilus edulis and the fish, Trachurus novaeezelandiae with similar concentrations, and both species depurated all accumulated phenols to concentrations below detection within 24 h when placed in clean seawater. Magaud et al. (1997) developed a quantitative model of the instantaneous death probability of juvenile rainbow trout as a function of time, concentrations of unionized ammonia (NH3), and dissolved oxygen (DO). This model found the survival probability of rainbow trout exposed simultaneously to NH3 and low DO was lower than the predicted survival probability derived from the simple addition of the individual effects. Moore and Farris (1997) conducted 48-h acute-toxicity tests with Ceriodaphnia dubia (cladoceran) and Pimphales promelas (fathead minnow) on stormwater runoff, laboratory synthetic water, and irrigation (ground) water with the herbicide Stam®M-4 (active ingredient Propanil [3',4'-dichloropropionanilide]). No effects on survival were observed in this study following 48-h toxicity testing with the stormwater. Siewicki (1997) estimated the risks posed by fluoranthene (a four-ring PAH) in urban stormwater runoff by modeling and exposure assessment of a portion of Murrells Inlet in South Carolina. Results suggested bioconcentration of fluoranthene in oysters is related to adjacent land uses and can be predicted by understanding the major factors affecting its transport and fate. An approach is described to test alternate landscape modifications for minimizing impacts on both resident fauna and seafood consumers. Villeneuve et al. (1997) used an in vitro bioassay with PLHC-1 (Poeciliopsis lucida) fish hepatoma cells to assess potential toxic potency of aryl hydrocarbon receptor (AhR-active) compounds, collected by semipermeable membrane devices (SPMD) exposed to Lincoln Creek water Milwaukee County, Wis. as part of a comprehensive study on the effects of stormwater runoff. A log-log correlation of total PAH and toxic potency of dialysates (expressed as bioassay-derived 2,3,7,8-tetrachlorodibenzo-p-dioxin equivalents [TCDD-EQ]) yielded an r² = 0.802 and empirical evidence suggested that AhR-active PAH can account for about 20% — 50% of the potency observed.

The detection and assessment of pollution in the aquatic environment and their effects upon the biological community are rapidly becoming a central focus of state agency water-resource programs. Bioassessments are particularly useful because they reflect the condition of the resident biota from cumulative effects as a result of both nonpoint and point source impacts (Barbour, 1996). Barbour and Stribling (1996) presented a summary of the physical instream and riparian habitat features of a visual-based habitat assessment and their relationship to and influence on biological communities. The quality and stability of stream and riparian-physical habitat, rated in relation to unimpaired streams of similar site-specific and regional characteristics, provide an estimate of the biological potential of a stream system. Preliminary results of research on the application of an aquatic-invertebrate-bioassessment protocol suitable for wetland conditions indicate that ecological integrity of wetlands is affected by the amount of impervious surface in the watershed and that aquatic-macroinvertebrate communities serve as indicators of wetland condition (Hicks and Larson, 1996). Jones et al. (1996) reported that macroinvertebrate bioassessment indicated substantial impairment of streams in a heavily-suburbanized Virginia watershed relative to a companion forested watershed, while a lightly developed adjacent watershed showed an intermediate level of impairment. Severe impairment of the benthic-macroinvertebrate community was found further downstream below the discharge of large quantities of unmitigated stormwater. McCarron et al. (1996) discussed the need and rationale for alternative sampling and assessment procedures that provide a more ecologically-based manner of determining the cumulative environmental effects of nonpoint sources of pollution. The Florida Department of Environmental Protection’s multi-year effort to refine and enhance current biological-community-assessment methods was described.

Evaluation of Central Texas streams using the bioassessment techniques developed for perennial streams indicates that these methods fail to accurately assess the degree of impact on the local community structure due to biological seasonality and intermittent flow (Hansen, 1996). Current assessment techniques need to be modified or new techniques developed for intermittent streams that will enable investigators to distinguish between aquatic-biota impacts due to natural, environmental variations and impairments related to anthropogenic activities in the local watershed. A study was conducted to provide the Texas Natural Resource Conservation Commission with information concerning the nonpoint source discharges from the City of Uvalde to assist in developing appropriate rules to implement provisions in the Texas Water Code requiring cities with populations over 5,000 to develop and submit Water Pollution Control and Abatement
Plans (Coonan et al., 1996). The results indicated that the samples taken from areas subject to urban storm runoff from the City exhibited statistically lower concentrations for numerous parameters; an impact on aquatic communities in the urban storm-runoff receiving-water was not observed.

Claytor (1996a) summarized the approach developed by the Center for Watershed Protection as part of their EPA sponsored research on stormwater indicators (Claytor and Brown, 1996). The 26 stormwater indicators used for assessing receiving-water conditions were divided into six broad categories: water quality, physical/hydrological, biological, social, programmatic, and site, and were presented as tools to measure stress (impacting receiving waters), to assess the resource itself, and to indicate stormwater control program implementation effectiveness.

Pereira et al. (1996) assessed the effects of human activities and land use on the water quality of the San Joaquin River and its major tributaries. This study focused on pesticides and organic contaminants and examined water, particulate forms, sediment, and bivalve shellfish.

The biological communities in Delaware’s Piedmont streams have been severely impacted by stormwater, after the extent of imperviousness in the watersheds exceeds 8-15%, according to a review article (Claytor 1996c). If just conventional water quality measures are used, almost all (87%) of the state’s nontidal streams supported their designated biological uses. However, when biological assessments are included, only 13% of the streams satisfactorily meet their uses.

Weed invasion in the bushland surrounding the Lane Cove catchment in Australia was related to contamination of the floodplain by heavy metals and nutrients, plus increased flooding from the urban development surrounding the bushland (Riley and Banks, 1996). Aesthetics has historically been difficult to quantify in urban receiving-water studies, but it has been an important parameter for many uses, especially recreation. Heidtke and Tauriainen (1996) developed an aesthetic rating system for the Rouge River (Detroit, MI), using a combination of water clarity, water color, odor, and visible debris. Preliminary work suggests that the index is an effective tool for tracking time and space trends in aesthetic characteristics of the receiving water and for public education.

Microbiological impacts
Turner, et al. (2002) reported that urban wet weather pollution has been identified as a major cause of high bacteria levels found in the Ohio River near Cincinnati. Calibrated and validated hydrodynamic (RMA-2V) and water quality (WASP5) models were linked to provide a two-dimensional representation of the study area. Improvements in water quality were evaluated using screening level combined sewer overflow (CSO) control alternatives. This work indicated that bacteria loadings originating from CSOs have an adverse impact on water quality, and that controls were expected to have mixed results. They found that the amount of rainfall obviously influences the significance of the CSO loadings and the effectiveness of the CSO controls. However, the in-stream concentrations were also found to exceed 400 #/100 mL during dry weather in some areas of the river.

An investigation of shoreline microbiological contamination conducted by Robertson et al. (2000) in Orange County, California, showed that the likely cause of the elevated fecal coliforms was dry weather urban runoff from the San Gabriel River and storm drains up the coast, rather than the Orange County’s WWTP effluent ocean outfall. As a result of seventeen E. coli O157:H7 cases, investigation of the potential contamination on the Mar del Plata beaches due to combined sewer overflows was performed by Perez Guzzi et al. (2000). Their investigation detected no E. coli O157:H7, although other strains of E. coli were detected in 75% of the samples. None of the 98 strains detected in the outfalls were the strains that were known to cause human illness. However, the presence of E. coli in the drainage water indicated fecal contamination and the resulting potential for illness should a toxic strain be present in the sewage. Rose et al. (2000), through climate and epidemiological records, demonstrated a potential correlation between extreme precipitation events and waterborne disease outbreaks. The authors found that statistically significant relationships could be developed between large precipitation events and waterborne disease outbreaks for both surface and ground water, although the relationship was much stronger for surface water outbreaks. The impact of urban runoff and the potential resuspension of settled parasites in Paris rivers at the drinking water intakes was investigated by Rouquet et al. (2000). Their results showed that parasite sedimentation was high, but that resuspension due to urban runoff was also likely. Rangarajan et al. (2000) developed a model for the City of Edmonton for predicting the impact of rainfall on combined sewer overflows and hence on river water quality. This model would be used to predict elevated fecal coliforms in the river, and hence, for determining when microbiological standards for recreational waters would be exceeded.

Crabill et al. (1999) presented their analysis of the water and sediment in Oak Creek in Arizona, which showed that the
sediment fecal coliform counts were on average 2200 times greater than that in the water column. Water quality standards for fecal coliforms were regularly violated during the summer due to the high recreational activity and animal activity in the watershed, as well as the storm surges due to the summer storm season. Lemke and Leff (1999) analyzed the bacterial populations at five sites, including two in disturbed urban streams. The results indicated that anthropogenic disturbance of watershed and stream can alter some bacterial populations (Acinetobacter calcoaceticus) but not others (Burkholderia cepacia, Pseudomonas putida). Haile et al. (1999) presented the results of an epidemiological cohort study of swimmers in Santa Monica Bay, California where untreated urban runoff from Los Angeles was discharged. Higher risks of upper respiratory and gastrointestinal infections were found for swimmers near storm-drain outfalls, in waters with a low ratio of total to fecal coliforms, and in waters where enteric viruses were detected. Herrmann et al. (1999b) demonstrated through modeling that, for a German city with a combined sewer system, blackwater separation by vacuum toilets and urine separation can reduce nutrient discharges during overflow events by 90%, especially in the summer when the river water may contain up to 50% sewage. These reductions in nutrient discharges might improve the river water quality sufficiently to meet swimming water quality criteria during most, if not all, of the year.

Water Environ. & Technol. (1996c) reported on an epidemiology study conducted at Santa Monica Bay, CA that found that swimmers who swim near stormwater outfalls were 50% more likely to develop a variety of symptoms than those who swam 400m from the same outfalls. This was a follow-up study after previous investigations found that human-fecal waste was present in the stormwater-collection systems. Environ. Sci. & Technol. (1996b) also reported on this Santa Monica Bay study. More than 1% of the swimmers who swim in front of the outfalls were affected by fevers, chills, ear discharges, vomiting, and coughing, based on surveys of more than 15,000 swimmers. The health effects were more common for swimmers who were exposed on days when viruses were found in the outfall-water samples.

Eggleston et al. (1996) reported that closures of the Boston area’s Tenean Beach were due to either exceedance of Massachusetts’ fecal-coliform limit (200MPN/100mL) or both the fecal coliform and the EPA’s criterion for Enterococcus in bathing beaches in marine waters (104 MPN/100mL). It was cited that past epidemiological research demonstrating fecal-coliform concentration to be a poor indicator of public-health risk in marine waters and the exceedance of the EPA’s Enterococcus standard as the basis for questioning the degree of public-health risk posed by swimming in these waters. Su et al. (1996) further documented problems with the fecal-coliform test. It was concluded that the E. coli criteria can do a superior job of reflecting the public perception of a desirable water body for swimming.

Chemical Impacts

Diamond et al (2001) found that the effects of toxicants depended on a combination of both chemical and flow characteristics. Conventional laboratory testing of toxicants with constant exposure concentrations are not very applicable to wet weather flow conditions. They surveyed more than 30 toxicological investigations that have used time-dose or pulsed/intermittent exposure, 15 contaminants, and 10 different species. They concluded that it is possible to predict the chronic effects of fluctuating exposures of fast-acting contaminants (such as ammonia or sodium chloride) using available acute toxicological models. Wong et al. (2001) developed a monitoring method using the green alga Selenastrum capricornutum to predict levels of heavy metals in water. When exposed to stormwater samples, the specific activity of the peroxidase in the cell extract was directly related to the copper and lead concentrations. The peroxidase responses were also correlated with the 96 hr biomass toxicity assay of S. capricornutum. They concluded that the use of this peroxidase can be used as a marker for testing heavy metal toxicity in the water.

Work by Standley et al. (2000) demonstrated that the source of the impacts on a receiving water could be determined using molecular tracers. Polycyclic aromatic hydrocarbons were seen to be excellent tracers for evaluating pollution from urban runoff, while caffeine plus consumer product fragrance materials were excellent markers for WWTP effluent. The investigation by Foster et al. (2000) showed that higher amounts of PCBs, PAHs and organochlorine pesticides in the Anacostia River were associated primarily with the particulates and occurred during high flow events. Analysis of the PAHs showed that they were characteristic of weathered or combusted petroleum products. Aromatic hydrocarbons in urban runoff were found to be likely sources of PAH fluxes to the tidal waters of Chesapeake Bay. O’Meara et al. (2000) described the work done to remove 556,000 Mg of sediment and 12,700 kg of fish contaminated with PCBs from Newburgh Lake in Wayne County, Michigan. The result was that the lake was found to be fit for human recreational activity. Shinoya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Mutagenicity was appreciably associated with the PAHs in the particulate fraction, although the dissolved fraction also showed positive mutagenic response.
The impacts of combined sewer overflow solids were predicted using a model that could describe the solids movement and the erosion of previously-deposited solids in the sewers (Saul et al. 2000). This model was then used to predict the quantity and arrival time of the first flush of sewer solids into a receiving water after a rainfall.

Oberts et al. (2000) reviewed the impacts of snowmelt on urban water quality. They reviewed research on urban snowpacks accumulating large quantities of solids and other pollutants from sources such as airborne fallout, vehicular deposition, and applied grit and salt. They also reported on instances where the first flush of snowmelt has been found to be highly toxic and where water quality deterioration due to snowmelt runoff have been documented.

Stieber et al. (1999) statistically related the pollutant load in urban runoff to interevent dry period and rainfall intensity with the ultimate goal of developing a simple relationship between the rain variables and the pollutant loads. The relationship could be used by planners and engineers to evaluate the effectiveness of pollutant reduction mechanisms. Bamford et al. (1999) investigated the fluxes of PAH at the air-water interface of the Patapsco River and found that the fluxes were highest adjacent to stormwater discharges due to the elevated concentrations of PAH in the stormwater runoff. A major source of the PAH, benzo(ghi)perylene, pyrene and fluoranthene in the rivers in the Paris metropolitan area was found by Ollivon et al. (1999) to be car-park dust due to motor vehicle combustion. During heavy rainfall events, PAH primarily were leached from urban surfaces and transported to the rivers. Zheng et al. (1999) related the high concentrations of petroleum hydrocarbons and PAH in Hong Kong marine sediments to the heavily urbanized or industrialized areas surrounding the most heavily polluted sites. They showed that the oil and its products were the major sources of hydrocarbons in sediments. Stormwater runoff from an urban highway in Xi’an, China was shown by Zhao et al. (1999) to contain BOD, COD and suspended solids concentrations at least as strong as typical domestic effluents. However, the biodegradability of the organic compounds in the runoff (BOD:COD = 0.167) was low. Regression equations were developed for BOD and COD and for suspended solids and COD in urban runoff from the highway. Gupta et al. (1999) investigated the sources of pollutants to Talkatora Lake in Jaipur, India. They found, using a mass balance of the lake, that the major cause of pollution to the lake was the first flush of stormwater runoff from the adjacent residential and commercial areas.

Bendoricchio et al. (1999) demonstrated that nutrient concentrations in runoff varied during rain events and that the deterioration of water quality in the Lagoon of Venice, Italy, was related to the diffuse pollution sources in the watershed. As the point sources of pollution were controlled, the relative importance of NPS increased, and effectiveness of the Lagoon restoration would depend on controlling the diffuse sources of the nutrients. A water quality index (WQI) was developed by Peters and Kendell (1999) for streams in the Atlanta, Georgia region, and the sampling data showed that the WQI for nutrients was best for the low-density residential areas and worst for the industrial area. Yung et al. (1999) investigated the physico-chemical and biological changes in Victoria Harbor, Hong Kong and found that water temperature, total and ortho-phosphorus, and fecal bacteria were increasing, while pH, total nitrogen, TKN, BOD and chlorophyll a were decreasing. However, sampling sites not in the main Harbor did not reflect these trends, although all sites reflected the fact that Victoria Harbor and its vicinity were polluted by sewage effluent, stormwater runoff, marine traffic, construction, and industrial activities.

Crosbie and Chow-Fraser (1999) investigated the impact of land use on the water and sediment quality in 22 marshes in Ontario, Canada. The concentration of inorganic solids, sediment phosphorus, metolachlor, and ionic strength were positively correlated with the percentage of agricultural land in the watershed, while the concentrations of PAH were positively correlated with the percentage of urban land. Heal (1999) demonstrated the accumulation of copper, nickel and lead in the sediments of a wetland and two detention ponds receiving urban storm runoff in Scotland. Sediment metals concentrations, however, were highly variable within each structure, possibly indicating short-circuiting through the ponds and wetland. Platinum, palladium and rhodium were found in road sediments by Rauch et al. (1999) with their concentrations increasing since 1984. The increase in bioaccumulation of rhodium in Aseltus aquaticus in urban rivers was linked to the increased sediment concentrations of these automobile-derived metals. Shafer et al. (1999) investigated the partitioning of trace metal levels (Al, Cd, Cu, Pb, and Zn) in Wisconsin rivers and found that the concentrations in the rivers were comparable to recent data collected in the Great Lakes and other river systems where ‘modern’ clean methods were used for sampling and analysis. They also found that the variation in the partitioning coefficients of each metal between sampling locations could be explained by the amount of anthropogenic disturbance in the watershed and by the concentration of dissolved organic carbon (DOC) in the water.

Arid western rivers have many characteristics that distinguish them from rivers in more temperate areas. The Denver area’s South Platte River, in which flow is dominated by municipal effluent, has the following characteristics: nutrient
abundance; wide, shallow and unshaded channel; high primary productivity produces variations on pH that can have a strong influence on nonionized-ammonia concentrations (Harris et al., 1996).

Inaba et al. (1997) studied the effects of trace metals, e.g., cobalt (Co) and Fe in sanitary wastewater. Elevated concentrations have been shown to increase the frequency of algal blooms in water bodies. Haygarth and Jarvis (1997) studied the transfer of P and N by stormwater runoff from cattle grasslands and concluded that grassland soils are a significant source of diffuse P inputs to surface and estuarine waters and may cause eutrophication.

The physical and chemical properties of sediment in a stormwater pond were studied. Analysis of the sediment determined that Cr, Cd, Cu, Fe, Pb, manganese (Mn), Ni, and Zn were present (Marsalek et al., 1997). In a study to investigate the fate of infiltrating stormwater runoff, natural-organic matter facilitated metal transport into near surface soils (Igloria et al., 1997). The metal transport was a function of volume and depth of stormwater and increased concentrations of natural-organic matter allowed for greater metal attenuation.

Hay and Battaglin (1996) described how an integrated system consisting of a large historical receiving-water-quality database, a geographic-information system (GIS), a scientific-visualization system, and multimedia software are used to produce an interactive data-analysis tool. The integrated system allows users to analyze the data in the U.S. Geologic Survey’s (USGS) National Stream Quality Accounting Network (NASQAN), describes the water quality of the Nation’s streams and rivers on a systematic basis and to identify temporal trends in the concentration of measured constituents. Stream water-quality data from NASQAN and USGS’s Hydrologic Benchmark network are now available on CD-ROM (Alexander et al., 1996). These networks provided some of the best available data for quantifying changes in the water quality of major United States streams during the past 20-30 years, estimating the rates of chemical flux from major continental watersheds of the United States, and investigating relations between water quality and streamflow as well as water quality to watershed characteristics and pollution sources.

Sampling and monitoring of New York City’s Jamaica Bay have confirmed the eutrophic state of some areas of the Bay (Fitzgerald et al., 1996). It is known that the probable root causes of this problem are both the extremely high nutrient loading to the Bay from anthropogenic sources as well as the lack of adequate flushing also resulting from human intervention.

Glazewski and Morrison (1996) presented results showing the effects of photoreduction of Cu in urban streams. It was concluded that pollutant speciation and potential toxicity of Cu, Cr, and Fe is greatly affected by photoreduction reactions.

Toxicity

Milam et al. (2000) investigated the effects of several pesticides (chlorpyrifos, malathion, Permanone(R), Abate(R), Scourge(R), B.t.i. and Biomist(R)) on both standard toxicity-testing organisms (Ceriodaphnia dubia, Daphnia magna, Daphnia pulex, and Pimephales promelas) and resident mosquito fish and mosquito larvae. They demonstrated that the current pesticide application rates were sufficient to affect non-target organisms when the pesticides were washed off in stormwater runoff.

Toxicity of river sediment near major cities on the Mississippi River was evaluated, both up- and down-river of the cities, and was not found to be toxic to the organisms studied (Winger and Lasier, 1998). Most stormwater samples from Ballona Creek which is one of the largest sources of stormwater inputs to Santa Monica Bay, Calif. were toxic (Jirik et al., 1998). Receiving water samples were also toxic, with the magnitude of effects generally corresponding to the concentration of runoff present. The study implicated divalent trace metals, particularly Zn as the probable toxic constituents.

One of the key objectives of the Chesapeake Bay restoration effort is to reduce the impacts of toxicants. Alden and Hall (1996) described the Toxics Reduction Strategy based on water-column- and sediment-chemical analyses, benthic-community health, and fish-body burdens. More than 40% of the sites have displayed some degree of water-column toxicity and about 70% of the sites have displayed sediment toxicity. Garries et al. (1996) further described how the list of Toxics of Concern was developed for Chesapeake Bay.

The need for endpoints for assessments using multiple stressors was discussed by Marcy and Gerritsen (1996). Five watershed-level ecological-risk assessments were used to develop appropriate endpoints based on specific-project
However, simple screening-toxicity tests are useful during preliminary assessments or for treatability tests. The most promising results are associated with using several complementary tests, instead of any one-test method. Pitt interpreted measured heavy-metal concentrations in urban-stream sediments. This book presents many topics that would enable the user to better understand the presence of a metal in an organism cannot directly prove whether that metal is poisoning the organism. However, if compared to concentrations in a suite of well-researched biomonitor, it is possible to determine if the accumulated concentrations are atypically high, with a possibility that toxic effects may be present. Allen (1996) also presented an overview of metal-contaminated-aquatic sediments. This book presents many topics that would enable the user to better interpret measured heavy-metal concentrations in urban-stream sediments.

Rainbow (1996) presented a detailed overview of heavy metals in aquatic invertebrates. It was concluded that the presence of a metal in an organism cannot directly prove whether that metal is poisoning the organism. However, if compared to concentrations in a suite of well-researched biomonitor, it is possible to determine if the accumulated concentrations are atypically high, with a possibility that toxic effects may be present. Allen (1996) also presented an overview of metal-contaminated-aquatic sediments. This book presents many topics that would enable the user to better interpret measured heavy-metal concentrations in urban-stream sediments.

Pitt et al., (1996b) reported on various laboratory-toxicity tests using 20-stormwater and -CSO samples. It was found that the most promising results are associated with using several complementary tests, instead of any one-test method. However, simple screening-toxicity tests are useful during preliminary assessments or for treatability tests.
Habitat Management and Restoration

Aquatic life impairments make up a large proportion of the 303(d) listed water bodies nationwide. Martin, et al. (2002) report that in Virginia, approximately 35 percent of the impaired streams are listed on the 303(d) list because of aquatic life impairments. Virginia and EPA, working with Tetra Tech, Inc., have developed a Total Maximum Daily Load (TMDL) methodology to evaluate streams having impaired benthic communities. The TMDL process establishes a link between the impairment and benthic community stressors. The reference watershed selection process is based upon a comparative analysis of key watershed attributes. The Virginia Ridge and Valley Multimetric Bioassessment Index (VRVMBI) was developed specifically for this project using metric discrimination analyses. This process reviewed water and sediment quality data, toxicity test results, and physical processes to determine the primary causes of impairment. Impaired and reference watersheds were modeled to determine the conditions necessary to support a healthy benthic community.

A number of stream restoration efforts have been carried out in small watersheds in Maryland for the past ten years. The goal of virtually all of the restoration projects was to reduce high sediment supply from bank and bed erosion and to increase sediment transport, thus restoring a condition of equilibrium between sediment supply and sediment transport.

The purpose of the EPA-funded Arid West Water Quality Research Project is to conduct scientific research to develop appropriate water quality criteria and improve the scientific basis for regulating wastewater and stormwater discharges in the arid and semi-arid West. Meyerhoff et al. (2001) described a study where historical and site reconnaissance level data were gathered on ten effluent dependent waters. They found that while the aquatic community may be limited, significant benefits occurred in the terrestrial communities that developed in response to the created aquatic environment. Based on the concerns raised during this research, the EPA’s Region IX published a “net ecological benefit” guidance document that provided an opportunity to recognize the non-aquatic benefits gained from effluent discharged to otherwise dry riverbeds.

Bragg and Kershner (1999) investigated another aspect of biological impacts – the impact on the habitats of aquatic life – and they found that coarse woody debris in riparian zones can be used successfully to maintain the integrity of these ecosystems. Larson (1999) evaluated the effectiveness in urban areas of these habitat restoration activities using large woody debris and found that in urban areas, the success of restoration may be hindered by the high sediment loads and increased flow associated with urbanization. Markowitz et al. (1999) documented the CSO Long Term Control Plan implemented by the City of Akron, Ohio which focused on habitat preservation and aquatic life use of the receiving waters. The plan included these non-traditional alternatives: riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration, and were found to cost less than five percent of the typical cost of controlling CSO flows. A methodology to investigate the chronic and cumulative degradation of the river Orne due to CSO and urban runoff was presented by Zobrist et al. (1999), with the results being used to evaluate management activities. O’Meara et al. (1999) reported on the restoration of Newburgh Lake on the Middle Rouge River in Wayne County, Michigan. The $11.8-million restoration consisted of removing PCB-contaminated sediment and fish, construction of new fish habitat, and restocking of beneficial fish and aquatic plants. Xu et al. (1999) reported on the improvement plan being used for a river passing through the downtown area of a city in Western Japan and the problems that were inherent with developing a compromise strategy between flood control and mitigation and the desire to have an attractive waterway through the city. The final improvement plan recommended construction of a new flood drain tunnel and a new underground flood control reservoir.
Cianfrani et al. (1999) used a GIS system to document the results of a comprehensive inventory of the natural resources of the Fairmount Park (Philadelphia, Pennsylvania) stream system, including vegetation communities, fish, aquatic and terrestrial insects, birds, mollusks, amphibians, reptiles, and streams. The stream assessment also included the characterization of stream reaches by in-stream habitat, geomorphology and riparian zone. This GIS inventory then was used in planning the restoration of sites in the Fairmount Park system. Derry et al. (1999) reported on the habitat management strategies implemented by the City of Olympia, Washington, to control the degradation of aquatic habitats by urban stormwater runoff. These management strategies provided a basis for resolving the conflict between growth and the protection of aquatic resources. Ishiakwa et al. (1999) reported on the efforts to restore the hydrological cycle in the Izumi River Basin in Yokohama, Japan while Saeki et al. (1999) have documented the efforts of the Tokyo Metropolitan Government and its Basin Committee to restore the natural water cycle in the Kanda River. Kennen (1999) investigated the relationship between selected basin and water-quality characteristics in New Jersey streams and the impact on the macroinvertebrate community and its habitat. He found that urban areas had the greatest probability of having impacted stream areas, with the amount of urban land and the total flow of treated sewage effluent being the strongest explanatory variables for the impact. He also found that levels of impairment were significantly different between the Atlantic Coastal Rivers drainage area and the Lower Delaware River drainage area.

Jarrett et al. (1999) analyzed the data collected from 1991 through 1998 as part of the stream-monitoring program implemented in Louisville and Jefferson County, Kentucky. They found that recreational contact standards for fecal coliforms were exceeded during WWF and that much of the pollutant loadings of suspended solids and BOD were also contributed by WWFs. However, they found that the nutrient loadings were more varied with some impact seen from wastewater treatment plants. The concentrations of phosphate, total phosphorus, and total volatile solids in the streams were reduced as more of the watershed was sewered. Reduction of eutrophication through the treatment of stormwater runoff with storage facilities and wetlands for Lake Biwa was proposed by Hidaka et al. (1999). It was estimated that this storage and treatment could reduce the COD load to the lake by nearly 70%. However, wetlands could be overloaded and the water quality of its effluent degraded, as demonstrated by Noguchi et al. (1999) in their study of the regulation pond/wetland in Ishahaya Bay, Japan. In order to prevent eutrophication of the regulatory pond it was found to be necessary to control nonpoint sources of nutrients in runoff.

Changes in physical stream channel characteristics can have a significant effect on the biological health of the stream. Schueler (1996a) stated that channel geometry stability can be a good indicator of the effectiveness of stormwater control practices. In addition, once a watershed area has more than about 10-15% effective impervious cover, noticeable changes in channel morphology occur, along with quantifiable impacts on water quality, and biological conditions. Stephenson (1996) studied changes in stream-flow volumes in South Africa during urbanization. Increased stormwater runoff, decreases in the groundwater table, and dramatically decreased times of concentration were found. The peak flowrates increased by about two-fold, about half caused by increased pavement (in an area having only about 5% effective-impervious cover), with the remainder caused by decreased times of concentration.

**Environmental Effects of CSO and SSO**

Yingling and Haywood (2002) discussed the strategies needed to reduce flooding in the Doan Brook watershed in northeast Ohio. The problem has been caused by CSOs, channelization through the park, and restrictive bridge crossings. Jones et al. (2002a) reviewed the difficulty of assessing CSO water quality impacts Kokomo, Indiana, when the CSOs discharge into two Operating Units of the Continental Steel Superfund Site with the pollutants of concern being heavy metals and organic chemicals.

O’Meara et al. (2002) reported on the Oxbow Restoration Project on the Rouge River. The purpose of the project is to enhance the ecological viability of the western-most Oxbow by creating valuable fish and wildlife habitat, restoring functioning riverine wetlands, improving water quality and modifying the existing CSO outfall.

Borchhardt and Reichert (2001) describe their study of the River Lahn, a moderately polluted 5th order stream in Germany for which the connectivity of surface/subsurface flows and mass fluxes within river sediments have been intensively investigated. The hyporheic flow between a downwelling and upwelling zone of a riffle-pool reach of the river was studied using tracers and continuous records of water chemical characteristics. High diurnal fluctuations of oxygen traveled to considerable depths in the sediment and oxygen levels in the interstitial water decreased considerably while traveling through the riffle reach. The resulting model is being used to examine the effects of CSO discharges. They found that CSOs may cause anoxic sediment oxygen conditions for extended periods of time. Michels (2001) described a CSO Basin study conducted on the Menominee River, MI, to see if the facility met the Michigan water quality standards.
and if it provided adequate treatment. Four sets of samples were collected upstream and downstream of the facility for comparison during discharge events. They found that the water quality standards were not violated during overflow discharges to the Menominee River.

CSO and SSO can have damaging impacts on receiving waters. Sanudo-Wilhelmy and Gill (1999) compared current pollutant concentrations in the Hudson River Estuary, New York with concentrations measured in the 1970s. The concentrations of Cu, Cd, Ni, and Zn have declined, while concentrations of dissolved nutrients (PO₄) have remained relatively constant during the same period of time, suggesting that wastewater treatment plant improvements in the New York/New Jersey Metropolitan area have not been as effective at reducing nutrient levels within the estuary. Rather than inputs from point sources, the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary. Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Colford et al. (1999) proposed and applied three analytic methods to evaluate the impact of such outflows on public health. David and Matos (1999) discussed the difficulties of modeling and regulating the effects of CSO and stormwater discharges on the water quality in Portugal’s rivers. Emphemeral river flows, rainfall patterns that differ from north to south, the effects of pollutant transport dynamics in sewers and pavements, and bed river resuspension during storms all influence river water quality. To understand the effect of CSO on the river Seine (France), a characterization of effluent in terms of organic matter and bacterial biomass was carried out during several sampling campaigns performed in a combined sewer located in Parisian suburbs under wet- and dry-weather conditions. The only two small differences in relative composition that could be observed between dry and wet weather were slightly lower content of organic carbon in suspended solids and a lower biodegradability of this material during rain events (Servais et al. 1999). Vollertsen et al. (1999a) characterized the biodegradability of combined-sewer organic matter based on settling velocity. Fast settling organic matter, which represents the largest fraction of the organic material, was found to be rather slowly biodegradable compared to the slow settling organic fraction. The biodegradability of sewer sediments was argued to be taken into account for detailed characterization when dealing with CSO impacts. Vollertsen et al. (1999b) investigated the effects of temperature and DO on kinetics of microbial transformation processes of suspended sewer sediment particles. No differences between sewer-sediment particles, wastewater particles and wastewater were found for the oxygen-saturation coefficients examined.

By means of measurements and numerical simulations, it was shown that the first flush of dissolved compounds effect caused a significant impact of dissolved compounds on the receiving water, when a CSO occurs, and also on the wastewater treatment plant when the sewer network was flat and catchment area was big (Krebs et al., 1999). Mason et al. (1999) showed that the Chesapeake Bay was an efficient trap for mercury. However, in the estuary, methylation of the mercury occurred, the Bay became a source of methylmercury, and on a watershed scale, only about 5% of the total atmospheric deposition of mercury was exported to the ocean. Venkatesan et al. (1999) investigated the potential for using sediment cores to determine the history of chlorinated pesticide and PCB application in a watershed. They found that the sediment cores accurately reflected the length of use of these chemicals in the watershed, and that the surface sediment layer, after mixing and resuspension was accounted for, reflected the reduction in use that had occurred during the last few years.

Bellefleur et al. (1999) summarized the data available on the water quality of combined sewer flow in Roeschwoog. The data that these flows impacted the physical and chemical water quality of the Sauer; however, an impact of CSO on the biological integrity was not easily seen. Classification of the rainfall into eleven types of events allowed the investigators to estimate the total loads from polluted overflows during a typical year. Herrmann et al. (1999a) found that the discharge of urea, which hydrolyzes to ammonia with a corresponding increase in pH, could cause fish toxicity after a CSO event. The concentration of ammonia plus urea in the combined sewer discharge was found to be a more relevant measure of the likelihood of a fish kill after an overflow event than the concentration of ammonia alone. Saul et al. (1999) investigated the production of undesirable solids in combined sewer flows as it related to social, economic and ethnic factors. The goals of the research were first to determine the differences in the characteristics of the solids in the sewers that were ultimately discharged to the receiving water and then to use the solids’ characteristics to predict the efficiency of CSO treatment devices, especially CSO chambers. St. Michelbach and Brombach (1999) showed that the nutrient content, especially of dissolved phosphorus, from CSO and existing wastewater treatment plants (WWTP) was endangering the health of Lake Constance. They proposed a simple methodology to estimate the nutrient loads from CSO to the Lake, the results of which can be used to determine the cost-effectiveness of CSO improvement versus WWTP improvement.

Fish and macroinvertebrate sampling defined and prioritized the needs of CSO systems and assessed where other
watershed pollutants caused more harm than CSO (Markowitz, 1998).

CE-QUALW2 was used to determine the impacts of CSO during a four-year study to mathematically model the water quality of Cheatham Lake on the Cumberland River below Nashville, Tenn. (Adams et al., 1997).

Mulliss et al. (1996) found that several wet-weather flow (WWF) discharge parameters regularly pose a serious threat with regard to freshwater aquatic life. Widera and Podraza (1996) investigated instream biological conditions and water quality during 52 CSO events in three years in a small stream near Essen, Germany. Notable observations were that ammonium concentrations increased by up to 70 times during CSO discharges, protozoa counts were significantly higher downstream of the CSO, while macroinvertebrate counts showed little difference. However, the composition of the aquatic-life communities differed substantially between upstream and downstream locations, showing that common ecological indices (such as the index of diversity) are not suitable tools for detecting these changes because they do not correctly reflect the differences in community structure.

The main impact of a CSO is generally a decreased level of oxygen in the receiving waters, according to Seidl et al. (1996). An extensive monitoring program in a Paris, France suburb to measure the bacteria and organic carbon content of a combined sewer under both wet- and dry-weather conditions in order to more accurately predict the resulting dissolved-oxygen (DO) conditions was conducted. Lammersen (1996) examined DO and ammonia (NH₃) conditions in receiving waters affected by stormwater in northern Germany. No events during a three-year-monitoring period were found to have caused critical conditions for these two parameters. Brosnan and O’Shea (1996) reported on the decrease in coliform bacteria concentrations in the receiving waters of New York’s Hudson-Raritan Estuary. Among the contributors to this water-quality improvement is the increased capture of wet-weather CSOs.

**Risk Assessment**

Bosley et al. (2001) described a study on the Upper Roanoke River Watershed (URRW) in southwest Virginia, using HSPF to evaluate the hydrologic impacts of land use change. Continuous simulations were conducted to investigate the hydrologic effects of various spatial arrangements of development in residential areas, with and without networks of primary and secondary roads. Beckers and Frind (2001) used a steady-state stormwater model of the Oro Moraine aquifer in Ontario to examine long-term temporal variations in the flow regime associated with changes in aquifer recharge. They found that nearby urban development would have a significant impact on the baseflow to the swamp, in addition to baseflow impacts to nearby local streams. The model also is being used as a guide to future data collection in the area.

The Office of Water at EPA (1999) published *CSO: Guidance for Monitoring and Modeling* as a reference for persons and institutions involved in evaluating the effects of CSO on all users of an impacted receiving water. Bickford et al. (1999) reported on the methodology developed and implemented by Sydney Water to assess the risk to humans and aquatic organisms in creeks, rivers, estuaries and ocean waters from WWF. The model used in this study was designed to predict concentrations of various chemicals in WWFs and compare the values to toxicity reference values. Brent and Herricks (1999) proposed a methodology for predicting and quantifying the toxic response of aquatic systems to brief exposures to pollutants such as the contaminants contained in stormwater runoff. The method contains an event-focused toxicity method, a test metric (ETU, event toxicity unit) to represent the toxicity of intermittent events, and an event-based index that would describe the acute toxicity of this brief exposure. The toxicity metric proposed (PE-LET50 [post-exposure lethal exposure time]) was the exposure duration required to kill 50% of the population during a pre-specified, post-exposure monitoring period. Colford et al. (1999) proposed three methods of analytically evaluating the impact of storm sewer and combined sewer outflows on public health, especially in areas that may receive through deposition the harmful agents in sewage and combined sewage. In the Puget Sound region of the U.S. Pacific Northwest, Greenberg et al. (1999) developed and evaluated the Urban Stream Baseline Evaluation Method to characterize baseline habitat conditions for salmonids. The methodology, based on assessment of geomorphic suitability, fish distribution and habitat alteration, was recommended for use to prioritize recovery actions. Stewart et al. (1999) collected diatoms (Bacillariophyta) and water quality samples from three streams that drain the Great Marsh in the Indiana Dunes National Lakeshore. They found that diatom species diversity could be used as indicators of water quality, which could then be linked to land use in a watershed. Diatom species diversity was most variable in areas with poorer water quality and was directly correlated to the total alkalinity, total hardness and specific conductance of the water in the stream.

Easton et al. (1999a and 1999b) presented the first phase of a project for determining the risk associated with human contact with waters contaminated with sewage-borne pathogens. Determination of the survival rates for these pathogens has been found to be crucial for determining the length of time after a contamination episode that the water was unsafe for
human contact such as wading, swimming, etc. Die-off rate studies for total coliforms, *E. coli* (including *E. coli* 0157:H7), *Enterococci*, and *Giardia lamblia* were performed in situ in a stream known to have SSO. The survival rates, when combined with local hydrologic data, would be used to predict fate and transport of these microorganisms. Wakeham (1999) reported on the results of the investigation to determine why an $800 million investment program designed to improve swimming water quality in the northwest coast of England was not effective. They found that the problem of compliance with water quality criteria for human exposure to pathogens was more complex than originally believed and that current data analysis techniques and models by themselves could not completely describe the complex environment.

**Groundwater Impact**

According to research by Dale et al. (2000), urban runoff, in addition to leaking underground fuel storage tanks and pipelines, has been shown to transport methyl tert-butyl ether (MTBE), a fuel oxygenate, to groundwater supplies. A survey performed by the authors also demonstrated that personal watercraft that use fuel containing MTBE is another potential source of MTBE to surface waters and groundwater. Di Carlo and Fuentes (2000) investigated the potential in Florida for monosodium methanearsonate (MSMA) to be transported to the groundwater after its application on golf courses. The results of their modeling showed that the unconfined Biscayne Aquifer was susceptible to MSMA and arsenate contamination. Uddin (2000) reported on the deterioration of groundwater in Malaysia due to agriculture, and industrial and human activities. The results showed that phenolic compounds, coliforms, iron, manganese and mercury had the highest frequencies of exceeding water quality standards. The water quality studies performed by Thomas (2000) indicated that the shallow groundwater near Detroit, Michigan, had higher median concentrations of nitrate, chloride and dissolved solids in areas with residential development. These groundwaters appeared to be impacted greatest by septic tank effluent in urban stormwater infiltration, especially runoff from paved surfaces. Zobrist et al. (2000) investigated the potential of using roof runoff for groundwater infiltration/recharge. The authors found that a first flush of pollutants was seen from the inclined tile and inclined polyester roofs and that corrosion of drains released copper in sufficient quantities to potentially damage the groundwater and surface receiving waters.

Standish-Lee (2000) reviewed the work performed by the Palmdale (California) Water District as part of their Wellhead Protection Plan. This project determined that the groundwater supply was most vulnerable to leaking septic tanks, illegal activities/dumping, trunk sewer lines, US Air Force Plant 42, dry wells, gas stations, junk/scrap yards and leaking underground storage tanks. Other locations of groundwater contamination sources included stormwater runoff detention basins, highways, railroads, golf courses, housing developments, hardware stores and repair shops. Stuurman (2000) outlined the Netherlands “National Groundwater Flow Systems Analysis (NGFSA)” project, which was designed to map the regional groundwater flow system and the associated groundwater/surface water interactions. The purpose of this project was to provide this information for urban planners in order to prevent the water systems from being stressed by drought, flooding, and/or pollution.

NPS contamination of surface and groundwater resources with nitrate-N (NO\textsubscript{3}-N) has been linked to agriculture across the midwestern United States (Cambardella et al., 1999). Moorman et al. (1999) reported that herbicide, mainly atrazine and metribuzin, transport in subsurface drainage and shallow groundwater can result in unacceptable levels of contamination in surface waters. An investigation of the Walnut Creek watershed, California was performed to characterize the geology, groundwater flow, and water quality in geological units impacted by agriculture (Eidem et al., 1999). The infiltration of dissolved herbicides and metabolites from a tributary stream can occur where the stream crosses a floodplain overlying an alluvial aquifer causing the contamination of shallow alluvial aquifers at rates that exceed in-field leaching by up to three orders of magnitude (Burkart et al., 1999).

Hatfield et al. (1999) examined a multi-disciplinary study on the effect of farming practices on subsurface drainage, surface runoff, stream discharge, groundwater, volatilization, and soil processes that influence water quality. Groundwater was vulnerable to contamination in karst areas where highway stormwater runoff may flow directly into karst aquifers with little or no natural attenuation and transport highway-derived contaminants rapidly from sinkholes to locations in the aquifer. Field testing sites were located in Knoxville, Tennessee and Frederick, Maryland. A pilot-scale stormwater runoff treatment system, in Knoxville (Tennessee) and Frederick (Maryland), has been designed using peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption prior to groundwater recharge.

Control of stormwater in sinkhole areas of Springfield, Missouri has involved the utilization of several standard approaches: concrete-lined channels draining into sinkholes; installation of drainage pipes into the sinkhole "eyes" (swallow holes); filling of sinkholes; elaborate drains or pumps to remove stormwater from one sinkhole and discharging...
into another drainage basin or sinkhole; and enlargement of swallow holes by excavation to increase drainage capacity. Three sites were analyzed to examine the effectiveness of contrasting design approaches to stormwater management. These sites differ in vegetation, on-site/off-site considerations, and types of development proposed (Barner, 1999). Since little was known about the influence of microorganisms which develop in urban stormwater infiltration basins on the transfer of heavy metals, Herbard and Delolme (1999) examined the transfer of zinc solutions (2-20 ppm) at different pH (4-7) by columns of sterile sand or sand colonized with Pseudomonas putida. By the analysis of the observed time series of streamflow from catchments, the main components of the underlying groundwater balance, namely, discharge, evapotranspiration loss, storage and recharge, can be identified and quantified. This holistic estimation method was demonstrated for the Harris River catchment in southwestern Western Australia (Wittenberg and Sivapalan, 1999).

Fan and Bras (1998) presented an analytical solution to a hillslope-based formulation of subsurface storm flow and saturation overland flow (Suzuki et al., 1998) examined pesticide concentrations in groundwater and in water leaching from a golf course in Japan and found that the golf course represented an area of high pollution potential compared to agricultural land. Their study emphasized the need to examine subsurface drainage in addition to runoff water when examining pesticide transport from golf courses. The relationship between stormwater and shallow groundwater in urban areas was evaluated (Lopes and Bender, 1998). Urban land surfaces were found to be the primary NPS of most VOC, with urban air being a secondary source. Using oxygen and deuterium isotopes, Iqbal (1998) traced the sources of storm runoff in a watershed in Iowa. The isotopes determined the relative contributions to river flow from rainwater and from ground water which had been flushed from the soil by infiltrating stormwater. The feasibility analysis of a simulation system to assess the impact on groundwater of various hypothetical situations (in the field of water management, land use, etc.) focused on the infiltration of stormwater in a periurban environment and involved space and time scales that apply to mid- and long-term management of groundwater resources (Bernard and Miramond, 1998).

Barrett and Charbeneau (1997) studied the impact of an urban watershed contributing recharge to the Barton Springs and Edwards Karst Aquifer in Austin, Tex. Results indicated that changes in N concentration in the aquifer would not be noticeable. Garrett and Petersen (1997) developed a series of lakes at Green Valley Park for both groundwater recharges and stormwater management in Payson, Ariz.

One of the major concerns of stormwater infiltration is the question of adversely impacting groundwater quality. Pitt et al. (1996a) reviewed many studies that investigated groundwater contamination from stormwater infiltration. A methodology was developed to evaluate the potential of stormwater contamination and it was concluded that there is only minimal potential of contaminating groundwaters from residential-area stormwaters (chlorides in northern areas remains a concern).

**Planned groundwater recharge**

Ammann et al. (2002) investigated where the infiltration of urban/industrial roof runoff into permeable subsurface material may adversely impact the groundwater quality and endanger drinking water resources. The pollution potential was found to be high and non-reactive tracers exhibited fast breakthrough and little sorption.

A water balance model was developed for a semiarid landscape of Spain (Bellot et al., 2001). The components were the soil water content, the actual evapotranspiration (Eta), and both the aquifer recharge (deep drainage) and runoff, which reflected water recharge, human use and soil erosion impacts. Combining the model predictions with the land cover vegetation units on the aquifer recharge area, the effects of some management policies on the deep drainage and runoff in five simulation scenarios were compared. Extreme precipitation during a wet year led to a higher erosion risk. Well clogging will impede the use of aquifer storage and recovery (ASR) wells (Dillon et al., 2001). In this study, the Membrane Filtration Index (MFI), a standard test of the rate at which water clogs a membrane filter, has been used with turbid and organic-rich waters. Waters from 12 sites (mains, urban stormwater and reclaimed water) which are or have the potential to be water sources for aquifer storage and recovery (ASR) in southern Australia, were analyzed for MFI, turbidity, total suspended solids, total organic carbon, particle size and SEM. Little more than half the variance in MFI could be explained with the measured water quality parameters, likely due to the complex nature of the inorganic and organic particles present in the waters. The ongoing field study has been designed to determine if MFI can be related to well clogging at one of the focus sites.

Dillon et al. (1999) reported on the use of storage aquifers under urban areas to enhance groundwater recharge and to decrease the volume of surface runoff and combined sewer effluent reaching the receiving waters. Similarly, Lin et al. (1999) discussed the use of reclaimed wastewater plus stormwater to recharge the groundwater in the Caprock Aquifer in...
Oahu, Hawaii. Munevar and Marino (1999) developed a model for evaluating the artificial recharge potential on alluvial fans in the Salinas Valley in California. They found that average recharge/infiltration rates ranged between 0.84 and 1.54 cm/hr and that recharge efficiency ranged from 51 to 79%. Their model results demonstrated that planned recharge and streamflow augmentation could significantly reduce the groundwater overdraft and seawater intrusion in the area.

Shentsis et al. (1999) reported on the transmission losses and groundwater recharge, including transmission losses from the vadose zone, from rainfall-runoff events in a wadi in Israel. They found that, during large events, evaporation was substantially smaller than the losses. However, in general, the annual recharge was very small, while losses were on the same order of magnitude as the stream flow. Wittenburg and Sivapalan (1999) used streamflow recession analysis and baseflow separation to quantify the components of the groundwater, i.e., discharge, evaporation losses, storage and recharge. Groundwater evaporation through water uptake by trees biased the recession curve. Data analysis of the data, stratified by time of the year, allowed the evaporation loss to be quantified as a function of time of the year and the used groundwater storage.

Generally, igneous and metamorphic rocks have been considered to be barriers to groundwater flow, while carbonates were assumed to allow flow through their fractures. Thyne et al. (1999) found, however, recharge occurring in the Indian Wells Valley through flow in a fractured bedrock that was originally thought to be impermeable. Their results demonstrated that using surface topography along with a knowledge of the location of the bedrock to estimate groundwater flow quantity and direction may not be suitable.

**Chemical groundwater impacts**

Marcos et al. (2002) performed a study and modeled zinc and lead migration in sandy soils due to stormwater infiltration of runoff from road surfaces. The potential existed for the heavy metals from the road to migrate through the soils down to the groundwater.

Barraud et al. (1999) reported on the quality of the groundwater below two infiltration sites in urban areas of France. Kayabali et al. (1999) investigated the chemical contamination of the groundwater in alluvial aquifers adjacent to Ankara Creek since it was believed that Ankara Creek pollution was contaminating the local groundwater. However, it was determined, using analysis of basic ions, organics and metals, that Ankara Creek was not responsible for groundwater contamination, partly because a blanket of fine sediment in the bottom of the creek was expected to adsorb pollutants and to reduce infiltration rates. Lerner et al. (1999) combined a water balance with multiple solute balances to model the flow of water and chemicals into the groundwater under Nottingham, UK. They found that sewers contributed only about 13% of the total nitrogen loading, while leaking drinking water mains was about 36% of the total. The remaining 50% of the nitrogen loading came from parks, gardens, landfills and industrial spillages. Reddy (1999) reviewed the available data from public water suppliers in Wyoming which use groundwater. Nitrate and pesticides were two of the most frequently detected contaminants in groundwater and two of the most frequently detected pesticides were aldicarb and atrazine. Groundwater contamination was found to be a problem especially in areas that were heavily agricultural. Stephenson et al. (1999) investigated the impact of highway stormwater runoff flowing through a karst area and found that little to no attenuation of the runoff pollutants occurred. For most of the contaminants analyzed, the peak loadings arrived at the groundwater table and at the spring it recharges approximately one hour after they were found in the sinkhole that received the highway drainage. Nowicki et al. (1999) found that denitrification of groundwater was not significant in a well-oxygenated vadose zone and aquifer. Denitrification was found to occur to a greater extent in the estuary which receives the groundwater.

Lin et al. (1999) used the boron isotope ratio to trace reclaimed wastewater in a directly recharged aquifer on the Island of Oahu in Hawaii. They also investigated other tracers, such as chloride and silica, and found that, because of the influence of seawater, they were not suitable tracers for the reclaimed water. The results of this study were used in conjunction with mixing curves to determine the fraction of reclaimed water in a well and could be used to calibrate or modify fate and transport models for this aquifer with regard to other pollutants in the recharged water. Mengis et al. (1999) used nitrate-to-chloride ion ratios, concentrations of 15-Nitrogen and 18-Oxygen and an in-situ nitrate/15-N tracer experiment to investigate whether nitrate was being attenuated in the vadose zone and/or the aquifer below a riparian zone. Their results confirmed that denitrification rates could be measured in situ using this procedure. They also confirmed that this methodology could distinguish between water being recharged from the riparian zone versus that being recharged from irrigation of the nearby agricultural fields.

The Technical University of Denmark (Mikkelsen et al., 1996c and 1996d) has been involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. It was found that heavy metals and PAHs
present little groundwater-contamination threat if surface infiltration systems are used. However, concern was expressed about pesticides which are much more mobile. Squillace et al. (1996) along with Zogorski et al. (1996) presented information concerning stormwater and its potential as a source of groundwater MTBE contamination. Mull (1996) stated that vehicular-traffic areas are the third most significant source of groundwater contamination in Germany (after abandoned industrial sites and leaky sewers). The most significant contaminants are chlorinated hydrocarbons, sulfate, organic compounds, and nitrates. Heavy metals are generally not significant groundwater contaminants because of their affinity for soils. Trauth and Xanthopoulus (1996) examined the long-term trends in groundwater quality at Karlsruhe, Germany. It was found that the urban-land use is having a long-term influence on the groundwater quality. The concentration of many pollutants have increased by about 30-40% over 20 years. Hütter and Remmler (1996) described a groundwater-monitoring plan including monitoring wells that were established during the construction of an infiltration trench for stormwater disposal in Dortmund, Germany. The worst-case problem expected is with zinc, if the infiltration water has a pH value of approximately 4.

Microbiological groundwater impacts
Barrett et al. (1999) suggested the use of chemical and biological markers for identification of urban groundwater recharge sources. Their paper documented only the sewage ‘fingerprint,’ a combination of stable nitrogen isotopes and microorganisms. Trihalomethanes had been proposed as a marker for leaks in the drinking water mains, but they were not found in sufficient quantity in the drinking water itself to be an effective measure of groundwater contamination. Markers were not presented for precipitation.

Soil application was proposed as a means of disposal of propylene glycol-based aircraft deicing fluids (ADF). ADF biodegradation was investigated by Bausmith and Neufeld (1999) and the results showed that biodegradation of solutions of less than 20% by weight ADF could be degraded in the soil profile prior to reaching the groundwater. Hebrard and Delolme (1999) investigated the ability of the soil to adsorb the zinc from the infiltration water. Their work showed that the adsorption of zinc retarded the arrival of zinc to the groundwater. Adsorption was found to be reversible except at pH 6 and 7 and was found to be non-instantaneous. These results demonstrated that contact time and conditions control the amount of biofilm removal and retention of zinc from percolation water. Degradation of the groundwater by human and animal excrement was documented by Buckles et al. (1999) for an area in Ecuador where the groundwater table was rising. The degradation of the groundwater in combination with the rising water table produced swamp-like conditions where the water and land were not suitable even for subsistence farming.

Decision-Support Systems
Numerical Models
Rainfall analyses
Improving the accuracy of rainfall data and reducing the uncertainty associated with design information extracted from rainfall data is crucial for wet weather flow modeling activities. Crisci et al. (2002) performed a comprehensive analysis of extreme rainfalls in Tuscany, Italy to assess the hydrological consequences of climate variability and the impact on the design of hydraulic structures. Seremet et al. (2002) recommended temporal and spatial resolution requirements for rainfall monitoring to obtain data suitable for infiltration/inflow assessments. Einfalt and Maul-Kotter (2002) compiled survey results from potential users of radar data for hydrological services and found that besides better technical information of the concept, more education and training of radar derived information use in hydrology was needed. Jacquet et al. (2002) reviewed the requirements of radar data services in urban environments for accurate use as inputs into hydrologic simulation models. Spies et al. (2002) described efforts to develop standards for collection and data processing of rainfall measurements with time increments suitable for urban hydrology.

Rainfall – runoff modeling parameter estimation
A genetic algorithm (GA) method was developed by Wan and James (2002) to optimize the SWMM RUNOFF parameters. The method was coupled with the sensitivity wizard in PCSWMM to produce a sensitivity-based method for automating the calibration process. Testing of the method indicated that the calibrated model was within 97% of the target dataset after approximately 58 cycles of the GA. The GA method was successfully incorporated into PCSWMM and applied by James et al. (2002) to a sample SWMM calibration process. The automated calibration tool significantly reduced the effort required for calibration and design optimization. Inference models were developed by Choi and Ball (2002) to estimate SWMM parameters for the Centennial Park Catchment in Sydney, Australia. The inference models ranged from spatially invariant parameter values to different values for each subcatchment. The results of the study provided insight into the complexity and structure of models used in the calibration process.
The educational experiment was that a GDSS could be used to enhance user performance. Hatchett et al. (2002) using nineteen graduate students and five professors from four Universities during the spring of 2000. The conclusion of user quality and effort than on model structure. The use of the GDSS concept in urban drainage design was tested (GDSS) for the design of urban water systems. Experience has shown that achievable model accuracy is more a product of model quality than on model structure. Rivard and Dupuis (2002) introduced a set of tools combining computational hydraulic modeling and information technology with a clear focus on model problem solving. James (2002b) described the evaluation of a web instructional use of a group decision support system (GDSS) for the design of urban water systems. Experience has shown that achievable model accuracy is more a product of user quality and effort than on model structure. The use of the GDSS concept in urban drainage design was tested using nineteen graduate students and five professors from four Universities during the spring of 2000. The conclusion of the educational experiment was that a GDSS could be used to enhance user performance. Hatchett et al. (2002)
introduced an automated storm sewer design procedure after discussing the differences between available storm sewer design models.

**Water quality modeling and pollutant transport**

Maglionico and Barausse (2002) developed a water quality model to evaluate the response of natural streams to sewer overflows. Fang and Yang (2002) developed a two-dimensional depth-averaged mathematical model to simulate the hydrodynamics and sediment deposition from stormwater entering urban lakes. The model takes into account the wind and Coriolis forces and solves the governing equations on triangular grids using the time-split hybrid scheme. Application of the model to Lake Dian in China indicated that the most sedimentation occurred near the stormwater outfalls into the lake, as expected. Overall, the model predicted reasonably well. Garcia-Barcina et al. (2002) simulated the effect of fecal coliform pollution on the water quality of Bilboa Estuary in North Spain arising from CSO. Results suggested disinfection of the discharges might be needed. Harris et al. (2002) described, in general, models used for flow and water quality predictions in coastal and inland water bodies and discussed the limitations and restrictions of both physical and numerical models. They also described the development of a three-dimensional layer-integrated model to predict water elevations, layer-average velocity components, and the distribution of water quality indicators within Cardiff Bay, Wales. Kashefipour et al. (2002) developed a numerical model combining a depth integrated two-dimensional coastal model and a cross-sectionally integrated one-dimensional river model to predict water surface elevations, velocity fields, and fecal coliform concentration distributions across the entire model domain for the Ribble Estuary system along the northwest coast of England. Ahern and Hazelton (2002) reported on an extensive field data collection effort in the Lower Savannah River Estuary in support of the development of a three-dimensional hydrodynamic and water quality model of the estuary.

Linker et al. (2002) summarized the history of linked airshed, watershed, and water body modeling of the Chesapeake Bay. The first version of the Chesapeake Bay Watershed Model was completed in 1982, and then in progressive phases the watershed model was refined and linked with an estuarine model and to an airshed model. Recent work has incorporated the simulations of under groundwater in the Chesapeake. These cross-media models have been used to estimate nutrient waste loads and set waste load allocations for major basins of the Chesapeake. The next generation of models will be developed as “community models” with source codes and model preprocessors and postprocessors freely available over the web.

Besides the Chesapeake Bay modeling activities, other regional integrated modeling systems have been initiated. Hussein et al. (2002) described the expansion of the capabilities of the next generation regional model for managing water resources in South Florida to include simulation of the fate and transport of dissolved constituents. Moskus et al. (2002) reported on the development and application of linked watershed (Generalized Watershed Loading Function) and water quality model (WASP) for the Pumpkinvine Creek watershed in Georgia. David and Matos (2002) used deterministic water quality modeling integrated with urban stormwater modeling to assess impacts of stormwater discharges on ephemeral watercourses.

Faulkner and Lyon (2002) introduced a new screening model to predict the fate and transport of viruses in percolating water. The leaching fraction model has been implemented in the EPA VirMod computer program. The leaching fraction model can be integrated with GIS to easily incorporate spatial data layers and visualize model output. Schneiderman et al. (2002) updated previous estimates of nutrient and sediment loads to the Cannonsville Reservoir using a revision of the Generalized Watershed Loading Functions (GWLF) model of the West Branch Delaware River watershed.

Brezonik and Stadelmann (2002) compiled a large database of urban runoff data for the twin cities metropolitan area in Minnesota. Relationships between runoff variables and storm and watershed characteristics were examined. Results of the data analysis indicated that median EMCs tended to be higher in snowmelt runoff than in rainfall runoff and simple correlations between explanatory variables and stormwater loads and EMCS were weak. Rainfall amount and intensity and drainage area were the most important variables in multiple linear regression models to predict event loads, but uncertainty was high.

Sutherland and Jelen (2002) presented a technique to more accurately estimate urban runoff loads. The load estimation procedure involved selecting and monitoring specific pilot test areas that are representative of the various land uses found within the watershed. Instead of the costly monitoring of actual stormwater quality at each test area, the load estimation procedure called for the intensive monitoring of the accumulation and physical/chemical characteristics of the sediment found on the streets or parking lots and within the catchbasins of a given land use. This data along with monitored rainfall
was then used to calibrate a stormwater quality model called SIMPTM. Once the model was calibrated to the various monitoring periods, an average or representative rainfall year was used to evaluate various street and catchbasin cleaning practices.

**Watershed model water balance**

Snowmelt prediction is often lacking in urban hydrologic models. Matheussen and Thorolfsson (2002) developed the lumped Risvollan Urban Hydrological Model (RUHM) that solves the full mass and energy balance equations when calculating snowmelt, evapotranspiration, infiltration, and runoff within a watershed. RUHM was applied to the Risvollan urban watershed in Trondheim, Norway and found to predict both runoff, water balance, and snow water equivalent with reasonable agreement.

Many enhancements have been made to the EPA SWMM model since the last official EPA release in 1994 (Huber et al. 2000). These have included improvements to the model engine, enhancements to input/output options, and “hooks” for easier interfacing with graphical user interfaces and ancillary software. The U.S. EPA Office of Research and Development (ORD) Urban Watershed Management Branch (UWMB) has identified two major objectives for urban modeling research: to develop a standard operating procedure for the user community, and to develop a BASINS-compatible SWMM – GIS interface (Koustas 2000). Koustas provided the SWMM-user community with a description of the UWMB approach to urban watershed modeling research and provided an update on ORD SWMM-related projects.

Distributed models were more and more used in regional hydrology. One of the main reasons was their essential compatibility with raster data in Geographical Information Systems. Zech and Escarmelle (1999) investigated the possibility of using other kinds of databases designed more specifically for cartography. Casser and Verworn (1999) described the upgrading of the existing hydrodynamic rainfall runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

Modelers were often faced with data gaps and other problems which may not even come to light until well into the modeling process. Greer (1999) addressed these issues in the context of a case study of a watershed management project conducted in Silver Lake Watershed in central Delaware. A suite of hydrologic, sewer system and riverine water quality models have been used to address technical questions that have been asked in Rouge River Watershed (Michigan) planning (Kluitenberg et al., 1999).

Zug et al. (1999) described modeling efforts to address both flood control and pollution prevention at Gentilly, France. A mathematical model was satisfactorily calibrated and validated and was now being used to simulate the operation of the catchment area and its associated sewerage system.

Schlater and Koehler (1998) asserted that expectations between owner and consultant regarding model applicability and associated development cost are misaligned and that matter-of-fact information concerning what a typical model can and cannot do needs to be clear in the minds of both parties. A checklist is provided to address what an owner needs to know about model development but does not know how to ask. Ahyerre et al. (1998) examined stormwater runoff quality models to determine why no model has achieved widespread use and indicate that the generation and transport of polluted runoff in an urban setting is complex, involves many media and many time and space scales, which renders stormwater quality models difficult and expensive to utilize. The authors suggested that a clear distinction should be made between management tools and research models. Gaume et al. (1998) studied the estimation and interpretation of the parameter uncertainties of conceptual models used in hydrology using a global approach. They concluded that the lack of measured data and its relative redundancy cause a significant interaction between the parameters which hinders calibration and that the data available in hydrology are only sufficient to support the development of models with limited complexity.

The Stormwater and Water Quality Management Modeling Conference, held in Toronto, Ont., Can. in February 1996 yielded a collection of articles which addressed a wide range of modeling applications for WWF impacts management. This accumulation of articles is the fifth in a series of monographs published and includes presented information on methods for urban- watershed management and planning; modeling stormwater quality; storage and treatment practices; and a stormwater-system evaluation (James, 1997).

Within the United States, users continue to rely on existing urban-stormwater models. TenBroek and Brink (1996)
compared several continuous-stormwater-simulation models including STORM and SWMM. Donigian et al. (1996) compared the attributes of six urban- and seven nonurban-stormwater models. Mercer et al. (1996) summarized the use of a variety of stormwater models including SWMM, WASP, the Watershed Management Model, and P8 as part of the Rouge Project in the Detroit, MI area. Donahue et al. (1996) summarized the use of modeling and evaluation tools to select a cost-effective CSO-control plan within a watershed perspective. The attributes of six stormwater models are compared by Shoemaker et al. (1996). Swarner and Thompson (1996) presented the results of extensive measurements and modeling of SSO problems in Seattle, WA. The results of an extensive SSO evaluation using XP SWMM for the Miami, FL sewer system are described by Walch et al. (1996). Kachalsky et al. (1996) described modeling and evaluation methods of optimizing CSO control in New York, NY. Herrmann and Klaus (1996) did general water and nutrient budgets for urban-water systems including stormwater.

A variety of international urban-stormwater models have been released in recent years. Neylen et al. (1996) described the first version of the HydroWorks-stormwater-quality-management model being developed by Wallingford Software in the United Kingdom. Foller et al. (1996) showed how MOUSE can be used to optimize a combined-sewer system in East Germany. Dempsey et al. (1996) described SIMPOL, a simplified urban-pollution-modeling tool developed as part of the United Kingdom’s Urban Pollution Management Research Program. SIMPOL models the stormwater system as series of tanks. Bente and Schilling (1996) proposed an object-oriented approach for an urban-hydrologic-simulation system. Davies (1996) discussed the importance of the appropriate blend of modeling and data for SSO evaluations including a discussion of the advantages and disadvantages of SWMM and HydroWorks. A very extensive evaluation of the Sydney, Australia SSO problem was done with MOUSENAM and SEEKER to simulate and optimize control options (Hayes, 1996). Ji et al. (1996) describe a fast model for evaluating the hydraulics of sewers and open channels. This work showed the implicit-solution scheme in the SUPERLINK model to be much faster than EXTRAN’s explicit solution. Gent et al. (1996) surveyed models that can simulate solid deposition and resuspension in sewers. MOUSETRAP and HydroWorks QM that supersedes WALLRUS and MOSQITO were described. Jack et al. (1996) described several models for characterizing sewer sediments. Brief descriptions of the WALLRUS/HydroWorks PM hydraulics model, the STOAT wastewater-treatment-performance model, and the MOSQITO, HydroWorks-DM and MOUSETRAP sewer-flow-water-quality models were provided. Imbe et al. (1996) used a water budget to establish the effect of urbanization on the hydrological cycle of a new development near Tokyo, Japan. This development is trying to reduce hydrologic impacts by encouraging infiltration systems and storing rainwater. Mitchell et al. (1996) described a water-budget approach to integrated-water management in Australia. Budgeting is done at the individual parcel, neighborhood, and wider catchment scale. A current gap in urban stormwater modeling is the inability to properly incorporate the impact of rainfall on frozen surfaces in urban areas. Thorolfsson and Brandt (1996) described Norwegian experience in which “worst case” conditions occur during these winter periods. The development of new mathematical models to handle this special case were recommended.

Model Applications

An integrated system in Flanders consisting of a sewer, a wastewater treatment plant and a river component was selected for a modelling project (Fronteau and Bauwens 1999). The purpose of that project was to assess the impact of CSO on the receiving water and to investigate on the effects of different operating scenarios within the sewer system. Commercial mathematical models were used, i.e. both the sewer network and the WWTP were modelled with Kosim, while Isis was used to represent the river system. An overview of extended stormwater treatment alternatives is discussed and as well as the possibility of including these practices in simulation models (Mehler and Ostrowski, 1998).

Watanabe et al. (1999a) described a distributed simulation model of water quality and stormwater runoff, which can simulate both open-channel and surcharged flows and at a temporal and spatial variation of runoff-water quality in the pipe systems. The proposed model consists of two models: one was PWRI (the Public Works Research Institute, the Ministry of Construction, Japan) Model for water quality simulations; the other was the SLOT Model for stormwater runoff simulations.

The distributed parameter (grid cell) agricultural nonpoint source runoff (AGNPS) model compared stormwater-runoff volumes, flowrates, and sediment loads from a forested watershed and urbanized watershed for ten simulated rainfall events and included the effects of impervious surfaces on runoff and sediment transport. The rainfall volume to runoff volume ratio was 14.5% higher in the urban watershed with the maximum differences occurring at rainfall depths < 75 mm (Corbett et al., 1997). A complex watershed-scale water-quality-simulation model, the Hydrological Simulation Program-FORTRAN (HSPF) model, was calibrated for a 16 km² catchment. It was necessary to apply a critical process that included sensitivity analysis, numerical optimization, and testing of derived-model-parameter sets to evaluate their
significant error. That one of the proposed disaggregation schemes could be used in hydrological applications without introducing variable roughness for circular pipes on routed hydrograph attenuation and lag time (Zaghloul, 1997). Routing simulations using variable roughness resulted in hydrographs with significant peak-flow attenuation and lag time.

Rainfall variability and effects on modeling.

James (2002c) investigated the robustness of an algorithm for storm direction and speed used in the Rainpak utility of PCSWMM. An extensive sensitivity analysis indicated that standard data collection time steps of 1 or 5 minutes were sufficient for resolving storm dynamics and highlighted the importance of more rain gauges and the arrangement of rain gauge networks for describing storm event dynamics. Willems and Berlamont (2002a) evaluated the influence of the spatial variability of rainfall on the results of urban hydrologic models. Results of the study included a combination of unified IDF relationships, spatial correction factors, a stochastic simulation model for spatial rainfall, and a methodology for improving the spatial correction factors in a case-specific way by performing simulations with the model.

One common problem encountered when performing continuous simulation is the availability of rainfall data at the location of interest and with an appropriate time increment. One solution to the time increment problem is to perform a temporal disaggregation step to produce a rainfall record with finer time resolution from a coarser resolution dataset. Burian and Durrans (2002) compared a quadratic spline and a quadratic polynomial technique, a method based on geometric similarity, a uniform distribution approach, and an artificial neural network method to disaggregate hourly rainfall records to sub-hourly increments. The methods were evaluated based on their ability to accurately disaggregate hourly rainfall data from Alabama and Arkansas to 15-minute and 5-minute increments and results indicated the artificial neural network approach and geometric similarity technique provided the most accurate disaggregation. In addition to the disaggregation of recorded rainfall data, stochastic generation of rainfall is a viable option to provide input data with adequate time resolution for wet weather flow simulation models. Hingray et al. (2002) presented a comprehensive detention facility-design modeling framework including a stochastic component to generate long-term rainfall series with short time step, a rainfall-runoff model to transform the rainfall series into a runoff series with a short time step, and a model to describe the hydraulics of the detention facility.

The evaluation of radar rainfall data products for use in wet weather flow modeling has expanded considerably as the technology continues to develop. Koran et al. (2002) described the use of radar rainfall technology in the development and calibration of the System Wide Model for the collection system of the Metropolitan Sewer District of Greater Cincinnati. Quirmbach and Schultz (2002) evaluated the suitability of using radar data versus rain gauge data for urban rainfall-runoff modeling. Results indicated that radar data should be used in urban hydrology if distances between rain gauges exceed 4 km and if rain gauge density for a catchment is less than 1 gauge/16 km².

NEXRAD (WSR-88D) radars have made spatially distributed rainfall data available in an operational environment (Carpenter et al., 2001). The present study addressed the use of NEXRAD data using a Monte-Carlo sensitivity analysis of event streamflow to parameter and radar input for the Illinois River basin in Oklahoma and Arkansas. The main conclusions was that the distributed model forced by NEXRAD data produces results comparable to those produced by the operational spatially-lumped models using raingage data. Detection of rain/no-rain condition on the ground is needed to apply radar rainfall algorithms to hydrological models (Lui et al., 2001d). A radial basis function (RBF) neural network-based scheme for rain/no-rain determination on the ground using vertical profiles of radar data was described in this paper. Evaluation based on WSR-88D radar over central Florida indicates that rain/no-rain condition could be inferred fairly accurately. Lui et al. (2001e) presented a novel scheme for adaptively updating the structure and parameters of the neural network for rainfall estimation. The network can account for any variability in the relationship between radar measurements and precipitation estimation and also incorporate new information to the network without retraining the complete network from the beginning. To make the monthly satellite data useful for hydrological applications (i.e. water balance studies, rainfall-runoff modeling, etc.), the monthly precipitation estimates must be disaggregated into shorter time intervals (Margulis and Entekhabi 2001). In this study, two simple statistical disaggregation schemes were developed for use with monthly precipitation estimates from satellites. Results suggested that one of the proposed disaggregation schemes could be used in hydrological applications without introducing significant error.
Rainfall data collected since the publication of NWS’ Technical Paper 40 and HYDRO-35, and NOAA’s Atlas 2, and the development of improved statistical methods, motivated several states to initiate update studies of precipitation distributions (Durrans and Brown 2001). Results of the Alabama study were disseminated via an Internet-based graphical user interface, which permits users to interactively point and click on a location of interest and have IDF curves or storm hyetographs returned on demand. The study by Kim and Barros (2001) modified the existing ANN model to include the evolving structure and frequency of intense weather systems in the mid-Atlantic region of the US for improved flood forecasting. Besides using radiosonde and rainfall data, the model also used the satellite-derived characteristics of storm systems such as tropical cyclones, mesoscale convective complex systems, and convective cloud clusters as input. The results from the application of the quantitative flood forecasting model in four watersheds on the leeward side of the Appalachian mountains in the mid-Atlantic region were presented.

Aerial variations in rainfall were investigated by Balascio (2001), using unbiased multiquadric analyses to reduce the problem of negative rain gauge weighting when determining the representative rain depth for an area. Willems (2001) developed a stochastic spatial rainfall generator for use in small urban catchments. For applications at small scales, the individual rain cells need detailed descriptions. Data from a dense network of rain gauges at Antwerp were used for verification of the process. Cameron et al. (2001) successfully modeled extreme rainfalls using a generalized Pareto distribution to represent the rain depths of high intensity rain cells. Trefry et al. (2001) used a partial duration series/generalized Pareto regional index flood procedure for updating rainfall intensity-duration-frequency estimates for the State of Michigan. Porras and Porras (2001) examined all series of extreme rainfall depths to produce less ambiguous depth-duration-frequency and intensity-duration-frequency curves for Venezuela. Cheng et al. (2001) used a simple scaling property of rainfall to guarantee that the normalized rainfall rates of different storm durations are identically distributed. They proposed a nonstationary Gauss-Markov model, based on the annual maximum events that arise from the dominant storm type to obtain the most likely hyetograph. This method allows translating hyetographs between storms of different durations. Koutsoyiannis and Onof (2001) developed a rainfall disaggregation method using adjusting procedures on a Poisson cluster model. This method allows the possible extension of a short hourly time-series with the use of longer-term daily rain data.

The National Weather Service’s WSR-88D radar (NEXRAD) was used to estimate the spatial distribution of rainfall for three storms over the Brays Bayou watershed in Houston for hydrologic modeling purposes (Bedient et al. 2000). The results from the radar proved to be as accurate, and in some cases more accurate, than the rain gauge model when predicting runoff volume, peak flow, and peak time. Chan (2000) explored the spectral behavior of rainfall of various temporal resolutions and presented a method of generating rainfall data that combined the approaches of stochastic modeling with a disaggregation goal. The total rainfall volumes of the generated data compared well with observed values but tended to produce lower rainfall intensities and longer rainfall durations per event.

Sempere-Torres et al. (1999) presented a case study where the use of rainfall estimates from weather radar pictures was compared with the use of a rain-gauge network in terms of the ability to predict sewer flows in an urban basin in Barcelona, Spain. The results showed that the use of radar data enables the combined sewer systems model to better simulate observed flows, and provide support for the idea that the spatial description of rainfall was a key problem in modeling the events giving rise to CSO.

Luk et al. (1999) described a rainfall forecasting model that integrates an artificial neural network (ANN) with a GIS. The ANN was trained to recognize historical rainfall patterns recorded from a number of gauge of the study catchment and to make point forecasts of rainfall. The GIS was used to spatially distribute the point rainfall forecasts produced by the ANN. Mikkelsen et al. (1999) used regional modeling of a range of rainfall variable statistics to assess the performance of different historical rain time series. Sufficiently long rain series were rarely available from the exact catchment in question and for this reason simulations were often based on available rain series from other locations. Nnadi et al. (1999) tested the ability of various design storm distributions to simulate the actual rainfall pattern and to compare the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. Peak-runoff rates from design storms based on the various distributions were compared to those that would result from actual rainfall events. The results show that the behavior of the design storm distributions varies across the state.

Willems (1999) reported on data collected from a dense network of rain-gauges in Antwerp, Belgium to study the stochastic structure of spatial rainfall at the small spatial scale of small hydrographic or urban catchments. The derived spatial rainfall model contains two structures: a deterministic structure for the physical description of individual rain cells.
and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Durrans et al. (1999) compared a number of approaches to the problem of how to disaggregate rainfall time series using polynomial approximating functions. Results of these evaluations indicate that a disaggregation method presented by Ormsbee was a relatively good performer when storm durations were short (2 h), and that a quadratic spline-based approach was a good choice for longer-duration storms. Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters could be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

Useful variables for defining the state and evolution of a rain system include rainfall rate, vertically integrated rainwater content and advection velocity. The forecast model proposed in this work complements recent dynamical formulations by focusing on a formulation incorporating these variables using volumetric radar data to define the model state variables, determining the rainfall source term directly from multi-scan radar data, explicitly accounting for orographic enhancement, and explicitly incorporating the dynamical model components in an advection-diffusion scheme. An evaluation of this model was presented for four rain events collected in the south of France and in the northeast of Italy (Dolcine et al., 1999). A procedure to generate rainfall input for the EUROpean Soil Erosion Model was presented. To develop such a procedure, first of all the influence of rainfall event amount, rainfall event duration, and time to peak intensity of event rainfall on soil losses, calculated with EUROSEM, has been tested for several rainfall stations. It seems possible to produce site specific appropriate rainfall input for EUROSEM, only with the knowledge of distributions for the investigated basic rainfall parameters; however, to improve the procedure and make it practically useful, it will be necessary to account for seasonal changes of distributions of basic rainfall event parameters (Sterr et al., 1999).

Data from a dense network of rain gauges in the city of Antwerp (Belgium) has been used to study the stochastic structure of spatial rainfall at the small spatial scale of small hydrographic or urban catchments. The derived spatial rainfall model contains two structures: a deterministic structure for the physical description of individual rain cells and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Such a model forms the basis of the stochastic generation of spatial rainfall for urban catchments (Willems, 1999). Gyasi-Agyei and Willgoose (1999) presented a generalized hybrid model to generate point rainfall for a wide range of aggregation levels. The rainfall process was expressed as a product of a binary chain model which preserves the dry and wet sequences as well as the mean, and a correlated jitter, a second-order autoregressive Gaussian process, used to improve the deficiencies in the second-order properties of the binary chain. Two possible binary chain models were analyzed, a non-randomized Bartlett-Lewis model and a Markov chain.

Daily rainfall records for durations of 30, 20, 10, 5, 4, 3, 2, and 1 years from six stations were analyzed revealing positive evidence of the existence of chaotic behavior in daily rainfall data for Singapore (Sivakumar et al., 1998). Results also suggested that the attractor dimensions of rainfall data of longer time periods are higher than that of shorter time periods. DeGaetano (1998) developed a clustering algorithm to form regions with similar extreme rainfall cumulative distribution function (CDF) characteristics and applied it to extreme rainfall data from W.V. Lambert and Kuczera (1998) modeled interstorm and storm durations for several Australian state capitals, illustrated practical issues in calibration and identification, and concluded that a generalized exponential model can replace 12 monthly models to describe the seasonal stochastic variation of interstorm time. Data for four rain gauge stations were analyzed by the fuzzy mode recognition method. The distributive character of a rainfall pattern for a short duration storm was given and the design-storm pattern was satisfied for the urban drainage by simulation and comparison (Cen et al., 1998).

Hromadka (1997) used a set of realizations of error data from rainfall-runoff hydrological models and generated a set of error transfer function realizations to equate to the original data using a four-section algorithm. Fernando and Jayawardena (1998) used artificial neural networks (ANN) to model the rainfall-runoff process. The radial basis function type of ANN saved considerable modeling time and effort.

Rainfall-runoff quantity models.

Ostrowski (2002) discussed the issues of spatial and temporal scales in urban drainage modeling. The focus of the discussion was the effect of urbanization on floods, in particular the effect of source control measures for controlling floods in large river basins. Working at the lot scale, Huber and Cannon (2002) used SWMM to simulate runoff from a residential neighborhood in Portland, Oregon for low impact development alternatives. Both an aggregated model representation and a disaggregated model representation were tested. The simulation results showed the hypothetical LID improvements at the lot scale would produce more than a 50% reduction in hydrograph peaks and volumes at the
watershed outlet. At a larger scale, Schulte and Grace (2002) used SWMM to simulate runoff and storm drain hydraulics for a military base re-development project in San Diego. Overall, the drainage infrastructure was in poor condition and lacked hydraulic capacity to meet today’s design standards. Additionally, the project required SWMM simulations to correlate closely with the Modified Rational Method. Several rules-of-thumb were developed to apply the Rational Method with SWMM.

Applying a calibrated SWMM model, Holder et al. (2002) simulated the catchment scale response of Harris Gully to Tropical Storm Allison. The simulation had to account for submerged conditions at the outlet into Brays Bayou that could reduce outflow capacity of the Harris Gully by 60-80%. The high water levels in Harris Gully for Tropical Storm Allison were successfully simulated with the model. A hydrodynamic model for the Nine Mile Run combined sewer system in Pittsburgh, Pennsylvania was coupled with a drainage model for the adjacent urban stream (Heineman and Meeneghan, 2002). The linked models were used to develop frequency-duration statistics for ecosystem restoration design purposes.

The detection of urbanization in hydrologic records and the representation of urbanization impacts on hydrological response require new data analysis approaches and the incorporation of additional data sources into modeling. Beighley and Moglen (2002) evaluated the use of an annual maximum discharge to precipitation ratio to detect nonstationary signals in stream gauge records. Using the discharge to precipitation ratio was found to reduce the climate signal present in the annual maximum discharge series. They also developed three threshold measures of urbanization to predict the existence of a significant trend in the flood series. A method was proposed by Chen and Wang (2002) to incorporate available meteorological data to define the degree of change in a runoff hydrograph for urbanizing basins. Simulation results for the Wu-Tu watershed in Taiwan indicated that three decades of urbanization had increased peak flow by 27% and reduced the time to peak by four hours.

Incorporating probability and uncertainty into modeling results is critical in order to effectively use the results for informed decision-making. A probabilistic modeling approach to stormwater management was tested by Kreikenbaum et al. (2002). Decision-making becomes more complex with the additional degree of freedom associated with the probability of the modeling results. Planners must be adequately trained to understand the uncertainties in order to effectively use probabilistic tools. Hauger et al. (2002) presented a model-based approach using long-term Monte Carlo simulations for risk assessment of different alternative control measures for wet weather flow control. The approach is elaborated for oxygen depletion in urban rivers caused by CSO.

Bergman et al. (2002) performed a calibration of storm loads in the South Prong watershed, Florida using BASINS/HSPF. Results included calibration of the hydrology and calibration of the individual storm loads. The hydrologic calibration was continuous over the period 1994 through 1999. Simulated storm runoff, storm loads, and event mean concentrations were compared with their corresponding observed values. The hydrologic calibration showed good results. The outcome of the individual storm calibrations was mixed. Overall, however, the simulated storm loads agreed reasonably well with measured loads for a majority of the storms. Barlage et al. (2002) reviewed the impacts of climate and land use change on runoff from a Great Lakes watershed. Model results showed that changing climate and changing land use will increase the percentage of precipitation that results in surface runoff from 17.1% to 21.4%. This 4.3% increase partitioned into a 2.5% increase due to climate change and a 1.6% increase due to land use change.

One can use regional regression equations or hydrologic modeling to estimate streamflows at ungauged sites. Bell and Wade (2002) evaluated the transfer method to estimate flows at an ungauged site using data from a gauged site, based on the proportionality of contributing drainage areas. The flow estimates using the transfer method are made at a gauged site to assess the predictions. Bledsoe (2002a) presented a process-oriented view of what is known about the physical response of streams to urbanization and stormwater controls, identified some critical information gaps, and suggested useful approaches and analysis tools for filling these gaps. In particular, variable responses to altered flow and sediment regimes across different stream types, riparian conditions, and spatio-temporal scales were considered.

Bledsoe (2002b) used hydrologic and sediment transport models to examine the effectiveness of typical stormwater management policies in reducing the potential for stream-channel erosion. The various sediment-transport relationships yielded widely diverging estimates of sediment-transport capacity and yet suggested detention volume requirements that agreed within 20%. Detention design for control of cumulative sediment load required a detention storage volume 61% greater than a peak control detention facility and resulted in an altered temporal distribution of sub-bank-full shear stress. Design of stormwater facilities based on time-integrated sediment-transport capacity may inadvertently result in channel
instability and substrate changes unless the approach accounts for the frequency distribution of sub-bank-full flows, the capacity to transport heterogeneous bed and bank materials, and potential shifts in inflowing sediment loads.

ANN methodology was applied to solve various problems concerned with hydrology and water resources engineering and planning, in particular the prediction of the index flood for several ungauged catchments in the UK (Dastorani and Wright 2001). A network with 7 inputs provided the best results. The Multi-Layer Perceptron network with three layers, Tanh function for hidden layer, and the Sigmoid function for output layer were the most accurate. The review by Dawson and Wilby (2001) considered the application of ANNs to rainfall-runoff modeling and flood forecasting, including the related themes of the division and preprocessing of data for model calibration/validation; data standardization techniques; and methods of evaluating ANN model performance. A template was proposed to assist the construction of future ANN rainfall-runoff models. ANNs was shown to be an efficient way to model the runoff process where explicit knowledge of the internal hydrology is not required (Ahmad and Simonovic 2001). ANN was used for the Red River in Manitoba, Canada to predict the peak flow, timing and shape of runoff hydrograph, based on the antecedent precipitation index, melt index, winter precipitation, spring precipitation, and timing. The percent error in simulated and observed peak flow and time of peak was 6 and 3.6 %, respectively.

A rainfall-runoff model was developed based on water balance equations (Abulohom et al., 2001). The model inputs were precipitation and potential evapotranspiration (both on monthly basis) and the output was the simulated runoff at the watershed outlet. The model was calibrated and tested for four watersheds, with a correlation coefficient between the simulated and measured data ranging between 77% and 93%. Croke and Jakeman (2001) assessed the model types available to improve the prediction of catchment flows and transport in Australia where the flows are typically peakier, base flows are of lower proportion, runoff coefficients are smaller, and dry periods are longer and more variable, than in European and North American catchments. Improvement of predictions relied on the following: more rigorous testing of models; the use of improved interpretation of spatial data; more and better monitoring of hydrological response; complementary use of conceptual and distributed models; and integration of modeling with other information.

The Garg and Sen (2001) study presented a physically based hydrologic model using derived watershed features to simulate rainfall-runoff response of a catchment. The finite-element concept was used to obtain the time-invariant weighting coefficients for estimating the rainfall on the cascade planes. Overland flow was simulated using a kinematic wave model. The fundamental premise of the AFDC approach is that maintenance of a stream’s ecological integrity depends upon maintaining an appropriate flow regime (magnitude and frequency) (Good and Jacobs 2001). The AFDC provided a graphical tool to illustrate the quantity and frequency of streamflow available in a river basin and facilitated the simulation of the modified streamflow regime based on historic time series data. The AFDC methodology was illustrated in the lower Suwannee River basin in Florida. The Long-Term Hydrologic Impact Assessment (LTHIA) model run on a GIS is a relatively simple model that uses the Curve Number method to estimate changes in surface runoff between different stages of development (Grove et al., 2001). Application to a large, rapidly urbanizing watershed near Indianapolis, Indiana suggested that average annual runoff depths increased by more than 60% from 1973 to 1991. A sensitivity analysis showed that a precipitation record length of 15 years or more was required to produce consistent results with LTHIA.

Chen and Cai (2001) used the Kinematic Wave method to model the rainfall-runoff process in an idealized drainage basin. The simulation results showed that for basins with moderate to high rates of infiltration losses, the critical rainfall duration associated with the maximum peak discharge may be shorter than the time of concentration \( t_c \) for the basin, implying that a storm with a spatial coverage of only part of the basin may generate the maximum peak discharge. For basins with low or negligible infiltration losses, the critical rainfall duration approaches \( t_c \). The geomorphological instantaneous unit hydrograph (GIUH) was used to relate the shape and scale of the catchment transfer function to stream network topology and channel characteristics (Hall et al., 2001c). GIUH derivation depended on a series of assumptions, including the estimation of a “characteristic velocity.” If this velocity is expressed in terms of the kinematic wave approximation, the peak and time-to-peak of the IUH may be expressed by a group of catchment and channel characteristics and by the intensity of rainfall excess. The study by Guo (2001a) expanded the rational method into the rational hydrograph method in which the time of concentration is considered the system memory and the contributing rainfall depth to the present runoff rate is defined as the accumulated precipitation over the past up to the time of concentration. Using this method, the complete runoff hydrograph could be generated under a continuous nonuniform hyetograph. A new formula for estimating the time of concentration was derived from 25 rainfall/runoff events in four urban watersheds and was confirmed in watersheds in Maryland and Colorado.
Neither the index antecedent precipitation index and the Natural Resource Conservation Service's antecedent moisture condition triad consistently characterized the runoff consequence of watershed moisture preceding a rainfall event (Heggen 2001). A normalized antecedent precipitation index that modified the conventional index in three ways (inclusion of antecedent precipitation earlier in the day of the event, normalization to the station mean, and normalization to the antecedent series length) was proposed. Initial results showed the proposed index outperformed single curve number-based results, even when the curve number is fit to historic rainfall-runoff records.

Kroll et al. (2001) tested whether the inclusion of new watershed characteristics improved the prediction of extreme hydrologic events, in particular, low streamflow prediction. Preliminary results indicated that regional regression models of low streamflow quantiles, which traditionally have very high model errors, might be improved in some regions by including topographic, climatic, and hydrogeologic statistics. Lee et al. (2001a) developed a stochastic differential equation (SDE) for a lumped rainfall-runoff model and applied it to a watershed that consisted of a number of subwatersheds in series in Taiwan. The development of the moment equations of simulated outflow was based on a SDE. The outflow hydrograph was obtained by applying the Laplace transform method to the equations that describe rainfall excess. A second paper by Lee et al. (2001b) presented a geomorphic and hydrologic information system for calculating the discharge in small and midsize ungaged watersheds. A compound module, based on a digital elevation model, frequency analysis theory, kinematic-wave approximations, and geomorphic-based runoff modeling, provided enough information for calculating the design discharge for different return periods. The stochastic-conceptual rainfall-runoff simulator (SCRRS) developed by Freeze in 1980 was used to demonstrate quantitatively the interplay of the factors that control overland flow by the Horton and Dunne mechanisms (Loague and Abrams 2001). The simulation domain and input data were abstracted from the R-5 catchment (Chickasha, OK) data sets. The SCRRS simulations showed that the Horton and Dunne processes can (i) occur simultaneously at different locations during a given rainfall event, (ii) change from one process to the other with time depending on the characteristics of the rainfall event, and (iii) be strongly dependent on the initial conditions.

Corrêa et al. (2001) presented the outcome of recent work for the cities of Springfield and Columbia, Missouri using high spatial resolution satellite data to enhance or effectively replace conventional data sources for mapping impervious and bare ground surfaces, and for determining runoff curve numbers (CNs) required by hydrologic and environmental computer models. The estimated accuracy of high-spatial resolution imagery was approximately 80%. Spatial data of primary importance to hydrologic modeling include Digital Elevation Models (DEM) for topography, imagery such as Digital Raster Graphics (DRG), hydrologic soil type, and land use for infiltration losses (Hartman and Nelson 2001). Other supporting data types may include Triangulated Irregular Networks (TIN), hydrography, precipitation, and stream stage. The GSDA website offered detailed explanations, tips, and direct links to hydrologic data sources. A case study modeling the Lost Creek watershed in Northeastern Utah provided an overview of the data acquisition process, and can also be found at the GSDA website. Land use changes over a 30 year period (1961-1990) were incorporated into a continuous simulation rainfall runoff model to investigate the effect of these changes on flood frequency in the Thames catchment at Kingston (Crooks and Davies 2001). Broad scale changes in land use over the last 120 years in the Thames catchment were determined from a variety of sources.

PCSWMM was used to calibrate the kernel function in the central rain-runoff algorithm in SWMM and to generate plots that were compared to the experimental results obtained from a laboratory rig whose impervious pavement had a 0.025 m/m² slope over an area of 2.11 m² (James 2001). Results indicated that the RUNOFF algorithm produces reasonable results, even when supercritical laminar flow cases were included in the validation tests. Andreassian et al. (2001) proposed a new approach to sensitivity analysis for watershed models through a comparison between the efficiency ratings and parameter values of the models and the quality of rainfall input estimate (GORE and BALANCE indices). Although the watershed size was generally immaterial, smaller watersheds appeared to need more precise areal rainfall estimates to ensure good modeling results.

Engineering practice and works design requires the calculation of the “design flood” (Paoli et al., 2001). When there are no available records for the flood frequency analysis, different formulations, semi-empirical methods and hydrological simulation models have been used with the design storm then transformed into a maximum flow. This research concluded that the procedure to determine the design flood from frequency analysis of flow peaks (obtained of the transformation P-Q) provided better results that the one that transformed the storm design. Three indirect techniques for index flood estimation were analyzed in order to evaluate their applicability and effectiveness (Brath et al., 2001). The results showed that the statistical model had a better descriptive ability than the physically-based models. The results highlighted that direct estimation techniques were advisable for catchments with peculiar geomorphoclimatic properties.
One-dimensional floodplain models of the proposed modifications to William Cannon Drive in Austin, Texas, indicated no significant upstream impact during the 100-year flood (Buechter 2001). Given the limitations of traditional one-dimensional tools in this application TxDOT decided that to model this project using two-dimensional floodplain modeling techniques. The two-dimensional model better identified the potential impacts associated with the proposed highway reconstruction. Radar-rainfall data, remotely-sensed land-use and land-cover data, measured streamflows, and meteorological data were incorporated into the distributed flood forecasting model WATFLOOD to synthesize runoff hydrographs for three significant rainfall events that occurred in 1995 in the Duffins Creek drainage basin in southern Ontario (Cranmer et al., 2001). These results indicated that WATFLOOD could accurately model the nonlinear rainfall-runoff processes for increasing rainfall intensities with respect to peak flow, basin lag, and time to peak flow. Iturbe et al. (2001) used the spatial structure of storms to enhance flood estimation using a rainfall runoff process. The results suggested that interpolation was insensitive to the variogram selection. The applications of the estimation error (and of the method in general) were discussed.

Bates and Campbell (2001) and Campbell and Bates (2001) used a Markov chain Monte Carlo procedure to select rainfall–runoff model parameters. Regionalization of the model parameters was accomplished for all parameters simultaneously via a regional function that links the posterior means to watershed characteristics. They demonstrated the methodology using an eight-parameter conceptual rainfall-runoff model and two case studies from southeastern Australia. Perrin et al. (2001a) questioned whether the use of large numbers of modeling parameters improve model performance. They conducted an extensive comparative assessment using 19 lumped models on 429 catchments, mostly in France, and with some located in the United States, Australia, the Ivory Coast, and Brazil. They found that the bulk treatment of the data showed that the complex models outperformed the simple models in the calibration mode, but not in the verification mode. They concluded that some simple models can yield promising results, although they are not able to handle all types of problems. Kokkonen and Jakeman (2001) also found that a model with less conceptualization could provide a more accurate reproduction of streamflow for some situations. They conclude that the more complexity one wants to include in the model structure, the more types of data and higher information content are required. When only rainfall-runoff data are available, it is difficult to justify substantial conceptualization of complex processes. Wagener et al. (2001) state that many existing hydrological models do not make the best use of available information, resulting in additional uncertainties in model structure and parameters, and a lack of detailed information regarding model behavior. They propose a framework for appropriate levels of model complexity as a function of available data, hydrological system characteristics, and modeling purpose.


The Hydrologic Modeling System (HEC-HMS) is “next generation” software for precipitation-runoff simulation and will supersede the HEC-1 Flood Hydrograph Package. The program is a significant advancement over HEC-1 in terms of both hydrologic engineering and computer science (Scharrfenberg and Feldman 2000). Current capabilities of the HEC-HMS program that are not found in HEC-1 are discussed. Nguyen et al. (2000a) applied two different optimization methods to calibrate the RUNOFF block of the SWMM model: the Downhill Simplex Method, and the Shuffled Complex Evolution (SCE) Approach. Better results were found using the SCE approach. A semi-distributed conceptual rainfall-runoff model for urban catchments was developed (Aronica and Cannarozzo 2000). The urban drainage network was idealized as a cascade of non-linear cells with kinematic wave routing. The results indicated that both the variation in the spatial representation of the rainfall and the variation in the spatial discretization of the catchment influence the outlet hydrographs.

New developments in information technology were proposed to estimate spatially variable parameters for hydrologic simulation systems (Ball 2000c and 2000d). Control parameter estimation philosophies were discussed, and techniques were demonstrated on the use of hydroinformatic systems in parameter estimation. The development of urban databases provided a convenient means of accessing information for the purpose of hydrological modeling (Rodriguez et al. 2000a). A recently developed model, 'SURF' (semi-urbanized runoff flow), was specifically designed to couple with a GIS. SURF was evaluated with a 7-year continuous data series and was shown to compare favorably to both measured data and results from URBAN, another urban hydrologic model.

Hydrologic losses were estimated on the basis of rainfall-runoff data recorded in 21 urban experimental catchments.
(Becciu and Paoletti 2000). From analysis of experimental data, the probability distribution function of the runoff coefficient was found to be approximately normal, and simple relationships for estimation of main moments were developed. The impact of grid-cell size on calibrated parameters and on the performance of a variable source area model intended for urbanizing catchments was examined by modifying TOPMODEL concepts to accommodate urban surfaces (Valeo and Moin 2000a). Results showed that in this integrated model of urban and rural areas, predicted processes based on calibrated parameters were dependent on grid resolution. The snow accumulation and melt routines of three drainage models that have been applied to urban settings were reviewed; two of these, MouseNAM and SWMM, were designed for urbanized catchments; the third, HBV, was a regional-scale model for rural catchments (Šemádeni-Davies 2000). All contained a temperature index for melt—this method is shown to be theoretically unsound without modification for urban simulations. Literature on model development, validation, and application was found to be lacking.

In many cities of the world, urban cells may be hydraulically defined where built-up areas are highly subpartitioned into walled properties (Hicks et al. 2000). A method was proposed to quantify flood damage vulnerability based on hydraulic properties of the urban cell and on peak flow and time to peak. A flood inundation model was developed by combining a SWMM-based model of a storm sewer network and a two-dimensional (2D) overland-flow model (Hsu et al. 2000). SWMM was employed to solve the storm sewer flow component and to provide the surcharged flow hydrographs for surface runoff exceeding the capacity of the storm sewers.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a three-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations and Variable Source Areas (Chen and Beschta, 1999).

Donnelly-Makowecki et al. (1999) examined whether the quasi-distributed response function used in TOPMODEL provides superior performance for event simulation in small, temperate forested catchments, compared to lumped reservoir representations of runoff routing similar to those employed in many catchment hydrology models. The alternatives were a two-reservoir black-box model and a three-reservoir model structured to represent our perceptual model of runoff processes based on held observations. A second objective was to test the statistical significance of differences in model performance using a new approach that combines the Jackknife with analysis of variance (ANOVA).

A procedure was introduced for applying the statistical approach to water-table management models, e.g., DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water-table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

Matheussen and Thorolfsson (1999) presented research on the simulation errors due to insufficient temporal resolution in urban snowmelt models. Storm-sewer overflow was calculated from an artificial overflow for all time resolution. Based on this research, the authors propose that snowmelt-produced runoff in urban areas should be measured and modeled with no more than a 1-hour time resolution.

Vertessy and Elsenbeer (1999) described a process-based storm-flow generation model, Topog SBM consisting of a simple bucket model for soil water accounting, a one-dimensional kinematic wave overland flow scheme, and a contour-based element network for routing surface and subsurface flows. Aside from topographic data and rainfall the model has only six input parameters: soil depth, saturated hydraulic conductivity at the soil surface, the rate of decay of saturated hydraulic conductivity at the soil surface with depth, the Manning surface roughness parameter, the maximum (saturated) soil water content, and the minimum (residual) soil water content. The model was applied to La Cuenca, a very small rainforest catchment in western Amazonia that has been well characterized in several hydrometric and hydrochemical investigations.

Ando et al. (1999) described how the effects of urbanization on the hydrological water cycle were estimated by using a simulation model to quantify the constituent elements of the hydrological-water cycle. A questionnaire survey was conducted among residents of the river basin to identify the problems that the residents wish to have resolved through the restoration of the hydrological-water cycle in the Azuma River and to set target values for the desired improvements.
Becker et al. (1999) presented a few examples where detailed field studies described the essential elements of runoff generation and thus help to achieve a more realistic representation of the underlying mechanisms within process-oriented rainfall-runoff models.

An approach was developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds. Monte-Carlos simulation was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the SCS unit hydrograph model. This approach was demonstrated for the Pluit Polder flood protection system for the City of Jakarta, Indonesia. Although, the SCS model was limited to agricultural conditions, the approach presented herein may be applied to other flood control systems if appropriate storm-runoff models were selected (Yulianti and Lence, 1999).

A modified Rational Formula approach for designing urban storm sewer systems included the conventional detention pond and the double detention pond (Wu et al., 1998). This approach also estimated the hydrographs which may be applied to design the conventional detention pond or the double detention pond with results showing the double can hold up to 50% of the volume compared to the conventional. The calibration of the Soil Conservation Service (SCS) runoff equation using rainfall and runoff data from six storms in Fla. showed that the CN for impervious surfaces may differ from the value of 98 suggested by SCS, and in warm climates may be closer to 94 or 95 (Pandit and Regan, 1998). Due to the nonlinear behavior of sewer systems, hydrodynamic simulations using single storm events often do not lead to a good probability estimation of the overflows. Well calibrated, simplified models using long-time simulations give better results (Vaes and Berlamont, 1998). Guo and Adams (1998) derived closed-form analytical expressions for average annual runoff volume and runoff event volume return period based on an equation which describes the rainfall-runoff transformation on an event basis, and the exponential probability density functions of rainfall event characteristics. Guo and Adams (1998) also derived analytical expressions or probabilistic models for peak discharge rates that are proposed as an alternative to simulation modeling or regional analyses for the determination of flood frequencies for urban catchments.

Hromadka and Whitley (1999) developed a mathematical formalization of link-node hydrologic models using HEC-1. By subdividing a watershed into numerous subareas, and connecting the subareas by a network of links, a link-node model representation of the watershed was constructed. King et al. (1999) compared two methods of simulating excess rainfall on a large basin with multiple rain gages. The SCS daily curve number method (CN) was compared with the Green-Ampt, Mein-Larson (GAML) method on the Goodwin Creek Watershed. Li and Joksimovic (1999) presented a methodology to define the average conditions for urban drainage system modelling. The drainage system performance should be first analyzed in a cursory manner to identify the average conditions and the "typical rainfall year". A detailed analysis of the drainage system performance should then be conducted for the "average rainfall year" and the "typical rainfall year." If the discrepancy in performance was large, the "typical rainfall year" should be used in the analysis of average conditions of urban drainage systems. Loke et al. (1999) compared Artificial Neural Networks (ANN) and Grey-Box Models (GBM), implementing them in three practical urban storm drainage case studies. The advantages of ANN included good generalization, high fault tolerance, high execution speed, and the ability to adapt automatically without human intervention. However, ANN relied strongly on the availability of data examples, and they were not transparent and obstruct any direct analysis and interpretation of their performance. On this basis the GBM was superior, as it enables the user to get a better insight into the involved uncertainties. Mehlhorn and Leibundgut (1999) discussed the use of tracer time parameters to calibrate the baseflow time of concentration in a conceptual rainfall-runoff model. A comparison showed that the modeling approaches in tracer hydrology and rainfall-runoff modeling were mathematically equivalent. Therefore, it was assumed that tracer time parameters were suitable to calibrate baseflow runoff models. Coupling water age and turnover time made it possible to simulate the baseflow in more detail.

Milina et al. (1999) showed that, for Norwegian cities, large flood events have only been affected to a minor degree by urban development whereas short-term events occurring after dry-weather conditions show a significant increase in runoff. The effects of urbanization on runoff have been studied where many catchments have yielded maximum flow from autumn and winter frontal rains, often concurrent with snowmelt or rain on frozen ground. Morita and Yen (1999) presented further developments of the conjunctive urban runoff model and focus on the interaction between surface and subsurface flow components. This interaction was directly related to the estimation of effective rainfall or initial loss of hyetographs. The model reproduced the initiation of overland flow and initial loss process and enables the estimation of the effective rainfall reasonably and theoretically.

Nania et al. (1999) designed and conducted experiments on flow patterns at street crossings and intersections. A
one-dimensional formulation was proposed in order to predict the dividing flow in street crossings. Rigby et al. (1999) developed a sophisticated event based urban hydrology model from very simple beginnings. It highlighted the capabilities of earlier models and how they have increased in complexity and functionality over the last two decades. Shen et al. (1999) proposed the fuzzy neural network model called "FUZZY STORMNET" to estimate volumetric flow from rainfall intensity. This model for flow estimation could be calibrated automatically by use of known storm events, and no knowledge on the field and the sewer system was needed. Smith (1999) presented a decision support system for drainage engineers involved in the design of stormwater management facilities. The runoff model was versatile and involved a variety of methods for storm description, rainfall loss estimation and overland flow routing. In addition to normal pipe and channel sizing, the design options include a number of detention devices for on-site controls such as rooftop and parking lot storage, in-line storage super-pipes and exfiltration trenches. Stephens and Kuczera (1999) tested the widely used time-area method at the parcel scale. The time of concentration for impervious areas at the allotment scale was found to be of the order of 2 min and not the 5 min as assumed in Australian practice. This result has implications for the design of sub-catchment scale pipes, storage basins and outflow control devices.

Terayama (1999) developed a stormwater runoff model based on the modified Road Research Laboratory method, to express the effects of on-site storage considering temporary storage of the effective rainfall and its disposal. An example application of this model in a local city, which has introduced the on-site storage facilities, was also presented. A nonlinear rainfall-runoff model was developed and applied to flood runoff analysis in Japan. Sugiyama et al. (1999) extended the model’s applicability by developing practical equations for estimating model parameters that were appropriate on a regional basis. The utility of the estimating equations was tested by computing runoff hydrographs for lumped basins. Vaes and Berlamont (1999) showed that a well-calibrated reservoir model can predict CSO emissions as well as a detailed hydrodynamic model, taking into account the uncertainties in the input data. Such simplified models were ideal tools to perform quickly various scenario analyses. Physically based conceptual models give an optimal balance between model uncertainty and uncertainty in the input data.

Wong and Kho (1999) studied the increase of flood peaks due to urbanization. Four urbanization scenarios were simulated and subjected to the Singapore 2-year rainfall. The degree of urbanization was expressed in terms of the percentage of developed area and the percentage of channelized area. Their results showed that the patterns of the flood peak increase for the downstream to upstream and the inside to outside urbanization sequences were concave. Wong and Li (1999) reported on a conceptual study of the hydrological effects of urbanization. By considering urbanization on an overland plane as a process whereby a relatively rough, permeable surface was gradually replaced by a relatively smooth, less permeable surface, the effect of urbanization sequence on the flood peak was theoretically assessed by the kinematic wave method.

Yen et al. (1999) presented details of the runoff model ILUCAT. The model allowed temporally variable rainfall in incremental times as input to each catchment, and deducts abstractions to yield the rainfall excess to be routed through the urban catchment. Each catchment was divided into five types of areas, namely, direct impervious, direct pervious, supplemental impervious, supplemental pervious, and noncontributing areas. The rain excess was routed through two flow paths of the first four contributing areas using the time-area method to produce the runoff hydrograph. Cagiao et al. (1999) presented two different methodologies for a study of the runoff generated in an urban watershed with a separate sewer system during stormwater events. The first approach used a process simulator (SWMM), and a non-linear parameter estimation tool (PEST), while the second used artificial neural networks. A pilot project of a subcatchment in the city of Santiago de Compostela was studied. Campolo et al. (1999) used neural networks to forecast flow rates in the Arno River downstream of the city of Florence, Italy during low-flow conditions. The model used basin-averaged rainfall measurements, water level, and hydropower production data. Model predictions were found to be accurate with root-mean-square error on the predicted river flow rate, less then 8% over the entire time horizon of prediction. Chang and Hwang (1999) used the group method of data handling (GMDH) algorithm to evaluate complex rainfall-runoff processes in a heterogeneous watershed in Taiwan. Two versions of the revised GMDH model were implemented: a stepwise regression procedure and a recursive formula. The prediction results of the revised GMDH models and the instantaneous unit hydrograph (IUH) model were compared. Much better performance was obtained with the revised GMDH models.

Dinicola (1999) presented recent efforts to develop regionalized HSPF parameters for King and Snohomish Counties in Washington that were useful for urbanizing watersheds. Djordjevic et al. (1999) described a model for dual drainage - an approach to rainfall runoff simulation in which the numerical model takes into account not only the flow through the sewer system, but also the flow on the surface. The numerical model simultaneously handled the full dynamic equations of flow through the sewer system and simplified equations of the surface flow. The surface excess water (due to the
limited capacity of inlets or to the hydraulic head in the sewer system reaching the ground level) was routed to the neighbor subcatchment (not necessarily the one attached to the downstream network node), using surface retentions, if any. Edijatno et al. (1999) described a new empirical watershed model that involves only three free parameters. In spite of its crude simplicity, it achieved, on average, worthwhile results on a set of 140 French catchments and overwhelmingly outperformed a linear model involving 16 parameters. It performed roughly as well as a conceptual model with five free parameters, derived from the well-known TOPMODEL.

Escarameia and Swaffield (1999) summarized the results of research on monitoring and modeling stormwater runoff from roofs in the UK. This paper presented important new data for the design of rainwater systems and concludes that numerical simulations of unsteady flows were a useful tool for complementing the design recommendations in current design guides. Four simple conceptual daily rainfall-runoff models were applied to a 25-basin data set in the UK, covering a range of sizes, topographies, soils and climates (Houghton-Carr, 1999). Model performance was judged by a range of quantitative and qualitative measures of fit, applied to both the calibration and validation periods. These included efficiency, mean annual runoff, baseflow index, the synthetic monthly and daily flow regimes, and the flow duration curve. With increases in computing power of recent years, fully two dimensional, unsteady hydraulic modelling was becoming increasingly common for applications involving large, complex floodplains. Bishop et al. (1999) described the results of a recent study of a highly urbanized area along the Gold Coast, Queensland, Australia. With the increasing focus on ecologically sustainable development, and concerns regarding class actions by flood affected communities, many agencies in Australia were requiring that new proposed urban development have zero impact. With regard to flooding impacts, this requirement has resulted in the need for assessment of effects, in terms of water level changes, down to 1 cm or less accuracy. Details were provided on the requirements of and approach to full two dimensional flow modelling including the required grid definition and size, structure modelling, fine scale nesting and model stability and accuracy (Collins et al., 1999). A distributed, field-based rainfall-runoff model was developed for the 1400-km² arid catchment of Nahal Zin, Israel. No calibration with measured flow data was performed; the model used rainfall radar input applied over a catchment that was spatially disaggregated into different terrain types according to hydrologically relevant surface characteristics. In general, this study showed that field-based data on generation and losses of runoff may be incorporated into a distributed hydrologic model to overcome calibration with the poor data records of arid high-magnitude events (Lange et al., 1999).

Miles et al. (1999) presented a method of analyzing flow and rainfall monitoring data that has successfully documented rainfall dependent infiltration and inflow (RDI/I) reduction in Charlotte, North Carolina and Greenville, South Carolina. The method relies on scientific principles including good data quality control practices and the use of control areas to establish changes in RDI/I between monitoring periods because of environmental factors. Schultz et al. (1999) summarized research, conducted by a team of consultants and cooperating municipal agencies, which identified and tested eight major categories of rainfall derived infiltration and inflow (RDI/I) analysis methods in several diverse sewersheds. They identified metrics suitable for objective comparison of the RDI/I analyses, and concluded with recommendations for selecting RDI/I methods appropriate to a variety of applications. In the Netherlands, a very simple criterion for flooding was used to check the hydraulic behavior of a drainage system, whereas The European approach was more strict but not applicable. Therefore, van Luijtenbaal (1999) presented an alternative approach to eliminate hydraulic bottlenecks in drainage systems in flat and moderately sloped areas.

A topographic index predicted patterns of runoff, reproduced spatial patterns of subsurface-storm flow for a variety of prestorm conditions, and was used as a basis for a rainfall-runoff model (Woods et al., 1997). Three conceptual rainfall-runoff models (i.e., GSFB, IHACRES, and LASCAM) were assessed and provided accurate predictions of rainfall-runoff relationships (Ye et al., 1997). Tan et al. (1997) developed an algorithm for simulating tropical rainfall using a one-step-Markov-chain model. The results indicated that the synthetic-rainfall time series reproduces the characteristics of tropical rainfall. The model may also be capable of estimating extreme-annual rainfall. A geomorphology-based-unit hydrograph and a Runge-Kutta-time-discrete scheme were applied to predict direct-runoff volumes. The hydraulic-routing scheme presented was highly accurate in predicting runoff volumes and may be useful in managing major-rainfall storms (Sepulveda, 1997).

Nine flood-estimation models used for ungauged-urban watersheds were evaluated in Louisiana. Flood-quantile predictions from simple regression models calibrated by local data were found to be more reliable than those more complicated models or models with many parameters that may not be accurately estimated (Yu and Adrian, 1997). A newly digitized record of precipitation for 304 sites in the Midwest United States that extends back to 1901 challenged the assumption that extreme-rainfall time series are stationary and without trends. It was suggested that rainfall-frequency
studies be updated on a regular basis for maximum usefulness because of observed changes in the annual maximum time series (Angel and Huff, 1997).

Hydrological studies of rainfall-runoff processes provided the basis for estimating design flows for urban-stormwater-drainage systems which control floods and the transport of sediments and pollutants. O’Loughlin et al. (1997) summarized the theory of urban rainfall-runoff processes, the development of modeling practice, and the current use of computer models. Agbodo et al. (1997) reviewed HYDRA, HydroWorks, MOUSE, and XP-SWMM, which are widely used hydraulic-modeling tools utilized in determining optimum improvements of sanitary-sewer systems that have excessive I/I. Zhu and Schilling (1997) presented a method to predict errors of calculated mean-annual-overflow volume due to coarse temporal resolution of rainfall data that was used as input to rainfall-runoff models. Errors were quantified by comparison of overflow volumes based on rain-data series with different temporal resolution. The pattern of the temporal rainfall variation of the two data series were too different to derive error-prediction rules that were generally applicable for all rainfall regimes.

Hydraulic models
Niemann et al. (2002) examined the pump station modeling capability of EPANET, XP-SWMM, MOUSE, and INFOWORKS and presented considerations necessary for models to represent actual conditions and their projected impacts on the public and environment. Despotivc et al. (2002) developed and calibrated detailed BEMUS and Visual OTTHYMO models for a catchment served by combined sewers in Belgrade. The calibrated models were used to assess catchment flooding for design flows at four locations in the catchment. Yeboah et al. (2002) presented work evaluating a 500-cfs pumping station to address flooding problems in the South End neighborhood in Boston. They conducted a comprehensive flow-monitoring campaign, developed pump head-capacity curves, and created a SWMM model of the station. The calibrated model was successfully used as a tool to evaluate the facility planning alternatives. Vallabhaneni et al. (2002a) used SWMM RUNOFF and EXTRAN to simulate infiltration and inflow to sanitary sewer lines and the impact on sewer hydraulics. Sharek et al. (2002) described their efforts constructing and analyzing hydraulic models coupled with continuous infiltration and inflow models and specifically highlighted their work evaluating the alternatives for improving the performance of the Western Lake Superior Sanitation District East Service Area collection system.

Rainfall-runoff quality models.
Burian et al. (2001b) investigated the suitability of integrating deterministic models to estimate the relative contributions of atmospheric dry and wet deposition by stormwater runoff. The CIT airshed model and the SWMM were linked to simulate the fate and transport of nitrogen species through the atmosphere and storm drainage system in Los Angeles, California, USA. Coupling CIT and SWMM involved defining and resolving five critical issues: (1) reconciling the different modeling domain sizes, (2) accounting for dry deposition due to plant uptake, (3) estimating the fraction of deposited contaminant available for washoff, (4) defining wet deposition inputs to SWMM, and (5) parameterizing the SWMM washoff algorithm.

A mass-balance model for calculation of annual metal loads to lakes dominated by diffuse inflow and urban runoff was presented by Lindstrom and Hakanson (2001). In the lake, the variations in runoff concentrations were smoothed, making it possible to get a more stable flow assessment. The model accounted for inflow, outflow and sediment interactions (sediment resuspension is modeled using new approaches) with the most important factors in the uncertainty of model predictions being the settling velocity of particulate matter, the percentage of accumulation areas for fine particles, and the dissolved fraction of the total metal concentration. High correlations between metal accumulation and phosphorous and nitrogen concentrations indicated that the autochthonous lake production was crucial. The sources, distribution and fate of fecal coliform populations in the North Fork of the New River in Fort Lauderdale, Florida were investigated by Scarlatos (2001). In order to facilitate field sampling, computer simulations using WASP were applied to assess the likelihood of the various possible pollution scenarios. WASP accurately simulated the water hydrodynamics and coliform concentrations within the North Fork, while the neural network identified correlations between fecal coliform and the other parameters.

Swanson and Ward (2001) presented a series of applications of WQMAP, an integrated model of the circulation and pollutant transport in estuarine and coastal waters, to Narragansett Bay. Applications included circulation and temperature distributions in Mt. Hope Bay; consideration of the effects of a once-through cooling water discharge from a fossil fueled power plant; circulation in the Providence River and Upper Narragansett Bay; fecal coliform transport from combined sewer overflow (CSO) loads; and a eutrophication study of the Providence River.
Sanders et al. (2001) developed a hydraulic model to examine the tidal transport of stormwater bacteria near the southern California network of flood control channels that drain to near-shore bathing waters. Yuan and Oldham (2001) prepared a model describing the accumulation and washoff of urban area particulates, specifically examining metal binding. They monitored 47 rain events with short time intervals and obtained good agreement for predicting lead transport. Zoppou (2001) compared several different stormwater models, including statistical, empirical, hydraulic and hydrological model types.

Whigham and Crapper (2001) provided the following definition: “Genetic programming is an inductive form of machine learning that evolves a computer program to perform a task defined by a set of presented (training) examples and has been successfully applied to problems that are complex, nonlinear and where the size, shape, and overall form of the solution are not explicitly known in advance.” Genetic programming of rainfall-runoff model has also been used by Muttil and Liong (2001). Mathematical methods using linguistic variables (such as the application of fuzzy rule-based modeling), rather than conventional numerical variables, are starting to be used for hydrological studies (Hundecha et al., 2001). Ozelkan and Duckstein (2001) also recently applied fuzzy logic to rainfall-runoff modeling.

The results of a number of investigations indicated that contaminant transport should consider the speciation of nutrients and metals in stormwater runoff (Ball 2000c). From the results of these studies, a new approach for the simulation of contaminant transport was presented which considers the speciation of the contaminants. Statistical models were proposed to predict the total mass of specific pollutants removed with stormwater runoff from an urban residential catchment (LeBoutillier et al. 2000). The models were based on analysis of data collected during an on-going research program in Saskatchewan. A method for predicting the thermal enhancement of stormwater runoff from paved surfaces was documented for a test facility in Kingston, Ontario, Canada (Van Buren et al. 2000b). Prediction of runoff temperature was based on TRMPAVE, a mathematical model that was developed using a thermal energy balance approach and the one-dimensional heat equation to predict the surface temperature and temperature gradient in asphalt during dry-wet and wet-weather periods. An export coefficient modeling approach was used to assess the influence of land use on phosphorus loading to a Southern Ontario stream (Winter and Duthie 2000). It was found that runoff from urban areas contributed most to the loading of phosphorus to the stream. An existing model of sediment wash-off from paved surfaces was extended to predict fine granular sediment inputs into drainage systems via roadside gully-pots (Deletic et al. 2000). The model was applied to two catchments in Dundee, Scotland where it was concluded that only two calibration parameters are required to estimate the input of fine granular sediment into storm drainage systems via gully-pots.

Tsanis (2000) developed a program named RUNMEAN (RUNOffMEAN) for estimating toxic-contaminant event mean concentrations (EMCs) in stormwater runoff.

Bent et al. (1999) evaluated the runoff and erosion response of two perennial grass species on simulated waste burial covers at Idaho National Engineering and Environmental Laboratory. The Agricultural Non-Point Source Model (AGNPS) permits the incorporation of important spatial information (soils, landuse, topography, hydrology) in simulating surface hydrology and NPS runoff. The AGNPS model was adapted for developed coastal watersheds by deriving urban coefficients that reflect urban landuse classes and the amount of impervious surface area (Choi and Blood, 1999).

Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999).

Arnbjerg-Nielsen et al. (1999) compared trends in annual loads of pollutants to receiving waters in Denmark during the past decade. For N and COD, models were suggested that explain some of the variation between and during events. However, a large residual variation was identified and possible refinements of the model were discussed. Ball (1999) presented a new approach for simulation of the transport of the soluble contaminant in urban stormwater runoff. This modeling system was based on a decoupled solution of the kinematic wave equations for simulation of the surface flows and an advection-diffusion model for simulation of the contaminant motion. Use of deicing chemicals and abrasives to provide traffic safety during winter caused water quality problems for urban receiving waters (Bartosova and Novotny,
1999). Their model was calibrated using data from the Lincoln Creek watershed (Milwaukee, Wisconsin), and verified on 30th Avenue watershed (Edmonton, Alberta). The results of simulation for chlorides, suspended solids, and lead were presented.

Carr et al. (1999) discussed the benefits of a time series approach which provided the information necessary for design of water quality control structures and for assessment of ecological sustainability. An advantage of the time series approach was that it provides an integrated evaluation of performance during a variety of wet-weather conditions. Chiew and McMahon (1999) presented a simple approach for estimating long-term runoff and diffuse pollution loads in urban catchments, and discussed conceptual modeling methods for simulating daily runoff and pollution loads. The modeling results for several catchments in Australian capital cities were presented. The study indicated that long-term and daily runoff can be estimated reasonably accurately using simple approaches. However, the water quality characteristic can vary considerably between catchments.

Commonly measured fecal bacteria concentrations in water and rainfall data were utilized as inputs for training a neural network model to distinguish between urban and agricultural fecal contamination present in inputs to a drinking water reservoir (Brion and Lingireddy, 1999). A neural network model was written that used bacterial and weather data to differentiate between three site classifications: urban, agricultural and a mixture. The validity of the source identification, neural network model was verified through a case study. Roadside gully pots form a common and important part of many surface water drainage networks (Butler and Mernon, 1999). Their primary function was to retain larger solids from road runoff in order to minimize the problems associated with sediment deposition in downstream drainage structures and receiving waters. A dynamic water quality model has been developed to simulate these processes. Moulton et al. (1999) described NPDES monitoring for New Orleans, Louisiana. This paper asked the question, “How reliable were load estimates that were extrapolated from landuse based monitoring of small subcatchments?” The age of the developed areas was found to be responsible for differences in monitored nutrient loading from modeled runoff loads based on land use.

Several models related land use categories of urban, forest, agriculture, and wetland to in-stream concentrations of total nitrogen (N) and total P in eight low-order watersheds on the coastal plain of S.C. (Tufford et al., 1998). The models with highest predictive strength were those which used land closest to the stream channel. Vezjak et al. (1998) modeled the effects of eutrophication on plankton seasonal dynamics in lakes using state variables for the rates of change of phytoplankton, zooplankton, N and P. The influence of P concentration on eutrophication was one of the most important processes in the lake ecosystem. Bartolini et al. (1998) stressed the need for a complete rainfall-runoff model of the rainfall-runoff transformation that includes the underground portion of the hydrograph even if the maximum discharge during a flood is mainly due to the surface runoff. The proposed solution, taking into account the unknown time-lag between rainfalls and discharges as an extra parameter to be estimated in the calibration phase showed some benefits. An examination of several models for estimating stormwater pollutant loads from urban watersheds indicated that SS loads are largely a function of runoff volume, and that the use of a single event-mean concentration of SS for all urban land uses provided reasonable estimates of stormwater pollutant loads. Water quality data did not indicate a strong correlation between pollutant loads in runoff and the duration of the antecedent dry period (Charbeneau and Barrett, 1998).

The response of rain on ammonium loads for an urban sewer system using AQUASIM and MOUSE TRAP 3.0 was simulated. The study showed that a sewage storage tank performed better for the integrated load discharged into the system but a combined sewer storage tank would be more efficient in decreasing peak values and the duration of high concentrations in the river (Holzer and Krebs, 1998). A semi-empirical model quantified the hysteresis of river water constituents during a storm based on discharge data collected from several river sites over a storm hydrograph. Results showed that most constituents had higher concentrations during the rising limb of the hydrograph and lower concentrations during the falling limb (House and Warwick, 1998). The COD of a sewer network was modeled using a ratio of COD/SS as a function of the maximum rainfall intensity over a five minute period, SS and time. Simultaneous measurements of rainfall, hydraulics, SS and COD in three catchments with different characteristics and not used in the calibration phase validated the model (Zug et al., 1998). Osuch-Pajdzinska and Zawilski (1998) presented the results of calibration and verification of mathematical models for calculating hydrographs and pollutographs of urban stormwater based on results obtained from field studies for a mixed industrial and residential catchment. Tsihrintzis and Sidan (1998a) calibrated and verified the Santa Barbara Method for computing runoff hydrographs for small urban watersheds. The PC version of ILLUDAS was shown to predict hydrographs that compared well with measured hydrographs for small urban watersheds in Fla. (Tsihrintzis and Sidan, 1998b).
Mas (1998) used a relatively simplistic modeling approach to quantify the stormwater impacts of a proposed commercial development in southern N. Engl. A ten-year simulation assessed the impact of current and future nutrient loads and sediment runoff to a multipurpose reservoir scheduled to open in 1999 in Sarpy County, Nebr. and recommended BMP (Fowler et al., 1998). Brown et al. (1998) examined the interactions of land use, topography, soil, and surface water hydrology in modeling stormwater quality variations in subbasins of the Tijuana River watershed. Concentrations in Onondaga Lake, N.Y. of total Hg and MMHg in the water column, sediments and fish tissue are elevated due to industrial inputs, wastewater discharge and urban runoff. The steady-state Regional Mercury Cycling Model suggested that elimination of Hg inputs from wastewater effluent and drainage from a former chlor-alkali facility would decrease Hg concentrations in fish tissue (Gbondo-Tugbawa and Driscoll, 1998).

The South Africa Water Research Commission funded a project to adopt an existing urban-stormwater-runoff model to data from several catchments and showed that urban-stormwater runoff was highly polluted with nutrients, heavy metals, organics, and bacteria (Water Qual. Int., 1997a).

The spatial distribution of the water-quality equivalent of a snow cover on various landscapes were synthesized through log-normal distributions to predict snowmelt and runoff (Shook and Gray, 1997). When snow produces a significant portion of runoff, a smaller number of quality records could be more valuable for modeling than a much larger number of records of lower quality because the overall value of an operational-hydrometeorological network depends on the consistency and representativeness of average conditions of the collected records (Peck, 1997).

Collection system, CSO and SSO models.
Harwood (2002) presented three strategies for the application of Computational Fluid Dynamics (CFD) to the modeling, design, and performance assessment of CSO chambers. Pollert and Stránský (2002) demonstrated the use of the one-dimensional MOUSE model and the three-dimensional FLUENT model for evaluation of separation efficiency of suspended solids in CSO. The 1D model simulated the runoff and pipe flow in the CSO catchment and the 3D model simulated the water flow and the dynamics of the suspended solids inside the CSO structure. Okamoto et al. (2002) used the Algebraic Slip Mixture model of the CFD code FLUENT-5 to predict the solids removal performance of a hydrodynamic vortex separator. Results from lab tests with a scaled model verified the model predictions of solids concentration at outlet points. Burt et al. (2002) described the application of CFD to simulate flows and suspended solids retention efficiencies in a high side weir CSO. Evaluation of three modeling approaches indicated that a multi-fluid, multiphase approach was found to be superior to coupling a single-phase flow calculation with Lagrangian particle tracking. van der Tak et al. (2002) developed and tested both a physical model and a CFD model of a CSO screening structure designed for CSO outfalls along the Hudson River in Hoboken, Weehawken, Union City, and West New York in New Jersey. Studies with the models were conducted to test a typical screening chamber and to optimize baffle and bar rack positions to minimize head loss, maximize the capture of solids/floatales, and facilitate maintenance of the chamber.

Stirrup and Marchant (2002) modeled the performance of a CSO storage tank in Hamilton, Ontario. When the simulated performance was compared to performance data collected by a SCADA system several limitations associated with their continuous simulation were identified and discussed. Vallabhaneni et al. (2002b) described the use of water billing records to establish base flow rates for dry-weather flow simulations in the Metropolitan Sewer District of Greater Cincinnati collection system computer model. After calibration and testing the authors concluded that the use of water billing records provided a reliable basis to establish base flow rates in sewer systems.

Huisman and Gujer (2002) presented a deterministic model for wastewater transformations in sewers, including activity in the wastewater and in the developed sewer wall biofilm. The model was based on the Activated Sludge Model No. 3 (ASM3). The resulting model described the oxygen concentration and wastewater respiration well and could easily be linked with the WWTP Activated Sludge Model and the newly proposed River Water Quality Model No. 1. The use of a balanced scorecard model by Union City, California, and the City of Eugene, Oregon to implement improvement strategies for SSO reduction, treatment plant effectiveness and environmental management was described by Ruffier and Wies (2002). The paper described the model, the strategies where it has been used, the reasons why the balanced scorecard model was chosen. Korving and Clemens (2002) reviewed Bayesian decision analysis as a methodology for rational decision-making when evaluating the effects of CSOs on receiving waters. Bayes’ rule was used to combine prior impressions with new observations to reduce the risks associated with the planning of sewer system reconstructions. The presentation by Korving et al. (2002) reviewed the use of single computations of CSO volumes using a time series of rainfall for system loads to make decisions on sewer system rehabilitation. The problem highlighted in the paper was that
uncertainties in knowledge of sewer system dimension are not typically taken into account. Testing of this potential problem using Bayes factors regarding sewer system dimensions demonstrated that uncertainties in sewer system dimensions cause a considerable variability in return periods of calculated CSO volumes.

Modeling tools such as SWMM typically have been used to model I/I with sanitary collection systems (Czachorski and Van Pelt 2001). The hydrograph theory used by these models explicitly assumes that the system can be accurately modeled by linear dynamics; however, in general, this assumption is inaccurate. Nonlinear dynamics result from complex flow patterns and other transport mechanisms, but typically the dominant nonlinearity can be attributed to antecedent moisture effects. SWMM was used by Onondaga County, New York to simulate the hydrologic and hydraulic elements of its combined sewer system and to project the effects of a range of abatement alternatives (Davis et al., 2001c). The models successfully identified the maximum conveyance capacity of the collection system and showed that, following abatement, 85% of the combined sewage would be captured for primary treatment at the WWTP. To assist with hydraulic analysis for a Portland, Oregon project to reduce the potential for basement flooding, a detailed SWMM model of the basin using a suite of GIS and database tools was developed. The detailed GIS approach with virtual raingages produced model results that correlated very well with flow monitoring data. The detailed SWMM model identified the location of much of the system capacity problems. The City of Winnipeg initiated a basement flood relief program in the mid-1960s to provide a minimum five-year level of protection to the residents (Steiss and Watters 2001). Since 1977, this program has been modeled with SWMM, and to date, sewer relief works have been implemented in 21 of the City’s combined sewer districts. The public notification method developed for the City of Detroit uses a continuous SWMM model for determining the occurrence and time of overflow and was approved as an interim reporting method until an instrumentation project currently under way is completed (Brink et al., 2001).

James and Young (2001b and c) developed new code for radial gates that was integrated into the Extended Transport (EXTRAN) module of SWMM. The new program, called RGEXTRAN, was capable of handling unsteady flow conditions occurring in real sewer systems with radial and regular sluice gates. The program also provided for dynamic control of the radial gates (or other gate types) based on flow conditions at remote locations in the sewer system. James and Young (2001a) demonstrated that RGEXTRAN could be used to optimize a combined sewer system operation by fully utilizing all available storage and conveyance capacity in the existing facilities. The program was applied to the combined sewer system in Vancouver, British Columbia, and verification tests demonstrated that the new program accurately represents the operation and hydraulic response of the dynamic radial gates and siphon-weirs found in the system. Due to the complex number of available pathways that RDII may enter a sanitary sewer, rainfall dependent infiltration and inflow (RDII) has been one of the most difficult components of the urban wet-weather water budget to estimate (Wright et al., 2001). Various tools have been applied to estimating this special hydrologic response, including the rational method and several unit-estimation methods. The paper highlighted results from a relatively new physically based conceptual method first introduced by Kadota and Djebbar in 1998, a modification to the SWMM RUNOFF module that includes the response of a conceptual non-linear reservoir to changes in groundwater elevations resulting from permeable-area infiltration.

MOUSE, an Arcview-GIS based dynamic model, was selected to analyze the performance of the combined sewer overflow (CSO) system operated by the City of New Haven (Connecticut) and the New Haven Water Pollution Control Authority for 3-month, 6-month, 1-year and 2-year design storms (Cheung et al., 2001). In addition, an average rainfall year was simulated to determine the performance of the system under typical rainfall conditions. The short-term control plan identified minor adjustments to overflow weirs and orifices, and to pump rates, while a long-term control plan included major capital works such as storage tanks or pump station and trunk sewer replacement. Long term numerical modeling was used to verify design parameters for the new King County 7-million-gallon CSO storage and conveyance tunnel, including gate- and pump-operation rule sets for operating the storage systems (Crawford and Swarner 2001). Additional modeling was performed to determine operation strategies for extreme events such as combinations of large storms, high tides, or unusual flow diversions. The long term numerical modeling verified the suitability of rule sets for conditions which often cannot be anticipated.

Harwood and Saul (2001) reviewed some of the physical model studies which have been carried out in the UK to determine the performance of combined-sewer overflow chambers. The limitations of both physical modeling and computational fluid dynamics approaches were discussed, and it was concluded that the future of chamber modeling combine both approaches. The impacts on DO in the Rouge River from CSO-treatment basins were evaluated using basin effluent monitoring, river monitoring and dynamic water quality modeling (Kluitenberg et al., 2001). Using a consensus-based approach, work groups including State personnel, CSO community representatives and consultants concluded that
the demonstration basins could eliminate raw sewage, protect public health and achieve water quality standards, including the DO standard.

Reeves and Lewy (2001) discussed the representation of long term, highly attenuated runoff in collection systems, focusing on rainfall dependent groundwater infiltration. Contributions to urban drainage systems by stream ingress or from large permeable areas do not fall easily into either the runoff or baseflow categories. In addition, the increasing prevalence of Sustainable Urban Development (SUD) structures is promoting a need to represent highly attenuated groundwater contribution. The paper by Miralles et al. (2001) described the methodology that was used to evaluate wet weather flows within the sanitary sewer system in Luquillo, Puerto Rico. The methodology, based on a unit hydrograph model to predict (RDII), was calibrated by comparing predicted wet weather flows to those observed in the five flowmeter locations.

For municipalities to cost-effectively plan, organize, and implement infrastructure improvements, they require improved information on structural conditions, decision-making tools, operation and maintenance practices, and techniques for repair and rehabilitation (Tafuri et al., 2001). The paper reviewed European approaches for diagnosing and analyzing water and wastewater systems, and in particular the use of performance indicators and non-hydraulic models for predicting failures in these systems.

An abatement strategy was developed for three CSO outfalls in the Bronx, New York (Brilhante, et al. 2000). EPA SWMM was used along with cost and receiving water quality modeling to define the optimal level of in-line storage required to meet regulatory requirements. To achieve desired CSO control for the City of Edmonton's Gold Bar Wastewater Treatment Plant (GBWWTP), the hydraulic relationship between the upstream collection system and the GBWWTP was evaluated by including a detailed hydraulic model of the treatment plant as part of the collection system hydraulic model (Gray et al. 2000). This study provided details on the approach used to simulate these two system components in an integrated model. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/relocation project in South Boston (Walker et al. 2000b). Findings indicated that an original facilities planning model was reasonably accurate in predicting peak flows in extreme storm events, despite only being calibrated to a 3-month storm.

The U.S. EPA is in the final stage of issuing an SSO Rule that will add control of SSOs to the NPDES permit requirements (Lai et al. 2000). This paper provided a preview of the rule and described the advantages of employing a modeling approach for capacity assurance of various components of a collection system and development of an SSO mitigation plan.

The City of Columbus Inflow and Infiltration Program utilized a comprehensive sewer system evaluation and hydraulic modeling approach to mitigate sanitary sewer overflow and water-in-basement occurrences (Chase et al. 2000). By identifying problems in the collection system and incorporating them into a hydraulic model prior to SSO mitigation alternatives analysis, the City of Columbus will be able to target capital improvement and maintenance dollars to correct the problems in the collection system and reduce SSOs. The Miami-Dade Water and Sewer Department used wet weather data from a supervisory Control and Data Acquisition telemetry system to quantify rainfall dependent infiltration and inflow (RDII) (Christ et al. 2000). The MS Access application developed to quantify the individual pump station’s RDII response is discussed in this paper. A detailed computer model of the Metropolitan Sewerage District of Buncombe County, North Carolina collection system was used to identify collection system improvement alternatives (Harris 2000). Alternatives included strategic application of sewer rehabilitation and upgrades, off-line storage and additional treatment capacity. The Encina Wastewater Authority developed a Peak Flow Management Plan, in which effluent equalization storage as an alternative to a new ocean outfall was evaluated using a risk-based approach (Hogan et al. 2000). A continuous simulation model of wet weather flows and storage/outfall facilities was used to generate estimates of peak flows, storage volume requirements, and project costs over a range of return periods.

A global mathematical model for simultaneously obtaining the optimal layout and design of urban drainage systems for foul sewage and stormwater was presented (Diogo et al. 2000). The global strategy adopted combined dynamic programming and metaheuristics to develop a sequence of optimal design and plan layout subproblems. A computational method for the optimal design of highway drainage inlets was formulated as a discrete-time optimal control problem (Nicklow and Hellman 2000). The example revealed that genetic algorithms and the discrete-time optimal control methodology comprised a comprehensive decision-making mechanism that could be used for cost-effective design of storm water inlets.
The FORTRAN source code in EXTRAN block of SWMM has been modified to take advantage of parallel processing for faster program execution (Burgess et al. 2000). Reductions in run times exceeding 30% were achieved. SWEHYDRO and MOUSE were combined to model both the collection and treatment system for Edmonton, Alberta (Ward et al. 2000). A detailed simulation of the treatment plant hydraulics was performed to optimize its operation during wet weather periods.

The pros and cons of design storm and continuous simulation techniques were compared for treatment plant and collection system design purposes (Dent et al. 2000). Examples were included from several municipal master-planning studies that illustrated how results can vary from one approach to another. The shear stress distribution over the sediment bed in a pipe with deposited sediments was quite uniform but larger than the mean shear stress in the cross section (Berlamont et al. 2000). Comparisons between numerical calculations and (unsteady) sediment transport measurements confirmed these results qualitatively.

Modeling and analysis of combined sewer systems received considerable attention. Milina et al. (1999) described the development of an integrated model and its application to the Hovringen wastewater system in Trondheim, Norway. The model integrates sewage production, transport and treatment simulation, the interface with existing databases and the simulation of processes that were controlled in real time, and has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system. Krebs et al., (1999) use measurements and numerical simulations to show that the first flush effect may cause a significant impact on the receiving water when CSO occurs, or on a wastewater treatment plant when the sewer network was flat and catchment area was large. Alvarez et al. (1999) analyzed, from an environmental point of view, the structural and functional scheme considered for the sewage management of a small coastal community in the Bay of Biscay in Spain, where the presence of overflows in the system during storms leads to the release of a great deal of pollutants.

Furumai et al. (1999) applied a distributed model to study the reduction of CSO pollution for a combined sewer system in Japan, which contains a storage pipe with 3 weirs for inundation control. Results indicate that the model can be applied for evaluating effectiveness of modified operation or new installation in the sewer system for suspended sediment load reductions, once initial conditions on surface deposits and sediments were properly determined. Grum and Aalderink (1999) performed a return period analysis of CSO effects using embedded Monte-Carlo simulations, putting all quantities described by probability distribution in either an inner layer consisting of quantities varying from event to event or an outer layer consisting of uncertain but constant quantities. This resulted in a band of return period curves representing the return period distribution for which confidence limits may be calculated. Jack et al. (1999) described a study which utilized detailed simulation models of the sewerage and treatment plant performance for the City of Perth in Scotland in order to investigate the potential problems caused by introducing system storage to control both flooding and polluting spills. The Jefferson County, Alabama Environmental Services Department was currently implementing a program to address the need for collection system rehabilitation and capacity improvements in its wastewater collection systems, and Keckley (1999) discussed the use of an extensive network of flow monitors and rain gauges in each collection system to assess the extent of needed capacity improvements as well as the impact of rehabilitation. Milina et al. (1999) described some results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. The developed integrated model has been used to design, in both the catchment and the sewer system, the treatment process as well as static and dynamic measures including extended pumping, adjustment of overflows, retention and real-time control of the sewer tunnel volume.

The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet weather conditions. It includes: (1) Establishment of the site specific statutory requirements and environmental objectives, (2) Design of sewer system components with specific reference to influences on marine water quality, and (3) Development of monitoring programs (Alvarez et al., 1999).

Aronica (1999) presented a simple numerical model based on the method of continuity for flood routing in urban networks. The network was represented as a cascade of cells and the flood routing was schematized as a flux transfer between adjacent cells. Preliminary tests were carried out by means of the reproduction of flood wave propagation for some examples of urban drainage systems, both hypothetical and real. The results showed satisfactory numerical stability and an excellent computational efficiency. Barnett and MacMurray (1999) stressed the importance of correctly modeling
overland secondary flow paths. At drainage network nodes such as street intersections, the distribution of outflow depends on nodal compatibility conditions, particularly when one or more of the outflow paths was steep, and large errors accumulated from the application of incorrect conditions at a succession of nodes.

Welker et al. (1999) investigated possible changes to quantity and composition of sewage in the combined sewer system and the WWTP caused by new stormwater management strategies (mainly by disconnecting areas from the sewer system). Various scenarios were developed and the consequences on the water systems were calculated by using the simulation model KOSMO, in a fictional catchment.

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999).

Ideta and Kariya (1999) used hydraulic simulation to maximize inline storage and reduce flooding. Kleckley (1999) described estimating sanitary sewer system surcharging during wet weather using measured rainfall and flow. A rainfall-peak flow relationship was developed and used to analyze capacity improvements and the impact of rehabilitation on peak rates. This method should not be used exclusively as it does not assess the impact of rehabilitation on high groundwater infiltration. Lorenz and Weikopf (1999) presented a form of combined sewerage network storage management called the cascade technique. This technique utilized fully adjustable weirs to dynamically control the flow in the sewerage system. The cascade technique can be seen as an approach to decrease both the water pollution and the investment and operation costs caused by combined sewerage systems. Maitland et al. (1999) presented new features of XP-SWMM32, a model for complex open and closed conduit drainage systems. The application of these new and existing features of the XP-SWMM32 package to real-world drainage problems was outlined through the presentation of several case studies of representative drainage systems in the United States, Japan, and Australia.

Merlein and Valentin (1999) investigated design features of sewer systems to increase the capacity of sewerage systems under pressurized flow. A mathematical model was used to compare the results of the hydraulic model under steady conditions with unsteady conditions as they were during a cloudburst.

Morrow (1999) outlined the hydraulic modeling requirements of a program to meet a new, demanding discharge consent standard (average of 3 spills per bathing season per outfall) at specific coastal discharge points. A program costing over $105M had to be designed, approved by the regulator, procured, built, and commissioned in a period of 15 months. Continuous simulation was the only valid way of confidently establishing the additional storage volumes required to meet the new consents. Vazquez et al. (1999) proposed a new set of parameters for the Muskingum model for routing in a circular main in a sewer network for a wide range of lengths, slopes and diameters. A neural network was used to design the parameters of this model. This new application of Muskingum equations enables mean relative errors of less than 6% to be obtained for the value and the point in time of the flood in the case of mains up to 6500 m long, with slopes varying from 0.5% to 1% and with diameters ranging from 150 to 2000 mm.

Watanabe et al. (1999b) proposed a practical lumping method for manholes under surcharged flow, in which all the water surface areas of ignored manholes were preserved in the water surface areas of the adjacent manholes. The lumping method was applied to a combined sewer pipe system in Matsuyama City drainage basin in Japan and the adaptability of the method was investigated through stormwater runoff simulations. Wong et al. (1999) discussed the City of San Diego’s (California) program for monitoring and modeling of its wastewater facilities. This sustainability concept had implications in terms of the databases, modeling tools, and applications of the model. Two key elements that were highlighted were the value of developing a custom GIS application to integrate and process data that was developed and updated by other City and County agencies, and applications of the model for both planning and operational studies that resulted in reduced capital and operating costs. During urban storms, the overloading of a sewer system or river bank overflow produced flows which were essentially routed by the road infrastructure and cause flooding of adjacent built-up areas (Hingray et al., 1999).

The evaluation of the damage suffered by these built-up areas required the determination of important hydraulic parameters of the inundation, such as the maximum water depth or the inundation duration. This paper described the
hydraulic behavior of flooded built-up areas at different scales: individual plot, block of plots. Online sewer flow forecasting was simulated in this study using an autoregressive transfer function rainfall-runoff model and a recursive procedure for parameter estimation (Gelfan et al., 1999). Three recursive estimation algorithms were used: the time-invariant and time-varying versions of the recursive least-squares algorithm, and the Kalman filter interpretation of this algorithm. The sensitivity of the forecasting accuracy to the model order and to the initial conditions of the algorithm was studied using sewer flow data from the Milwaukee (Wisconsin) Metropolitan Sewerage District. In the UK, current river quality monitoring programs provide little information for management of CSO discharges, or objective assessment of their pollution impact. Balmforth et al. (1999) described a methodology that uses existing river flow data, which was available at sub-catchment level in the UK, to identify intermittent discharges by a development of the unit hydrograph method, based on the hypothesis that intermittent discharges produce unit hydrographs that lie outside the 'normal' correlation between effective rainfall and surface runoff for a catchment.

The EPA and the Miami-Dade (Miami, Florida) Waster and Sewer Department negotiated a Consent Decree settlement, which required them to undertake the installation and maintenance of a computerized collection and transmission system model. The “Virtual Dynamic Computer Model” has the ability to predict potential SSO resulting from peak flow conditions (Walch et al., 1999). The Metropolitan St. Louis Sewer District has responsibility for the management of stormwater drainage as well as conveyance and treatment of sanitary sewage within its boundaries. The Watershed Master Plan’s hydrologic and hydraulic analyses were conducted using the SWMM (Miller and Loucks, 1999). The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet-weather conditions and includes: 1) establishment of the site specific statutory requirements and environmental objectives; 2) design of sewer system components with specific reference to influences on marine water quality; and 3) development of monitoring programs (Alvarez et al., 1999). Hsieh and Wang (1999) introduced a semi-distributed parallel surface rainfall-runoff conceptual model. To evaluate the adaptability of this model, three watersheds around the city of Taipei in Taiwan were chosen to test the effectiveness of the model.

Hvitved-Jacobsen et al. (1999) presented a conceptual model for wastewater quality changes during transport in sewer systems. Emphasis was on microbial transformations of heterotrophic biomass and soluble and particulate fractions of organic substrate; the inclusion of sulfate respiration in the model concept was outlined. The model was exemplified as a tool for evaluation of wastewater quality changes in an intercepting gravity sewer. The model concept was tested in gravity sewers as well as in pressure mains.

Schlutter (1999) presented a numerical model capable of simulating sediment transport in combined sewer systems. The main objectives were to model mass transport rates at the outlet from a catchment and at the same time obtaining qualitative information on erosion and deposition going on at different locations in the sewer system. An example was given of a calibration event from a case study. Vollertsen et al. (1999) reported on the biotransformation of wastewater particles with different settling velocities. This was based on analysis of long term oxygen uptake rate measurements and a conceptual model describing aerobic transformations of organic matter. No significant changed in the biodegradability of wastewater particles with different settling velocities were found.

Yagi and Shiba (1999) used fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. Current pump operations could be improved by adding sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters. Zug et al. (1999a) presented a conceptual model for solid production and transfer in combined or separate sewerage systems called HORUS. The objective of this model was to reproduce the hydrographs, taking into account the characteristics of the catchment and the structure of the sewerage system. Simultaneous measurements of rainfall, hydraulic, TSS and COD concentrations on nine very different catchments and about one hundred rainfall events allowed a large range of validation which can be considered of good quality. Zug et al. (1999b) presented the results of a study whose objectives were the definition of the exceptional rain event compared to the capacity of the sewerage system and the development of recommendations for the design and operation of the sewerage system to efficiently manage most rainfall events. The measurements allowed the calibration and validation of a model (HYDROWORKS), which included hydraulics and masses of total suspended solids. Artina et al. (1999) showed the results obtained from the ongoing investigation in an experimental catchment in Bologna (Italy), monitored in order to acquire data on the pollutant loads entering the sewer network and then spilled to the receiving stream by some CSO. These data were being used to calibrate a detailed model for both the sewer system and the river reach. Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-
grained, organic, cohesive-like sediment deposit analogous to those found in sewers.

The Metropolitan St. Louis Sewer District developed a computer model to improve the control of SSO which incorporated the system’s physical features, dry-weather flow and WWF, and the impact of bypass flow on receiving waters (Moore et al., 1997). Gall et al. (1997) outlined a process-modeling and simulation program which is part of a pilot-scale study of satellite-treatment options for the control of CSO.

Three case studies (force main shut-down analysis, rehabilitation of gravity interceptors, and WWF diversion) demonstrated the benefits of using dynamic hydraulic modeling to improve the operation and maintenance of collection systems (Hwang et al., 1997). A physical model and the HydroWorks model were used to balance hydraulic criteria for an inline-storage tunnel intended for multiple uses (e.g., the control of CSO and SSO; and the reduction of urban flooding) (Switalski et al., 1997).

Arthur and Ashley (1997) proposed to estimate the extent to which sediment in transport near the bed of sewers contributes to the first foul-flush phenomena by describing the movement of a storm wave along a conceptual sewer length. Sweden and the Slovenian Republic have applied the computer model MIKE 11 HD to solve CSO pollution problems. The model provided solutions which would protect the countries’ receiving waters (Water Qual. Int., 1997b).

Detroit, Mich. tested and modeled the primary and secondary capacities at their WWTP as part of their Long Term Control Plan (Lieberman et al., 1997). They found that the maximum solids processing and storage capabilities are sufficient to handle additional CSO loads, thereby reducing the need for additional CSO facilities. Results using the Direct Random Search optimization technique, with the planning level model HIRATE as the simulator, are presented for one of the facilities investigated in the Greater Cincinnati, Ohio CSO program (Pisano and Hui, 1997). Houston, Tex. devised a proactive approach by providing adequate planning and design time and realistic construction schedules to correct future potential SSO problems (Kidder et al., 1997). Flanders, Belg. conducted an experimental program to identify the important parameters for evaluating the impact of overflow events on receiving waters, improving the design of storage-sedimentation tanks and overflow structures, and improving the capability of numerical models to predict emissions from CSS (Berlamont et al., 1997).

Ruan and Wiggers (1997a) investigated the application potentials of the methodology of time-series models for predicting some values related to CSO characteristics, e.g., CSO discharge and water level versus rainfall intensity, pollutant load versus CSO discharge, etc. Sewsim, a conceptual CSO-emission model was developed from Matlab and Simulink and can model rainfall-runoff, surface solids buildup and washoff, and sewer-sediment erosion and deposition. Some Sewsim simulation results predict pollution load of CSO more effectively than deterministic models (Ruan and Wiggers, 1997b). Physical theory was incorporated in a stochastic model of water level and particulate COD of a Dutch CSO. Results suggested that most of the deviation between model prediction and observation were due to sewer-system behavior, which is not explained by the model (Grum, 1997). The particle-tracking routine in the FLUENT computational-fluid-dynamics (CFD) software has been employed in the prediction of storage-chamber sedimentation efficiencies, which are influential in the management of CSO events. FLUENT was shown to be highly sensitive to the particle injection location but less sensitive to either the particle size or density (Stovin and Saul, 1997).

Worm and Carstensen (1997) applied a stochastic-modeling technique to analyze a subcatchment sewer system in Sydney, Aust.

**Modeling solids transport in sewers.**

Many computational models are available to simulate the flow and transport of suspended solids and other water quality pollutants through urban drainage systems to wastewater treatment facilities and CSO. However, models capable of predicting the quantity and temporal distribution of gross solids entering treatment works and CSO are less available. Digman et al. (2002) developed a model to predict the modeling of gross solids in a combined sewerage system. The Gross Solids Simulator (GSS) links directly with Hydroworks to obtain network data and flow depth and velocity. The model also uses a series of diurnal solids profiles based on work performed at the Imperial College in London. The GSS has been calibrated using an extensive set of data sampled from combined sewerage systems. In a separate study, results from a thorough analysis of the water quality modeling components of MOUSE and HydroWorks/InfoWorks CS suggests that results obtained for pollutant transport in the sewers is not as accurate as the hydrodynamics (Bouteligier et al., 2002). Consequently, caution should be exercised when using the water quality modules of the two software packages.
Integrated drainage network, treatment plant, and receiving water modeling. Zug et al. (2002) are creating an integrated model (sewer networks, storage tank, and wastewater treatment plant (WWTP)) for the Grand Couronne sewer system and parts of the Berlin sewer system. The integrated model has been built, calibrated, and validated for hydraulic and pollution load prediction during dry and wet weather. Mark et al. (2002) used integrated modeling of the drainage system, WWTP, and receiving water to evaluate real time control and alternative WWTP operations to protect beachfront water quality. The integrated modeling used MOUSE TRAP to simulate the drainage system, historical data to represent the WWTP operation, and MIKE21 to represent the beach water quality in two dimensions. An assessment of the benefits of an integrated urban drainage modeling approach linking the operation of the sewer system, WWTP, and receiving water was evaluated by Erbe et al. (2002). Mailhot et al. (2002) evaluated the impacts of watershed management and wastewater treatment activities on water quality of the Chaudiere River using an integrated modeling system. Wolff et al. (2002) assessed the use of hydraulic models of the collection system coupled with steady state models of the WWTP hydraulics. Willems and Berlamont (2002b) used deterministic and probabilistic modeling to simulate the impact of combined urban drainage and WWTP system discharges on receiving water quality.

**Pollutant sources and transport.**

A study procedure used to quantify urban pollutant loadings and provide accurate estimates of street and catchbasin cleaning practices was tested by Sutherland and Jelen (2002) for two case studies in Michigan. The procedure involves intensive monitoring of accumulation and both the physical and chemical characteristics of the contaminated sediment found on streets or parking lots and within catchbasins of a given land use. The accumulation data along with monitored rainfall is then used to calibrate SIMPTM, a continuous stormwater quality model. The procedure was applied to the two case studies and classical economic production theory and marginal cost analyses were used to identify the optimal mix of street and catchbasin cleaning practices. An enhanced version of SWMM was developed by Chen et al. (2002) and applied to the Castro Valley Creek watershed to simulate the process of diazinon application, decay, washoff, and transport. The model was calibrated and validated before simulating the diazinon dynamics in the watershed. Simulated diazinon concentrations in the creek matched observed data when monthly application rates were assumed proportional to the population within each subdivision of the watershed.

The level of uncertainty associated of stormwater quality model predictions generally limits the usefulness of the results for precise decision-making. Substantial calibration data is necessary to obtain reliable predictions. Calabrò and Maglionico (2002) compared the calibration and performance of SWMM, UPSIM (Urban Pollution SIMulator), and COSMOSS (Conceptual Simplified Model for Sewer System Simulation). Each model was calibrated and validated for two drainage catchments, one in Bologna and the other in Belgrade. The results of the study indicated that all calibrated models predicted the hydrographs and pollutographs well for both catchments. The simpler models (UPSIM and COSMOSS) required less effort because of their simplicity relative to SWMM. The authors identified several key parameters used for calibration of water quality routines in the three models.

Grum and Aalerink (2002) evaluated the potential of applying random coefficient modeling to describe pollutant concentrations in combined sewers during rainfall. The concept was tested by developing a random coefficient model for suspended chemical oxygen demand (COD) in a combined sewer and compares the model results to those predicted by an equivalent constant coefficient model. Ahlman and Svensson (2002a) applied the SEWSYS model to analyze the flow of substances within an urban catchment. The model keeps track of where each substance originates and where it finally ends up. SEWSYS was also applied by Ahlman and Svensson (2002b) to model substance flows in urban sewer systems. A simple conceptual-modeling approach was used by David (2002) to find a useful relationship between precipitation and total suspended solids loads at several monitored locations in a small urban watershed located in Lisbon. The paper by Pandit et al. (2002) demonstrated how the fully calibrated Continuous Annual Load Simulation model, CALSIM, was used to predict the annual total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) loads, under wet-weather conditions, for the Briar Creek drainage basin, located in the town of Malabar on the east-central coast of Florida, during an average water year. CALSIM was used to predict the annual loads under historical (1943), current, and future conditions.

**Models of controls.**

Traver (2002) investigated the appropriateness of using traditional storage-indication routing to model stormwater wetlands. The contributing area and stormwater wetland were simulated using HEC-HMS and HEC-RAS. The wetland configuration was modeled as a single pond and multiple ponds representing the sediment forebay and primary storage area. The results indicated that traditional routing techniques may not be appropriate for modeling stormwater wetlands, especially for smaller water quality storms. Gómez et al. (2002) performed numerical simulations using a simple detention basin and downstream sewer configuration in order to derive the peak flow attenuation and maximum water
depths with a wide variation of detention basin parameters and discharge hydrograph characteristics. The simulation results were programmed into an expert model in an Excel spreadsheet for estimating the size of detention basins.

Jensen and Thomsen (2002) used a 1D linear convection-dispersion-deposition model to compute the variation over distance and time of the vertical mean concentration of suspended solids in rectangular storage tanks. The model simulates steady flow and keeps a record of mass of solids suspended, retained on tank bottom, and contained in outflow. Comparison of the model to laboratory experiments shows the particle deposition velocity increases with free fall settling velocity, but decreases when discharge increases. A CFD simulation study was performed by Faram and Harwood (2002) to compare the pollutant capture efficiency of four generic “flow-through” technology stormwater treatment chambers. The authors concluded that chambers in which the storage region is isolated from the main treatment region are likely to be far more effective than those chambers in which this is not the case.

Calabrò (2002) presented a procedure based on a design storm to configure detention tanks for different levels of suspended solids removal. The accuracy of the technique was evaluated using continuous simulation. Comparison of tank performance predictions by the new technique and continuous simulations were close indicating that the new approach can provide fairly accurate performance estimates when rainfall data is not available for continuous simulation. Using SWMM continuous simulations and classical economic production theory, Burian et al. (2002) analyzed the long-term performance of stormwater storage/release systems. The results of the long-term performance evaluation were coupled with a simple economic analysis to select the most cost-effective combination of storage capacity and release rate that met the receiving water protection goal. Rathnam et al. (2002) presented a case study design of a detention facility using a design storm approach coupled with dynamic programming to optimally configure the facility taking into account the specified quantity of runoff and quality standards of the receiving water system. The optimization approach is tested and validated using data from experimental facilities. Morris and Asunskis (2002) used SWMM to evaluate different outlet structure configurations for detention basin designs for catchments located in Missouri. Conclusions from the study suggest there is no simple universal procedure that can be applied for modification of outlet structures of other problematic detention basins; instead a case-by-case evaluation is necessary. Venkata et al. (2002) used a design storm approach coupled with dynamic programming to predict runoff from a watershed and design a detention facility.

Nehrke and Roesner (2002b) examined the effect of detention basin controls on the peak flow frequency curve, and how well the post-development flows are controlled to pre-development levels. They used SWMM to simulate 50 years of rainfall runoff from a 24-acre portion of a hypothetical subdivision with a detention basin used for flow control. The study compared peak flow frequency curves for a detention basin with its outlet sized to control a series of design storms, plus an extended detention BMP option. The results demonstrated that increasing levels of imperviousness affect high frequency events much more than low frequency events. Moreover, the detention basin configuration with an outlet designed for the 100-yr & 10-yr design storms used in conjunction with the extended detention BMP option was found to provide the peak flow frequency curve closest to pre-development levels for storms smaller than the 6-month storm, as well as lowering the post-development peak discharges of low frequency events towards pre-development levels. Heaney (2002a) described a general optimization methodology for evaluating micro-scale urban wet-weather flow controls. The method allows one to optimize over several controls for each user, aggregate into a single performance curve for each user, and if necessary to find the optimal solution for groups of users. Li and Kyriopoulous (2002) presented a derived probabilistic rainfall-runoff model and a treatment train efficiency model to predict the cumulative reduction of runoff volume and solids loading for a series of retrofit stormwater management practices. Brasch et al. (2002) developed a Site Assessment Tool to help evaluate the hydrologic and pollutant loading impacts of new development projects and evaluate alternative BMP plans.

Stormwater infiltration and vegetative practices have been highlighted as key components of alternative development practices to reduce runoff volume and peak discharges. Several researchers have been developing models of infiltration devices for design and analysis purposes. de Souza et al. (2002) applied the Bouwer Model to simulate the hydraulic function of two infiltration trenches in Porte Alegre, Brazil. Results indicated that the model was able to represent infiltration well for one trench, but not the other. The authors attribute the poor model fit for the one trench to three possible reasons: preferential flow out of the trench, lack of a sufficiently clogged restriction layer, and oversimplification of the model. The authors proposed a modification of the model to account for variations of hydraulic conductivity and capillary tension associated with the soils where the trenches are located. Schaffner and Ostrowski (2002) presented a modeling approach to aid in the design and analysis of a flume-gravel trench stormwater infiltration system. Gharabaghi et al. (2002) developed a vegetative filter strip (VFS) model based on results from comprehensive field experiments that
quantified the performance of VFS under different flow conditions, pollutant loads, and vegetation covers. The VFS model is being validated and coupled with a nonpoint source pollution model to evaluate watershed management plans.

Watershed Management and TMDLs. Byun et al. (2002a) used SWMM continuous simulations to estimate runoff contaminant loads for the Schuylkill River watershed Source Water Assessment Program. Wagner and Schmidt (2002) compared the annual load predictions from calibrated SWMM and BASINS models of the Big Creek watershed north of Atlanta, Georgia to predictions from the simpler Watershed Management Model (WMM) to discern the advantages of using continuous simulation models for annual and seasonal load predictions. Richards and Stein (2002) introduced the U.S. EPA Smart Growth Water Assessment Tool for Estimating Runoff (SG WATER). The tool can estimate levels of stormwater runoff and associated pollutants (nitrogen, phosphorus, and total suspended solids) from specific development sites or regions.

Bhimani et al. (2002a) performed an integrated modeling approach on the Truckee River to evaluate water quality impacts of various watershed management alternatives in order to implement a trading program for TMDL modifications. Rousseau et al. (2002) used the GIBSI integrated modeling system to assess the probability of exceeding load allocations from point and nonpoint sources associated with TMDLs. Fitzpatrick (2002) described the use of water quality models to develop pathogen, nutrient, and toxics TMDLs for the New York/New Jersey Harbor.

Quantifying and overcoming uncertainty during TMDL development is a difficult challenge. Zhang and Yu (2002) applied first-order error analysis to quantify the margin of safety for the nitrate during TMDL development for the Muddy Creek/Dry River in Virginia. Precipitation was found to be the most dominant uncertainty source. Benaman and Shoemaker (2002) described a methodology to quantify the effect of multiple model parameter uncertainty on the calibration of the Soil and Water Assessment Tool (SWAT). The sensitivity and uncertainty analysis steps of the methodology were applied to a calibrated and validated model for the Cannonsville Reservoir watershed. Sokulsky et al. (2002) overcame model uncertainty in their efforts to develop a copper TMDL for the Haiwee Reservoir in California by developing a model based on extensive rainfall, flow, copper application, and in-system copper concentration data.

Managing the urban sewershed is a data intensive task, which requires sophisticated data management tools. Mihocko et al. (2002) described the development of a Decision Support System (DSS) to complement the Philadelphia Water Department’s Real-Time Control system in the City’s Southwest Drainage District. The DSS is being developed as part of the department’s Long Term Control Plan and will contain a variety of data views and analysis tools for use by agencies for various kinds of decision-making. Heltzel and Dunn (2002) described efforts to address data management needs through the development of an information management platform called Environmental Management and Analysis System (EMAS). EMAS provides a means to store and organize environmental data, analyze data, and link to modeling software.

Stormwater management systems for new urban development were traditionally analyzed using computer models employing design storm events, rather than continuous modeling using long term historical rainfall data and associated frequency analyses (Farrell et al., 2001). The differences in the results (i.e., designs) generated by the two methods have not typically been understood during the planning and design process. The different flow and storage regimes in the Town of Milton (Sixteen Mile Creek Watershed) generated by the alternate methods have been highlighted, along with a number of modeling and physical factors which are considered to contribute to the differing results. The Clinton River Watershed Council selected the Source Loading and Management Model (SLAMM) as the main instrument in its watershed plan development (Myllyoja et al., 2001). SLAMM accurately computed runoff pollutant loads and flows associated with small storm events, which was critical because most of the pollutant load was associated with the smaller, frequent runoff events. SLAMM evaluated several control practices including detention ponds, infiltration devices, porous pavements, grass swales, catchbasin cleaning, and street cleaning. A numerical model (sediment trap efficiency for small ponds-STEP) was developed to simulate sediment deposition in small ponds (less than or equal 1 ha) and to calculate the sediment trap efficiency (STE) (Verstraeten and Poesen 2001). Eight runs with an experimental pond in Belgium were used to test the model. The STEP model produced reasonable predictions of STE as well as the shape and magnitude of the effluent sediment concentration graph.

Huber (2001) summarized the ability of SWMM to simulate wet-weather controls favored in current practice, including those related to LID. The model simulated some practices well, such as storage, and other options not as well, such as wetlands and filtration. In designing a permeable pavement installation, surface infiltration capacity that allows an adequate volume of stormwater to be captured and treated by the facility must be provided and maintained (James et al.,
The paper detailed the underlying method and function of a free-ware program that uses SWMM for the design of permeable pavement installations.

The water balance model (Aquacycle) developed in this study represents water flows through the urban water supply, stormwater, and wastewater systems (Mitchell et al., 2001b). The daily time step provides temporal flow distribution and enables comparison of the different components of urban water demand. Aquacycle was tested using data from the Woden Valley urban catchment in Canberra, Australia and could satisfactorily replicate its water supply, stormwater and wastewater flows.

The micro- and macro-management of stormwater design was examined from a design engineer’s viewpoint based upon the traditional establishment of design values and not just meeting regulatory edicts (Olenik, 1999). Software was discussed by Smith (1999) that provides a decision support system for drainage engineers involved in the design of stormwater management facilities. The program provides suggested design parameter values that the user can modify, test and accept. A special feature allows the output file from one design session to be used as input to automatically test the design for a different storm, test a change in catchment or design parameters or simply to complete a design in two or more sessions (Smith, 1999).

Hushka et al. (1997) applied AGNPS to estimate erosion and nutrient loadings to the Mirror Lake watershed in North Dakota from five different scenarios of land use and management practices. AGNPS was also applied to a 72,000 acre watershed in south-western North Dakota for simulating the water quality of runoff overflowing the dam and to investigate the lake’s responses to eutrophication (Yoon and Disrud, 1997).

Hrabak et al. (1999) use three-dimensional computational fluid-dynamic (CFD) models to simulate various complex sewer and CSO components including mixing tanks, sedimentation basins, clarifiers and contact tanks. The modeling was used in lieu of physical modeling to support design. Vaes et al. (1999) described a conceptual model of storage sedimentation basins based on uniform flow, but taking into account anomalies due to non-uniform flow and turbulence. These anomalies were based on experiments in a physical model and simulations using CFD. This model can deal with time varying input and can be used for continuous simulations. Ta (1999) simulated the flow characteristics in a storm tank using CFD. The efficiency of the storm tank acting as a sedimentation basin to retain the suspended particle was evaluated using a dispersed phase model. A range of particle sizes was included to evaluate the sediment profile at the end of the storm event and the carry-over of suspended particles during the spill. Tyack and Fenner (1999) described a CFD model of a 1600 mm diameter prototype hydrodynamic separator. The result showed that the high vertical velocities within the device permit only particles with a high settling velocity to be removed, with the fine suspended solids (mostly organic) being passed forward for treatment in the WWTP.

CSO and SSO control. Hrabak et al. (1999) use three-dimensional computational fluid-dynamic (CFD) models to simulate various complex sewer and CSO components including mixing tanks, sedimentation basins, clarifiers and contact tanks. The modeling was used in lieu of physical modeling to support design. Vaes et al. (1999) described a conceptual model of storage sedimentation basins based on uniform flow, but taking into account anomalies due to non-uniform flow and turbulence. These anomalies were based on experiments in a physical model and simulations using CFD. This model can deal with time varying input and can be used for continuous simulations. Ta (1999) simulated the flow characteristics in a storm tank using CFD. The efficiency of the storm tank acting as a sedimentation basin to retain the suspended particle was evaluated using a dispersed phase model. A range of particle sizes was included to evaluate the sediment profile at the end of the storm event and the carry-over of suspended particles during the spill. Tyack and Fenner (1999) described a CFD model of a 1600 mm diameter prototype hydrodynamic separator. The result showed that the high vertical velocities within the device permit only particles with a high settling velocity to be removed, with the fine suspended solids (mostly organic) being passed forward for treatment in the WWTP.

 Mathematical modeling efforts of Monroe County, N.Y. initially used in the 1970’s for a CSO abatement program are being brought into use for current modeling applications in the 1990’s (Matzat et al., 1998). The city of Columbus, Ohio conducted a study to upgrade a WPCP and the collection system which included WWF (Abdel-Latif et al., 1998). The comprehensive modeling approach optimized the capacity of the collection system and its relationship to the WPCP. The U.S. EPA and the Miami–Dade Water and Sewer Department in Fla. negotiated a consent decree settlement which required the installation and maintenance of a computerized collection and transmission system model. This model, the “Virtual Dynamic Computer Model” has the ability to predict potential SSO from peak flow conditions (Walch et al., 1998b). The system demonstrated its value in determining that $20 million of proposed construction was unnecessary (Walch et al., 1998a).

A dynamic hydraulic model of the Baton Rouge, La. sanitary sewerage system was developed and calibrated against recorded flow and rainfall and a number of operational modifications and system augmentations were proposed to optimize the use of the tanks to reduce the frequency of SSO (Moody and Baldwin, 1998). Model construction included the development of Real Time Control (RTC) code to simulate the operation and performance of two major offline storage facilities during the recorded storm events. Three RTC simulations demonstrated that RTC provided an alternative to traditional approaches for handling WWF in separate sanitary sewers. The three simulations all met the specific constraints of the example sewer system, i.e., reduction in the number and volume of SSO without exceeding the existing pump station capacity at the drainage outlet (Pierce and Dillard, 1998). Costs for developing RTC for stormwater treatment range from $0.055 to $0.082 /Lyr ($0.21 to $0.31 /gal-yr) compared to the cost of building storage facilities for the equivalent CSO reduction which would cost between $0.40 and $0.53 /Lyr ($1.50 and $2.00 /gal-yr) (Agbodo and Nelson, 1998). Colas et al. (1998) presented the technological advances made in a five year R & D project in which
methods, software and technology specifically designed for CSO control made RTC a more feasible and accessible solution.

Dorn and Miles (1997) developed a preliminary sanitary-sewer system improvement cost-estimating method by using the U.S. Army Corps of Engineers’ Storage, Treatment, Overflow, Runoff Model (STORM) and U.S. EPA Needs Survey Database.

**Pond treatment.** XP-SWMM was used to evaluate the performance of a retention treatment facility in Oakland County, Michigan (Buchholz et al. 2000). The results showed the amount of storage that is necessary to reduce the number of overflow events by 30%. A two-dimensional, vertically averaged hydrodynamic model was adapted to predict the circulation and sedimentation patterns in stormwater detention ponds (Dewey et al. 2000). The performance of the model for a pond system in Toronto was presented. The Storage-Treatment block of SWMM was used to model the effectiveness of extended detention ponds (Newman et al. 2000b). The results showed much improved designs over using traditional methods. The Corrugated Steel Pipe Institute developed software for designing underground stormwater detention tanks (Finlay, 2000). Designers could use the program to quickly perform the calculations associated with the design of underground storage detention facilities. Analytical probabilistic models were applied to analyze the runoff quantity/quality control performance of various combinations of storage and treatment systems (Li and Adams 2000). These models provided closed-formed solutions of the performance equations that were efficient in both a conceptual and computational sense.

Ponce and Klabunde (1999) tested the feasibility of temporarily holding stormwater in parking lots by using a diffusion wave model of catchment dynamics. Four extreme storm types were applied to four typical parking lot sizes to assess the sensitivity of the resulting storm hydrograph to the choice of design slope. Results show the promise of parking lot storage in urban stormwater management. Ristenpart (1999) presented detailed information about a new stormwater management concept. Dimensioning and proof of performance of the different drainage structures was carried out with the help of an innovative rainfall-runoff model that was also briefly described.

Zheng and Baetz (1999) investigated a range of suburban development alternatives from an urban hydrology perspective. An analysis of design scenarios was conducted for a representative urban fringe development application, with the aid of a stormwater runoff simulation model (QUALHYMO) and geographical information systems software. In developing countries like India, the use of stormwater models for modeling and sizing detention basins has yet to acquire widespread application as a standard practice. Currently, design was carried out using the rational method, which was grossly inadequate, particularly as an abundance of sophisticated software was available. Gupta et al. (1999) described the application of Australian software, ILSAX, for modeling the onsite detention basins for the Central Hospital catchment of Jaipur City, India.

Baird and Rogers (1997) reported on a case study using SWMM to determine detention volumes for a series of wet-detection ponds to mitigate increased stormwater runoff due to new urban development in Williamson, Tex.

**Wetland treatment.** Constructed wetlands used for stormwater treatment accumulate metals primarily in their sediment, which has the potential to produce toxic effects in benthic or aquatic organisms. A system dynamics model was developed to represent these processes and the major influences affecting pore water metal activity in a treatment wetland receiving stormwater influent. Simulation results demonstrate that chemical processes of acid volatile sulfide (AVS) and organic carbon in binding metal in reduced sediments were the greatest influences in controlling metal bioavailability (Wood et al., 1999). The wetland model utilizes a hydrology model coupled to a hydraulic stream-routing model. A depth-averaged laminar flow model was used to simulate the horizontal movement of stormwater both through and over the wetland sediments, a 400-ha first-order headwater swamp located within the Teeswater River watershed in southern Ontario, Canada. An analysis revealed that the simulated wetland streamflows were sensitive to the antecedent saturation of the wetland sediments, the storage and flow transport characteristics of the wetland sediments, and the conveyance capabilities of the wetland channel system (McKillop et al., 1999).

According to Moustafa (1999), long-term data collected at Boney Marsh, Florida and the EPA wetland database were analyzed to develop a simple tool that can be used to predict and optimize phosphorus retention in wetland treatment systems. Wetland properties such as water loading rate, water depth, P-loading rate, and water retention time were examined for their influence on phosphorus retention. The relationship between wetland properties and phosphorus removal efficiency was reduced to a simple quantitative diagram (The Phosphorus Removal Efficiency Diagram) a simple
A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe biochemical oxygen demand removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an \( n \)-th order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer functions and Laplace transform (Chen et al., 1999).

Traver (1999) examined the calibration and performance of a hydrologic model in recreating recorded storm events from both the stormwater wetlands and the wetlands stream, and the nutrient removal effectiveness of the stormwater wetland basin.

Nnadi et al. (1999) compared the ability of various design storm distributions to simulate the actual rainfall pattern to the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe biochemical oxygen demand removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an \( n \)-th order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer function “Laplace transform” (Chen et al., 1999).

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**Infiltration/biofiltration control practices.** Munoz-Carpena et al. (1999) developed and field-tested a single event model for simulating the hydrology and sediment filtration in buffer strips. The model was developed by linking three submodels to describe the principal mechanisms found in natural buffers. They found that the performance of vegetative filter strips was governed by complex mechanisms and developed a model by linking three submodels to describe the principal mechanisms found in natural buffers: a Petrov-Galerkin finite element kinematic wave overland flow submodel, a modified Green-Ampt infiltration submodel, and the University of Kentucky sediment filtration model. A set of 27 natural runoff events (having rainfall amounts ranging from 0.003 to 0.03 m) from a North Carolina Piedmont site were used to test the hydrology component, and a subset of nine events were used to test the sediment trapping component. Good predictions were obtained with the model if shallow uniform sheet flow (no channelization) occurred within the grass filter.

Urban stormwater quality can be protected by maximizing the infiltration of frequent micro storms that account for the majority of the precipitation in urban areas. A proposed criterion was that the pre-development initial abstraction of precipitation should not be decreased by development. Heaney et al. (1999) used a linear programming model, which in turn uses information from the GIS as input data, to find the mix of functional land use types that minimizes the cost of retaining the initial abstraction at its pre-development level. To assist local governments in their efforts to develop more effective stormwater management programs, Prince George’s County, Maryland Department of Environmental Resources in cooperation with the EPA developed a guidance manual for an innovative alternative comprehensive approach to stormwater management referred to as LID (Coffman et al., 1999).

**Best management practices.** A study of a physical model of the design of litter traps for urban storm sewers was carried out at the hydraulic laboratories at the Universities of Cape Town and Stellenbosch (Armitage and Rooseboom 2000).
This study clearly showed why most designs fail and identified the use of declined screens as an approach that holds considerable promise. Low Impact Development (LID) is an innovative micro-scale runoff control strategy for WWF management issues based on the incorporation of distributed micro-scale Best Management Practices (BMP's) throughout the subcatchment (Wright et al. 2000). The potential and limitations of existing models to evaluate the effectiveness of this design approach were explored in this study. Numerical techniques for modeling overland flow from pavements were described (James and Wylie, 2000). The efficiencies of various approaches were reviewed and compared. The feasibility of a permeable pavement option in SWMM for long-term continuous modeling was explored by Kipkie and James (2000). The results indicated that it would be feasible but further testing would be needed.

A two-phase decision-making software, DELTANOE, was used for the choice of BMP in urban stormwater drainage (Barraud et al., 1999). Two phases: (1) an elimination phase - to exclude solutions which were identified as unworkable according to site considerations and (2) a decision phase - to compare and at least to choose a scenario with feasible solutions.

According to Murphy and Lokey (1999) a model was developed to assess urban BMP efficiency on the total pollutant load using a simple spreadsheet and Monte-Carlo style simulator. The model suggests that many BMP used to comply with the National Pollutant Discharge Elimination System (NPDES) requirements appear to have little impact on the annual load. It might be argued that many BMP need to be evaluated at the source, not the receiving stream.

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A calibrated particulate transport model showed that high efficiency sweeping at weekly intervals combined with annual catchbasin cleaning provided removals approaching those of wet vaults for SS and associated pollutants, and possibly better than wet vaults for dissolved pollutants (Sutherland et al., 1998).

**Real-time control.**

Several papers examined real-time predictions of stream flows. Chang and Chen (2001) employed neural network and fuzzy arithmetic tools to enhance predictions for the Da-cha River, in central Taiwan. They (Chen et al., 2001b) also used the method to predict floods one hour in the future for the Chingshui River during tropical storms using the new models. Khu et al. (2001) and Soon et al. (2001) employed genetic programming to improve real time forecasting for the Orgeval catchment in France. They successfully improved the forecasting for future periods up to the time of concentration of the watershed. Their comparisons showed that genetic programming was a better updating tool for real-time flow forecasting than previous methods. Xiong et al. (2001) combined the simulation results from different models to improve real-time forecasts.

Fuzzy logic models were used to do real time flow prediction for an urban catchment near Brussels, Belgium (Debede and Bauwens, 2000). A general method to design fast and stable mathematical models for the computation of sewer system outflow hydrographs were shown to be essential for real-time control of urban storm drainage systems (Hermann and Eberl 2000). The unknown inflow-outflow function was developed into a power series resulting in a nonlinear model. The new model formulation was tested with several urban subcatchments of a larger storm drainage network.

A real-time sensor fault detection method applicable to sewer networks was used to aid in real time control applications during wet weather (Piatyszek et al. 2000). This method consisted of comparing the sensor response with a forecast of this response provided by a model in the form of a state estimator called a Kalman filter. The Philadelphia Water Department investigated the application of real time control (RTC) to maximize the utilization of its existing combined sewer network.
facilities in its Southwest Drainage District (Vitasovic et al. 2000). A version of the SWMM EXTRAN routing model was compiled as a Microsoft Window Dynamic Link Library and included as part of the SewerCAT modeling environment to meet RTC requirements and exploit existing EXTRAN models of the system.

Despite considerable modeling efforts in recent years, a tool was still lacking which allows the simulation of sewer system, treatment plant and river as well as the analysis of real-time control (RTC) strategies using information from all parts of the urban wastewater system. Real-time-control (RTC) systems will be an integral part of future urban-stormwater-decision-support systems. Schutze et al. (1999) presented a software package for synchronous optimization and simulation of the urban wastewater system (SYNOPSIS) that integrated the simulation of the sewer system, treatment plant and receiving water and can be used for RTC. Marti et al. (1999) described an optimization procedure for RTC of a combined sewer system in the city of Barcelona, Spain. The control system involves measuring the variables at various points, collecting the data at the control center, processing and analyzing the data, and deciding on what actions should be taken by the actuators on the basis of the real time, self-calibrating hydraulic model. Moller et al. (1999) described a predictive urban drainage RTC system, which was based on a standard urban drainage modeling tool. The potential operational benefits associated with predictive RTC were illustrated through a test case. Reda and Beck (1999) studied the impacts of CSO on river water quality using the Multiple Continuously Stirred Tank Reactor (MCSTR) dynamic model. The potential for applying this model in a real-time context was demonstrated as a tool to support decisions regarding treatment plant operation during storm events, when it was often not possible to sustain full treatment of the incoming sewage flow.

The city of Barcelona, Spain has a 1,450 km-long combined sewer system with 10 pumping stations, 16 gates and 3 holding tanks. Marques et al. (1999) presented a remote control system that enables images obtained from a meteorological radar to predict current and future rain levels in the city of Barcelona, Spain. The received images were calibrated with the remote-controlled rain gauges in real time. Vazquez et al. (1999) examined the value of real-time management of a sewer system to reduce the impact of effluents and thus improve the quality of the host environment. The aim was to make better use of the storage capacities in the mains and tanks to reduce discharges into the environment. A multi-criteria optimization algorithm was used to provide control strategies for the components of the sewer system, e.g., sluices and pumps. Graph theory has been chosen as the mathematical tool. The study was applied to the sewer network of Saverne. Worm et al. (1999) used control strategies to equalize the hydraulic loading of a WWTP using a grey-box model of the sewer system that was based on correlation properties of flow, water level and pumping activity. The influent flow pattern showed fast transitions due to two major pumping stations in the sewer system that were operated by means of local control. By applying a stochastic flow model, calibration can be avoided since the parameters were estimated directly from the data. Hernebring et al. (1999) described the three Swedish pilot projects carried out as part of the Technology Validation Project "Integrated Wastewater" (1997-2000), supported by the European Commission.

The three Swedish projects were carried out in the cities of Helsingborg, Halmstad and Sundsvall. All three projects focus on the interaction between the sewer system and the wastewater treatment plant under variable operational conditions, created by the application of RTC in the sewer network. Pfister and Cassar (1999) described a research project that focuses on minimizing total emissions from sewer systems using RTC. The main goals of the study cover the optimum use of storage capacities, the best performance of the treatment plant, or by the dynamic management of the combined sewer system. The benefit of RTC increases if forecasted information of rainfall and runoff was taken into account. Casser and Verworn (1999) described the upgrading of the existing hydrodynamic-rainfall-runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

A near real-time, stream-flow-simulation system utilizing continuous simulation rainfall-runoff generation with dynamic-wave routing is being developed by the U.S. Geological Survey (USGS) in cooperation with the Du Page County Department of Environmental Concerns for a 34-km reach of Salt Creek in Du Page County, Ill. (Ishii et al., 1998). The system is critical for more effective management of the Elmhurst Quarry Flood Control Facility, an offline stormwater diversion reservoir located along Salt Creek. A $1.5 million Capital Improvement Project in the Lake City drainage basin in the northeast area of Seattle, Wash. was evaluated using XP-SWMM32. With an automatic calibration module the stormwater model showed that the system was reliable and took less time than the typical manual, trial and error approach (Ovbiebo and Kuch, 1998). Data collection and computer modeling identified deficiencies in a group of subbasins.
tributary to a treatment plant operated by Tulsa (Okla.) Metropolitan Utility Authority (Dillard et al., 1998). A model of Tulsa’s major (≥250 mm) gravity lines evaluated the system’s ability to pass design flow. The Greater Vancouver Sewerage and Drainage District in Can. modified the Stormwater Management Model’s (SWMM) RUNOFF block to improve simulation of WWF in sanitary sewers with the addition of an effective infiltration/inflow (I/I) area factor and improvements in tracking head differences between the groundwater stage and pipe tailwater level. Calibrated results were plus or minus 15% of measurements (Kadota and Djebbar, 1998). Tsihrintzis and Hamid (1998) examined the applicability of the SWMM RUNOFF block in small subtropical urban catchments with emphasis on parameters used to calibrate the model. Balascio et al. (1998) used genetic algorithm to calibrate the RUNOFF block of SWMM. The calibrated model was used to simulate two storms with good accuracy. Los Angeles, Calif. has a wastewater collection system that serves 3.5 million people in a 1 680 km² area. The existing wastewater collection system was modeled using MOUSE (Model of Urban Sewer Systems) for dry and wet weather conditions (Price and Gonzalez, 1998). SWMM and the Corps of Engineers’ unsteady flow channel network model was applied to the Big Cypress Basin Watershed in southern Fla., an area of low relief and high water table conditions, with a complex network of drainage design (Walters et al., 1998).

Petrucci et al. (1997) developed two real-time control (RTC) strategies. The first is a pollution-based RTC and the second is a water-quality based RTC (WBRRTC); these strategies seek to improve the water quality of a stream by reducing CSO volume and pollution load. The Department of Hauts de Seine which covers more than 30 urban districts on the west side of Paris, Fr. has decided to implement RTC in order to confront the problem of CSO from its CSS by using the MOUSE computer model. Preliminary studies show it would allow an 80% annual reduction of the volumes of wastewater discharged into the Seine River (Entem et al., 1997). Pfister (1997) outlined the need and use of an integrated approach to combine existing model components to optimize dynamic management of CSS and WWTP.

Schilling (1996) summarized the state-of-the-practice regarding the use of RTC including applications around the world. Nelen and Broks (1996) summarized RTC use in eight Netherlands’ cities. Lavallée et al. (1996) reported 30-60% reduction in the volume and frequency of CSOs in Quebec City, PQ, Canada using RTC. Rauch and Harremoes (1996a, 1996b) described an RTC system that includes optimization using Genetic Algorithms. Schmitt (1996a) evaluated improvements in two German combined-sewer systems from using RTC. Volume reductions were 30% in one case and 9% in the other. Sirkin (1996) cautioned that RTC should only be used after determining some necessary, preliminary information for the stormwater system. Kjaer et al. (1996) described using MOUSE ONLINE, an extension of the Danish Hydraulic Institutes’ MOUSE model, for RTC. MacArthur et al. (1996) described a computer-based system for conjunctive operation of the WWTP and stormwater controls in Monroe County in upstate New York that includes the City of Rochester. Cantrell et al. (1996) summarized an application of HydroWorks developed specifically to use with an existing RTC system in Lima, OH, an early RTC application in the United States. Miles et al. (1996) described methods and models for evaluating I/I problems associated with SSO.

**Optimization models.**

Behera et al. (1999) present an optimization methodology for determining the design parameters (storage volume, release rate, and pond depth) of a single stormwater management pond. The methodology was extended, using a dynamic-programming procedure, to parallel catchments (each with a single detention pond). The least-cost values of pond design variables were subjected to system performance constraints, in the form of specified levels of runoff and pollution control at the outfall to a receiving water. Ndiritu and Daniell (1999) assessed the application of varying levels of optimization on model simulation performance and parameter identification using a genetic algorithm (GA) and a 10-parameter version of the MODHYDROLOG rainfall-runoff model. Four levels of optimization were obtained through the use of two GA formulations, the traditional and an improved GA, and by varying the optimization parameters with each formulation. It was proposed that the systematic verification of the adequacy of optimization should be an integral part of model calibration exercises.

Thomas et al. (1999) described the hydraulic verification of optimal control models that have been developed for large interceptor sewer systems. Both linear- and dynamic-programming models were tested using idealized interceptor sewers. The models include a simple hydraulic verification routine in which a quasi-steady approach was used to estimate interceptor sewer water profiles at each time step in the solution. Veltri and Pecora (1999) applied genetic techniques using data measured from an urban catchment to calibrate parameters from two well-known commercial modeling tools. These genetic techniques can be successfully applied to emulate a modelling environment and subsequently to calibrate indirectly the same model. Blanpain et al. (1999) described how stochastic search algorithms to be used to more fully explain the flows in a sewer network with incomplete information on its physical characteristics. The comparison, based
on hydraulic simulations, showed that their method allows reduced flow and water depth deviations by at least 50%. Choi and Ball (1999) presented a decision support system for estimating optimum values of model control parameters. SWMM was used to simulate the runoff response of an urban catchment, while ARC/INFO and an optimization algorithm were employed to enhance spatial data handling and to optimise model control parameters.

Heaney et al. (1999) described a new method for optimizing the design of urban storm-sewer systems. The vertical alignment design problem was defined by a set of discrete pipe diameters and costs, excavation costs as a function of soil type, and a pre-defined horizontal arrangement of pipes and manholes for a gravity sewer. Genetic algorithms were used in place of classical techniques to arrive at the least-cost solution for a specified design storm. An example was presented to illustrate the technique. Use of mathematical models requires the estimation of model parameters. Parameter optimization was preferred to the trial and error visual comparison of observed and modelled output response, due to subjectivity and time-consuming nature of the latter approach. Dayaratne and Perera (1999) described an optimization procedure to estimate the model parameters of the urban stormwater drainage model called ILSAX. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999).

Pleau et al. (1998) proposed a tool to optimize long-term CSO plans which is linked to an hydraulic/hydrologic model in order to find the CSO plan that best suits the situation and reduces up to 30% of the cost of traditional approaches. A stochastic model based on physical mechanisms and formulated in continuous time to simulate water level and particulate COD at the overflow point of a Dutch combined sewer system was investigated (Grum, 1998). Preliminary results suggested that further work is needed in order to fully appreciate the method's potential and limitations in the field of urban runoff pollution modeling.

**Stochastic models.**

Lei et al. (1999) presented a new Stepwise Hypothesis Test Model Calibration (SHYTMC) procedure that includes explicit recognition of modeling uncertainty and system identifiability. Central in the SHYTMC procedure was the estimate of upper and lower bounds of the modeled output time series. A comparison with the result from 1,000 Monte-Carlo simulations suggests that the worst scenario approach was sufficient in the context of the SHYTMC procedure. Rauch et al. (1999) outlined the background of engineering analysis and applied the methodology to a probabilistic design problem concerning CSO reduction. The geometrical data used in stormwater models were hardly ever 100 percent correct and the process data like hydraulic roughness, overflow coefficients etc. were based upon accepted average values.

Clemens and von der Heide (1999) used Monte-Carlo simulation to evaluate the stochastic nature of this uncertain input data. The uncertainty or reliability of results produced by rain-fall-runoff models was a function of uncertainties in model parameters, input data, and model structure. Hoybye and Rosbjerg (1999) presented a stochastic instantaneous unit hydrograph model describing the catchment as a single linear reservoir with input and transfer functions treated as random processes. Errors in runoff predictions caused by errors in input data and model parameters were analyzed by solving the governing stochastic differential equation (SDE) analytically, thus quantifying - in a general way - the error propagation structure and the relative importance of input errors and parameter errors. Data from 34 rainstorms were selected to verify the analytical SDE approach. Monte-Carlo simulation, an approach developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds, was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the U.S. Soil Conservation Service (SCS) unit hydrograph model (Yulianti and Lence, 1999).

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO (CSO) loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999). A procedure was introduced for applying the statistical approach to water table management models such as DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in
the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

Receiving water models.
Kellershohn and Tsanis (1999) used WASP to create a three-dimensional eutrophication model for Hamilton Harbor, Ontario, Canada. Four remedial options, namely improvements to the WWTP, the CSO, industrial discharges, and removal of WWTP, CSO, and industrial discharges were examined. Improvements in the harbor’s water quality were found to range from minor in the case of CSO improvements to significant in the case of WWTP improvements. Lung and Sobeck (1999) demonstrated that modeling continues to be the most cost-effective method of water quality planning and that water resource managers should apply water quality modeling on a regular basis to support the present and future needs of the watershed. They indicated that there was a need for increased use of water quality models to review the assimilative capacity of the receiving water for regulatory control and water quality management. Petruck et al. (1999) described the water quality simulation model FGSM, developed by the German Association for Water Pollution Control (ATV) to simulate major water quality parameters of a small urban stream. The FGSM appeared to be a valuable tool for assessing not only the chronic, but also the acute effects of combined sewage overflow events.

Walker and Stedinger (1999) described the movement and fate of pathogens from wastewater and dairy sources and the resulting raw water quality for New York City, New York. Manure and Cryptosporidium oocysts were modeled as surface pollutants and assumed to move in response to runoff events in the six watershed-reservoir systems within the Catskill-Delaware watershed. This research highlights the importance of wastewater-derived oocysts, the need for expanded research into oocyst fate in streams and reservoirs, and the concentration of oocysts in sewage effluent. Fitzpatrick et al. (1999) presented an overview of the development and application of a time-variable nutrient based emergent macrophyte model to a southern Florida Everglades wetlands system. The model formulation included the effects of nutrient concentrations on sawgrass and cattail plant growth, nutrient uptake, and nutrient composition.

Three-dimensional simulations of estuarine circulation in the New York Harbor complex, Long Island Sound, and the New York Bight were conducted using the Estuarine, Coastal, and Ocean Model (ECOM) within the framework of a single grid system (Blumberg et al. 1999). The model forcing functions consist of (1) meteorological data; (2) water level elevation and temperature and salinity fields along the open boundary; and (3) freshwater inflows from 30 rivers, 110 wastewater treatment plants, and 268 point sources from CSO and surface runoff.

Hsu et al. (1999) described a flood and inundation forecasting model to be used for flood damage mitigation. The simulated results from the river flood model and the cell inundation model were used to calculate the flow exchanges between the river and inundation area. The results were accurate enough to be used to simulate the water stage in the river and map out the inundation area for the various design rainfalls. Huberlant et al. (1999) described the Urban Pollution Management Procedure that was developed to address the problem of protecting rivers from urban stress in a holistic and cost effective way. The procedure allowed river systems to be modeled, with input from sewer overflows and sewage treatment works discharges, to enable assessment of minimum cost solutions. With the support of the European Commission, five pilot studies were carried out in different countries to test and demonstrate the effectiveness of this approach.

The responses of ADAPT, a daily water table management simulation model, to variations in the principal input parameters which define hydrologic response units on a watershed were evaluated (Gowda et al., 1999).

Shanahan et al. (1998) found that QUAL2E was best suited for point-source discharges and was limited when examining the contribution of NPS pollutants to river-quality degradation. The combination of models that describe the dynamic behavior of the sewer system, the WPCP and receiving water for the assessment of water pollution gives rise to a complexity far beyond what is needed (Rauch et al., 1998). Simplifications are possible because only a few types of wastewater discharge impacts typically affect the ecological state of the receiving water. Pitt (1998) described the Source Loading and Management Model (SLAMM), and gave an brief overview of its history, as well as its unique attributes and its value in determining the relationships between sources of urban runoff pollutants and runoff quality.

Watershed evaluations
Donigian (2002) discussed watershed model calibration and validation drawing from more than 20 years experience with HSPF. Ackerman and Schiff (2002) developed and calibrated an HSPF model for the Santa Monica Bay watershed. Model development was based on detailed land use and stream geometry and calibration was based on rainfall and runoff.
data from 1988 to 1998 and stormwater quality data from 1993 to 1998. Model validation indicated that predicted bacteria levels were reasonably comparable to observed data. Love and Donigian (2002) presented a statewide watershed model for Connecticut to help identify all key sources of nutrients to the Long Island Sound using the U.S. EPA Hydrological Simulation Program – FORTRAN (HSPF) and the U.S. Geological Survey’s (USGS) graphical user interface GenScn. Effectiveness of three nonpoint source BMP implementation scenarios were evaluated and simulated for buildout conditions by year 2020. HSPF was also applied to simulate the Chesapeake Bay watershed by Shenk et al. (2002). They developed an intermediate processor between the land and water simulations to represent the changes in management practices and land use that may affect the pollutant export from the land surface and the pollutant transport in streams. Wang et al. (2002) are developing an watershed model using HSPF for the Sinclair Inlet and Dyes Inlet drainage basins. To better understand the relationship between rainfall and freshwater inflows to the Inlets an Artificial Neural Network (ANN) was developed. The feedforward ANN was trained using concurrent rainfall and creekflow data. Comparisons between the ANN and the HSPF model showed the two models had similar accuracy levels for predicting rainfall-runoff entering the Inlets.

Luzio et al. (2002) modified the BASINS modeling system by incorporating a tool that optimizes the automatic definition and segmentation of the watershed and stream network based on topography and the National Hydrography Dataset or other stream data, a tool that defines the Hydrologic Response Units (HRUs) over the watershed and subwatersheds, and the SWAT model. The enhanced BASINS system was demonstrated with an application to the Upper North Bosque River watershed in Texas. The Watershed Characterization System (WCS) was originally developed for the EPA Region 4 to facilitate physical characterization of watersheds, evaluate water quality conditions, and to assess potential sources of impairment using spatial databases and GIS technology. Greenfield et al. (2002) described the updating of the WCS to include erosion and sediment delivery models, a mercury loading model, and SWMM and NPSM GIS interfaces.

Samuels et al. (2002) developed a GIS-based tool to calculate the time of travel, decay, and dispersion of a pollutant introduced into surface waters. Ponnambalam et al. (2002) demonstrated a GIS-based multi-criteria evaluation decision-making tool for use in wetlands management. Mohamed and Plante (2002) stressed the need for geospatial information technologies in developing countries to support sustainable development. Donigan and Love (2002) reviewed the Connecticut Watershed Model (CTWM). The interface and framework of the CTWM was specifically designed to promote continuing use by CT DEP staff to assess multiple BMPs, implementation levels, and relative impacts of point source controls for nutrient reductions to Long Island Sound. The paper presented procedures and results of using the CTWM to evaluate the loading impacts of alternative future growth conditions, and mitigative impact of BMPs for reducing nutrient loads to LIS.

Jia et al. (2001) developed a distributed hydrological model, the Water and Energy Transfer Processes Model (WEP), to simulate spatially variable water and energy processes in watersheds having complex land covers. Variables include depression storage on land surfaces and canopies, soil moisture content, land surface temperature, groundwater tables, and water stages in rivers. Infiltration excess during heavy rains is simulated using a generalized Green-Ampt model, while flow routing is simulated using a one-dimensional kinematic wave method. The model was applied to the Ebi River watershed (27 km2) with a grid size of 50 m and a time step of 1 h. The model was verified through comparisons of simulated river discharges, groundwater levels, and land surface temperatures with the observed values. A comparison between the water balances at the present time and in the future was also conducted. It was found that the hydrological cycle in the future can be improved through the use of stormwater infiltration. Santini et al. (2001) modeled the Detroit Water & Sewerage Department collection system to identify flow sources. They also modeled the time needed to return to base flow conditions after wet weather events.

A methodology was developed by the Greater Vancouver Sewerage & Drainage District to estimate future percent total impervious area using population density (Hicks et al. 2000). Percent total impervious area has been found to be an indicator of watershed health, therefore, it would be beneficial if future imperviousness could be forecast based on population growth and land use estimates. The value of benefit-cost evaluation for stormwater quality management decisions at a local level was explored using a benefit-cost analysis (BCA) screening method (Kalman et al. 2000). Ballona Creek, a major urban storm drain in Los Angeles, was used to illustrate the practicality of the benefit-cost evaluation.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a 3-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations
and Variable Source Areas (Chen and Beschta, 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999). The HSPF has been calibrated for a sub-watershed of the Upper Roanoke River system. The model will provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999).

Kornecki et al. (1999) evaluated the Spatially Integrated Models for Phosphorus Loading and Erosion (SIMPLE) for predicting runoff volume, sediment loss, and phosphorus loading from two watersheds. SIMPLE tended to underestimate runoff volumes during the dormant period, from November to March. Results of model evaluation indicated that SIMPLE's predictive ability was acceptable for screening applications but not for site-specific quantitative predictions. Schwartz and Naiman (1999) derived the mean and variance of planning level load estimators under mild parametric assumptions and using a distribution free approximation. Common use of the mean, median, or geometric mean of event concentrations was shown to result, in general, in biased estimates of the mean annual load. Substantive implications for regional assessments, planning, and watershed management were illustrated with a simple example drawn from Chesapeake Bay, Maryland. Alex et al. (1999) described a system of numerical models (PLASKI, SIMBA sewer and SIMBA) for simulation of wastewater production, transport and treatment, respectively. The three modules were all running under MATLAB/SIMULINK and allow integrated simulation of processes in all three-system components.

The Hydrologic Simulation Program Fortran (HSPF) has been calibrated for a sub-watershed of the Upper Roanoke River system. The model would provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999). SWMM was applied to study stream-water quality due to diffuse sources on a 14.25 km² watershed in Castro Valley, Calif. The simulation was performed over a two-year period for flowrate, Cu, Pb, and SS (Khan et al., 1997).

The responses of ADAPT, a daily water-table management simulation model, to variations in the principal input parameters which define hydrologic response units on a watershed was evaluated (Gowda et al., 1999). Simulated agricultural runoff amended with sediment, nitrogen, and phosphorus, was passed through an experimental sedimentation basin. A series of six sequential runoff events was run through the basin for each of two treatments. The treatments consisted of one-day and three-day detention times, created using a perforated riser outlet structure (Edwards et al., 1999). Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters can be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

The UP (Upscaled Physically-based) hydrological modeling system to the Arkansas-Red River basin, United States was designed for macroscale simulations of land surface processes, and aims for a physical basis and, avoids the use of discharge records in the direct calibration of parameters. This was achieved in a two stage process: in the first stage parameterizations were derived from detailed modeling of selected representative small catchments and then used in a second stage in which a simple distributed model was used to simulate the dynamic behavior of the whole basin. Outputs from the model were discussed, and include river discharge at gauging stations and space-time fields of evaporation and soil moisture (Kilsby et al., 1999). The UP modeling system has been applied to the 570,000 km² Arkansas-Red River Basin (ARRB) as part of the UK NERC Terrestrial Initiative in Global Environmental Research (TIGER). The parameters of the ARRB model were physically-based, being derived either from fine-scale, sub-grid, data on the topography and physical properties of the soils, aquifers and vegetation of the basin, or from the results of fine-scale physically-based simulations. The ARRB model, as described here was a first attempt at large-scale physically-based hydrological modeling of the type outlined in the 'blueprint' for the UP system, and gives a clear, positive, indication of the nature and quality of what was currently practical with the approach (Ewen et al., 1999).

A physically-based model was used to simulate runoff in agricultural watersheds with tile drainage systems. The TOPMODEL, which was based on the detailed topographical information provided by a digital elevation model (DEM), was modified for this simulation study. The simulated hydrologic response was designed to produce several components of the outflow hydrograph which were associated with the various possible flow generation scenarios (Kim et al., 1999).

The geomorphic characteristics of an ungauged watershed were analyzed using a digital elevation model and were used to construct a runoff simulation model. A design storm was applied to the geomorphic runoff simulation model to obtain the
design hydrograph (Lee, 1998). The time of concentration for a plane with urbanization from downstream to upstream could be more than four times longer than that for a plane with urbanization from upstream to downstream (Wong and Li, 1998). A physically based, distributed model, applied to a small urban watershed in Japan with an area of 66.18 ha provided a reasonable interpretation of the overall runoff and pollutant generation process in urban areas (Haiping and Yamada, 1998). Motivated by planning and rehabilitation of stormwater overflow tanks in municipal drainage systems, Haberlandt (1998) presented a simple stochastic model with spatially interpolated parameters for the synthesis of short-time increment precipitation at ungauged points. A hydrological model, based on a semi-distributed parameter, was coupled to a simple pollutant transport model to analyze the alternative solutions for reduction of CSO from an urban catchment to the river Nidelva in Trondheim, Nor. (Milina, 1998). A watershed management model predicted monthly and annual water yields in two watersheds based on hydrological, geological and land use data. A subwatershed exhibited the same hydrologic behavior as the main watershed (Fuentes and Ribiero-Matos, 1998). Snowmelt Runoff Model (SRM) streamflow predictions for 1990, 1993, and 1994 seasons for the Towanda Creek basin, Pa., using a combination of elevation and land-use zones yielded more precise streamflow estimates than the use of standard elevation zones alone (Mitchell and DeWalle, 1998). The use of multiple-parameter zones was best in non rain-on-snow conditions where snowmelt was primarily driven by differences in solar radiation.

A modeling effort conducted in the Duwamish Estuary and Elliott Bay in King County, Wash. which used the 3-dimensional Environmental Fluid Dynamics Computer Code for a human and aquatic risk assessment compared potential exposure to humans, plants and animals from CSO pollutants and other sources (Schock et al., 1998). A model that described the spatial structure of hydraulic conductivity was developed using stochastic techniques and was then incorporated in the Green-Ampt and Mein-Larson infiltration models. Results showed the combined model was capable of representing the instantaneous infiltration process for spatially-variable soils under field conditions (Gupta et al., 1998). The Watershed Nutrient Transport and Transformation (NTT-Watershed) model was used to investigate the fate and transport of N in the Muddy Brook watershed in Conn. (Heng and Nikolaidis, 1998). The model captured the hydrologic and part of the N dynamics in the watershed.

**Watershed Management and TMDLs**

EPA’s Technical Support Document for Toxics (1991) provided recommendations on evaluating frequency, magnitude, and duration issues, including the use of statistical permit limit derivations and techniques for dynamic wasteload analysis (Butcher and Diamond 2001). A survey of state permitting agencies found that few of these recommendations have been put into practice. Instead, most jurisdictions continued to rely on steady-state wasteload analyses. The WERF research project (98-HHE-3) is developing an Implementation Guidance document (with software) to aid permittees in deciding whether to undertake these dynamic analyses and to aid in implementing the analyses under the existing guidance. Information technologies and watershed management approaches have enabled decision-makers to establish predictive relationships between different land-use activities and the sediment and nutrient loads discharged from the watershed (Khairy et al., 2001). These approaches then have been extended to assess the impacts of these wasteloads on the receiving aquatic systems. A case study on the simulation of Tangipahoa Watershed and Lake Ponchartrain Ecosystems was used. The Integrated Plan for the Wastewater Program (IPWP) was a public-driven effort designed to develop policies for the planning and implementation for future wastewater collection, treatment, reuse and disposal projects (Lopez-Calva 2001). The integrated systems model was developed to measure the performance of policy alternatives in relation to a set of objectives and performance measures established by stakeholders. The conceptual character of the model proved to be appropriate for this policy-planning project. Monte Carlo simulations, which account for uncertainty in model parameters, were performed for a model of a 10-km stretch of the River Cam in Cambridge in Eastern England (Duchesne et al., 2001). The simulation results were used to rank wastewater treatment plant control strategies according to their impacts on river water quality. It was found that ranking was robust even with the uncertainty in the parameter values for the control strategies.

The BASINS system was developed to provide technical tools to support EPA’s regulatory water quality programs, in particular the TMDL program (Cocca 2001). BASINS 3.0 provides a range of detail in watershed models and provides databases, data management tools, documentation, and other resources to make modeling waterbodies and watersheds easier. The three watershed models in BASINS 3.0 include the complex Hydrological Simulation Program Fortran (HSPF) model, the complex Soil and Water Assessment Tool (SWAT) model; and the simple PLOAD model. Each model has an automated GIS data extraction script. The paper by Dorn et al. (2001) reviewed BASINS-STAR (BASINS STRategy, Analysis, and Reporting system), a set of tools to assist decisions-makers identify alternative management strategies. The main engine of BASINS-STAR is a genetic algorithm-based optimization technique. BASINS-STAR forms a decision support framework for watershed management (Murray et al., 2001b). The capabilities of this framework
were demonstrated through several scenarios for the Suwanee Creek watershed in Georgia. The paper illustrated a means by which a decision-maker can determine maximum allowable level of land development in a given watershed while maintaining a target level of water quality. The effect of BMPs on land use planning was also explored.

The main concern of using continuous simulation approach is that the use of data during specific representative hydrologic period does not necessarily cover the most “critical” condition and it is very data intensive (Zhang et al., 2001). A practical, event-based Critical-Flow Storm (CFS) was developed with application in the Nitrate TMDL Development for Muddy Creek/Dry River in Virginia using BASINS/HSPF. As an alternative method for TMDL development, the CFS approach gives reasonable results and explicitly addresses the critical condition as a combination of stream flow, magnitude of storm event, and initial watershed condition. The Northeast Georgia Regional Development Center has taken a proactive stance in protecting the Alcovy River watershed (Jha et al., 2001). This project discusses the modeling portion of these larger studies. The purpose of this study was to develop a calibrated watershed water quality model in order to simulate the impact of different future scenarios. The BASINS interface to HSPF was selected as the watershed water quality model for the Alcovy River watershed. Water, sediment, phosphorus and fecal coliform were the constituents modeled. Eight future scenarios incorporating various management practices were modeled. These scenarios include the simulation of conservation subdivisions, riparian buffer ordinances, impervious surface restrictions, storm water quality controls and improved enforcement of erosion and sedimentation controls. Modeled results indicate that a combination of BMPs must be implemented in order to reduce pollutant loading to the Alcovy River.

Rockdale County, Georgia assessed its watershed in order to develop a management plan that combines water quality protection with other objectives, including expansion of water supply and wastewater treatment capacity (Clements et al., 2001). An innovative planning process linked management objectives, assessment information, predictive modeling tools, and stakeholder participation to risks. The results were effective for evaluating management options. The paper by Dymond et al. (2001) described the web-enabled integrated modeling system, including data sources, collection, analysis methods, system software and design, and issues of integrating the various component models. The integrated system contained three modeling components, namely hydrology, economics, and fish health. Earles and Jones (2001b) presented a water quality model developed for evaluating pollutant loading from development projects in the Aurora Reservoir watershed in the Denver metropolitan area, Colorado. Laing/Village Homes developed the model to evaluate pollutant loadings from the development; Aurora determined the allowable pollutant loadings to the reservoir. A linked watershed and water quality model was applied to the Little River watershed, Georgia (Moskus et al., 2001). The model was a modified version of the Generalized Watershed Loading Function (GWLF) model that had been linked to a simplified transport model based on Water Quality Analysis Simulation Program (WASP). This model was to forecast water quality under future development conditions for flow, sediment, phosphorus, bacteria, and metals. Future scenario runs showed that water quality standards likely will be violated in the future. The WERF project 97-IRM-5E modeled the trading market in Maryland under various assumptions with the results used to design and implement a statewide trading program (Bacon et al., 2001). Credits could be created and sold by POTWs, as well as nonpoint sources such as urban, agricultural, and undeveloped land. This paper presents preliminary results from the first round of several trading scenarios. Water quality modeling was conducted to examine the effects of growth in the McDowell Creek Basin on the water quality in Mountain Island Lake (Quinlan et al., 2001). The water quality modeling included both a watershed and a lake model. This study investigated the effects of effluent discharges ranging from the existing 6 mgd up to 24 mgd due to basin development. Nonpoint source loadings were estimated at each level of development and were included. Results of the modeling showed that as the treatment plant is expanded, a reduction in effluent nutrient concentrations will eventually be required to maintain acceptable water quality.

The watershed approach can be used as an integrated method for implementing Total Maximum Daily Loads (TMDLs) (Haas et al. 2000). A discussion of how this approach could be used in Massachusetts was presented. A watershed-based assessment program identified urban stormwater discharges to small streams to be one of the most significant environmental issues in the region’s long-term management plan (McCallum et al. 2000). A bacteria TMDL for the Shawsheen River in Massachusetts was described (Mockus et al. 2000). Urban stormwater was found to be the largest source of pathogens. Copper and nickel TMDLs for San Francisco Bay were integrated into the ongoing Santa Clara Basin Watershed Management Initiative with a major emphasis placed on establishing and maintaining public and industry involvement through a specially established TMDL stakeholder group (Olivieri et al. 2000). The TMDL process provided a systematic framework for dealing with long-standing water quality issues in the South Bay. The work by Jones-Lee and Lee (2000) investigated the toxicity to Ceriodaphnia dubia due to the contamination of runoff from residential use of organophosphate pesticides in several California cities. This paper provided guidance for the development of a TMDL for the pesticides and for controlling their impacts on the affected streams.
Controversy surrounds proposed revisions in access and recreation policy at central Massachusetts' Wachusett Reservoir, a crucial source of drinking water for metropolitan Boston (Steinberg and Clark 1999). Although tensions persist between Boston and the Wachusett region, area residents’ complex valuation of the reservoir as a space of utility and a place of everyday life suggests opportunities for consensual resource coalitions and initiatives. Duram and Brown (1999) present the results of a mail survey of 64 federally funded watershed initiatives in the United States. The perceived effects of participatory watershed planning include increasing awareness of watershed conditions, heightening interagency coordination, reaching consensus on resource management plans, and lending legitimacy to final plans.

Fifty-one municipalities and county and regional agencies in the Rouge River Watershed in metropolitan Detroit, Michigan were using the "watershed approach" to solve water-quality problems from CSO, stormwater, NPS and illicit discharges (Johnson et al. 1999). Latchaw and Jarrett (1999) described a watershed restoration strategy for an urban stream in Louisville, Kentucky that was damaged by a flood. The local flood management agency, the Louisville and Jefferson County Metropolitan Sewer District, chose to change its flood and environmental management practices to reduce similar problems in the future. Letey (1999) presented the results of a case study that illustrates the interaction between the political system and science on a water management issue. Irrigation projects in the western San Joaquin Valley, California led to a situation requiring subsurface drainage and disposal of the drainage water. The original plan was to discharge the drainage water in the Suisun Bay east of the San Francisco Bay, California. Severe damage to birds associated with selenium in the water led to a reevaluation of irrigation and drainage management options.

Norton (1999) outlines the Gulf of Mexico Program (GMP) that was envisioned as a multi-stakeholder endeavor to improve coordination among Federal and Gulf State agencies and to directly involve non-government organizations in the development and implementation of actions to address key environmental problems confronting the Gulf. The GMP works to identify and implement innovative and incentive-based approaches that support Gulf State and coastal community efforts to improve the quality of life for their citizens and their environment. Sneve et al. (1999) summarize a study by the Louisville and Jefferson County Metropolitan Sewer District (Kentucky) to develop and evaluate pretreatment program performance measures that were intended to lead toward a further reduction of pollution from industrial (indirect discharge) sources. The objective of this project was to develop, implement, and assess specific performance measures designed to measure the environmental impact of the pretreatment program in a selected sewershed or watershed. The State of Washington has pioneered the use of watershed analysis as a regulatory tool since 1992 (Starhan 1999). The rules and methods for conducting watershed analysis were developed by Timber/Fish/Wildlife, a cooperative of the timber industry, Indian tribes, environmental groups, and government agencies. Forested basins of about 10,000 to 50,000 acres were delineated across the state, and about 60 analyses have been completed, with another 35 in process.

A successful public outreach and stakeholder involvement campaign, together with a thorough engineering investigation and planning program, was helping the City of Edmonton, Alberta, Canada develop and obtain support for a cost-effective CSO control strategy (Barth et al. 1999). The Towards A Cleaner River (TACR) campaign was developed based on a need to inform and involve the public and interested stakeholders in the development of Edmonton’s CSO control strategy. Schroedel et al. (1999) described efforts to finance Wisconsin’s Rock River Watershed Partnership, a broad-based stakeholder group committed to addressing nutrient and other water quality management issues. Williams (1999) described the South Dade Watershed Project that analyzes the relationship between water and land use. It tries to establish consensus with stakeholders, and develops regional planning criteria that would assure a sustainable water supply and protection of species in the Everglades National park and the Biscayne Bay, while improving urban, agricultural and natural systems for south Dade County, Florida.

Australia's Landcare program was a community-based participatory program established by government to tackle the problem of land degradation. Landcare involves thousands of Australians working together in locally based groups, tackling problems of common concern. Ewing (1999) reviews how the State of Victoria has responded to these challenges and suggests what challenges remain. Concerns about stormwater pollution were relatively new in Australia, and the physical and administrative systems necessary to cope with these have not fully evolved. O’Loughlin and Robinson (1999) described the growth of these concerns and how they came to be important, dealing particularly with the Australian State of New South Wales (NSW). Stormwater management practice in NSW has developed in a somewhat haphazard manner (Robinson and O’Loughlin, 1999). The evolution of current practice was critiqued. The impact of recent government initiatives including the NSW requirement to prepare catchment based stormwater plans was reviewed and suggestions made. A more rational policy framework was proposed which may have additional advantages to the
Eckert et al. (1999) summarize a management plan for an urbanizing river in Australia. A management system, including gross pollutant traps, automatic flocculant dosing and 16 ha of lakes was designed to address many of the failings observed in similar systems. McAlister et al. (1999) summarize major scientific studies conducted in south-east Queensland that highlight the importance of stormwater runoff as a significant contributor to the degradation of the local environment that has occurred since European settlement. These studies have identified the fine sediment component of urban stormwater as a key cause to these environmental impacts. As a consequence of these studies, a ‘total catchment’ approach has been developed and applied to urban stormwater quality management in Brisbane. A 1996 amendment to New Zealand’s Local Government Act 1974 requires local authorities to complete asset management plans (Watts and Greenaway 1999). This required the identification and locating of all assets owned and operated by local authorities, condition and performance assessments, and the definition of accurately cost estimates of levels of service for all service delivery activities. It became clear in Christchurch that commonly accepted infrastructural asset management approaches threatened to undervalue or ignore assets with natural or social values. Currently over one hundred and sixty local government agencies in NSW, Australia have a legal requirement to prepare catchment-based stormwater management plans. Brown and Ball (1999) report on their efforts to gauge and evaluate responses by stormwater managers in the process of preparing these plans.

Clifforde et al. (1999) described developments that were currently taking place towards the creation of a comprehensive integrated management capability for urban wastewater systems. The principal vehicle by which these developments were taking place was a European Union (EU) funded collaborative project led by WRc and DHI together with numerous other partners. The project comprised both technological developments in terms of procedural issues, hardware and software and extensive practical testing via a series of pilot studies. Konig et al. (1999) described some results of an integrated model application in the Hovringen wastewater system in Trondheim, Norway. The model includes wastewater production, surface run-off, infiltration, transport and treatment under a joint Matlab/Simulink platform. The model also allows the effects of real time control to be simulated. The objective was to minimize pollution discharges to receiving waters and to define design loads for the extension of the treatment plant. Bazzurro et al. (1999) described a pilot project carried out in the framework of the EU Technology Validation Project. This pilot project was related to the combined urban drainage system of Genoa's historic center that consists of eight natural streams flowing in culverts under the urbanized area. The Venice, Italy study was one of the pilots of the “Integrated Wastewater Project under the EU sponsored Innovation Program (Pretnier et al. 1999). The project aims to demonstrate that an integrated approach to the planning and management of wastewater facilities was feasible and cost-effective. The project focuses on the integrated modelling of the sewer network, wastewater treatment plant and the Venice lagoon. The model will aid in optimizing the planning and management of the wastewater structures by adopting innovative monitoring and control technologies.

Musiake et al. (1999) discussed the basic concept of improving the water cycle to better support sustainable urban systems in Japan. An investigative procedure was presented that explains how to set up the project goals and how to evaluate the water cycle. Tsunoyama et al. (1999) described efforts to restore the hydrologic cycle in the Ebi River, which flows through Funabashi City in Japan. Using a physically-based distribution model, the authors studied quantitative changes in the water circulation system over time, and deduced future changes.

Sustainability. From definitions of sustainability, Rijsberman and van de Ven (1999) derived five key elements, by which sustainable development can be described. The most important differences in the approaches can be reduced to the basic attitude towards (a) people in their environment and (b) norms and values. Combining these two components led to four basic approaches to sustainability. The suitable definition of spatial scales of investigated systems was one of the most important questions within the water management (Stransky et al. 1999). The approach of transfer of global principles to local scale allowed determining major problems in areas investigated and establishing linkages to their causes. The urban water management objectives of ecological sustainability, economic efficiency and urban amenity required the adaptation of an integrated approach to water management. Lawrence et al. (1999) reviewed developments in the application of total water cycle based management approaches across Australia, Canada, United Kingdom and United States. The authors concluded that the need for a more integrated approach to urban water management was now being widely recognized, with a growing adoption of total-water cycle-based management, and substantial investment in ongoing studies and research related to its further application.

Loke et al. (1999) presented a framework that attempts to give an overview of the scientific tools used in urban storm drainage to water-quality problems. It tried to clarify the structure and terminology of current engineering methods by
using diagrams, namely the problem identification and management scheme, the decision-making process scheme and the actual methodology overview. Recent emphasis on citizen group or stakeholder involvement in a variety of urban stormwater related policy making situations has led to the need for the technical professional to become proficient in facilitating such groups. Reese (1999) described a series of related techniques, principles and a process that have been used successfully in a variety of stormwater-related policy making settings including stormwater financing credit approaches, rate making studies, master planning and program development. Langeveld and Wiggers (1999) look at urban storm drainage and urban sanitation, not as technical problems but as conceptual ones. This paper introduces a three-stage approach, first focusing on concepts of urban water systems by combining unit-flows (water and material flows). Then the concepts were classified, and an assessment of both the possibility and desirability of the selected concepts was made. The advocated approach offers opportunities for more appropriate urban water systems by proposing new concepts for urban water systems and by guiding existing urban water systems towards sustainability.

Three municipal treatment plants and stormwater runoff were designated as sources contributing to the impairment of South San Francisco Bay, California (Tucker et al. 1999). The City of San Jose, California believed that the TMDL process served as an important way to engage stakeholders in the development of regional-environmental-management strategies. Mooney et al. (1999) presented a new TMDL-modeling framework for the Delaware River to accurately represent the current condition of the river. Novotny (1999) provided direction for TMDL research. TMDL methodologies and concepts have several problems, including determination of loading capacity only for low-flow critical periods that preclude consideration of wet-weather sources in water-quality management. Research was needed to develop watershed pollutant loading and receiving-water loading-capacity models that link wet- and dry-weather-pollution loads to the probability of exceeding water-quality standards. Chen et al. (1999) presented a decision-support system (DSS) to calculate the TMDL of various pollutants for water-quality limited sections within a river basin. The DSS includes a watershed-simulation model, a database, a consensus building module, and a TMDL module that provides a worksheet for the calculations. The methodology was demonstrated with an example application in the Catawba River, Alabama.

Borst (1998) provided an outline of the U.S. EPA research direction for modeling efforts supporting the urban watershed over the next few years. The U.S. EPA released an updated version of its BASINS modeling system (Whittemore 1998). This software integrates database queries with environmental modeling and mapping and greatly reduces the time required to manually assemble and statistically summarize monitoring data from an array of spatial databases.

Wise and Palukiewicz (1997) presented a framework for implementing watershed approaches to protect water quality. Many communities were seeking to understand how future urban development could be used as a basis for developing long-term watershed management plans (Bhaduri et al., 1997). According to Pelley (1997) nearly half of the United States have adopted watershed approaches to tackle recalcitrant water-quality problems. Leland et al. (1997) reported that the future health of the Willamette River would depend on actions taken today. Bae et al. (1997) showed local environmental authorities can extend the watershed monitoring capacity through the development of a stream monitoring and stewardship program involving a partnership between community organizations. Ten watershed management projects were reviewed by the U.S. EPA (1997b) and in a separate report, successful watershed projects from State and Tribal NPS programs were also highlighted (U.S. EPA 1997c).

Kauffman and Marsh (1997) identified three classes of edge cities and assessed the impacts on stormwater runoff, groundwater contamination, and habitat fragmentation. The results indicate edge-cities may pose a significant threat of contamination to the groundwater and runoff volumes increase dramatically and water quality declines, as development displaces wetlands and creates impervious land cover. Black (1997) identified and discussed watershed functions that dominate the hydrologic environment in order to suggest a framework for understanding and managing the growing move to "restore watersheds". Such hydrological and ecological functions are considered in relation to the storm and annual hydrographs and to water quality. Sustainable urban drainage should maintain a good public health barrier, avoid local or distant pollution of the environment, minimize the utilization of natural resources (e.g., water, energy, materials), and be operable in the long term and adaptable to future requirements (Butler and Parkinson, 1997). An integrated approach was outlined containing both high- and low-technology solutions to appropriate problems but each case must be decided on its merits.

A public-private partnership approach to water-resources management was adopted in the San Pasqual Valley, San Diego, Calif. and included groundwater management, river-corridor management, and watershed management (Gagliardo, 1997) and control of fertilizers, pesticides, and livestock (Hon, 1997).
The strategies adopted by Singapore were to keep the flood situation under control despite the vast extent of new land developments that were continuously taking place (Check, 1997). A drainage-master plan and drainage-development programs were implemented over the years to maximize land use and the creation of aesthetic waterways to enhance the urban environment. The stormwater- and floodplan-management programs were outlined for Tulsa, Okla. and Maricopa County, Ariz. (Richman, 1997a).

Based on recent developments in urban-storm drainage, further advancement in drainage planning would require consideration of the catchment, drainage system, groundwater, treatment plant, and receiving waters as one entity and ensuring sustainable integrated development and ecological enhancement of urban streams and corridors (Girling and Marsalek 1997). Taylor (1997) reported a case study on a stormwater-management program for the Eastern Transportation Corridor in Orange County, Calif. to mitigate freeway and highway stormwater runoff. The management program included an new concept in water-quality assessment termed evaluation monitoring that incorporated a watershed approach to determine if real water quality beneficial-use impairment in the receiving waters was occurring. Watershed planners in Wisconsin Department of Natural Resources and in county governments applied a method to estimate chemical constituents loads in non-monitored areas based on the data from a monitored stream within the watershed (Corsi et al., 1997).

The community of Bellevue, Wash. resisted burdening itself with the exorbitant costs of stormwater-drainage systems. In 1974, Bellevue adopted a surface-drainage system originally out of a financial imperative and working cooperatively, stormwater engineers and parks planners wove a complex web of public open space and innovative stormwater management (Girling and Helphand, 1997). A multiobjective-mixed-integer-chance-constrained-optimization model was developed to determine design- and rehabilitation- management strategies for stormwater-drainage systems conditioned on the likelihood of exceeding the system’s conveyance capacity (Jacobs et al., 1997). Model objectives included the minimization of cost and probability of system failure.

Krebs and Larsen (1997) evaluated CSO problems and a series of possible measures to enhance the system performance for the development of urban drainage towards sustainability based on case studies of mature urban-drainage systems. CSO, receiving-water quality, and decreasing groundwater levels were considered. Sewerage system and centralized aerobic WWTP should not be considered as the only possible solution for wastewater disposal. Systems with source control could avoid many problems of end-of-pipe technology by respecting different qualities of wastewater and by treating them appropriately for reuse (Otterpohl et al., 1997).

The Richmond Transport Project of California, which addresses complex geologic conditions, control of surface settlement to avoid damaging adjacent residences, and an unconventional outfall design, will reduce future discharges at Baker Beach and reduce CSO into San Francisco Bay by 80% (Maiolini et al., 1997).

Interest in wet-weather impacts within watersheds is at an all-time high as evidenced by the more than 300 papers presented at Watershed '96 (Water Environ. Fed., 1996a). St. John et al. (1996) described using hydrodynamic and water-quality models to evaluate the overall impact of dry- and wet-weather loads on dissolved oxygen in receiving waters near New York City, NY. Brosseau (1996) explained how the Bay Area Stormwater Management Agencies Association in the San Francisco, CA area operates. This Association has membership from seven stormwater agencies in the area. A major motivation for watershed-based approaches is improved economic efficiency. Brewer and Clements (1996) described how organizations formed a consortium to share the cost of monitoring at the watershed scale. Another source of savings from watershed management is to remove pollutants within the watershed in the most cost-effective manner. Market-based pollutant upstream-downstream trading has emerged as a potentially valuable mechanism. Methods for discharge trading and case studies were presented by Podar et al. (1996); and Stephenson and Shabman (1996). Frederick et al. (1996) estimated the benefits of stormwater-detention systems as increased property values due to the waterfront amenity value. The results of property valuations in many areas were included. Marx et al. (1996) described how a watershed-based approach has resulted in more cost-effective CSO control in Boston, MA. Weiss and Lester (1996) outline how watershed ideas can be used to address SSO problems within The EPA’s regulatory program. Brady (1996) summarized the accomplishments of the first five years of the EPA’s watershed-protection approach. Stumpe and Hamid (1996) described how applying a watershed approach can develop more cost-effective SSO control programs. Urban stormwater is but one of many impacts in urban watersheds. Studies in Boulder, CO (Heaney et al., 1996) and in Quebec City, PQ, Canada watersheds (Vescovi and Villeneuve, 1996) illustrated the complexity of urban watersheds. This complexity may be typical for urban areas because man invariably makes significant modifications to the watershed system. Roesner et al.
Stephenson (1996) compared the water budgets of an undeveloped catchment with an urbanized catchment in Johannesburg, South Africa. The results show the expected increase in direct storm runoff and the need to import water for water supply. Nelen and Broks (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands. The three underlying environmental principles are sustainability, quality, and ecology. This area has a high groundwater table so groundwater management is an important part of the project. It is planned to incorporate water conserving hardware and divert the more polluted stormwater into the sanitary sewer and consideration is being given to a dual-water-supply system. Escartin (1996) provided an overview of how Spain has used the watershed approach since 1926 to achieve more efficient water management. Grottker and Otterpohl (1996) described and integrated neighborhood urban water system for a 100 unit development in Germany which operates as a quasi-closed system.

**Geographic-Information Systems (GIS)**

Nie et al. (2002a) connected a GIS to urban runoff and pipe flow models to make the modeling task more efficient. Connecting the GIS to the MOUSE runoff model indicated that the GIS connection made the subcatchment delineation and characteristics calculations much simpler and more accurate compared to conventional methods. The GIS urban runoff predictions were reasonably close to measured flow rates for the low flow part and the front peak discharge, but not for other flow rates later in the hydrograph. Nie et al. (2002b) applied a GIS-based hydrologic approach to incorporate buildings into urban watershed analyses and to evaluate the influence of grid cell size in distributed urban drainage modeling.

Hiramoto and Kariya (2002) presented a method to predict areas of inundation in cities even when rivers are not overflowing. The technique involves computing runoff flow paths using topography and other data in a GIS to derive the areas and depths of inundation. The technique was applied to a case study and found to provide fair predictions when compared to observed data. The model is concluded to be sufficient for production of forecast charts of inundation if human judgment and other model factors are incorporated into the analysis. Morita and Fukuda (2002) introduced a DSS for flood-control facility planning. The DSS is composed of a flood inundation prediction model and a flood damage estimation model. Analysis using the DSS yields damage reductions created by a flood-control facility. The DSS was demonstrated for a highly urbanized catchment located in the Tokyo Metropolis. Al-Sabhan et al. (2002) described a web-based hydrologic modeling system that integrates real-time rainfall data to predict runoff and display the results online using GIS-based platforms. Islam and Sado (2002) integrated NOAA Advanced Very High Resolution Radiometer (AVHRR) data with GIS data layers to develop a flood hazard map and land development priority map for Bangladesh to aid in the mitigation of future catastrophic flooding damages. Bedient et al. (2002) created a hydrologic modeling system for the Brays Bayou watershed in Houston, Texas that incorporates radar-rainfall data. The system was created for the Texas Medical Center to provide real-time predictions of flows in Brays Bayou for flood warning.

Reginato and Piechota (2002) used a GIS model based on the Simple Method to simulate the runoff and pollutant loads from the Las Vegas Valley watershed to Lake Mead. Model results indicated that nonpoint source nutrient loads were approximately 10% of the total nutrient loads to Lake Mead. The authors also highlighted several of the uncertainties associated with their modeling approach. Miller et al. (2002b) developed a landscape assessment tool using GIS that automates the parameterization of the Soil and Water Assessment Tool (SWAT) and KINematic Runoff and EROSion (KINEROS) hydrologic models. The tool was tested by simulating runoff and sediment yield for the Cannonsville and San Pedro watersheds. Moglen and Beighley (2002) presented a GIS-based method to derive spatially explicit time series of land use change and then a method based on TR-55 to predict peak discharges. Results from application of the technique can be used to produce graphical displays of the temporal and spatial distribution of peak discharge for a watershed. Pandit et al. (2002) used the Continuous Annual Load Simulation (CALSIM) model to predict the annual total suspended solids, total nitrogen, and total phosphorus loads under wet-weather conditions for the Briar Creek drainage basin in Malabar, Florida. The model predicted pollutant loading for historical, current, and future conditions and will be used to develop a wet-weather flow control plan to reduce annual stormwater pollutant discharges to historical levels. Lenz (2002) described the development of a comprehensive water quality management plan for Central Park in New York City consisting of a series of structural and non-structural BMPs. The BMP plan is being evaluated with an integrated modeling system composed of GIS, SWMM, and WASP. Chong et al. (2002) provided an overview of the results of applying a Geographical Information System (GIS) and Global Position System (GPS) application to the management of sanitary sewer infrastructure at the Environmental Management Flight of Nellis Air Force Base (NAFB) north of the City of Las Vegas, Nevada. The desired program implemented for this assessment project would be required to be user-friendly, upgradeable with the changing computer technologies, and be capable of managing massive amounts of
information and this study highlighted issues and methods associated with the system.

The collection and management of data is vital to the urban drainage planning process. Shamsi (2002) reviewed the application of GIS for wet weather flow management tasks including thematic mapping of system elements, facilities management, work order management, and management of data from TV inspection of sewers. van Luijtelaar and Baars (2002) introduced a wastewater planning system being developed as a planning tool in a GIS. The tool will connect important digital information for use in managing the urban watershed. Garrett (2002) described a GIS application to handle cost-effectively and efficiently SSO reporting and MOM requirements. Heltzel et al. (2002) collected sewer network data and created a GIS data layer of the system for the Allen County Sanitary Engineering Department. The GIS data served as the means to conduct a condition assessment process and to organize the resulting data. Ohlemutz et al. (2002) developed a set of WWW-based GIS tools that provides access for the Vallejo Sanitation and Flood Control District’s staff to engineering drawings, GIS data, and maintenance management information for their CMOM compliance efforts. Trypust et al. (2002) described the use of relational database management systems and GIS for managing the assets of the District of Columbia Water and Sewer Authority’s PotomacInterceptor. Rappaport and Loper (2002) described the GIS-based hydrologic modeling management system used by the City of Clearwater, Florida for the Stevenson Creek watershed. The system is linked with the AdICPR hydraulic model through a graphical user interface that allows the user to access engineering data in the form of GIS layers and to visualize input and output data. Wride et al. (2002) presented the use of GIS by the Metropolitan Sewer District of Greater Cincinnati staff to extract useful information from hydraulic model results of their system’s performance.

A proactive approach to sewer system management involves the rehabilitation of the correct sewer at the correct time by using the correct rehabilitation technique at a minimum total cost (Sægrov and Schilling, 2002). To enable the pro-active approach, Sægrov and Schilling (2002) are developing a rational framework for sewer network rehabilitation. Computer Aided Rehabilitation of Sewers and Storm water networks (CARE-S) is aimed to improve the structural and functional reliability of the wastewater networks (risk of in- and exfiltration, collapse and blockage due to pipe deterioration, hydraulic overloading resulting in flooding and/or receiving water pollution). Kathula and McKim (2002) presented the preliminary developments of field-tested sewer-deterioration prediction models. Models based on survey responses of municipal infrastructure management experts have been developed for five common degradation states: cracks, open joints, displaced joints, corrosion, and deformation for both clay and concrete sewers.

The residual inflow to combined sewers must be quantified it affects the CSO activation frequency and thus the degree of roof drainage separation that must be undertaken to eliminate CSOs (Ho et al., 2001a). Hydrologic models have employed coefficients to represent the directly connected impervious area (DCIA), with the coefficients being proportional to the total amount of impervious area in the region. Better estimation of the DCIA requires sufficient geographic information and field data. A GIS application was developed to automate the process of calculating drainage utility apportionment percentages (Hughes et al., 2001). The application used the rational formula to estimate stormwater runoff. The application was applied to the Twelve Towns Drainage District (Oakland County, Michigan) 2000 Apportionment for Improvements to their combined sewer overflow retention treatment facility.

The application of HEC-HMS, HEC-RAS and HEC-GeoRas, coupled with GIS and NEXRAD radar, efficiently analyzed proposed alternatives to previous Army Corps of Engineers’ plans including voluntary floodplain property buyouts and various, smaller-scale channelization schemes in Clear Creek (Benavides et al., 2001). Applying the latest HEC tools, NEXRAD and GIS to test the viability and effectiveness of specific flood control alternatives provided acceptable results. An ArcView GIS interface was created to view and facilitate the development of EPA’s SWMM RUNOFF and EXTRAN models (Heineman 2001). The interface contained Avenue scripts that allowed the user to visualize a SWMM model in conjunction with existing GIS data. The scripts permitted viewing of model input and output summary data within ArcView, but could not substitute for existing SWMM-commercial software interfaces, since they do not permit viewing of conduit profiles, dynamic display of results, or editing of input data. The EPA SWMM model was a major tool of the stormwater management master plan for Hillsborough County, Florida (Ho et al., 2001b). Hillsborough County coupled the SWMM model with a county-wide GIS model. Hussein (2001) reviewed the MODFLOW Hydrologic Modeling System (MODFLOW-HMS), a physically based model capable of simulating the land phase of the hydrologic cycle including overland and channel flow on the surface, variably saturated flow in the subsurface, as well as transport during flow in both systems. GIS utilities were developed to estimate model parameters. The paper discussed the algorithms used to process these data and estimate the spatial and temporal variation in parameters over the finite-difference mesh, using a Mad River, Ohio study as a case study. Johnson County, Kansas embarked on an aggressive program to complete stormwater master plans and new floodplain delineations county-wide (Koch et al., 2001). The primary goals included (1)
developing new hydrologic and hydraulic models for both existing and ultimate development conditions; (2) updating the existing FEMA floodplain boundaries for existing development conditions; (3) providing local communities with a floodplain management tool; (4) defining flood-prone areas; (5) developing sound engineering and bio-engineering solutions to alleviate identified problem areas; and (6) developing GIS-based stormwater data for ongoing asset management purposes. HEC-1 was used for hydrologic analyses, and HEC-RAS for hydraulic analyses. GIS techniques were used to automate the process of model development.

Two of the most data-intensive programs in use include computerized maintenance management systems (CMMS) and GIS (Ratliff and Schmitz 2001). The integration of these systems would result in greater efficiency of resources, improved data collection processes, and reduced data redundancy and data maintenance requirements. The paper discussed the major phases of a project that included asset inventory and a multi-year condition assessment program for sanitary sewers and storm drains. This paper presented lessons learned from the project and highlighted recommendations for the successful integration of inventory and condition data into CMMS and GIS. Xu et al. (2001) reported on the integration of a physically-based distributed model with a GIS in watershed-based water resources management. The integration facilitated the examination of a wider range of alternatives than could be done using conventional methods, and provided a ‘living’ management tool that could be modified and updated if the watershed condition changed. With the increasing availability of digital and remotely sensed data such as land use, soil texture, and digital elevation models (DEMs), GIS has become indispensable in preprocessing data sets for watershed hydrologic modeling (Yu et al., 2001c). The transfer of inputs and outputs between the model and GIS can be greatly simplified by incorporating the model itself into the GIS environment. The authors incorporated a simple hydrologic model that used the curve number method of rainfall-runoff partitioning, a groundwater baseflow routine, and the Muskingum flow routing procedure, into the GIS model. Then the model was used to simulate the hydrologic response of the Upper West Branch of the Susquehanna to two different storms. The simulated hydrographs compared well with the observed hydrographs at the basin outlet.

Chester County, Pennsylvania municipalities have been working with Green Valleys Association to develop a “Sustainable Watershed Management Program” (Cahill et al., 2001). The heart of this program is a “Water Balance Model” that is interactively linked to a detailed GIS model. Municipalities can determine if the sustainable watershed goals are attainable or if changes are needed in municipal regulations. The visual component of the GIS allows the planners and municipal officials to quickly “see” the areas of concern, as well as the effects of regulatory changes. A comprehensive watershed approach to sewer separation planning was developed by the City of Atlanta, Georgia (Smith et al., 2001b). The holistic approach considered future land use and urban development within the combined sewer area basins, and determined the additional sewer conveyance capacity needed to accommodate the City’s future growth. The GIS-based tool will provide Atlanta with the ability to store and analyze data related to existing and proposed land uses, transportation improvements, storm water detention and other water quality enhancement projects. Due to the pending SSO Rule and CMOM requirements, the City of Phoenix (COP) needed to manage the large amount of data generated by the required studies (Malone et al., 2001). The COP used the Water Department’s GIS database as the format. Direct electronic collection of data and a “hands-off” data transfer and collection of data into the COP’s GIS was established.

A GIS model was developed for the Bushkill Creek in eastern Pennsylvania watershed to address the needs of various constituencies (Ruggles et al., 2001). This paper described the development of the GIS that supports the needs of each group having an interest in the Bushkill Creek watershed and provided examples of the information currently available. The application of GIS technology to the field of urban storm-water modeling was reviewed by Sample et al. (2001b), and an application in urban stormwater management at a neighborhood scale was presented. Using economic analysis to compare the cost of controls, including the total cost for land intensive controls, the optimal mix of BMPs was found. The paper by Shamsi and Cigana (2001) demonstrated the reduction of wet weather overflows by conducting TV inspection of sewers using multimedia computer technology and GIS, and using the information to improve the maintenance of sewer systems. The paper proposed a four-step method for implementing a GIS-based TV inspection program.

Shamsi (2001) showed how digital elevation models (DEM) can be used to develop hydrologic models using the off-the-shelf GIS software. The chapter showed how to automatically delineate watershed subbasins and streams using DEM. A case study was presented that compared the DEM results with the conventional manual delineation approach. The work described by Sibiga et al. (2001) attempted to quantify pollutant loading sources as a function of land use within the Cazenovia Creek sub-basin of the Upper Buffalo River watershed by applying a GIS-based Watershed Loading Model (WLM). The model was also used to evaluate reduction options for meeting water quality criteria in the Cazenovia Creek. A program developed within Arc-Info GIS was used to identify storm characteristics from a set of rainfall gages (Tsanis and Gad 2001). Three different interpolation techniques (spline, inverse distance weighted, and kriging) were used to
visualize the spatial distribution of rainfall using an example in the Hamilton-Wentworth Region in Ontario, Canada. Supported by GIS, snowmelt runoff simulation models have been built for the Qushenan basin in the west of China (Wang and Li 2001). Digital Terrain Factors (DTF) were employed to divide the basin. The results showed that this approach was significant and practical.

Models and decision-support systems are incorporating GIS. The EPA recently released a package called BASINS that includes a CD for each of the EPA regions (Lahlou et al., 1996). BASINS provides links to nonpoint models including HSPF and QUAL2E using ArcView. An American Water Resources Association (AWRA) conference proceedings contain several useful articles on evaluating urban-stormwater-management problems with GIS techniques (Hallam et al., 1996). Shamsi and Fletcher (1996) described how ArcView can be used for a variety of GIS-related linkages to urban-stormwater models and data management including AM/FM systems. Haubner and Joeres (1996) described using GIS as a preprocessor for the Source Loading and Management Model (SLAMM) to estimate pollutant loads in urban areas including a case study of Plymouth, MN.

Automated Mapping/Facilities Management, and geographical information system (AM/FM/GIS) applications for stormwater systems were reviewed by Shamsi and Fletcher (2000). Popular AM/FM/GIS software was reviewed and six case studies were presented of applications for urban stormwater systems. Traditional hydrologic models have focused on peak discharges and NPS pollution from high-magnitude storms, but were usually of limited use in assessing the long-term impacts of land-use change (Bhaduri et al. 2000). A long-term hydrologic impact assessment model was developed using the curve number (CN) method linked to a GIS for convenient generation and management of model input and output. The City of Greensboro, NC has developed a Municipal Stormwater and Watershed Management Program to prioritize infrastructure maintenance, assist with stormwater permitting, track water quality data, enhance floodplain management, and facilitate stormwater management master planning (Bryant et al. 2000). Due to the flexibility of GIS tools and databases, the program could be expanded to include water supply system optimization, sanitary sewer system inventory and modeling, and advanced water quality modeling to support TMDL programs. A successful approach was used by the Sanitary District of Decatur, IL to develop a flexible and expandable information management platform (Kuchy et al. 2000). The platform was used to integrate GIS and database applications, a collection system hydraulic model, and a graphical user interface built specifically to satisfy end-user needs. A macro urban inundation model was created for Yokohama City, Japan to support benefit-cost analyses of flood control projects (Nakata et al. 2000). While the accuracy of the macro model (250 meter grid size) did not produce highly accurate results, the solution speed has made it an effective planning and decision-screening tool. The City of Livonia, Michigan used GIS technology to enhance the implementation of its illicit discharge elimination program (Rohrer and Beckley 2000). As a result of the GIS integration, record keeping was improved, problem areas were identified earlier, and joint efforts with surrounding communities were simplified. A site in Novi-Sad, Yugoslavia was modeled using a GIS system and the results were used to control flows through the drainage system by improving predictions of where various flow reduction techniques would work best (Makropoulos et al. 2000).

A GIS-based system designed to manage both sewer maintenance and I/I reduction programs was developed to integrate a wide range of overlapping data types for these two activities (Shaffer and Greiner 2000). The system included inventory, complaints, and reporting components of the collection system. Methods for differentiating between agricultural and urban/suburban sources of water quality impairment were of interest in New England, where farms have been generally located in “mixed-use” land-use areas (Sturdevant Rees and Long 2000). This study utilized source-specific indicator monitoring techniques and a grid-based, distributed hydrologic model, incorporating them into a single GIS-based watershed management model. A spatially variable rainfall model for a small-urbanized catchment based on records stored in a time series database was developed in Australia (Umakhanthan and Ball 2000). From the spatial patterns of rainfall, it was possible to develop individual hyetographs for each of the 42 subcatchments within this catchment. The City of Columbus used an integrated GIS/hydraulic model to address SSOs and flooding (Wolff et al. 2000). Project goals included reduction of infiltration, reduction of basement and surface flooding and improved system operations and preventative maintenance. The methods and advantages of using a GIS to plan a future sanitary sewer expansion to minimize the likelihood of SSOs was presented by Young (2000). Future flows were projected for this study based on the number of proposed new homes with existing flows being added as a known quantity.

The integration of GIS and watershed modeling was moving hydrologic and hydraulic analysis to a new dimension (Preusch and Rezakhani, 1999). BASINS--Better Assessment Science Integrating Point and Non-point Sources, a GIS-based tool developed and released by the EPA, provided a convenient interactive framework for watershed management (Parandekar and Ranjithan, 1999). Walker et al. (1999) reported the integration of the EPA SWMM runoff model and
ESRI's ArcView GIS for utilization by the City of Phoenix, Arizona for decision support concerning land-use changes and pollutant loading.

The GIS Weasel, developed by the US Geological Survey, was a graphical user interface developed to aid hydrologists and other physical process modelers in the delineation, characterization, and parameterization of an area of interest, drainage nets, and modeling response units for distributed and lumped parameter models (Kenner and Love, 1999).

Fankhauser (1999) presented an automatic determination method of imperviousness from aerial photographs. The color infrared aerial photographs and orthophotos used have a ground resolution of 25 to 75 cm. A maximum likelihood classification algorithm was applied to assign each pixel to a surface category. Classification results were then overlaid with the subcatchments to determine the imperviousness of each subcatchment. Classification and overlay were carried out with the raster-based GIS IDRISI. The accuracy of the estimated imperviousness for the entire catchment areas was within 10%. Anderson (1999) described how hydraulic modeling, financial reporting and GIS have been integrated into a drainage management system in the city of Victoria in Australia. Butcher (1999) described a semi-lumped, GIS-based, transition matrix approach to estimate land use that was consistent with the level of complexity achievable in most watershed models. Several recent reservoir water supply projection studies were used to demonstrate a general framework for simulating changes in land use and resulting impacts on water quality. Butt et al. (1999) described a unified database for 14 Lake Tahoe Basin (Nevada) streams that included an inventory of riparian vegetation and stream morphology, using stream classification and riparian vegetation cover data sets. The authors provided detail on data collection and explain the development of the resultant database.

Calomino et al. (1999) described using GIS for large urban areas based on all the information needed for urban storm-water modeling. The GIS has been used together with a diffused rainfall-runoff model, MOUSE, to simulate a number of experimental events. Herath et al. (1999) presented a framework for rapid estimation of urban flood damage. The economic damage estimate was based on the property distribution within the inundated area, inundation depth and stage-damage functions. The stage-damage functions were derived from past flood data while the property distribution was represented in a detailed GIS. The method was applied to a recent flood in Chiba prefecture, Japan, and estimations and compared well with post damage assessments. Hijioka et al. (1999) described the use in Japan of distributed simulation for sewer systems to reduce inundation and water pollution events caused by CSO. An integrated system was developed to solve the problems of data-conversion from the existing sewer ledger data and the land use data. The values were generated using the detailed land use mesh database (10 x 10-m). The comparison of the simulation results with the existing rainfall data showed very good agreement. Preau and Ahmad (1999) described the components of a collection system model developed by the Sewerage and Water Board of New Orleans, Louisiana as part of a multi-year sewer system evaluation and rehabilitation program. The authors demonstrated how the utilization of a GIS in collecting and storing the data in a single location eased the model building and calibration process. Sieker et al. (1999) used GIS to process data related to the applicability of on-site, decentralized stormwater management.

Zech and Escarmelle (1999) described how distributed hydrologic models were promising but their development depends on the availability of high-resolution data able to represent urban features. Public databases from satellite imaging were not yet adequate. The authors investigated the possibility of using other kinds of databases designed more specifically for cartography. The advantages and inconveniences of such an approach were pointed out, based on two actual examples. According to Nelson et al. (1999), the Watershed Modeling System (WMS) was a comprehensive computer software application for watershed characterization and rainfall-runoff modeling in a graphical user interface environment. Through several GIS operations and tight integration with GIS databases, WMS enabled hydrologists and water resource engineers to perform rainfall-runoff modeling more efficiently than conventional modeling methods.

Difference in impervious cover estimates between land use/population density and digital vector land-based methods were as much as 55% for a single sub-sewershed (Angell et al., 1998). However, the difference in impervious cover estimates produced only minor differences in model estimates of sewershed hydrologic response. Bishop et al. (1998) evaluated maps of runoff with a 5-km and 10-km resolution from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) and found less interpolation errors in the 5-km resolution. Although geographic information system (GIS) allows sophisticated visualizations for modeling NPS pollution, this should never be allowed to disguise the legitimacy or overemphasize the certainty of model results (Loague et al., 1998).

Physical parameters for a digital elevation model (DEM) generated from satellite imagery for the Cumberland Pond Dam, in Cumberland County, N.J. varied less than one percent from measured (Hourani, 1998). Using spline surfaces within a
GIS, Ball and Lok (1998) produced robust and accurate estimates of rainfall and enabled real-time estimation of spatially distributed patterns. GIS enabled estimation of alternative hyetographs for different locations within the catchment. Kull and Feldman (1998) discuss the unit hydrograph method, as well as the incorporation of spatially distributed patterns and travel times, using radar data and GIS. The Sanitation District of Northern Kentucky developed a sophisticated implementation and response system based on GIS data to deal with wet-weather pollution (Martin et al., 1998).

Fort Worth, Tex. implemented a low budget GIS to evaluate field data and to develop recommendations for I/I and structural rehabilitation for a study area of approximately 130 km (81 mi) of the city’s sanitary sewer collection system (Hegwald et al., 1998). Moeller et al. (1998) reviewed the application of a Desktop GIS to the East Baton Rouge City/Parish (La.) Sanitary Sewer Overflow Corrective Action Plan. The key functionality of the GIS was in the areas of overlay analysis and network tracing. The effects of various types of NPS pollution on the degradation of surface and groundwater within the state of Pa. was assessed (Evans and Nizeyimana, 1998). Annual loads for N and P were computed for each watershed by NPS category, including on-lot septic systems, agricultural runoff, non-agricultural fertilization, urban runoff, and atmospheric deposition. Greensboro, N.C. instituted a comprehensive stormwater infrastructure and conveyance system inventory project to be used as a citywide preventive maintenance program in addition to stormwater and urban watershed modeling applications (Bryant et al., 1998). GIS tools were applied to the estimation and prediction of stormwater flows impacting a steel plant construction site. Data layers included USGS digital and scanned image maps, SCS soils maps and engineering drawings for the site (Lieberman et al., 1998).

In an effort to quantify the many flooding problems of the Norfolk Naval Base in Norfolk, Va., the existing storm drainage network was surveyed and inventoried, hydrologic model parameters were generated using GIS, and the Extraneous Block of SWMM was used. Fifty projects based on this work are planned over the next 10 to 20 years and should solve 90% of the flooding problem (Small et al., 1998). The HSPF model is being integrated with ArcView to facilitate hydrologic simulation with respect to water quality, urban storm runoff and flood damage modeling for the Dardenne Creek Watershed in Mo. (Bamett and Fulcher, 1998). The Marine Corps Recruit Depot (MCRD) in Parris Island, S.C. implemented an automated mapping and facility maintenance management program designed to create physical inspection and inventory databases of the sewer infrastructure and update the sewer system AutoCAD map (automapping) (Lynn, 1998). The program consisted of a link between ArcView 3.0 which views AutoCAD map and CASS WORKS (facility maintenance management program). The city of L.A., Calif. used GIS to prepare and analyze data for water quality to facilitate the city’s NPDES stormwater permit (Tam and Murillo, 1998). The system predicts water quality throughout the city and tracks identified polluters and violations.

According to Denes et al. (1997), an Arc/Info GIS package was used to conduct a cost-benefit evaluation study for the environmental restoration of the Passaic River adjacent to Newark, N.J. Yoon and Padmanabhan (1997) evaluated NPS pollution control for the upper Sand Hill River in eastern Minnesota by using a framework of a distributed-parameter-hydrologic model coupled with GIS and a relational-database-management system.

GIS was interfaced with a geomorphic-based-hydrologic and sediment-transport model to simulate six years of runoff and sediment data for a watershed in western Puerto Rico. The GIS/model interface is capable of modeling runoff and sediment yield over large spatial scales and is accomplished on an interactive basis in order to allow the user to have some decision-making ability (Mashrqui et al., 1997). Hromadka and Yen (1997) coupled a stormwater-pollutant estimation analog to a flood-control-master plan linked to a GIS capability. The GIS functions developed land use versus area tabulations that readily input into pollutant-loading equations. A GIS based-NPS-source-simulation model was developed to simulate the hydrologic and NPS processes for the Fall Creek Watershed of New York and produced a daily-time series of estimated NPS-pollutant loadings of N and P into the Cayuga Lake (Dikshit and Loucks, 1996-1997).

An empirical-urban-stormwater runoff model, in conjunction with a GIS, was implemented in Santa Monica Bay of California in order to help identify catchments with the largest pollutant contributions. Single-family land use was responsible for contributing the highest amount of pollution with the highest concentrations in ten out of the 11 water-quality parameters tested (Wong et al., 1997). Based on GIS analysis, increased preventive maintenance and rehabilitation of deteriorated sewers are two of the important elements in a program that San Diego, Calif. implemented in order to reduce SSO (Giguere et al., 1997).

A decision-support and educational-software system, WATERSHEDSS (Water, Soil, and Hydro-Environmental Decision Support System) defined water-quality problems and selected appropriate control measures. The program provided management/land-treatment decisions, assessed NPS pollution in watersheds, and used a GIS to model land-treatment
effects on water quality (Osmond et al., 1997). The use of the AGNPS or other ad-hoc interfaces between a distributed model and a GIS is a non-traditional method of watershed-water-quality modeling. These efficient interactive-modeling-environment systems have significantly reduced the task of watershed analysis through the use of coupled GIS databases and distributed models (Liao and Tim, 1997).

Haubner and Joeres (1997) applied a GIS to provide input parameters to the Source Loading and Management Model (SLAMM), an empirical urban-stormwater-quality model, for a small urban watershed located in Plymouth, Minn. The results demonstrated that the use of GIS in stormwater management could allow even small communities to reap the benefits of stormwater-quality modeling. Emrani (1997) addressed the integration of predictive modeling tools into a GIS which will serve as a decision-support tool to aid the development of improved maintenance plans associated with failure of storm drainage, water, and wastewater systems. Corwin et al. (1997) reviewed the modeling of NPS pollutants utilizing GIS as the environmental modeling tool.

**Regulatory Policies and Financial Aspects**

**Policy**

Agbodo et al. (2002a) reviewed the upcoming U.S. EPA CMOM regulations on SSOs. The paper highlighted the integrated watershed modeling approach for overall control, as opposed to the isolated capital improvement projects that address site-specific SSOs. Blackwell et al. (2002) presented the required elements for a system evaluation and capacity assurance plan, as required under the draft SSO regulations, if peak flow conditions contribute to an SSO discharge or to noncompliance at a treatment plant. The program elements include methods to determine the current capacity and the impacts of growth and new flows, confirming wet and dry weather flows in the system and a means of tracking existing legal obligations to accept new flows. Sullivan and Dwyer (2002) reported on the major findings of the EPA’s CSO report to Congress. The objective of the report was to describe the nature and extent of activities in EPA and in the states to implement and enforce the CSO control policy. The major findings included that progress has been made in implementing CSO controls; communities have made substantial progress and are seeing the benefits in public health and water quality; the CSO policy provides a sound approach to assess and implement cost-effective CSO controls; and the CSO Control Policy fosters and expects significant involvement of the public and authorities in the process.

Jensen et al. (2002) reviewed the need for applying appropriate criteria for contact recreation, especially in streams negatively affected by wet-weather flow. The paper presented two methods for reducing these types of possibly inappropriate listings. One would be to assess physical suitability in the field and only screen data collected when the stream is suitable for the use. The other, that does not require field suitability determination, would be to exclude some high flow data where the use is not likely to be supported, based on watershed size and flow distribution.

After over 20 years of progress, many rivers, lakes and streams still failed to meet water quality standards (Kwan 2001). Studies and monitoring data have shown that stormwater runoff was a major source of water quality impairment. Currently, five regional states have reported stormwater runoff as a major cause of water quality impairment. An effective, integrated and coordinated storm water enforcement strategy will need to be established in full partnership with the eight Region 4 states.

EPA has been completing a series of federal initiatives to address wet weather discharges due to CSOs and SSOs (Hall et al., 2001a). As a result, communities nationwide will need sewer system/treatment plant improvements to address these wet weather discharge issues. Little attention has been paid thus far to a series of subtle changes in EPA’s implementation of its existing bypass regulations and secondary treatment requirements for controllable CSO and SSO flows. Reducing wet weather discharges is a core activity of EPA’s Office of Wastewater Management (Cook 2001). The office’s programs include combined sewer overflows, sanitary sewer overflows, storm water, and animal feeding operations. Several current regulatory initiatives have been designed to improve water quality by reducing the environmental impacts of wet weather events. Bell and Powell (2001) described the pending SSO regulations, where there are three standard permit conditions for sanitary sewer collection system owners: capacity, management operation and maintenance (CMOM); prohibition on SSOs; and reporting, record keeping and public notification. The paper focused on the CMOM aspect of the permit conditions. Although the SSO Rule is not currently effective, Sowatzka et al. (2001) advocated using the draft Rule to provide system owners and operators guidance on EPA’s expectations for systems, including satellite facilities, for their (CMOM) program.

Centilla and Slack (2001) reported on the outreach efforts of the EPA. EPA has been working with stakeholders during
Augustenborg and Duke (2001) evaluated the effectiveness of current regulations for stormwater pollutant control from construction activities. The public sector is responsible for stormwater drainage from the development area. The private sector is responsible for the main part of RSIT for new town creation and urban renewal. The new system consisted of two elements: RSIT components based on Public-Private Partnership (PPP) and a stormwater drainage system. The private sector is responsible for the main part of RSIT, and the public sector is responsible for the stormwater drainage from the development area.

The Department of Natural Resources in Queensland, Australia, conducted the Queensland Water Recycling Strategy (QWRS) to determine future Government directions in water recycling (Gibson and Apostolidis 2001). This strategy considered the beneficial use of all waste streams such as domestic sewage, industrial and agricultural wastes, as well as urban stormwater. The Urban Development Corporation (UDC) in Japan developed a new system, a “Rainwater Recycle Sewer System” (Matsushita et al., 2001). This system is supported by “Rainwater Storage and Infiltration Technology (RSIT)” for new town creation and urban renewal. The new system consisted of two elements: RSIT components based on Public-Private Partnership (PPP) and a stormwater drainage system. The private sector is responsible for the main part of RSIT, and the public sector is responsible for the stormwater drainage from the development area.

Clark et al. (2001a) combined hydrologic models of flood control and biotic models of ecologic risk with economic models of willingness-to-pay and psychological models of risk processing and planned behavior in order to evaluate these two alternative policy objectives. The findings reveal that flood risk exposure does influence the willingness-to-pay of local residents for a flood control project. Other important determinants include demographic factors, such as income, and attitudinal measures of the respondent.

Gwinnett County, Georgia, recently revised their stormwater regulations in order to improve the water quality in the county’s receiving streams and to meet the designated uses of the waters for fishing and drinking water supply (Chastant 2001). To meet that goal, a Watershed Protection Plan was developed, with the six major components being public education/participation, pollution prevention, development regulation, planning, engineering and construction, and maintenance. The current management strategy has been based on four key storm events: protection from major flooding events, overbank flooding bank protection from moderate events, channel bank protection for the 1-year storm, and water quality treatment for rainfall events of 1.2 inches and smaller. Atlanta’s Clean Water Initiative was developed in order to coordinate water resource management for the Atlanta region and to generate the political momentum necessary for implementation (Green 2001). The task force recommended the creation of a “Metro Atlanta Water Planning District,” which would be charged with developing watershed protection, wastewater, water supply and conservation plans. These recommendations and the District were enacted into law in 2001. In 1999, the City of Atlanta completed negotiations with the EPA and the Georgia Environmental Protection Division (EPD). The consent decree and an amendment required implementation of management, operation and maintenance (MOM) plans for CSO treatment facilities, Water Reclamation Centers (WRCs) and gravity wastewater collection and transmission systems (Griffin and Sukenik 2001). The MOM plans for the wastewater collection and transmission systems included emergency response plans; long- and short-term operation plans; maintenance plans; pump station evaluations; grease management plans; sewer mapping plans; safety and general training plans; and a short-term capacity certification plan. Hamid et al. (2001) presented an overview of Atlanta’s Wastewater Systems Improvement Program. Three specific regulatory requirements drove this program: Senate Bill 500 enforcing phosphorus level compliance at WRCs and CSO control facilities by December 2000; the CSO Consent Decree requiring completion of the long-term plan by 2007; and a second Consent Decree requiring WRCs, pumping stations and sewer improvements by 2014. The City’s preferred option for the CSO plan included consolidated storage/conveyance tunnels, two CSO treatment facilities, and sewer separation in selected areas costing about $1 billion. The total capital cost of the program was estimated between $2.5 and 3 billion with a 14-year completion schedule. In November 1997, a Federal District judge ruled that the City of Atlanta’s CSO discharges violated water quality standards for metals and fecal coliform. In addition, the Georgia EPD required compliance with water quality standards at the point of discharge for CSO facilities with no allowance for dilution (Richards and Kreutzberger 2001). Data is being collected in order to characterize water quality related to metals toxicity.
Clean Water Act has been shown to impact both point and nonpoint sources of pollution. Programs related to TMDLs by various jurisdictions. Implementation of the Total Maximum Daily Load (TMDL) provisions of Section 303(d) of the countries, as well as states and localities within the US and offered discussions of some of the hardware systems required have stipulated a specific concentration allowable. Mohr (2000) presented the regulations governing effluents in many or from one country to another. Some countries have mandated hardware solutions to the effluent problem, while others hydrocarbons allowed in industrial and stormwater effluents has been found to vary greatly from one locality to another other organizations are taking to support scientifically sound and regulatory compliant WQSRRs. The amount of the water quality standards review and revision (WQSRR) process, and included a summary of the steps that EPA and water quality standards for CSO impact ed waters, provided an overview of the obstacles to undertaking and completing the year 2000 saw several new stormwater regulations issued nationally, and a variety of guidance documents published in support of new and existing regulations. USEPA publis hed the final Storm Water Phase II rules in December, 1999 (Anonymous 2000b), and the members of the Sanitary Sewer Overflow (SSO) Federal Advisory Subcommittee voted unanimously to support the EPA’s draft proposal for developing federal SSO regulations (Anonymous 2000a). EPA also announced plans to release a draft guidance on water quality and designated use reviews for combined sewer overflow (CSO) receiving waters in April, but not everyone was satisfied with the current guidance outline (Anonymous 2000c). Urban and agricultural wet weather sources were named as the most significant causes of impairment to our Nation’s rivers and streams. However, these “impairments” were typically assessed in reference to water quality standards developed in the context of historical efforts to control dry weather wastewater sources. Therefore, the significance of wet weather impairments and the need for costly controls was debatable. Freedman (2000) explored the issue of wet weather water quality standards for CSO impacted waters, provided an overview of the obstacles to undertaking and completing the water quality standards review and revision (WQSRR) process, and included a summary of the steps that EPA and other organizations are taking to support scientifically sound and regulatory compliant WQSRRs. The amount of hydrocarbons allowed in industrial and stormwater effluents has been found to vary greatly from one locality to another or from one country to another. Some countries have mandated hardware solutions to the effluent problem, while others have stipulated a specific concentration allowable. Mohr (2000) presented the regulations governing effluents in many countries, as well as states and localities within the US and offered discussions of some of the hardware systems required by various jurisdictions. Implementation of the Total Maximum Daily Load (TMDL) provisions of Section 303(d) of the Clean Water Act has been shown to impact both point and nonpoint sources of pollution. Programs related to TMDLs
often have reached beyond the purview of the agency responsible for the TMDL and have crossed into programs that operate under different regulations administered by other agencies. TMDLs thus will have significant cross-media and cross-programmatic impacts (Staveley and Christman 2000). The Center for Environmental Research and Service (2000) at Troy State University, Alabama published a guide to developing a storm water control program to comply with Phase II requirements.

Other regulatory issues involved local stormwater managers trying to develop stormwater management efforts that meet both local needs and regulatory requirements. As currently designed, TMDL limits are based on the assumptions that there is a direct correspondence between the total mass of waste loads and ambient water quality, and that an annual cap on total wasteload allocations (WLAs) can sufficiently maintain water quality. Based on a study of the nutrient loads and water quality in the tidal freshwater Potomac River over the period 1985-1995, Sklarew (2000) suggested that hydrology was an important factor to consider in developing adequate WLAs for metropolitan tidal rivers. Furthermore, the hydrograph could be a vital tool in designing flexible and adaptive TMDLs for such areas. The City of Portage, MI has pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The city has endeavored to define “Maximum Extent Practicable” (MEP) within the constraints of available space for treatment facilities, city budget, and community support. This approach could be used by other municipalities with existing infrastructure and limited controls that now face similar storm water regulations. The approach illustrated opportunities and benefits of storm water controls implemented beyond the minimum requirement (Breidenbach et al. 2000). In November 1999, the City of High Point, North Carolina adopted a watershed protection ordinance that initiated “Phosphorus Banking” and provided greater water quality protection than the state requirements while also accommodating planned growth. Brewer et al. (2000) documented the watershed assessment and modeling approach, the successful involvement of key stakeholders, and the innovative phosphorus banking strategy.

A major effort, the Use and Standards Attainment (USA) Project, was launched by the New York City Department of Environmental Protection in August 1999 as part of its continuing efforts to maintain and improve water quality in New York Harbor and its environs. With the active participation of major stakeholders, a watershed-based approach was used to conduct an integrated evaluation of the interdependent factors affecting receiving water uses, including storm water, combined sewer overflows (CSOs), wastewater treatment, upland uses, shoreline uses, habitats, sediment and water quality (McMillin et al. 2000). The New York City Department of Environmental Protection enacted final watershed regulations prohibiting surface discharges from wastewater treatment plants, and subsequently stopped the Kent Manor housing project in the Town of Kent, Putnam County, New York. The watershed regulations included provisions for a pilot phosphorus offset program, whereby projects within the watershed with surface discharges would be approved, provided that any increase in phosphorus loading would be offset somewhere else in the watershed. van der Heijden (2000) described the steps taken to offset expected phosphorous loadings from the Kent Manor project by reducing phosphorous discharges elsewhere in the watershed. Vlier and Sandquist (2000) highlight some lessons, guidelines, and patterns emerging from the growing field of watershed-based trading, by identifying the similarities and differences in program design and linking key elements to scientific, economic, and institutional conditions in the watershed community.

The Rouge River National Wet Weather Demonstration Project in Michigan (Rouge Project) has attempted to identify the requirements of a generic comprehensive watershed management plan to meet multiple program objectives, requirements or recommendations in a wide range of individual Federal, State, and local programs to restore and protect water resources. Cave et al. (2000) identified what the Project found to be the crucial elements of a “comprehensive watershed management plan” in order to achieve multiple program objectives, such as the reissuance of NPDES permits on a watershed basis, implementation of the water quality trading programs that are currently under development, implementation of the Section 319 non-point source program, development and implementation of Watershed Restoration Action Strategies envisioned under the Clean Water Action Plan, implementation of monitoring programs and for addressing the requirements of the TMDL program. McDonald et al. (2000a) presented the preliminary findings, conclusions, and recommendations for the development of a pollutant load trading program and the modification of the existing nutrient (nitrogen and phosphorous) and TDS TMDLs and WLAs on the Truckee River, Nevada. As a result of the TMDL process, the Truckee Meadows Water Reclamation Facility had WLAs incorporated into their NPDES permit, resulting in potential restrictions on planned growth. In order to accommodate for planned growth and to meet water quality objectives, a pollutant load trading program to develop “watershed offsets” was beginning implementation. McDonald et al. (2000b) described a multiyear project to develop revised TMDLs and a pollutant-load trading program for the Truckee River.
Additional papers examined community and political issues related to WWF control programs. Lindsey et al. (2000) explore five programs led by EPA’s Office of Water that address today’s environmental issues in wastewater management. Many of the programs are voluntary but regulatory programs continue to play a role in wastewater management. Through humor, Jones (2000) focused upon constraints that now inhibit a watershed solution to environmental, multi-media problems, and proposed potential remedies. The Tollgate Drainage District (Ingham County, Mich.) had to convince reluctant stakeholders that a sewer separation and stormwater outlet project had to be undertaken (and locally funded). After 2 years of education and outreach, the stakeholders not only accepted that a solution was needed, but approved a nontraditional approach (Lindemann 2000). Tonning (2000) reviewed what the business community was hearing about planning and linking the planning directly to a watershed approach. Lessons from management consultants were matched to startlarily similar advice from watershed experts from federal, state and private organizations. Recommendations to focus on action and avoid “paralysis by analysis” provided a refreshing perspective for those burdened with the minutiae of the often interminable planning process (Tonning 2000). It was shown that if all social and political needs of the community were not considered and addressed in a watershed protection effort, a proposed project, though technically sound and within budget, likely still would meet with significant community opposition. Halloran et al. (2000) presented one project where a front-end loaded, proactive, community oriented approach turned neighborhood opposition into enthusiasm. A new comprehensive land use plan was recently adopted to guide development of the undeveloped land area in the City of Battle Creek, Michigan. The results of this project would allow the City to gain a Certificate of Coverage under Michigan’s Voluntary General Permit for Municipal Storm Water Discharges, which has been accepted by the EPA as fulfilling the requirements of the Phase II Storm Water Regulations. As a result of performing this project, the City of Battle Creek, Michigan has learned the value of gaining stakeholder input during the watershed planning process, and has formed a Steering Committee to guide the implementation of the proposed Watershed Management Plan (Scholl et al. 2000). The decision to include the public in public works and utility projects has often been made without any ‘real’ consultation with the public or consideration of the issues that the public would be interested in. Kunz et al. (2000) discussed how the right amount and type of public involvement early in the project planning process could mean the difference between a successful project completed on time and within budget or a cancelled project after millions have been spent on design.

WWF control policy in the United States, including the ongoing implementation of EPA’s Phase II stormwater regulations, prompted a number of publications. Despite the world’s most sophisticated regulatory system, and an unprecedented level of public and private investment in wastewater infrastructure, 44% of the United State’s waterways were still unsafe for fishing and swimming, largely due to urban WWFs such as CSO and stormwater discharges. Guta (1999) discussed the challenges of identifying and managing this ubiquitous source of pollution and building sustainable cities for the future. Calamita (1999) reviewed legislation that was considered in Congress, especially the CSO Control and Partnership Act of 1999 - H.R. 828 and S. 914, and the draft Urban Wet Weather Priorities Act, both of which were intended to help create wet weather uses and standards in the United States. The paper also reviewed EPA’s efforts to comply with language added to their budget for this year that requires that they develop a guidance document to facilitate wet weather use reviews nationwide. EPA has made significant efforts to comply with this congressional mandate thereby greatly enhancing the prospects for wet weather use reviews nationwide. While the apparent direction of EPA’s Phase II stormwater regulations due to be promulgated in September 1999 appeared to encourage the use of the watershed approach, the details in the regulation do not reflect that theme.

A comparison of the directions the Phase II regulations appear to be taking and the approach of the Rouge River National Wet Weather Demonstration Project in Southeast Michigan was made and discussed by Cave et al. (1999). Murray et al. (1999) described the lessons learned in building institutional and regulatory frameworks necessary to accommodate a watershed approach to wet weather pollution management by Wayne County’s (Michigan) Rouge River National Wet Weather Demonstration Project. Also described were the consensus building strategies that were used to engage numerous stakeholders, provide them opportunities to influence decisions, and participate in the Rouge River restoration.

Hudson (1999) discussed EPA efforts to encourage the use of decentralized wastewater treatment systems by focusing on encouraging alternative technology where appropriate, promoting management systems, and coordinating its initiatives with other ongoing efforts nationwide. The EPA Long-term CSO Control Policy “Presumptive Approach” provides guidance for specific levels of control, namely, no more than four overflows on average per year or the elimination of no less than 85% of volume of the combined sewage collected in the entire system on an annual basis. The EPA believed that there was a general “equivalence” between the performance criteria that specify “percent capture” and the “number of overflows.” However, Morgan et al. (1999) demonstrated a wide variation between the storage controls developed under either of these criteria, and recommended that the municipalities should look at the site-specific nature of the CSO
problem, and develop control alternatives accordingly.

A Natural Resources Defense Council report supported EPA’s proposed rules to clean up stormwater runoff and storm sewer discharges in small cities and noted that the proposal’s cleanup strategies have been successfully employed by more than 150 urban towns. At the same time, however, some states were complaining that the EPA proposal would undermine many state-run programs already in place (Environmental Science & Technology, 1999). Until now, no legal principle has been used to ensure that equity and economics were incorporated into the TMDL adoption and allocation processes. However, Clean Water Act section 305(b) may be a viable vehicle for finally including these concepts into the TMDL process (Thorne, 1999).

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor estimators of discharging facilities. This research evaluated usefulness, flaws, and limitations of multiple forms of existing databases; then demonstrated methods to assess, combine, and correct databases to refine estimates of potentially discharging facilities in a given region (Duke et al., 1999). This research evaluated compliance with U.S. pollution prevention regulations from stormwater discharges associated with industrial activities, focusing on facilities that had failed to complete first-stage compliance requirements (“filed”) approximately 5 years after the regulations took effect (Duke and Shaver, 1999). In the City of Bergen, Norway, extensive measures against point pollution sources were implemented and to be finished before the end of year 2000 for improving the receiving water conditions. Future improvements in the receiving water quality was planned through different measures aimed at reducing stormwater-meltwater runoff which causes surface pollution washoff and CSO (Thorolfsson, 1999).

Field et al. (1998) described the U.S. EPA’s WWF management and pollution control research needs and anticipated research directions for the next five years, and covered areas of characterization and problem assessment; watershed management; toxic substance impacts; CSO, SSO, and stormwater runoff pollution control; and infrastructure improvement. A summary of Volume 1 of a two volume manual developed by the U.S. EPA’s Office of Wastewater Management and Office of Research and Development provides a process for effective decision making and long-term planning, suggested practical guidance for municipalities to best implement their stormwater management programs, and provides a watershed protection approach (Liao et al., 1998b).

Weatherbe et al. (1998) highlighted the findings and status of implementation for WWF management of the Pollution Prevention and Control Plans funded by Environment Canada’s Great Lakes 2000 Cleanup Fund and the Ontario Ministry of the Environment. American cities evolved from dense urban areas to contemporary low-density suburbs with open space. Multi-functional urban stormwater projects can be integrated into the drainage structures of cities’ civic, recreational and ecological fabrics and the redevelopment of the Stapleton International Airport in Denver, Colo. is presented as an example (Wenk, 1998).

A proposed method to assess and communicate the relative public-health risk associated with coastal recreational water use in San Diego County, Calif. is based on point-source and NPS information and will be displayed geographically (Gerheart et al., 1998). Elliott (1998) determined expected rate of illness for ocean bathers near an outfall based on temporal frequency distributions of indicator bacteria concentration coupled with a concentration-response relation. Hurt (1998) presented some methodologies used to heighten public awareness for CSO related issues using Detroit (Mich.) Water & Sewerage Long Term CSO Control Program policies as an example. The Surfrider Foundation started the Blue Water Task Force in 1990 and initiated a water testing program designed to evaluate human health risks from swimming and surfing in polluted water. The water testing program taught the activists that the problem with the beach-water quality was urban runoff and Surfrider activists stenciled signs on street gutters to educate people that all street gutters were connected directly to the beach (Labedz, 1998).

After 100 years of industrial development, the Emscher area in Ger. has been presented with the need for environmental restoration and social changes (Geiger and Becker, 1998). Special attention has been paid for the choice of the future drainage system linking source control by infiltration of stormwater with collection and treatment of polluted runoff and currently a large number of pilot projects are underway which show the need for public participation to accept new technologies. Geldof (1998) reviewed urban water management in the Neth. over the last few years and provided some suggestions to cope with emissions from sewer systems, peak discharges, high ground water levels and dehydration of soil in agricultural areas and nature reserves. The solution for urban runoff and water quality management in the Birkeland basin Sandsli, Bergen, Nor. is based on urban hydrological planning and the new blue-green concept in the

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urban stormwater management that uses the capabilities of the basin to store runoff and melt water and to reduce pollution (Thorolfsson, 1998). The goal is to manage runoff and water quality in a way that reduces environmental damage at the lowest possible cost. The Oakland Ravine Stormwater Treatment System project was developed as part of the NYC comprehensive program to reduce CSO discharges into receiving waters (Dinkle, et al., 1998). The project reduced discharges into Alley Creek in Queens, addressed stresses and disturbances identified within Oakland Ravine and Oakland Lake, i.e., erosion and lack of vegetation on the slopes of the ravine and deterioration of water quality, and created a natural park setting in an urbanized area. As the principal permittee of the new Los Angeles (L.A.) County Municipal Stormwater NPDES Permit, the L.A. County Department of Public Works, Calif. is undertaking one of the most comprehensive water quality monitoring programs of any municipal stormwater program in the country. The program features water quality monitoring of storm and dry weather flows from both mass emission and land-use specific drainage areas, an illegal connection elimination program, a critical source monitoring program, and a receiving-waters impact study (DePoto et al., 1998). Swamikannu (1998) reported on the process followed to reach agreement on the municipal stormwater and urban runoff program in L.A. County, Calif., the progress to date and imminent challenges that lie ahead.

Most industrial facilities in the L.A., Calif. area inadequately evaluated activities with the potential for stormwater pollution and most prepared incomplete plans for stormwater sampling and inspection procedures (Duke and Bausersachs, 1998). Only 35 to 40% of the metal plating facilities in the L.A. region recognized the need for first stage compliance to stormwater pollutant regulations. Preliminary results in evaluating compliance with stormwater regulations by industrial facilities in Calif. suggested that many facilities identified in broad-based databases do not need to comply because activities on site do not meet conditions specified in regulations (Duke and Shaver, 1998). Although industrial activities are identified as one source of pollutants in stormwater discharges from urban watersheds, the proportion of specific pollutants from industrial activities relative to other urban activities remains poorly understood. Doll et al. (1998) reviewed the key legal, financial, institutional, and political issues in setting up a stormwater facility.

A comparative study of variations in stormwater management approaches and regulations revealed additional commitment is needed to improve the water quality of the bay for several states in the Chesapeake Bay watershed (Sherman and Dee, 1998). The Mass. Water Resources Authority (MWRA) (Hornbrook et al., 1998b) developed a long-term plan for CSO control based on U.S. EPA’s CSO control policy using the demonstration approach. Review of the plan by the U.S. EPA and the Mass. Department of Environmental Protection indicated that the demonstration approach was not a clear-cut process, in part due to different interpretations of the CSO control policy by the parties involved. Heath et al. (1998a) presented the process followed by MWRA to document compliance with the criteria for a successful demonstration under the U.S. EPA CSO control policy. Facilities planning for controlling CSO in the greater Boston, Mass. area in accordance with a federal court schedule were finished in July, 1997. In a study comparing four midwestern stormwater ordinances and their effects on a hypothetical subdivision, Schuller et al. (1998) found that although detention storage is required virtually everywhere in the midwest, the requirements and the resulting storage basin sizes can differ greatly. A reoriented stormwater management approach (Swietlik, 1998) should continue to address undesirable chemical changes, changes in flow rates and volumes, changes in other physical characteristics such as habitat, temperature, and DO, and maintain targeted watershed balances for nutrient cycling.

The new national water policy adopted by the S. Afr. Parliament established an integrated catchment management system for ambient water quality and point and NPS of aquatic pollution (Marjanovic and Miloradov, 1998). The repercussions of this policy and a proposed method for continuous water quality assessment are considered. D’Arcy (1998) presents a review of Scottish policies dealing with stormwater management including the formation of the Scottish and Northern Ireland Forum for Environmental Research (SNIFFER), the Scottish Environmental Protection Agency (SEPA), and some homegrown Scottish BMP to deal with poor water conditions as a result of urban runoff. Lawrence (1998) outlined the national approach to stormwater management in Aust. including implementation practices by both state and local government powers.

Lee (1997) discussed issues and regulatory requirements related to the privatization of water and wastewater services in Latin America. Lyon (1997) examined privatization law as it applies to water management in Europe and in the United States and classified it into three categories: institutional, management, and product law. In addition, Corssmit and Brunsdon (1997) discussed the transition of the Fairbanks Municipal Utilities System to private ownership, including water, wastewater, electric, steam heat, and telephone utility in and around greater Fairbanks, Alaska.

The degree of compliance in the industrial sector for General National Pollution Discharge Elimination System (NPDES)
permits is not readily determined (Duke and Beswick 1997). Data for California statewide and for the Los Angeles region show about 8% — 15% of motor-vehicle transportation facilities have complied with first-stage requirements and facility-specific evaluation in one Los Angeles County watershed suggests <50% of facilities in the industry conduct industrial activities of the kind covered by regulations; others need not comply. Luppold (1997) found considerable variation in permit cost and requirements of state and federal stormwater-discharge permits for the wood-products industry and sawmills versus chromium-copper-arsenic treating facilities. The variations in monitoring requirements appeared to be the result of different priorities and varying levels of human and financial resources and the continuous evolution of federal regulations. The renewal of the deadline for the NPDES permits was discussed. Phase I and II applications were outlined with listings of facilities covered by phase I and II permits (Christou, 1997). Ford et al. (1997) demonstrated and outlined the proper completion of a NPDES application.

Small CSO communities may not be required to complete each of the formal steps outlined in the National CSO Policy. Shamsi and Scally (1997) provided insight into the small community aspects of the CSO Policy as well as identified the opportunities to take advantage of the small system considerations of the Policy. Morgan and Rowe (1997) presented how the Water Works and Sanitary Sewer Board of Montgomery, Ala. reorganized to meet the uniform operational and maintenance requirements and other provisions of the U.S. EPA’s draft SSO Policy/guidance document.

The U.S. EPA is working with farmers, state regulators, and environmental groups to craft a program to address NPS runoff from farming operations. These efforts are an attempt to comply with the expanded Clean Water Act’s (CWA) discharge permit requirement for large pollution sources (Cooney, 1997). The U.S. EPA (1997f) published a comprehensive report on the monitoring of NPS which defined and categorized NPS, described analytical and biological-monitoring techniques and provided data-analysis techniques, quality assurance and quality control. The total maximum daily load (TMDL) program is a water quality policy, released by the U.S. EPA, requiring state controls on NPS of water pollution (Environ. Sci. Technol., 1997a). The U.S. EPA and the Environmental Law Association have teamed up on a project which consists of the assessment of relevant state laws and incentives in order to help states combat NPS water pollution (Environ. Sci. Technol., 1997b). The U.S. EPA is funding 20 National Monitoring Program projects implemented to determine the most cost-effective BMP for preventing NPS pollution (Richman, 1997b).

Roesner and Rowney (1997) reviewed the stormwater-quality regulations of six major industrialized nations: the United States, Canada, the United Kingdom, Germany, Australia, and Japan. The differences among these countries reflected the culture of each individual country.

Reuse and Water Resources
The International Rainwater Catchment Systems Association was formed in 1989 and developed affordable rainwater catchment systems development guidelines to provide a common ground for the public and private sectors to solve water supply problems (Fok, 1998a and b). Mitchell et al. (1998) described the components of urban water demand in terms of quantity and quality and discussed the opportunity for using stormwater and wastewater in Aust. Górnansson (1998) proposed and reviewed stormwater projects that have aesthetic and architectural qualities for future urban environmental developments. The town of Mersing, Johor, Malaysia, identified the importance of beautification and landscaping of drains and waterways as part of the drainage and flood control plan. The landscaping of the drainage reserves and waterways will not only improve the urban drainage system and the aesthetic visual quality of the area, but will also promote the image of Mersing as a tourist destination (Chin et al., 1998a).

Anderson (1996a, 1996b) described new initiatives for reusing stormwater for urban-residential- and industrial-water-supply systems in Australia. Mitchell et al. (1996) analyzed urban-catchment drainage by using a water-budget approach to integrate storage and reuse of stormwater and treated wastewaters for two sites in suburban Melbourne, Australia. Nelen et al. (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands considering a dual-water-supply system. Storing the treated wastewater on-site during wet-weather periods can be more attractive than only using black water for reuse (Pruel, 1996). Herrmann and Hase (1996) described rainwater-utilization systems (RWUS) in Bavaria, Germany saving drinking water and reducing the roof runoff to the sewerage system.

Watershed Management
Arhontes (2002) reviewed the Collection System Outreach Program of OCSD that was developed in response to the SSO program and the CMOM program. The goals of the program have been to improve the knowledge of the assets, leverage expertise in the region, and promote improved networking among cities and collection system owners, operators and managers. Coppes (2002) reviewed the challenges of stormwater management, including the implications of NPDES for
this management. The development of economical and effective technologies was discussed with reference to new standards for stormwater products, testing and performance.

Bandy et al. (2002) presented an overview of the Hillsborough River watershed management plan. Cave et al. (2002) reviewed the Main 3-4 Subwatershed Plan in the Rouge River. The group established several long-term goals: improve water quality and restore impaired uses; remove pollution sources that threaten health; educate the public; increase recreational opportunities; enhance and preserve habitat; and reduce water volumes and velocities in the river during storms to minimize bank erosion and flooding. Turner et al. (2002) reviewed the programs implemented by the Columbus Water Works on the Chattahoochee River. Overall program findings include load generation rates and yields for various pollutants correlated to watershed impervious area and aquatic biology indices. Wieske and Penna (2002) reviewed the stormwater strategy of Laguna Beach, California. The papers reviewed the methodology that engineers have used to manage the urban runoff problems plaguing the city. Zimmerman and Thomas (2002) presented the Clayton County Watershed Management Team’s approach to watershed management plan implementation. Plan implementation relies heavily on teamwork and enhancing existing water quality programs versus creating new mechanisms to protect Clayton County waterbodies. Gassman and Lee (2002) discussed the planning needed for Broward’s Countywide Integrated Water Resource Plan, which required a regional perspective at the local level in order to meet the Everglades’ restoration goals and the county’s growing water needs. The plan has four integrated components: Natural Systems, Canal Systems, Utilities and Policies. Rose (2002) reviewed the Lake Allatoona water resource planning and source water protection activities, which required working across jurisdictional boundaries. This paper explored the various trends, policies and planning that the Lake Allatoona Preservation Authority initiated for water resource planning and source water protection within the Lake Allatoona watershed, including the development of public and private partnerships for watershed protection, a Comprehensive Watershed Management Plan that included the development of “unified” planning across jurisdictional boundaries. Hiscock (2002) presented The West Palm Beach Renaissance Project, which is an integrated water resource management plan for diverting runoff from a 375-acre urban watershed and conveying the water through a settling basin and wetlands before it becomes part of the City’s potable water supply. The Renaissance Project has been developed with the combined expertise of City staff, local engineering consultants and other governmental agencies, including the United States Environmental Protection Agency (EPA), the Army Corps of Engineers (ACOE), the Florida Department of Environmental Protection (DEP) and the South Florida Water Management District (SFWMD). Morgan and Ricketts (2002) reviewed the Alabama Clean Water Partnership. The new approach was addressing water resources on a watershed basis and addressing watershed concerns at the local level through the development of grassroots efforts and the Partnerships were created to develop inclusive public/private stakeholder committees to support community-based river basin protection and management efforts. Schrameck and Andrews (2002) reviewed the development of subwatershed pollution prevention initiatives in the Rouge River watershed. The Storm Water Pollution Prevention Initiative (SWPPI) was designed to reduce the discharge of pollutants to the maximum extent practicable; be consistent with the watershed management plan and emphasize the mitigation of undesirable impacts; include actions expected to be implemented over the term of the permit; and address specific actions to be taken by each permittee to meet the goals.

Chen (2002) presented the use of Watershed Analysis Risk Management Framework (WARMF), a decision support system that presents scientific information for stakeholders to evaluate alternatives, by the Truckee River, Muddy Creek and Blue River stakeholders. Alternatives included in the model include combinations of controls on atmospheric deposition, point source loads, water diversions, fertilizer application, street sweeping and buffer strips. Philadelphia’s Source Water Protection Program’s Source Water Assessment Project was reviewed by Byun et al. (2002b). The project has been designed to identify and prioritize potential sources of contamination across the watersheds and to assess the vulnerability and susceptibility of the water supplies to these sources. The use of comprehensive, watershed-wide, long-term continuous simulation models were used and were combined with GIS to show areas of high pollutant loads and of high protection priority. Clark et al. (2002a) studied combining hydrologic models for flood control, biotic models of ecologic risk, economic models of willingness-to-pay, and psychological models of risk processing and planned behavior to evaluate two policy alternatives. The findings reveal that flood risk exposure, especially for those individuals who would remain outside the 100 year flood plain if the project were enacted, does influence the financial support that local residents would be willing to make to a flood control project. McMillan et al. (2002) reviewed waterbody/watershed planning for New York City. A watershed-based approach was used to conduct an integrated evaluation of the interdependent factors affecting receiving water uses, including storm water, CSOs, wastewater treatment, upland uses, shoreline uses, habitats, sediment and water quality with the active participation of major stakeholders from the start of the process. Zimmerman (2002) postulated that a watershed-level approach to planning is well accepted today. However, he noted that there is a continued reliance on planning models that fall far short of understanding the complex interactions between wet weather, groundwater and water infrastructure on a watershed scale.
King et al. (2002) reviewed the implementation of watershed management recommendations through stormwater master planning in Gwinnett County, Georgia. The major components of the stormwater master plan involve 1) a flood study, 2) infrastructure inventory, 3) BMP analysis, and 4) stream restoration. This paper presented a method for prioritizing subwatersheds to focus stream restoration recommendations and develop water quantity and quality BMPs to improve watershed biotic integrity. MacGregor and Tichy (2002) presented an implementation tool for a developing watershed: The Regional Alcovy River Watershed Protection Plan. The goals of the plan included protecting water supplies; developing an economical, basin-wide approach for water quality protection; providing local government with tools to make decisions related to water quality easier; defining clearly strategies that meet state requirements for watershed protection; preserving the unique ecology of the watershed; fostering informed public opinion; involving the public in watershed protection planning and implementation; and working with existing organization to create an ongoing program. Miller et al. (2002a) reviewed alternative wet weather permitting strategies that recognize real-time conditions in the Indiana systems. The City of Indianapolis considered several strategies (mass, seasonal and tiered limit strategies) used in other places, as well as a ‘flow-proportional limit’ strategy.

Tuomari and Thompson (2002) reviewed the success of Wayne County’s IDEP Training Program. The key goals of the training program are sharing our expertise with other local units of government involved in stormwater management and collaborating efforts in reducing improper discharges to surface water. The modules of the training program are: Overview, Basic Investigations, Advanced Investigations, Construction Related Illicit Discharges, Combined Basic/Advanced Investigations, and two (2) specialty training sessions.

British Columbia’s Stormwater Management Guidebook was reviewed by Stephens et al. (2002). The Guidebook describes the adverse impacts of past stormwater management practices and walks its audience through stormwater management planning, including: how to develop goals, objectives and priorities; how to undertake public consultation; how to assess watershed health; how to select, implement and monitor best management practices (BMPs); and how to finance the long-term implementation of a stormwater management program. The Stormwater ‘Source Control’ Handbook for Australian practice was presented by Argue (20020. The Handbook attempts to provide ‘step-by-step’ advice regarding sustainable drainage systems and it is geared toward the student, the novice practitioner and the busy municipal engineer. Crabtree and Morris (2002) reviewed the Urban Pollution Management procedure and associated standards in England and Wales, and how they encourage the use of integrated wastewater planning and therefore, ensure the anticipated environmental improvements are delivered. Calcagno et al. (2002) wrote about the establishment of a non-governmental regional approach to integrated watershed management in the La Plata River Basin. As a concrete response to this need, the efforts of a number of organizations from various countries within the basin, with the support of international and national governmental organizations, resulted in the foundation of La Plata River Basin Environmental Research and Management Network (RIGA). Backstrom et al. (2002) discussed the future of Swedish stormwater management and what activities are not helpful in creating a sustainable system. The Swedish environmental objectives, which try to encapsulate all aspects of sustainability, may be used a foundation for a “sustainability screen,” which will then be used to evaluate programs and activities.

Fulton County has begun addressing the surface water issues created by stormwater runoff (Ammons 2001). The resulting Water Resource Management Plans have a 15-year program to improve the surface waters of Fulton County. In order to increase wastewater plant capacity and effluent discharge, the Georgia EPD required development and implementation of a watershed protection plan to address the “secondary” pollution impacts created by stormwater runoff from the development supported by the increased wastewater treatment capacity. The State of Georgia required watershed assessments to control nonpoint source pollution associated with degradation of surface water quality and non-attainment of designated uses (Ahmad 2001). EPD required local governments to conduct watershed assessments as a part of the NPDES permitting process for wastewater treatment plant expansion. The study objectives included identifying the current aquatic health of the watershed; predicting the impacts from the proposed development; and identifying and assessing the performance of BMPs. The conclusions were that the creek currently meets all adopted and recommended water quality standards; the aquatic habitat show some degradation of biotic integrity; the planned level of development in the watershed will increase pollutant (and sediment) loads; the structural BMPs will mitigate the increased pollutant loads; nonstructural BMPs should be implemented as part of a long-term Water Resources Management Plan (WRMP); and a long-term water quality monitoring and sampling program should be implemented.

Batchelor and Rogers (2001), in response to the lack of improvement in some of the nation’s waters, advocated finding smarter, more cost-effective ways of water quality and watershed restoration. Work in the Saginaw Bay Region showed
that a point-source and non-point source trading program could be effective (Faeth, 1995). Two important points were made. (1) The current regulatory system needs to change to incentive-based systems. (2) Trading systems work for integrated water quality, air quality and natural resource programs. A trading program, on a watershed basis for trading, should provide major watershed restoration in the fastest time and for the least money. Bhimini et al. (2001) presented the findings, conclusions, and recommendations from a trading program for TMDLs on the Truckee River. In addition, the viability of a seasonal TMDL and a discussion on the phased approach towards developing pollutant trading permits were discussed. The development of the trading program included establishing the technical basis for modifying the TMDLs and WLAs and for identifying the optimum mix of structural and nonstructural BMPs. Kochoba and Wilber (2001) reviewed TMDLs in several states. The reviews indicated that TMDLs, and the resulting Load Allocations (LAs) and Wasteload Allocations (WLAs), often were based on limited data, unsound modeling and poor characterization of non-point source loads. Active involvement in the TMDL development process by contributing entities was advocated to help ensure that TMDLs are based on good science and result in reasonable, achievable WLAs and LAs.

As the first phase in its Integrated Resources Planning (IRP) process, the City of Los Angeles embarked on a program to restructure and redefine the future of water resources for the City and its neighbors (Boyle et al., 2001). The City developed the Integrated Plan for the Wastewater Program (IPWP), a set of policies to guide the next phases of wastewater facilities planning. The IPWP process used by the City integrated water supply, water conservation, water recycling, and stormwater management issues with wastewater facilities planning through a regional watershed approach. It also solicited and relied on public input in establishing planning-level policies. Philadelphia Water Department's Office of Watersheds was charged with integrating traditionally separate tasked programs, including the Combined Sewer Overflow (CSO) Program, the Stormwater Management Program, and the Source Water Protection Program (Dahme 2001). The goal was to maximize the resources allocated to these programs and to ensure the comprehensive achievement of each of their goals. The paper focused on the Darby-Cobbs Watershed Partnership.

The watershed storm water regulatory framework from the Rouge River National Wet Weather Demonstration Project (Rouge Project) in southeast Michigan was institutionalized in 1997 as a new statewide watershed-based general storm water National Pollutant Discharge Elimination System (NPDES) permit (“General Permit”) (Cave et al., 2001). The General Permit required the immediate initiation of some activities such as illicit discharge elimination and participation in watershed management planning. The paper reported on the effectiveness of the subwatershed management plans developed under the General Permit in (1) contributing to the overall restoration of the Rouge River; (2) meeting the requirements of the state’s Storm Water General Permit, and (3) satisfying the federal mandates contained in the Phase II Storm Water Regulations. Two years ago, most of the Rouge River Watershed communities became covered under the state’s voluntary general stormwater permit program (Powell and Ball 2001). The permit required that the communities create a public education plan that included programs on the Rouge River, its impairments, stormwater pollution, and individual responsibility and stewardship. This paper discussed the initiatives and tools used by Wayne County’s Rouge River National Wet Weather Demonstration Project and the involved communities to obtain public input during the subwatershed management planning process. In most cases, public meeting participation was the most difficult to predict and ultimately the least dependable, and many approaches were required.

Disaster mitigation related to floods and debris flows were discussed in the context of sustainable land and water management in Taiwan (Chen et al., 2001a). Engineering approaches to modify natural systems were contrasted with approaches that require changing human behavior. Mitigation success depended not only on the characteristics and magnitudes of the disasters but also on human responses related to socioeconomic, cultural, and political factors. Herricks (2001) discussed the renewed emphasis on watershed management programs that are based on ecosystem protection and restoration. The integration of ecosystem-based objectives into watershed management programs has demanded a substantial shift from past practices. This new paradigm integrated past management science and practice with ecosystem protection. This has assisted in the development of projects that produce needed ecosystem benefits.

Public involvement in watershed protection and stormwater management was reviewed by Cole (2001). Focused public involvement has encouraged residents to acknowledge individual responsibility for the impact of their actions on area waterways. It also fostered voluntary participation in Watershed Management Plan recommendations. The paper discussed the objectives of a well-managed public involvement plan. Ames and Neilson (2001) presented an Internet-based, Bayesian Decision Network model to aid watershed stakeholders in collaborative decision-making. Bayesian Decision Networks (BDNs) have been shown to be a useful tool for diagramming the decision process, for describing relationships between variables, and for analyzing the anticipated effects of management decisions while still accounting for the associated uncertainties. An Internet-based BDN was described using the East Canyon watershed in Utah. Public
Sweeney (2001) advocated the use of the Internet by wastewater utilities to achieve closer customer and production catchment, specifically the River Tame in the West Midlands. The following were considered: (a) rainfall-runoff al. (2001) considered the problems of developing a perceptive and efficient rehabilitation strategy for a large urbanized three datasets (Santa Ana River in California, South Platte River in Colorado, and Cuyahoga River in Ohio). Webster et al. identified using a three-dimensional modeling program. The method was refined using Impact Analysis method, used existing analytical methods, including Principle Components Analysis, All Possible chemical and physical parameters on aquatic life (Reeves et al., 2001). The resulting method, termed the Integrated ecologically sustainable flood control. Reeves et al. (2001) developed a method that would incorporate the effects of both ecological impairment and flooding caused by urbanization was expressed numerically by calculating the risks throughout the watershed (floodplain) and along the main stems of the streams (Novotny et al., 2001). The methodologies for ascertaining the risks in the Geographical Information Systems (GIS) environment were described. The objectives of urban flood controls and ecological preservation/restoration of urban waters often have conflicted. A solution to this may be achieved by linking the risks to the concepts of risk communication, risk perception, and public willingness to pay for projects with ecological restoration and ecologically sustainable flood control. Reeves et al. (2001) developed a method that would incorporate the effects of both chemical and physical parameters on aquatic life (Reeves et al., 2001). The resulting method, termed the Integrated Impact Analysis method, used existing analytical methods, including Principle Components Analysis, All Possible Regressions, and Chi-Square Automatic Interaction Detection (CHAID), to identify key variables. Non-linear interactions between the key variables were identified using a three-dimensional modeling program. The method was refined using three datasets (Santa Ana River in California, South Platte River in Colorado, and Cuyahoga River in Ohio). Webster et al. (2001) considered the problems of developing a perceptive and efficient rehabilitation strategy for a large urbanized catchment, specifically the River Tame in the West Midlands. The following were considered: (a) rainfall-runoff relationships, (b) water quality and ecological status, and (c) the impact of various management strategies. Spalding and Sweeney (2001) advocated the use of the Internet by wastewater utilities to achieve closer customer and production.
integration. A “Digital Utility” approach using the Internet to create new, robust, customer-oriented applications was described.

In Cleveland, Ohio, channel erosion and flooding, water quality, and aquatic life and habitat were evaluated (Yingling 2001). The purpose of both the Mill Creek and Doan Brook Watershed Studies was to develop comprehensive approaches for controlling wet-weather impacts on the respective streams. The cost and effort involved in actually performing the watershed studies, as well as the potential for overall cost savings and creativity in developing final solutions, were reviewed. Although watershed studies require a significant investment in data collection and in public involvement, the resulting solutions were typically more cost-effective and accepted by the public. Waterific, an interactive science program about water, was created to educate the public about water-related issues (Ziegler et al., 2001). The focus of Waterific was to enhance environmental awareness, education and celebration. In addition, the program is a fun, hands-on activity that meets the core content required by the Kentucky Department of Education for sixth-grade science. By pooling talent from various water quality agencies, the school students saw first-hand how all the agencies work together and independently to maintain the water quality in Northern Kentucky.

According to the U.S. EPA’s Index of Watershed Indicators, at least 21% of watersheds have serious problems, 36% have some problems, 16% have good water quality and 28% lack sufficient information to analyze (Hun, 1998). Managers for the Joshua’s Creek, a 21 km² watershed in southern Ont., Can. used a three stage process to sustain water resources in the face of rapid urban development. The process included a macro-scale watershed plan, detailed subwatershed plans, and specific stormwater management plans (Bishop, 1998). The Tualatin River Basin in northwest Oreg. experienced rapid urbanization bringing changes in land uses, increased pollutant loads to the river and its tributaries from the WPCP and urban runoff (Jackson, 1998). Requirements defined by the Clean Water Act such as NH₃ and P load limitations were implemented in 1988 and temperature allocations were scheduled for 1997.

Municipalities are required to implement multiple regulations with regard to water resource protection including erosion and sediment control laws and stormwater requirements under NPDES. Integration of these regulation requirements under a comprehensive watershed management plan would enhance enforcement and reduce implementation costs (Pasquel et al., 1998). Coherent watershed management must rest on clear political goals regarding environmental use, risk protection and urban development (Cyr et al., 1998). The stormwater master plan must become permanently part of the water resource master plan for the whole watershed, with its objectives of flood control, erosion control and maintenance of acceptable physical-chemical and biochemical water quality, as well as assured resource use.

Sixteen state and federal agencies with management and regulatory responsibilities in the San Francisco Bay and Sacramento-San Joaquin River Estuary (Bay-Delta) in Calif. have come together in a collaborative effort with Bay-Delta stakeholders, urban and agriculture water users, fishing interests, environmental organizations, businesses and other public interests to develop a long-term solution the CALFED Bay-Delta Program (Yaeger and Ott, 1998). Integrating traditional stormwater management techniques and the watershed management approach into the city of San Francisco’s existing water quality control programs reduced potential impacts of CSO and facilitated the city’s efforts to comply with Phase II stormwater regulations ahead of schedule (Rourke and Brosseau, 1998). The U.S. Army Corps of Engineers, North Central Texas Council of Governments and its member local governments have cooperated in a regional initiative to more comprehensively assess the problems and opportunities of the Trinity River corridor of the Dallas/Fort Worth metroplex (Promise, 1998). The Lake County Stormwater Management Commission (SMC) of Ill. performed a multi-phase project on one residential subdivision that experienced chronic flood damages (Royal, 1998). Alternative management measures included modification of detention basins and wetlands, drainage improvement, stream maintenance, and acquisition and demolition of flood damaged residential structures. The City Center of Johor Bahru, Malaysia has been undergoing intensive urban development and redevelopment since the early 1980's and is planning for the management of urban stormwater. The factors considered in the formulation of the plan include: (1) the level of minimum acceptable flood risk; (2) town planning and other related guidelines; (3) ease of maintenance; (4) future use of the waterways; (5) accessibility to the river reserve zones; (6) flora and fauna to be used for the systems; and (7) aesthetic and safety features for recreational purposes (Chin et al., 1998b).

The Lake Pontchartrain Basin Foundation of La. developed a plan to identify water-quality and habitat problems and make recommendations. The plan addressed the impact of designated use areas by microbial contamination and suggested BMP with emphasis on disinfection and engineered microbial reduction technologies (Engelnde et al., 1998). The King County Water Pollution Control Division in Wash. conducted a water-quality assessment for the Duwamish River and Elliott Bay to provide information for making decisions about the future of the CSO program (Munger et al., 1998a).
Wash. adopted a long-range standard for CSO control of one uncontrolled overflow per discharge point per average rainfall year. In March 1994, the city of Orlando, Fla. entered into a Joint Planning Agreement with Orange County which would facilitate the annexation of approximately 52 km² (20 mi²) of underdeveloped land southeast of the Orlando International Airport (Roesner et al., 1998). This planning effort would include the development of a Master Stormwater Management Plan (MSMP) for the annexed area using a “watershed based” approach to the management of the water quantity and quality to provide regional flood control and water maintenance of existing wetlands. Schaefer et al. (1998) described the development of a comprehensive management plan that addresses flooding, protection of environmental resources, and stormwater management regulations for a study reach within the context of existing and future development conditions throughout the watershed of Tyler Creek, Elgin, Ill.

As part of N. J.’s watershed management approach, water-resource programs, e.g., stormwater management, wastewater management, source-water protection and CSO control, will be coordinated and implemented through a statewide watershed-management process (Cohen, 1998). N. J. has maintained a federally approved coastal-zone management program for 18 years and used the Coastal Management Act to implement the State Development and Redevelopment Plan (SDRP) and the Statewide Watershed Management Plan (Frizzera 1998). The Rock River Watershed Partnership was established to conduct a full watershed study of the Wisc. portion of the Rock River as a result of stricter P restrictions imposed in 1996 (Schroedel et al., 1998). The Partnership is a cooperation of communities that line the Rock River Watershed area and efforts have been made to share information. Rudolph et al. (1998) gave an overview of the Northeast Ohio Regional Sewer District’s (NORSD) comprehensive watershed investigation of the Doan Brook, which serves the cities of Beachwood, Cleveland, Cleveland Heights, and University Heights and receives CSO during wet weather.

Lexington-Fayette County, Ky. began a watershed-management program that included the use of greenways, establishment of community water-quality standards, stormwater modeling, retrofitting BMP to improve stormwater quality, and stream morphology (Tapp and Uckotter, 1998). The stormwater program of the Lexington-Fayette Urban County Government used chemical monitoring techniques and biological and stream-morphological studies to quantify the current condition of the resources (Robson and Kramer, 1998). The Columbus Water Works of Columbus, Ga. developed a watershed plan to identify and quantify urban and rural wet-weather pollution sources and assess instream results of existing CSO control facilities (Turner et al., 1998). The study area of the Metro Atlanta Urban Watersheds Initiative (MAUWI) in Ga. was divided into subbasins based on factors including basin size, hydrography, land use, impervious surface and location of CSO. Each subbasin was sampled for one or more biological parameters (Hall and Richards, 1998). The MAUWI, a stakeholder driven process, produced a Watershed Improvement Guidance Document which is based on habitat, biotic integrity and water-quality data and assessments of impacts on the watersheds. The information provided communities and governmental agencies, the current state of the urban streams, pollution sources, alternatives for improvements and guidance on implementation (Richards, 1998).

A planning study for the Ile-de-France Region which includes Paris was conducted to meet dry and wet weather water quality criteria in the year 2015 (Renard et al., 1998). A watershed approach was used, and four remedial scenarios were developed including the construction of 1.4 x 10⁶ — 1.6 x 10⁷ Mm³ of new retention capacity and 2.5 — 8.5 m³/s of high-rate treatment plant capacity. Fujita (1998) presented examples of restoration of polluted or dried urban watercourses in Tokyo, Japan. Parsons Engineering Science developed the Basin Master Plan for South Creek in Sarasota County, Fla. (Cabezas, 1998) which addressed watershed-management issues. During heavy rain events, South Creek contributed to flooding and violations of levels of service in adjacent basins. A computer model summarized technical information and allowed a citizen task force to make decisions about a cost-effective management plan for development of Lake Sammanish in King County, Wash. (Richey et al., 1998).

**Effluent Trading and Water-Quality Planning**

Bloom (2002) provided a national review of known proposed or issued TMDLs or TMDL implementation plans that call for the imposition of numeric effluent limitations in MS4 permits as a means to achieve TMDL-derived load reductions. The paper also highlighted some of the policy implications of this emerging trend. Dors and Tsatsaras (2002) reviewed the determination of a margin of safety for TMDLs for water bodies that are determined to be water quality limited. Freedman et al. (2002) discussed the results of the WERF-funded research project on navigating and improving the TMDL process. The objective of this research was to investigate issues and concerns with the TMDL program, and to develop and identify ways to improve the TMDL process. Clark (2002) used the Cascade Reservoir TMDL Implementation Plan as an example for the development and application of a database project tracking tool. The tracking system serves as a master summary of all projects and BMPs constructed for the purpose of reducing the phosphorus load.
Bhimani et al. (2002b) presented the findings, conclusion and recommendations for the implementation of a water-quality trading program for TMDL modifications on the Truckee River using a phased-permitting approach. The paper also addressed the viability of a seasonal TMDL and discussed the phased approach toward developing water-quality trading permit language. Al-Ebus and Jacobson (2002) reviewed the protocol for developing fecal coliform TMDLs in New Jersey. Percent-load reductions will be assigned to stream segments based on the use of a geometric mean and the aid of load-duration curves and sources will be identified using one of several reliable bacterial source tracking (BST) methods. Cleland (2002) reported on the use of duration curves in TMDL development in Kansas. The expanded use of flow duration curves has enabled enhanced targeting, both in TMDL development and in water quality restoration efforts. Duration curves also provided a context for evaluating monitoring data and modeling information. Lee and Jones-Lee (2002) reviewed the development of nutrient criteria/TMDLs to manage excessive fertilization of waterbodies. The paper discussed recommended approaches for developing site-specific nutrient criteria that will protect the nutrient impact-related beneficial uses of a waterbody, without significant unnecessary expenditures for nutrient control. The paper by Schechter et al. (2002) presented guidance on incorporating stormwater and other urban wet weather sources into TMDLs. Using a broad-based review of nearly 200 approved TMDLs, combined with interviews of state TMDL staff, and detailed study of selected case studies, the research team developed several key findings related to wet weather sources in TMDLs. The paper provided recommendations for possible improvements for states, dischargers, and other stakeholders to use when confronting a wet weather TMDL. The paper also presented a case for the development of separate and distinct event-related wet weather TMDLs independent of dry weather TMDLs. In many cases, these wet weather TMDLs will have different sources, and often, different water quality endpoints.

Bowman (2002) reviewed the Nutrioso Creek (Arizona) TMDL partnerships between landowners and the state and federal agencies for TSS control. Ranchers received grant money and technical assistance to change the way the land is used and to install land improvement structures and BMPs, and efforts have shown improving stream water quality and riparian areas after only a year of implementation. The development of the Ohio River TMDL for PCBs was reviewed by Dinkins et al. (2002). The plan included characterizing the extent and severity of water quality impairment, inventorying potential sources and quantifying source loadings, defining load reductions needed to meet water quality standards, assigning load allocations to the sources, and providing recommendations for actions to address the contamination. Based on the data analysis, direct deposition to the Ohio River may contribute over 40 percent of the allowable load for some segments of the river. O’Dea (2002) presented TMDLs in New Mexico which provided a case study in managing court orders, tribal interests and endangered species in a desert area. In the Middle Rio Grande, point sources and non-point sources are trying to understand what requirements might result from the recently finalized TMDL for fecal coliforms and might require permit holders to implement stringent BMP requirements or numerical standards in the permits.

Jones et al. (2002b) discussed how stakeholders’ involvement can positively affect the development of TMDLs using the West Branch of the DuPage River as an example. Mumley and Speare (2002) presented an effort to optimize stakeholder involvement in the TMDL process in the San Francisco Bay Region. Lessons learned in San Francisco Bay Region TMDLs provide useful examples of how to conduct effective stakeholder outreach. Shanks and Grovhoug (2002) presented a case study of stakeholder involvement in the development of TMDLs in the Sacramento River watershed. This presentation focused on the benefits and drawbacks of the stakeholder process as a forum for problem solving, the approach taken to foster collaboration and connection between stakeholder activities and the TMDL development process, the work products developed by the stakeholder groups, and the lessons learned from the process.

Effluent trading to maintain water quality on a watershed has gained momentum recently, however the method is complex. Kerns and Stephenson (1996) addressed the key elements for a successful trading operation. The EPA (1996d) acknowledged the benefits of pollutant trading among the various sources within a watershed as a means of reducing costs, and a framework for watershed-based trading was drafted (EPA, 1996e). Imbe et al. (1996) did a water budget to determine the impact of urbanization on the hydrological cycle of a new development near Tokyo, Japan. A cost-effectiveness study on point sources and nonpoint sources control of phosphorus was conducted in Chatfield Basin, CO (Little and Zander, 1996). Podar et al. (1996) summarized progress on trading programs across the nation.

Taff and Senjem (1996) outlined four major classes of regulatory uncertainty of point-nonpoint pollutant trading systems and offered practical measures for these uncertainties.
In planning a water-quality strategy for urban areas, public relations and upfront development of partnerships were found to be critical to facilitate implementation of pollution-control plans as illustrated in the St. Catharines’ case study (Toth, 1996). An ecology-based, integrated-stormwater-management approach in relation to the regulatory requirements was initiated in Germany (Schmitt, 1996b). The Rock Creek community development in Superior, CO (Galuzzi and Pflaum, 1996) used an integrated approach for the planning, design, and construction of multiuse drainage systems, including the regional-stormwater channels and detention facilities. Robbins (1996) used GIS for establishing infrastructure-inventory databases for planning and monitoring stormwater-management programs. The City of Detroit’s Water and Sewerage Department developed a long-term CSO-control plan, including interconnections of drainage systems between districts and their overflow outfalls to the Detroit and Rouge Rivers (Fujita and Graziolesi, 1996).

After more than a decade of research of the Water Industry’s Urban Pollution Management (UPM) in the United Kingdom, its products, a UPM Manual and software tools have been widely used by major cities for evaluating their flooding- and CSO-pollution problems (Morres and Clifford, 1996). The goals for mitigating urban-wet-weather pollution and the fundamental methodologies employed to achieve those goals were determined to be similar, according to a comparative study of urban-wet-weather-pollution-management approaches in the United States and the United Kingdom (Brashear and Drinkwater, 1996).

The Minnesota Pollution Control Agency has allowed the reduction of NPS pollution to be credited to industries’ point-source discharges. Now that point- and NPS-trading standards have been established, opportunities exist for industries to take advantage of NPS trading (Wallace and Sparks, 1997). An alternative permitting approach for the release of Pb-contaminated wastewater was discussed (Kratcl, 1997a). Innovative stormwater sampling allowed a Pb-acid-battery manufacturer to obtain a new Kentucky Pollutant Discharge Elimination System permit and saved the company two-million dollars.

Schroeter (1997) discussed a methodology (and the databases used) in computing planning-level loading estimates for urban NPS from Ontario, Can. communities. Li et al. (1997) described the steps required to develop a preliminary stormwater-quality-management-planning strategy and presented a case study from the city of Scarborough, Ont., Can. Bolstad and Swank (1997) indicated that although most water-quality regulations, legislation, and sampling are promulgated for baseflow conditions, storm-flow conditions also warrant consideration during the promulgation process.

San Francisco, Calif. implemented a proactive water-pollution-prevention program, consisting of > 300 automotive facilities, in order to minimize wastewater- and stormwater-pollutant discharges into its CSO (Rourke et al., 1997). According to Buke (1997), national “green taxes” were environmentally effective and the European Environment Agency in Copenhagen, Den. reported that these taxes were gaining acceptance. Streiner and Loomis (1997) assessed the economic benefits of urban-stream restoration and reported that property prices in areas with restored streams increased by 3% — 13%.

**Permitting**

Cook and DeBell (2002) reviewed EPA’s focus on improving the management of urban wet weather flows under the NPDES program. The methods of particular interest are methods for improving urban wet weather flows, watershed management, best management practices, innovative funding mechanisms, and locally-developed TMDLs. DeBell and Weiss (2002) reviewed the development of a Federal Register notice to provide guidance, policies and regulations to clarify NPDES requirements for municipal sanitary sewer collection systems and sanitary sewer overflows. The paper provided an overview of the Agency’s approach. EPA’s watershed approach to managing urban nonpoint source pollution was discussed by Frederick et al. (2002). EPA’s guidance contained a set of management measures that EPA recommends to states, local governments, and community groups to incorporate into their urban pollution control programs to protect surface and groundwater quality. For each management measure, EPA has provided a list of practices that can be used to implement the objectives of the management measure. Cost and effectiveness data are provided for most practices and references to the most up-to-date and useful publications and web sites are cited.

Barnard (2002) reviewed the Phase II regulations that were published by EPA on December 8, 1999, and that address stormwater discharges from small municipal separate storm sewers and construction sites between one and five acres. The affected municipalities are required to develop stormwater control programs to address the pollution problems. Collins et al. (2002) discussed the compilation of regulatory requirements for stormwater runoff. The analysis suggested the usefulness of conducting qualitative and quantitative assessments about available control technologies. Hall et al. (2002) discussed the EPA’s developing of numerous requirements for the design and permitting of facilities intended to manage
from the sanitary sewer system was established at the Stege Sanitary District in 1996. The paper reviewed the
limiting situations in the collection system” (Ruggard 2001). The goal of the ultimate elimination of any type of overflow
system management framework that encourages evaluating and prioritizing efforts to identify and correct performance-
and what, if any, funding assistance may be available. The CMOM approach in the SSO Rule will requ ire “a dynamic
available, what types of permits may be available, what minimum information on permit applications may be necessary,
questions of who is affected, what is required, when permit applications are to be submitted, what permitting options are
requirements for the new EPA Phase II Stormwater regulations. The description of the proposed Pennsylvania State
use. Patel (2001) provided a general background and state perspective for municipalities to approach the regulatory
County and recommend a watershed protection strategy to improve the streams which were not meeting the designated
use in Georgia. The purpose of the Gwinnett County Watershed Assessment was to evaluate stream conditions within the
compliance. Therefore, it is important for the Industrial community to understand what these regulations are trying to
classical command -and-control approaches, but instead agencies have devoted far fewer resources and relied on voluntary
effective implementation of the pollution prevention approach may require more resources by regulators compared to
industrial activities (Duke 2001). However, evidence suggests the pollution prevention approach is widely failing. In
targeted case studies, evaluation of chemical constituents in runoff shows no evidence of pollutant reduction over time.
Harrison (2002) reviewed the municipal perspective on zero -impact policy issues and the concerns that it raises. While
the inventory of stormwater quality management measures to reduce pollutant discharges is growing, they do not achieve
the zero-discharge mandate and do not reduce the vulnerability to statutory enforcement action.

Kosco and Keefe (2002) discussed the EPA requirements of the Phase II regulations to develop measurable goals for each
BMP in the stormwater program. These markers will be used to track the progress and effectiveness of BMPs, and are
enforceable elements of the permit. Woelkers (2002) reviewed the Phase II NPDES stormwater regulations as the
deadline nears for implementation. There are six minimum measurement requirements of Phase II and these will be met
using best management practices and associated goals rather than analytical testing. The six measurement requirements
relate to public education and outreach, public participation and involvement, elicit discharge detection and elimination,
construction site run-off control, post-construction run-off controls and pollution prevention and good housekeeping. The
paper by Briglio and Macrina (2002) reviewed the consultants’ role in developing NPDES Phase II programs. Bateman
(2002) reviewed the outsourcing of the bulk of Florida’s NPDES program activities. Private contractors write and monitor
permits, and inspect construction, industrial and municipal permittees.

Schrameck (2002) presented Michigan’s General Storm Water Permit and Phase II Stormwater regulations and the
innovative approach for the Rouge River. The permit incorporated some of the better aspects of the Phase I Federal Storm
Water program, such as the Illicit Discharge Elimination Program and the Public Education program, without the onerous
aspects of the intense sampling found under that program. The permit also mandated that the communities/agencies
within the various subwatersheds of the Rouge cooperate together to format a plan for public involvement in the
restoration process and, most uniquely, required that the various parties within the subwatersheds develop a
comprehensive watershed management plan for their separate areas that will be linked together to form a basin wide
Remedial Action program for the Rouge River.

Harrison (2002) reviewed the municipal perspective on zero -impact policy issues and the concerns that it raises. While
the inventory of stormwater quality management measures to reduce pollutant discharges is growing, they do not achieve
the zero-discharge mandate and do not reduce the vulnerability to statutory enforcement action.

Under Phase I of the NPDES permit requirement, permits were required for stormwater discharges associated with
industrial activity (Daniel 2001). Typically these discharges were material handling and storage areas at certain industries.
Authorized dischargers were required to develop and implement stormwater pollution prevention plans to prevent the
discharge of pollutants in runoff. Pollution prevention has been the key for stormwater discharges associated with
industrial activities (Duke 2001). However, evidence suggests the pollution prevention approach is widely failing. In
targeted case studies, evaluation of chemical constituents in runoff shows no evidence of pollutant reduction over time.
Effective implementation of the pollution prevention approach may require more resources by regulators compared to
classical command-and-control approaches, but instead agencies have devoted far fewer resources and relied on voluntary
compliance. Therefore, it is important for the Industrial community to understand what these regulations are trying to
accomplish and how these regulations will be locally specific. The paper by Gates and Resiak (2001) discussed when the
State of Indiana will implement the Phase II regulations, who will need to apply for Phase II permit coverage, and what
requirements will be in those permits. These were illustrated by a specific case study.

Georgia EPD and the Board of Natural Resources have to decide how and who should do watershed protection
(Scarborough 2001). Georgia concluded that POTWs should be the responsible party since the County/City controls land
use in Georgia. The purpose of the Gwinnett County Watershed Assessment was to evaluate stream conditions within the
County and recommend a watershed protection strategy to improve the streams which were not meeting the designated
use. Patel (2001) provided a general background and state perspective for municipalities to approach the regulatory
requirements for the new EPA Phase II Stormwater regulations. The description of the proposed Pennsylvania State
Strategy summarized what the Phase II regulations will require of the regulated communities, and answered basic
questions of who is affected, what is required, when permit applications are to be submitted, what permitting options are
available, what types of permits may be available, what minimum information on permit applications may be necessary,
and what, if any, funding assistance may be available. The CMOM approach in the SSO Rule will require “a dynamic
system management framework that encourages evaluating and prioritizing efforts to identify and correct performance-
limiting situations in the collection system” (Ruggard 2001). The goal of the ultimate elimination of any type of overflow
from the sanitary sewer system was established at the Stege Sanitary District in 1996. The paper reviewed the
improvements to the District’s management, engineering, maintenance and data management systems in order to achieve that goal.

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor identifiers of discharging facilities and poor estimators of discharges. In 1996, the General Electric Plastics (GE Plastics) resin production facility located in Bay Saint Louis, Mississippi, embarked on a capital program to improve stormwater management at the facility by permitting and installing a structural BMP consisting of a first flush capture and treatment system for critical areas of the facility that had a potential to contribute acrylonitrile to stormwater discharges from the facility. Bennett et al. (1999) discussed the issues encountered during the permitting, implementation, and operation of the first flush system. A number of small cities across the United States were finding it difficult to comply with the national CSO policy issued by the EPA and have proposed alternative solutions to the CSO problem such as the site-specific designated-use reviews. In response, the EPA has begun to develop guidelines for designated-use reviews and provide technical and financial aid to several states (Mealey, 1999).

WWF control often involves unfamiliar institutional alliances, diverse groups of stakeholders, varied goals, and social or institutional resistance to new approaches. Bateman et al. (1999) reviewed the institutional framework the state of Florida has implemented to address stormwater problems associated with land uses. Karaitiana et al. (1999) discussed a partnership between the City Council of Christchurch, New Zealand and the indigenous Moari people to sustainably manage the wetlands and waterways of Christchurch. The partners have identified six generic values, including ecology, landscape, culture, heritage, recreation and drainage, which will replace only drainage as the goals of the management approach. The government of New South Wales (Australia) has initiated a stormwater management planning program to mitigate the environmental impacts of stormwater runoff from urban areas throughout the State (Sharpin et al. 1999). The urban stormwater management plan addresses environmental protection issues, including stormwater quality, river flow, riparian vegetation and aquatic habitat management, and was tailored to the state’s climatic, ecological, social, land use and administrative characteristics. Nielsen and Elle (1999) argued that current infrastructure hold a considerable momentum, and this momentum was a barrier to transformation to newer more sustainable technologies. The sewage sector in Denmark was an example of a technical infrastructure system whose technical, economic, and social momentum acts as a barrier to the implementation of small-scale stormwater infiltration.

Geldof (1999) discussed the impact of “qwerties” on the implementation of source-oriented approaches to stormwater management in Holland. A qwertie was an ingrained pattern that occurs in a complex process which can be eliminated only by taking measures which have sufficient critical mass and doing so at the right moment. Nine qwerties were detailed, including those of conservatism and the use of different languages. McElroy (1999) outlined efforts in the Palestinian West Bank and Gaza Strip to develop sustainable water use and reuse practices and to improve wastewater treatment so that water quality standards and regulations can be adopted that will be meaningful, measurable and enforceable. Cooperating agencies included the Palestinian Water Authority, the Palestinian Ministry for Environmental Affairs, and The United States Agency for International Development. The development of a stormwater management strategy for the City of Clarence in Tasmania illustrated a number of difficulties faced by local government agencies and communities seeking to be more environmentally and socially responsive to ecological sustainable development goals, and the strategies available to address these difficulties. Philips et al. (1999) outlined a number of innovative approaches to the technical analysis which were used by the City of Clarence, and the principles guiding the selection of particular options. In 1994, Northern Kentucky’s three counties, including 28 cities, consolidated their sewer collection systems under Sanitation District No. 1, creating the second largest public sewer utility in Kentucky, which maintained more than 1,200 miles of sanitary sewer lines. Many participating jurisdictions believe that the Sanitation District were now looking to the District to take over the operation and maintenance of Northern Kentucky’s stormwater drainage systems and controls (Higdon and Eger, 1999). Because of the diverse, multi-agency and interactive nature of the watershed management approach model, both drinking and wastewater utilities often found it difficult to establish and define their role in a watershed management program. Shablen and Lauria (1999) outlined how the city of Columbus, Ohio, Division of Water and corresponding watershed stakeholders have adopted unique roles integrating federal, state and local resources to develop a source water protection partnership.

In March 1998, Portland Oregon became the first major urban area with a threatened salmonid listed under the United States’ Endangered Species Act (ESA). This marked the first time the ESA has been applied in a major urban area and would result in new challenges in how best to apply and meet the Act. It would also require fundamental changes in a broad suite of activities conducted in planning, developing, and maintaining a city (Abrams and Prescott, 1999). The city
of Indianapolis, Minnesota was currently fighting state permitting provisions that would make it illegal for the city’s treatment facility to discharge combined sewer and stormwater flows without secondary treatment. The new regulations could cost the city $2 billion over the next decade (Civil Engineering, 1999). Odeal (1999) described efforts by the Northeast Ohio Regional Sewer District to fashion a program to develop future employees and leaders for the district, which provides wastewater conveyance, CSO control, and wastewater treatment for the Greater Cleveland area (Ohio). After years of failing to meet WWTP discharge requirements, the city of Waterton, South Dakota evaluated the existing treatment process, to determine whether or not the City was truly on a path to compliance, and to assist with making any projects affordable. Schrodel and Boerger (1999) presented the success of one of the resulting recommendations, using a program manager to track all required activities to achieve compliance. Van der Heijden (1999) discussed a system of BMP intended to reduce the phosphorus loading from an area of new development and existing commercial and mixed land use. This effort was part of the New York City Department of Environmental Protection’s pilot phosphorus offset program.

The Mich. Department of Environmental Quality initiated a limited Voluntary General Storm Water Permit until the U.S. EPA Phase II stormwater regulations become effective (Cowles, 1998). The Wis. Department of Natural Resources recognized that a comprehensive urban stormwater permitting program was needed for the Milwaukee River Basin as water quality in area streams and the near-shore area of Lake Michigan did not meet state standards. Aggressive voluntary efforts to control sources of rural and urban NPS pollution did not achieve desired results (D’Antuono, 1998a and 1998b). Wayne County’s Rouge River National Wet Weather Demonstration Project (Rouge Project) is a comprehensive program to restore the water quality and beneficial uses of the Rouge River, a tributary to the Detroit River in southeast Mich. with significant sources of pollution from industrial and municipal point sources, stormwater runoff, and CSO (Murray, 1998). One of the Rouge Project’s key findings was that major barriers to effective pollution control and water resources management are often institutional, not technical. The Rouge Project supplemented the existing regulatory program with a general permit for a sub-watershed policy in an effort to control NPS pollution (Ridgway, 1998). The NORDS service area contains approximately 20 000 ha (50 000 acres) of combined sewer area and 125 CSO for which it has an NPDES Permit (Greenland, 1998). Part of the CSO Permit requires completion of CSO control plans before 2002 and an outline was given for the plans to meet these requirements. The Community Discharge Permit Program was established as a result of grant conditions (U.S. EPA funded) for the NORDS’ Heights-Hilltop and Southwest interceptors (Duke, 1998). Member communities made significant expenditures to control and alleviate SSO and the program has increased community awareness for the need for BMP to meet the performance objectives stated in the permit.

On January 9, 1998, the U.S. EPA published in the Federal Register “Proposed Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges” or the NPDES Storm Water Phase II proposed rule. The proposal designated two classes of facilities for automatic coverage on a nationwide basis under the NPDES program, small municipal separate storm sewer systems located in urbanized areas (about 3 500 municipalities) and construction activities (pollutants include sediment and erosion from these sites) that disturb between 0.4 and 2 ha (1 and 5 acres) of land (about 110 000 sites per year) (Kosco, 1998; EST, 1998). The U.S. EPA considered a framework for “watershed permitting” as an alternative to separate permitting of individual pollutant discharge sources which, in urban areas, would include a coordinated approach to addressing many sources in one permit or few permits, including both urban wet weather and continuous sources of pollution (Cook et al., 1998). This system of permitting helps to highlight the most critical pollution control needs of a watershed and community and allows those needs to be addressed in the most effective and least costly manner consistent with the goals of the Clean Water Act. The Mass. Department of Environmental Protection revised the state’s water quality standards to include water body classifications that reflect a range of circumstances under which combined sewers discharge and issued a new CSO Policy and Guidance Document, incorporating increased flexibility for permittees to demonstrate the combined sewer discharges were being controlled to the maximum extent feasible (Hornbrook et al., 1998a). This revision came in response to the U.S. EPA’s publication of its final CSO Control Policy in April of 1994.

The EPA is adopting an interim-permitting approach for regulating stormwater discharges under its NPDES program (EPA, 1996c). The EPA developed three stormwater-discharge-permit options for industrial facilities: (1) an individual application, (2) a group application, or (3) a notice of intent for a general permit. The facility should be more cautious to select a general permit versus a multisector NPDES stormwater permit (Espey et al., 1996). Stormwater discharged from iron and steel industries are regulated by the EPA Industrial Stormwater Permits Program that require the submission of a notification as soon as possible to the EPA under the Clean Water Act (Chalfant, 1996; Bralower, 1996).

Dinnison (1996) discussed the EPA’s regulatory requirements for stormwater discharges and offered a practical approach
to compliance with the complex federal and state stormwater regulations. A guide for obtaining a stormwater permit for construction activities at Army installations provides detailed administrative procedures for environmental staff regarding their compliance duties (Dzuray and Tang, 1996).

The California Water Resources Control Board has developed an industrial facilities database to identify the status of compliance with a facility’s General Industrial Permit conditions (Duke and Chung, 1996). The Rouge River National Wet Weather Demonstration Project provided an opportunity for alternate watershed-wide NPDES permit programs to municipal stormwater discharge regulation under the Clean Water Act (Murray et al., 1996).

Roth (1996) reviewed the current German law that exists for municipalities to promote alternative stormwater management, including changes in the sewage regulations and wastewater fee assessment.

Cost Analysis and Financing

Bacon et al. (2002) reported on an initiative of the Joyce Foundation that is investigating how conservation development projects could create tradable/bankable credits for nutrient reduction as part of a TMDL or other watershed protection program in the Great Lakes region. The two pilot projects for this are located in the Kalamazoo River – Lake Allegan watershed and in the Saginaw Bay watershed (Michigan). Fischer (2002) discussed the Governmental Accounting Standards Board’s 34th Statement (GASB-34) that has the stated purpose of having units of government in the U.S. make annual reports more comprehensive and easier to understand and use. One of the most revolutionary requirements in GASB-34 is the reporting of infrastructure assets (roads, bridges, traffic signals, sanitary and storm sewer systems and public water supply systems).

The paper by Benson (2002) reviewed the recent survey by Black & Veatch Corporation of North American user-fee-funded stormwater utility financial practices. It profiled current practices and potential future trends. Ambrose et al. (2002) presented the approach of Wheeling, West Virginia, to separately identify system wastewater and stormwater allocation costs and then to share the costs equitably between residential and commercial customers. This study was beneficial because it identified what the services actually cost, it verified whether customer classes were paying their fair share, and it provided useful information for forming a separate stormwater enterprise fund. An update of the City of Jefferson, Missouri’s stormwater management program was provided by Brizendine et al. (2002). A funded integrated stormwater management program was developed to address capital improvement needs, program needs, and regulatory needs in order to prevent water quality degradation and reduce flooding. Foster et al. (2002) reviewed the integrated partnering approach that was used to determine cost responsibility for Detroit’s investment in combined sewer overflow facilities. Rothstein et al. (2002) discussed the development of the strategic financial planning model that was created to support Atlanta’s CSO-SSO program implementation. The SFP model enabled program planners and policy makers to efficiently construct and evaluate financing plans and rate increase projections associated with alternative capital programs and schedules involving hundreds of individual projects. Salem, Oregon’s strategic financial planning was reviewed by Galardi et al. (2002). The $1 billion planning process followed four main tracks of analysis: system development charges, long-term financial planning, cost-of-service analysis, and public education and involvement.

Stormwater controls and Best Management Practices (BMPs) were evaluated within a land development context (Sample et al., 2001a). Costs were developed from published literature and standard cost estimation guides. Data gaps and research needs were then explored. Many communities across the country have developed user-charges – and their delivery vehicles, stormwater utilities – as the primary funding source for expanded maintenance and new infrastructure (Rose 2001). With the implementation of a new funding source (e.g., user fee or special assessment) for stormwater management programs, a municipality imposes a new financial burden on the public (McClelland 2001). Therefore, the key to a successful stormwater utility implementation is public approval. The article presented methods for public education and approval, particularly the shift in focus from the fees to the stormwater service the new revenue will provide. Sound rate methodology should draw upon key concepts from public finance, utility theory, economics, law and engineering science. Most rate structures have been built around the “runoff” theory. Within this “runoff” theory are four related but different basic models: (1) the “impervious area” model, (2) the “weighted pervious plus impervious area” model, (3) the “land use” or “density” model, and (4) the newly emerging “pollutant loading” model. Fitting a basic model to a community is largely a matter of community political context.

Hall et al. (2001a and b) reviewed EPA’s development of requirements applicable to design and permitting of wet weather flow management facilities. These include issuance of various combined sewer overflow policies, development of regulations to require elimination of SSOs, enforcement actions against municipal entities, objections to state program
permits; informal guidance to Regional Offices, and Regional Office initiatives. The paper reviewed the major inconsistencies in current program implementation, evaluated the applicable federal regulations and permit approaches, and recommended broadly, how communities with SSOs and CSOs should approach state and federal agencies to resolve these matters. Salo (2001) reported on the comprehensive assessment of the City of Atlanta’s water and wastewater operations. Internal and external management approaches were considered after it was found that a substantial rate increase would be required to fund a Capital Improvement Program. The adopted plan combined approaches through contract operation of the entire Water System, contract operation of the largest wastewater treatment plant, and reengineering of the other City wastewater and sewer operations.

Present worth is often used to select among alternatives in the public works arena (Bate et al., 2001). This is adequate if the options are technically equal and operations and maintenance costs are controlling, but it overlooks are intangible criterion such as social impacts, meeting the design criteria, construction, traffic and utility impacts, constructability, as well as service life and reliability. “Paired comparisons” allow comparisons of intangible criterion that impact the project. Case histories illustrated the use of the “paired comparison” process. Booth et al. (2001) reviewed a survey of residents in the Oak Creek and Menomonee River watersheds, both located in Milwaukee County, Wisconsin to determine the willingness to support ecological restoration of urban streams. One purpose of the project was to assess the willingness to pay (WTP) of urban watershed residents for urban stream restoration and to identify the underlying economic, psychological, and social motivations for WTP. The basic hypothesis tested here was that psychological variables, environmental attitudes, and ethical values are more important than strictly economic phenomenon.

In the future, systematic and ongoing asset management programs are expected to influence evaluations by bond rating agencies, budget allocations, decisions by enforcement authorities, and acceptance of rate increases (Morgan and Wagner 2001). This approach incorporates life-cycle analysis, longer planning horizons and more intensive tracking of asset conditions. Of the nine primary program components in the CMOM/SSO guidance, most are related directly or indirectly to asset management activities. The privatized operation of the Milwaukee Wisconsin, sewerage facilities has lowered costs of operation ($14 million per year) and increased service performance (Tobel and Jankowski 2001). Additional benefits include increased asset and performance accountability and state-of-the-art operations and maintenance (O&M) technologies. The Kansas City Missouri Water Services Department (WSD) developed a Competitive Business Plan (CBP) (Salo and Turner 2001). The CBP identified how WSD will improve service levels and minimize annual operating costs. Implementation of this CBP will require significant additional capital investment. O&M savings are expected to be between $129 and $217 million over the next 10 years.

New federal funding sources have become available in the US for WWF control activities. The proposed budget for the U.S. EPA in fiscal year (FY) 2001 will continue the agency’s efforts to reduce funding of traditional clean water infrastructure and boost spending for projects addressing nonpoint source pollution (Calamita 2000). The Water Pollution Program Enhancements Act of 2000 ($ 2417), introduced to congress in April 2000, would significantly increase federal funding for states to implement programs to address nonpoint source pollution, to assess the quality of their rivers and streams, and to collect the data needed to prepare TMDLs (Anonymous 2000d).

Several authors examined the costs of stormwater and non-point source pollution control programs. Butt and Brown (2000) report that over $3.5 billion were spent toward nutrient controls in the Chesapeake Bay watershed between 1985 and 1996. Despite nutrient reductions, no significant improvements in dissolved oxygen levels at the bottom of the Chesapeake Bay were detected along the Bay mainstem during the warmer months, and the mouth of Bay showed marginally significant degradation during the 11-year-period. It was determined that dissolved oxygen conditions were influenced more by nitrogen than phosphorus reductions and that nutrient controls aimed at the mid-Bay region had the greatest potential for improving low dissolved oxygen conditions in the Bay's bottom waters. Fan et al. (2000a) presented a critical review of information on the costs of stormwater pollution control facilities in urban areas, including collection, control, and treatment systems. Jorgensen and Syme (2000) examined contingent valuation (CV) surveys that were used to evaluate public support for stormwater pollution abatement efforts. Their study revealed that attitude toward paying underpinned protest beliefs regarding the role of government in stormwater management and individual rights to unpolluted waterways. They cautioned that censoring protest responses in the present study would bias CV samples toward those individuals who were favorably disposed toward paying for environmental public goods and those from higher income households. Kalman et al. (2000) explored the potential value of benefit-cost evaluation for stormwater quality management decisions at a local level. A preliminary benefit-cost analysis screening method was used for a maximum extent practicable (MEP) analysis, identifying promising management practices, and identifying societal and economic tradeoffs for local stormwater problems. In the case of Ballona Creek, a major urban storm drain in Los
Angeles, California, USA, benefit-cost analysis was found to be useful for evaluating and understanding stormwater management alternatives despite the uncertainties in characterizing stormwater quality and the effects of stormwater management on improving receiving water quality (Kalman et al. 2000).

The Clean Water State Revolving Fund is the United States’ largest source of continuing financing for water quality projects. The 50-state managed funds are specifically authorized to, among other things, finance nonpoint source water quality projects that implement the states’ nonpoint source water quality management plans that they have developed pursuant to Section 319 of the federal Clean Water Act. Steinborn (2000) described the Clean Water State Revolving Fund program and discusses potential uses of the funds for nonpoint source water quality projects. The Minnesota Legislature commissioned a six-month study to investigate the framework for a cost-benefit model to analyze water quality standards through a watershed-based approach that evaluates both point and nonpoint pollution sources (Laws of Minnesota 1998, Chapter 401, Section 59). Although watershed management has been practiced in Minnesota for decades to protect and restore water quality, this study was undertaken because of the growing understanding of the complex and often conflicting choices facing those who live in, use, and manage watersheds if watershed integrity is to be maintained over the long term (Ward 2000).

The costs for controlling sanitary sewer overflows (SSO) and combined sewer overflows (CSO) have also been examined. A problem common to many SSO equalization facilities was that the planning level cost estimates were significantly less than the final implementation costs. Keller et al. (2000) presented guidance for developing the costs of SSO equalization facilities so that their cost-effectiveness can be properly evaluated during the planning phase. New regulations governing discharge of untreated combined sewage (defined as wastewater consisting of both sanitary and storm flows during rain events) to the nation’s receiving streams have challenged the traditional methods for determining cost responsibility and sewer rates for municipal wastewater utilities for the City of Detroit and Southeastern Michigan (Foster and Fujita 2000). A number of asset management tools and techniques that have been used in utilities, including wastewater utilities, were discussed by Morgan and Wagner (2000). The authors outlined a new approach for integrating these tools called Infrastructure Capital Assets Management (ICAM). The approach included modeling tools, decision support tools, and rational methodology to provide decision-makers the tools needed to develop strategies and justify retaining revenues as part of informed management of their assets (Morgan and Wagner 2000). Spartanburg Sanitary Sewer District (SSSD) in Spartanburg County, South Carolina, experienced rapid growth during the last decade, occurring primarily in rural areas. This growth created a demand for investments in all types of infrastructure. Through the use of an innovative and unique financing structure, SSSD was able to raise the required capital to finance significant sewer system improvements with minimal rate impact on existing customers, while contemporaneously improving wastewater treatment facility permit (“NPDES”) compliance and reducing pollutant loading into area streams (Rich et al. 2000). In January 1998, the Milwaukee Metropolitan Sewerage District approved a ten-year Operations and Maintenance service contract with United Water Services. Tobel and Jankowski (2000) discussed the ongoing success of this award-winning project.

A survey conducted by the U.S. EPA showed that $140 billion is needed to build, upgrade and maintain publicly owned WPCP and control stormwater and other runoff sources during the next 20 years (Christen, 1998). The mid-1999 extension of the U.S. EPA’s stormwater protection scheme to 3 600 cities with populations below 100 000 will involve considerable cost. These “Phase II” cities will have to implement BMP in six different areas to receive the stormwater permits. According to the U.S. EPA, BMP implementation will cost between $19.5 million and $351.4 million per year, besides project start-up costs (Barlas 1998). Experiences from the city of Malmö, Swed. have shown integrated stormwater facilities are cost-effective means of achieving both quantity and quality control of urban stormwater runoff (Larsson and Kärppä, 1998). The Comprehensive Stormwater Management Plan (CSWMP) was initiated to bring various stormwater issues together so that an effective and economical policy framework and management approach could be developed for the city of Eugene, Oreg. (Andersen, 1998).

England (1998a) evaluated maintenance costs of BMP including wet ponds, dry ponds, exfiltration and infiltration trenches, porous pavement, baffle boxes, inlet weirs, grate inlet baskets, curb inlet baskets, and sediment sumps. In order for stormwater retrofit projects to successfully remove pollutants on a long-term basis, the type of maintenance needs should be considered in their design and construction. Baffle boxes were found to be effective for removal of sedimentation in small to medium size drainage basins when installed inline with existing pipe and required minimal easements and utility relocation, while grate inlet baskets and curb inlet baskets are more appropriate for small flows and drainage basins (England, 1998b). The tradeoff for these low-cost treatment methods are the perpetual maintenance expenses.
A case study of Ballona Creek in L.A., Calif. (Wilchfort-Kalman et al., 1998) showed that benefit-cost analysis helped in stormwater quality management decisions. Flexible CSO facilities that integrated the controls into the whole system have the greatest potential for cost savings from the tradeoff potential between centralized and de-centralized treatment and between the storage and treatment level (Geiger, 1998a and 1998b). Switalski (1998) documented the Hilltop Interceptor Contract for Greater Cleveland (Ohio) from its beginning in 1991 to its completion in 1993. Six biofilters each 1 m (3 ft) deep with a treatment bed 27 m (85 ft) long and 8 m (25 ft) wide will be used to counter odor problems on the Heights-Hilltop and another interceptor with maintenance costs including periodic replacement of the substrate projected at $0.6 million per biofilter. Up to 18,400 Singapore dollars a month could be saved in the north spine of the Republic of Singapore with the use of a dual-mode system (DMS) which uses collected rooftopwater for nonpotable uses. This amounts to 12.4% the current average monthly expenditure on water (Appan, 1998).

In Columbus, Ohio, (El-Hosseiny et al., 1998a) uncertainty of model results increased as model complexity decreased for small and medium storms (25—50 mm/d), however system performance was unpredictable for high hourly intensity, e.g., 100 mm/h. In determining the optimal complexity level, there was no difference between using total cost of an alternative versus design costs plus uncertainty costs. The city of Indianapolis, Indiana performed traditional sewer system evaluation surveys to eliminate I/I, costing between $8.20 and $9.80/m ($2.50 and $3.00/ft). An alternative approach addressed wet weather collection system overflows in two phases costing $2.80 and $1.50/m ($0.85 and $0.45/ft), respectively (Westropp and Bellucci, 1998). A Nashville, Tenn. study indicated that an I/I removal of approximately 14 700 m³/yr /100 m of lining may be expected from rehabilitating deteriorated sewers (Kurz et al., 1998).

The U.S. EPA (1997g) published a catalog of Federal funding sources for supporting local governments to implement watershed projects. Financial capability, along with other factors listed, may be used to negotiate reasonable compliance schedules for implementation of CSO controls (U.S. EPA, 1997h). Austin, Tex. implemented a trenchless-sewer technology, the installation of U-liners. Along with a new maintenance agreement, this will permit the city to repair approximately 35,000 ft/yr and reduce its per foot sewerline-rehabilitation cost by 44% (Water Eng. Manage., 1997a).

A general Benders'-decomposition model, which deals with solving mixed-variable problems, was developed to optimize the repair and replacement strategy for a sewer network. The model determines the least-cost solution by minimizing combined-wastewater treatment and repair associated with I/I (deMonsabert and Thorton, 1997).

Sarnia, Can. planned to upgrade its WWTP, to install four CSO-storage tanks, and to intercept stormwater runoff to upgrade, restore, and protect water quality in the St. Clair River. The first CSO tank has been installed with a cost-effective-cleaning system (Parente and Stevens, 1997). Underflow baffles were identified as a potentially cost-effective alternative for controlling CSO floatables at relatively inactive CSO outfalls by the Massachusetts Water Resources Authority. A study indicated that underflow baffles could provide up to 70% capture of floatables under a wide range of flow conditions (Walker et al., 1997).

Battenfield et al. (1997) revealed some of the lessons learned in the development and implementation of a cost-effective solution to control the excess WWF of the Houston, Tex. sanitary system. Ahyerre et al. (1997) summarized three main difficulties of sewer-quality models, i.e., doubtful mathematical formulation, uncertainties on input and calibration data, and difficulties and cost of calibration. They further recommended that a clear distinction be made between management tools and research models.

Cost analysis. Onsite detention (OSD) of storm runoff decreases catchment peak flows through the routing effect of temporary storage; onsite retention (OSR) achieves the same objective by abstracting part of the urban flood wave and passing the retained water to disposal on site. Comparisons were made on the basis of site storage required (SSR) to achieve the same global peak flow reductions, environmental aspects and cost. OSR practice was shown to out-perform OSD generally in medium-large (14 ha to 210 ha) catchments with respect to SSR and, hence, cost; however, Scott et al. (1999) cautioned against use of OSR in unsuitable circumstances.

Koch et al. (1999) described an approach to the determination of flood frequency as a function of moneys that could be spent to address a road flooding problem caused by runoff from a 2-m² residential area near Washington, DC. Flood mitigation options included both culvert resizing and the provision of detention areas upstream. Challenges faced in completing this project included establishing a practical limit on the number of detention sites to be considered, and right-of-way issues in an area fully developed for single family homes.
Kreeger et al. (1999) presented a methodology for determining drainage system costs as the function of design storm recurrence interval. The Manning equation and sewer and swale cost data were combined to yield a relationship giving the cost per unit length of sewer or swale as a function of design flow. A typical residential development was created and a stormwater modeling computer program (Rational Method and Manning equation) along with derived cost functions were repeatedly used to design and cost the drainage system for a range of recurrence intervals.

Mangarella et al. (1999) described the retrofitting of a flood control basin in Sunnyvale California and subsequent monitoring to evaluate the pollutant removal cost effectiveness of the retrofitted basin. Costs, and particularly benefits, of WWF control were often hard to quantify. Bond (1999) examined the benefits of basic infrastructure investment - water and sanitation systems, new electricity lines, roads, stormwater drainage, and other services provided at municipal level - to South African society. The direct economic benefits of infrastructure for low-income people have long been recognized, and include construction jobs, improvements in work productivity; and the growth of small enterprises. Indirect benefits include more time and resources for women; dramatic environmental benefits, public health benefits (which require infrastructure of a sufficient quality so as to enhance rather than endanger health), and the desegregation of urban society (with respect to enhanced employment, educational and cultural opportunities). McDonald and Johns (1999) use an example from Bogotá, Colombia to demonstrate how Social Benefit-Cost Accounting (SBCA) can be used to value the benefits and costs of a watershed restoration and protection project. By addressing the benefits and costs to all stakeholders, the design of watershed management programs can be improved to achieve goals in a cost-effective manner.

Rein (1999) evaluates environmental costs and benefits of implementing vegetated buffer strips (VBS) at Elkhorn Slough, Monterey Bay, California, both to the grower and to society as a whole, as a means of capturing nonmarket ecosystem values and informing decision making. The results support installing VBS as a management strategy in an erosion-prone watershed to protect water quality and preserve soil fertility, as well as to protect economic interests.

Various authors examined the costs and benefits of new or rehabilitated sewer and storm drainage systems. Backstrom et al. (1999) compared resource use in a conventional buried pipe system and a grassed swale system. Based on usage of both physical and financial resources, the grassed swale was a more economic alternative than the pipe system in areas with moderate land prices. Hasegawa et al. (1999) presented a system for assessing the need for repair and improvement of sewer pipe networks based on; 1) Decrease in flow capacity of the sewer pipe, 2) Possibility of road collapse, 3) Sewer overflow and flooding by Infiltration/Inflow (I/I), 4) Increase of treatment cost by I/I. Hirai et al. (1999) applied the Analytic Hierarchy Process procedure to prioritize portions of a drainage system reconstruction project. This system was effective because it can take into account both quantitative and non-quantitative measures of reconstruction needs. An analysis of historical development and present status of urban drainage in Switzerland and Germany conducted by Krejci and Borchardt (1999) clearly indicated that according to identified problems the current practice was associated with a high risk of misdirected investments and was not consistent with optimum system operation. The authors identified research objectives and conclude that for the near future cost efficiency should be an important issue in urban drainage. Prato (1999) presents multiple attribute decision-making (MADM) as a means of evaluating and selecting land and water resource management systems (LWRMS). Advantages of MADM were that it facilitates community-based collaborative decision making, avoids some of the ethical, theoretical and practical shortcomings of conventional economic approaches, does not require assigning monetary values to ecological services, allows consideration of multiple attributes and was not culturally biased.

McCleary (1999) discussed the costs and savings of the stormwater banking approach adopted by DeiDOT and provided useful information regarding program implementation. Doll et al. (1999) provided examples of stormwater utilities with credits for onsite stormwater management, including credits for peak runoff controls, implementation of water quality BMP, and proper maintenance of onsite stormwater facilities.

Taxes or charges for stormwater discharges were becoming a more widespread method of funding WWF control efforts. The Augusta (Maine, U.S.A.) Sanitary District was facing a projected capital expenditure of roughly $30 million for CSO abatement alone over the next fifteen years. Recognizing that the costs for wet-weather controls could not be equitably distributed using its current system of charges, a new system was developed during 1998 and implemented in 1999 which took into account impervious areas as a means to generate appropriate levels of stormwater-based revenues (Freedman et al. 1999). Haarhoff (1999) reported on the introduction of a rainwater tax on runoff from sealed surfaces into receiving waters that was implemented by the Land (German Federal Region) of Schleswig-Holstein. The reactions of the communal authorities and their administrators responsible for the disposal of the wastewater including rainwater, and the level of success achieved by the District Water Authority in enforcing the creation of facilities for the treatment and
retention of surface runoff was discussed.

The greatest obstacle to implementing a storm-drainage plan is often lack of funds to support construction and operation of drainage facilities. Fort Bend County, TX created financial alternatives by issuing tax-exempt-revenue bonds and collecting impact fees to finance its drainage-improvement projects (Gilligan, 1996). Financing a stormwater-management program is a challenge for local governments. Collins (1996) described detailed plans for basinwide-capital-improvement plans for implementing a stormwater-management program. The establishment of an urban-stormwater-utility authority is one of the important alternatives for funding the implementation of stormwater-pollution-control systems (Benson, 1996; Reese, 1996). Roesner et al. (1996) described a stormwater-master plan that formulates an integrated way to finance necessary stormwater infrastructure for a new development near Orlando, FL. The EPA’s Environmental Financial Advisory Board (EFAB) and Environmental Financing Information Network (EFIN) are valuable sources for creating a financing strategy for implementing Comprehensive Conservation and Management Plans (Henkin and Mayer, 1996). The EPA State Revolving Fund provides loans to local governments for financing surface-water-related infrastructure projects with 0% interest rate and could cover 100% of eligible costs (Singelis, 1996). In New Jersey, funding for CSO projects is provided through a grants- and low-interest construction-loan program jointly administered by the New Jersey Department of Environmental Protection and the New Jersey Wastewater Treatment Trust (Binder, 1996). The mechanisms used by Prince William County, VA to fund its Watershed Management Program include a county-wide-stormwater-management fee, development fees, and grants and cooperative agreements (Pasquel et al., 1996).

The purpose of cost-benefit analysis of environmental projects is to assure that any development project with net environmental cost be off-set by projects with net environmental benefits. In reality, the processes are complex and their credibility is subject to question as a decision-support tool (George, 1996). A newly developed stormwater-management strategy (Mulden-Rigolen-system) that was designed to be both an ecologically and socially acceptable stormwater-drainage method was demonstrated and evaluated in the City of Zwickau, Germany (Huhn, 1996). Rudolph and Balke (1996) analyzed the cost-benefits of the new alternative stormwater-management systems for new residential developments in the cities of Dortmund and Zwickau, Germany.

Control and Treatment Technologies

The paper by Shaver and Ridley (2002) discussed a number of tools that were recently developed to reduce stormwater-related impacts. These tools could include low impact design approaches from an individual and comprehensive catchment perspective, recognition of urban stream values, offsetting mitigation approaches when adverse impacts are unavoidable, and the establishment of regional criteria for stormwater discharges.

Growing demands on drainage still challenge designers with respect to runoff quantity and quality; landscape aesthetics, ecology and beneficial uses; and operation of existing urban wastewater systems (Chocat et al., 2001). Integrated approaches, optimal operation of the existing infrastructure, advanced pollution and runoff source controls, improved resilience of receiving waters, and adaptive water management can achieve further advances in water quality protection. Specific research needs include new technologies and strategies for stormwater management, advanced treatment of urban wet-weather effluents, and tools for analysis and operation of drainage systems. Smith et al. (2001a) investigated a range of process technologies to assess their suitability for the treatment of different water sources for non-potable reuse. For this study, a large scale water reclamation evaluation and demonstration facility was constructed at the Millennium Dome, London, UK. Greywater, rainwater and poor quality groundwater were treated by a combination of processes including biological oxidation, constructed wetlands, chemical oxidation, adsorption, ultrafiltration and reverse osmosis. Chemical and bacteriological results for each process were presented and discussed.

The WERF report on controlling pollution at its source documented the application of effectiveness measurement tools at demonstration projects that controlled wastewater and stormwater pollution at its source (WERF 2001a). The report described the demonstration projects, the tools tested, identified the costs involved, and assessed the feasibility of measuring a source control program’s impact. The Minnehaha Creek Watershed District has funded a multi-component project focused on improving the water quality in Lake Nokomis (part of the chain of lakes in Minnesota) (Hettiarachchi et al., 2001). The project components included constructed wetlands and grit chambers to treat runoff from surrounding residential neighborhoods, an inflatable weir to prevent Minnehaha Creek water from flowing back into the lake, and rough fish removal and alum treatment to reduce the internal phosphorus loading.
Patty and Ahmed (2000) described the watershed assessment and protection plan being implemented in Peachtree City, Georgia, including both wet-weather and dry-weather sampling. These samples were to be used to ensure that standards are met and for model verification, where the model will be used to anticipate impacts from land development in the water.

Stinson et al. (1999) presented an overview of the EPA’s Environmental Technology Verification (ETV) program which was established to overcome the numerous impediments to commercialization experienced by developers of innovative environmental technologies. The purpose of ETV was to provide such data and information to the customer groups that require them in order to accelerate the real world implementation of improved technology. This publication described the ETV approach and two recently initiated pilot programs for verification testing of WWF and source-water protection technologies.

A case study was reviewed which applied urban design planning for a commercial redevelopment project in the City of Vista, California involving the replacement of a 1950 concrete flood control channel into a restored natural “river walk” linear park. The proposed creek restoration would provide the focal point for an economic revitalization of the downtown area that includes restaurants, shops, and entertainment center, with the creek providing the common linkage (Phillips, 1999). Wong et al. (1999) discussed the various issues and performance considerations associated with the comparisons of ponds and wetlands for stormwater pollution control. Ponds and wetlands were commonly used in urban design to meet a number of urban planning objectives including the management of urban stormwater for water quality improvement.

Brashear et al. (1999) described a project to deliver stormwater management information through the World Wide Web. The Texas Nonpoint SourceBOOK was a Web-based stormwater quality guidance document for public works professionals in the State of Texas. The SourceBOOK allowed users to access a wide variety of stormwater management information including the applicability and cost-effectiveness of stormwater management practices, legal authority issues, funding mechanisms for stormwater programs and local water-quality information. Most importantly, a database of over 100 BMP was available for users to access, allowing a diverse audience to become familiar with BMP principles and application procedures (sizing, design principles, etc.).

The site planning and design phase of land development projects presented the best opportunities for, and was critical to, reducing the impacts of development on the quality of the nation’s waters. Recognizing the need for guidance in site planning and design, the San Francisco Bay (California) Area Stormwater Management Agencies Association (BASMAA) published the document “Start at the Source - Residential Site Planning and Design Guidance Manual for Stormwater Quality Protection” and a second edition in 1999 that also included guidance for industrial and commercial development. The manual communicated basic stormwater management concepts and illustrates simple, practical techniques to preserve the natural hydrologic cycle (Richman and Bicknell, 1999).

**Drainage Design and Hydraulics**

Funayama et al. (2002) reported on the approach of the Tokyo region for using storage pipes and interconnecting network pipes to provide storage and prevent flooding, with the result being that this approach was cost-effective. Woods et al. (2002) reviewed the balancing of the water budget in the Ipswich River (Massachusetts) watershed. The framework of the “water balance” policy is a no net loss policy for water resources within the watershed, which will require each town to develop a hydrological budget. The tools under consideration to achieve this goal are water conservation measures, increasing stormwater recharge from new development within the basin at a 2:1 or 3:1 ratio, protection of recharge zones, encouraging either decentralized wastewater or sewered waste to stay within the basin or importing sewer from outside the basin.

As part of the Clean Water Act, EPA required local governments to control urban storm water runoff (Ports 2001). asked the General Accounting Office (GAO) to report on the amount of runoff from urban areas, particularly from roads and other impervious surfaces, and its effects on water quality, and to perform an overall evaluation of the urban runoff control programs that federal regulations require, including their cost and effectiveness. The results from the GAO evaluation were summarized in a report titled, “WATER QUALITY, Better Data and Evaluation of Urban Runoff Programs Needed to Assess Effectiveness.” The paper by Pazwash and Boswell (2001) presented an overview of design methodology of various stormwater management systems, including detention basins, wet ponds, infiltration beds and underground detention/retention chambers. It discussed shortcomings in design and recommended improvements. The paper also described differences in local and state stormwater management regulations in New Jersey and offered suggestions for unifying the regulations.
Parsons Engineering Science, Inc., as part of an EPA project, reviewed industry and state practices for sizing both new and rehabilitated sanitary sewers (Mauro et al., 2001). Several new tools for estimating peak flows with reflect current technology and water use habits were identified. The research has found that peak flows in sanitary sewers depended on a complex set of variables. Tools used by communities to evaluate the operation of sewer systems were identified through interviews with experienced practitioners, research on federal and local regulations and industry guidance documents. The wastewater industry has been performing detailed I/I studies for the past 25 years (Lyon and Nelson 2001). The lessons learned can be applied to sanitary sewer design criteria to reduce the future occurrence of SSOs. Data from I/I studies for 20 wastewater agencies in six states (Kansas, Kentucky, Minnesota, Missouri, Ohio, and Texas) were compared, and guidelines for appropriate sewer design criteria were developed. Due to the complex hydraulics in the vicinity of the Jackson Pike WWTP and as part of the West Columbus (Ohio) Local Protection Project (WCLPP), a detailed dynamic model was developed to assess the sewer system performance under different operating conditions (El-Hosseiny et al., 2001). The model used the sewershed approach to maximize system storage without affecting the current services and to satisfy the regulations. The sewershed approach and the developed model allowed the determination of the optimum operating conditions by maximizing in-line storage while meeting all required constraints (e.g., overflow, pumping capacity, control flow devices, sewer capacity). The paper by McConico et al. (2001b) described a mechanical flushing system located in the confined space of the CSO Outfall Structure for the Shockoe Creek Basin in Richmond, Virginia. Over time, deposition of solids in the twin river crossing has reduced the flow capacity of the inverted siphon pipelines, reducing transfer capacity to the wastewater treatment plant. The mechanical flushing system was designed to store and release a large volume of wastewater to flush the twin river crossing with a high volume, high velocity stream while avoiding accidental releases of dry weather overflow to the river.

Many areas in the United States have established stormwater detention pond ordinances that require the postdeveloped outflow from a site to discharge at a rate equal to or less than the predeveloped peak flow rate (Glazner 2001). The impacts of increased stormwater runoff volume due to development were reviewed. Using a hypothetical catchment in Chicago, Illinois, Guo (2001b) compared three different approaches for the hydrologic design of flood control detention ponds that service urban catchments: (1) design storm approach; (2) continuous simulation approach; and (3) analytical probabilistic approach. While all three approaches generated similar results, the results from the design storm approach were shown to vary by 40% to 50% depending on the choice of models and design storms. The results further verified the suitability of the analytical probabilistic approach for the hydrologic design of urban flood control detention ponds. Hsieh et al. (2001) evaluated the flood mitigation performance of various long-term regulated plans (protecting banks, pumping stations, diversion works, and retention reservoirs) for the middle-upstream of Kee-Lung River Basin in northern Taiwan through simulations of both 1-D unsteady flow and 2-D overland flow. The models evaluated the flood mitigation effect of each measure based on three criteria, including flood stages, runoff peaks, and inundation depths and ranges. The results showed that none of proposed regulated plans was best at resolving the flood and inundation problem. Storm water detention pond design is frequently part of each site or land development project (Ovcharovichova 2001). One critical aspect of the design is the determination of the boundaries of drainage areas for both existing and future conditions. The paper compared two different models of the same pond, with the only difference being in the existing and future drainage area delineation. Consequently, the results are different. The paper suggested which approach should be preferred to simulate the basin as it truly functions in the field. The paper by Wong (2001) contended that for drainage design to be based on a consistent theory, the kinematic wave time of travel formula for channel flow ought to be used in conjunction with the kinematic wave overland time of concentration formula. The paper contains the kinematic wave time of travel formulas for channels of seven different cross sections. A model of a hydrologically isolated section of the M6 motorway in the United Kingdom was used to calculate the times of travel in a channel with a vertical curb section for rainfall intensities ranging from 20 to 100 mm h\(^{-1}\). A comparison of the time of travel estimates from the computer model, and from the time of travel formula, shows that the differences are less than 5%. The derived time of travel formulas could be used to design drainage channels whose properties fit the kinematic wave approximation.

An exponential relationship exists for underflow baffles between the vertical velocity and the turbulent component of the horizontal velocity. Dimensioning analysis indicated that long chambers with intensive designs would be required for an 80% floatables removal efficiency (Cigana et al., 1998a, 1998b and 1998c).

A nine year, $186 million rehabilitation program in Dallas, Tex. used trenchless technology for the smallest pipes and 3 m (120 in.) diameter diversion pipes with the ability to throttle flow (Almeida, 1998). During wet-weather events the city now has the ability to fill pipelines in the wastewater collection system without creating overflows. The Rouge Project used several methods to identify illicit connections. Data suggested there were 5 260 illicit discharges and 3 600 failing
on-site sewage systems in the watershed (Johnson and Tuomari, 1998). Evanston, Ill. conducted a large-scale project to reduce the frequency of backups of combined sewers into residents’ basements. An inlet control project increased the protection against basement backup to 50 to 100 year recurrence levels while significantly lowering cost (50%) over traditional solutions (Figurelli et al., 1998). A study conducted in the city of Salem, Oreg. revealed modification of interior plumbing of homes and installation of backwater valves, and the modification of the interior plumbing of the homes and installation of new service and ejector pumps the most effective solution to flooding of residential basements with raw sewage during storm events (Roley, et al., 1998).

In Houston, Tex. a 15% reduction in the peak rainfall-dependent I/I was factored into the design of all overflow control projects as a credit for I/I estimated to be eliminated by structural rehabilitation. Because of the inherent variability of I/I, response in sewer systems flow reductions due to rehabilitation generally cannot be definitively quantified and at best, a range in reduction can be established (Samson et al., 1998). A slipline pipe was installed on the NORSD Westerly Interceptor project (Dell’Andrea, 1998) to relieve I/I and exfiltration at a cost significantly less than a total replacement would have been. A slightly smaller diameter pipe section is inserted inside the existing sewer and the annular space between the two is filled with grout. Montgomery, Ala. monitored the rehabilitation of manholes in a sanitary sewer system and found that a cementitious mortar, in places covered with a coal-tar epoxy liner effectively sealed out I/I from the system (Holmberg and Rowe 1998). Their experience also indicated that proper surface preparation is vital to ensure adhesion between the mortar and substrate for lasting benefits of the work. The NORSD assessed the condition of the interceptors and CSO (Duke and Knott, 1998). Guidelines for manhole and pipeline defect classification were established and procedures for condition assessment were also developed. Anderson and Curtis (1998) discussed how a hydraulic model can be developed that will ensure the level of accuracy that should be required as part of any hydraulic evaluation of wastewater piping systems involving technologies such as the Global Positioning System (GPS).

Because SSO and CSO pumped-relief force mains are normally emptied after use to prevent odors and deposition, the volume of air to be vented with each start up may exceed the capacity of typical air relief valves. Typical air relief designs include venting of full force mains where small amounts of entrained air are vented from the pipe while operating at the design working pressure (Cavaliere and Devlin, 1998). Hydraulic modeling indicated that a 1 m (42 in.) relief siphon with a 170 000 m³/d (45 MGD) capacity for Braintree and Weymouth, Mass. should result in a 78% reduction in overflow volume per year, with number of overflows reduced from 38 to 15 (Spearin et al., 1998). Flowmeters installed in the siphon at the Green Bay (Wis.) Metropolitan Sewage District’s Fox River Crossing and at three locations along the upstream interceptor sewer provided data used to develop projected peak flows to be expected during design storms ranging from 5 to 50 year frequencies. The evaluation showed that the siphon’s existing capacity was inadequate to handle the projected peak flow from even a five-year storm (McCarthy and Blauvelt, 1998). Although traditional studies interpreted Bellmans Creek near Jersey City, N.J., to be dominated by tides, Sela (1998) found that fluvial flooding from storm runoff was dominant on most of its length and that the corresponding design flood level exceeded estimates of previous studies by approximately 1 m (4 ft).

Several days of heavy precipitation induced flows which exceeded the capacity of pipes and basins at a site in Wash., causing a road failure, and 227 000 m³ of wastewater were discharged to Puget Sound. Emergency measures were undertaken to repair the damage within three weeks of the failure (Langer et al., 1998). An underground utility in Lynchburgh, Va. was restored to full capacity after a blockage was removed. Before the cleaning, any rain longer than ten minutes would cause raw sewage to bypass into the Blackwater Creek and James River (Water Engineering and Management, 1998). Stop-ups or backups caused by trash or grease accumulations have a significant probability of being caused by backwater effects in the collection system, rather than by illegal discharges (Conelgiano, 1998). Gow (1998) reviewed the NORSD wastewater collection system which includes 334 km (207 mi) of intercepting sewers within the boundaries of Cuyahoga County, Ohio.

Faced with declining water quality as a result of uncontrolled inflow of poor quality runoff from within the watershed, managers of Sweetwater Reservoir opted to construct the Sweetwater Urban Runoff Diversion System (URDS), a diversion system to intercept and divert poor quality runoff upstream of the reservoir and convey it downstream of the reservoir (Bottcher et al., 1998).

Roesner (1998) discussed the impact urbanization has on water runoff intensities and effects to the receiving waters. A guidance manual for WWF drainage systems in newly urbanized areas is being developed and will examine the history of WWF management and present some recommended strategies for newly developing areas (Pitt et al., 1998a). A related study (Heaney et al., 1998a and 1998b) presented some highlights of the initial phases of innovative urban stormwater
managements systems for the 21st century with results of an extensive literature review and preliminary evaluations of alternative future scenarios. The development of a combined sewer network for new urbanized areas, associated with inline retention and RTC was cheaper than separate sewers (despite provincial regulation providing new urban developments have separate sanitary and storm sewers) and reduced the impact of stormwater to the environment for Montreal, Can. (Charron et al., 1998).

The drainage system of Port St. Lucie, Fla. is made up of roadside swales, a series of drainage right-of-ways, and canals and waterways that eventually lead into the north fork of the St. Lucie River. To address swale drainage problems, the city purchased various types of all-terrain excavators including three 'Swamp-Meisters' which have large, powerful mulching/cutting heads (Thacker and Gonzales, 1998).

Grace (1997) described four case studies of marine-outfall rehabilitation and maintenance where obstructions had caused serious problems in wet-weather- and wastewater-effluent drainage. Larsen et al. (1997b) reported that after construction costs of 6.8 million dollars for regional-sewer rehabilitation in the Broward County, Fla. Southern Regional Wastewater Collection System, I/I is still a problem. The repair project eliminated 5.64 million gallons per day (mgd) of extraneous flow but an estimated 10.5 mgd still enters the system. An evaluation of eight basins in Seoul, Korea revealed that every five meters the sewer systems needed repair and this was made worse by I/I, resulting in poor operation of the WWTP. Trenchless-rehabilitation technology was recommended as a solution (Parks, 1997). Guajardo and Gogers (1997) developed a roadway drainage plan with improvements on existing discharge flows to the receiving stream in the Houston, Tex. Pazwash and Boswell (1997) presented specific methods to collect and use roof runoff for lawn and landscape watering, car washing, and deck and driveway cleaning.

Bhaskar et al. (1997) used a physically-based-rainfall-runoff-estimation method. The geomorphological-instantaneous-unit hydrograph (GIUH) estimated flooding from wet weather and obtained results comparable to observed events. Bonta (1997) derived frequency distributions as an alternative method for determining watershed curve numbers from measured data, treating rainfall and flowrate data as separate frequency distributions.


Burrows et al. (1997) reported on the development of a low-cost system based on monitoring the behavior of flap valves on numerous major outfalls along the Thames River in the United Kingdom. The modeling approach was based on the principle of conservation of angular momentum and its application to experimental data for circular gates. The recommended calibration offered ± 20 — 30% flow prediction accuracies for gate openings angles > 20°.

Djebbar and Wisner (1997) compared three unit hydrographs based on the ability of each to reproduce observed stormwater runoff in urban watersheds that had different hydroclimatic conditions. The study addressed the frequently reported problem of time-step selection in hydrological modeling. Pruski et al. (1997) developed a procedure to determine the maximum-surface-runoff (MSR) volume by employing a constant infiltration rate after prolonged wetting of the soil. This procedure is applicable where the rainfall intensity/duration/frequency relationship is known.

Holmberg (1997) addressed the techniques for proper project execution and quality control when applying cementitious coatings (in a sewer environment) performed in a sewer-basin-manhole-rehabilitation project in order to meet three goals: the elimination of I/I, limited structural rehabilitation, and general corrosion protection. Rajaratnam et al. (1997) performed physical-model studies on the hydraulics of stormwater-dropshafts. The energy loss in the dropshaft was about 80% — 95% of the total hydraulic loss.

O’Loughlin et al. (1996) presented examples of design problems and research and development work on small stormwater drainage systems, relating these to scale effects in space and time. There is a potential for extending the lower boundaries of current design methods through detailed studies of small drainage systems. Blaszczyk and Ashley (1996)
presented new approaches for the design and operation of combined sewers to control sediment problems. Results from a field study conducted in Poland and how application of these criteria aids in the development of self-cleansing velocities for full and partially-full flows were discussed.

**Stormwater Best Management Practices (BMP)**
The paper by Claytor (2002) presented a common nomenclature for structural stormwater BMPs and discussed several general elements for consideration in evaluating BMP pollutant removal effectiveness in the context of TMDL assessments for urban and suburban watersheds. In addition, the results and usefulness of the Center for Watershed Protection’s BMP pollutant removal database were presented.

Clary et al. (2002) reviewed the procedures used to develop, evaluate and maintain a standardized stormwater BMP effectiveness database. The national stormwater BMP data clearinghouse continues to screen and post new BMP data to the database, as well as respond to inquiries from the public. An overview of both of the database software and results of the data evaluation were provided in this paper.

Strecker et al. (2002) presented the Urban Stormwater BMP Performance Monitoring Manual that was developed by integrating field experience of ASCE’s Urban Water Resource Research Council and the development of the ASCE/EPA National Stormwater Best Management Practices Database. The Manual was intended to help achieve stormwater BMP monitoring project goals through the collection of more useful and representative rainfall, flow, and water quality information.

General stormwater control objectives and sustainable drainage design. Vaes et al. (2002) reviewed the impact that moving storms can have on combined sewer designs. They noted that when a storm moves over an urban catchment in the same direction as the main flow direction of the sewer system, higher peak discharges and water levels often result. The paper presented a procedure to simulate moving design storms over a combined sewer system in different directions.


Reference flow and water levels meters were field verified under the EPA’s ETV Program (Pelletier et al., 2002). The accuracy of three meters was verified: one four-path transit-time flowmeter and two level meters, a bubbler and an ultrasonic level meter. The Field Testing Organization recognized that the four-path transit-time flowmeter and both the bubbler and ultrasonic level meters did not meet the accuracy requirements specified in the Generic Protocol in order to be validated as the reference meters. Nevertheless, since the results obtained using the revised flow accuracy margins and considering the low accuracy of the tracer dilution analysis, as well as the good fit with the flow rates estimated with the “flow under the gate” equation, the four-path transit-time flowmeter was validated as the reference flowmeter to verify the vendors’ flowmeters.

Silveira (2002) presented the problems of establishing modern urban drainage in developing countries, including a 19th century philosophy on drainage, legal and clandestine settlements that limit the space for the system; contamination of stormwater by sewage and garbage; climatic and socio-economic factors, including water retention for flood-avoidance and infiltration; lack of technological basis for drainage management and design; lack of interaction between citizens and the government.

Harremoes (2002) presented a review of the status and perspectives on integrated urban drainage in general and as a professional discipline. New paradigms were introduced – risk of pollution due to system failure, technology for water reuse, sustainability, new architecture and greener upstream solutions.

BMPs can range from management operations (such as street sweeping or reducing pesticides used on urban lawns) to structural treatment options (such as detention/retention ponds, swales, filter/buffer strips and constructed wetlands) (Sullivan and Borst 2001). This paper focused on structural BMPs and reviewed the state of the knowledge, the unknowns, and research programs being undertaken by the U.S. Environmental Protection Agency and other key organizations to address the unknowns.

The final report will document the effectiveness of these BMPs to improve water quality and will address BMP stability, longevity, and operation and maintenance issues. BMP manuals have been developed that address the control of urban runoff to protect receiving water quality (Roesner et al., 2001). Investigations of both design practices and effectiveness
revealed that there is a lack of knowledge in the scientific and engineering community about what constitutes a properly designed BMP and what the BMP should achieve. This paper discussed the state-of-practice in BMP design in the US and pointed out the strengths and weaknesses with respect to water protection. An approach to design criteria development for a wide variety of climatologic, topologic, and geologic conditions was recommended to protect receiving waters systems. Strecker et al. (2001) reported on the EPA-funded cooperative research program with the ASCE to develop a more useful set of data on the effectiveness of stormwater BMPs in urban development. The paper described the comparability problems encountered between different BMP effectiveness studies and the considerations that affect data transferability, such as methods used for determining efficiency and statistical significance. Finally, it recommended that effluent quality be used to measure BMP efficiency. In the paper by Yu and Zhen (2001), a methodology is developed to assist in the determination of BMPs placement strategies at the watershed level. The Agricultural Non-Point Source Pollution Model 2001 (AGNPS 2001) developed by USDA, was used for BMP placement analysis, and the relative effectiveness of BMPs at three different spatial placement levels, i.e., on-site, sub-regional and regional levels, were compared. Based on the model simulation results, a BMP placement optimization approach was developed to determine a most cost-effective BMP placement strategy at the watershed scale.

Development projects in the high-altitude mountain environment of the Rocky Mountains such as Colorado often require innovative best management practices (BMPs) due to challenging runoff conditions, the relatively short growing season, vegetation and wildlife habitat considerations, and the high level of water quality of receiving waters (Earles and Jones 2001a). This paper described a variety of BMPs and stormwater/dewatering discharge management strategies that have been successfully employed on development projects. Case studies were presented for addressing runoff from snowmelt; shallow groundwater; soil erodibility, mobilization, and suspension; water chemistry; and regulatory requirements related to water quality and wetlands protection, and included examples of structural BMPs. Yamada et al. (2001a) analyzed the mass balance of pollutants during both dry periods and storm events on Lake Biwa and discussed the effects of pollutant removal systems, land use planning and new drainage systems by simulation. The project included estimation of influent pollutant loadings from existing data, collection of additional samples from road surfaces, house roofs and parking lots, and evaluation of ongoing BMP projects. Hambridge and Stein (2001) studied a 33-acre lake in Duke Power State Park where lake water quality is deteriorating. The EPA “Simple Method” screening model was used to estimate the contribution of pollutants from each land use category, and a goal for BMPs to reduce phosphorus loadings by 34% was determined. Restoration options included dredging; developing an in-lake wetland; and carp eradication. Watershed BMPs included regional stormwater treatment; parking lot bioretention; wetland treatment at a local high school; strengthening stream buffer restrictions; agricultural BMPs; education; and septic maintenance programs. In Onondaga County, an Amended Consent Judgment required the County to perform a NPS environmental benefit project (EPB) in Onondaga Lake watershed (LaGorga et al., 2001). BMPs were implemented on three farms and at two urban sites in the Onondaga Lake watershed. The Staten Island Bluebelt Program represents New York City’s first large-scale use of stormwater BMPs to alleviate chronic flooding and provide drainage infrastructure (Vokral et al., 2001). The BMPs used by the t Program included constructed wetlands with extended detention, stilling basins, underground sand filters, and meandering streams. These BMPs were effective on a large scale (even preventing flooding during Hurricane Floyd). The enhanced wetlands and improved water quality greatly promoted biodiversity. Public support was enthusiastic and valuable educational/recreational resources and cost-effective drainage infrastructure resulted.

Low Impact Development (LID) combines hydrologically-functional site designs with pollution prevention measures as compensation for land development impacts on receiving waters (Clar 2001). This paper summarized the results of a number of demonstration projects, and introduced a strategic framework for the application of LID technology to ultra urban areas. It reviewed the hydrologic characteristics of ultra urban areas and related them to identified stormwater management goals in ultra urban areas. LID combines conservation strategies, distributed micro-scale source control BMPs, and pollution prevention to control the volume and peak runoff rate, and to treat the pollutants (Weinstein et al. 2001). LID practices can be incorporated into buildings, sidewalks, streets and landscaping. Because they are small scale, the issues associated with conventional large-scale, end-of-pipe controls, such as large-scale traffic and property disruptions, utility conflicts and large capital costs, can be avoided. The paper documented the issues and efforts of a multi-year monitoring and construction effort of the Maryland State Highway Administration (MSHA) to determine the effectiveness of LID at addressing regulatory and ecological protection goals for highway construction. The development and use of environmentally sensitive construction materials as a low-cost component to stormwater management has gained interest recently (Pitt and Lalor 2001). However, there is little data for specific alternative building materials, although information exists targeting selected sources, especially the role of roof runoff as a significant source of zinc and other metals. Relative pollutant contributions from construction materials themselves are also a concern that has not been adequately addressed. Due to the common use of these materials in the urban environment, material substitution would
seem a good place to start in implementing source reduction.

To assess the effectiveness of sedimentation and erosion controls during highway construction, the impact on water quality in adjacent wetlands was monitored (Huang and Ehrlich 2001). Downstream measurements were equivalent statistically to upstream measurements except once when erosion controls were neglected and when culverts were constructed. Attention to sedimentation and erosion controls and seasonal scheduling of highway construction were advocated to protect adjacent wetlands. Clopper et al. (2001) reported on an erosion control study that examined the benefits of two different erosion control mulches; blown straw and a manufactured biodegradable erosion control blanket. Sprinkler-type simulators were used to create rainfalls having intensities of 2, 4, and 6 in/hr. The collected data indicated that some surface cover treatments consistently reduced soil losses, while others can actually increase soil losses under some test conditions. They concluded that the Revised Universal Soil Loss Equation can be used to estimate the benefits of mulches at construction sites. Shammam and Zhu (2001) presented a state-of-the-art review of TSS removal techniques. Three main techniques were reviewed: infiltration, filtration and detention. Infiltration trenches, infiltration basins and porous pavements were the common infiltration practices. Filtration systems included filter strips, grassed swales and media filters. Wet and dry detention ponds (including polymer-assisted ponds) and constructed wetlands were the most common detention practices. The function, performance and suitability of each technique were discussed, and a comprehensive review was provided to guide the selection of a suitable TSS control technique. Levee sump systems have been used by many riverine communities for temporary storage of urban wet weather flows (Smith et al., 2001d). This paper presented a case study that demonstrated a procedure for assessing the hydraulic performance of flood control sumps in an urban watershed. A hydrologic modeling package was used to estimate the flow hydrograph for each outfall as part of the flow balance for the sump. In addition, these sumps may function as sedimentation basins. Yu et al. (2001b) monitored several ultra-urban BMPs: manhole-type treatment structures (such as the Stormceptor), a bioretention area, and the Vortechs Stormwater Treatment System. Resuspension of sediment during large storm events has been a concern for these BMPs. A cost analysis showed that bioretention might be the most cost-effective in terms of cost per unit pollutant removal. However, the bioretention area may export pollutants before the soil-plant system stabilizes.

NPDES Stormwater Phase II and TMDL regulations have placed additional pressure on industrial facilities to reduce stormwater pollutant levels by implementing source controls and stormwater treatment (Mas and Curtis 2001). This paper presented an overview of the assessment and planning phases of industrial stormwater treatment evaluations, with a focus on structural control measures for removal of dissolved metals and other industrial stormwater pollutants common to the Northeast U.S. Chang and Duke (2001a) evaluated actions taken by auto dismantling facilities in the Los Angeles, California, region to comply with industrial stormwater discharge regulations. The research evaluated a sample of complying facilities, and involved stormwater sampling at a smaller number of case study facilities. The study found that a large proportion have measured effluent concentrations that exceed U.S. guidelines for stormwater. Estimates of pollutant loads contributed by the dismantling industry appear substantial. The Ford Rouge Center complex on the Rouge River is undergoing dramatic revitalization, including substantial redevelopment of the existing plant structures and the addition of several new buildings (Houston et al., 2001). Cahill Associates developed a stormwater master plan that provides offering the facility with onsite stormwater storage and water quality improvement for the smaller, more frequent storms. A general strategy of retention and treatment through water quality swales was adopted. The two-year storm volume was used as the minimum storage volume required for each system.

The Dubai International Airport expansion plans required a stormwater management strategy that met international regulatory authority requirements, addressed time-sensitive milestones, and remained cost-effective (Darnell et al., 2001a). The stormwater management system must achieve the minimum drainage requirements and also provide a multitude of management options that could address the unpredictability of desert-climate storms. When modifications were done to the Camarillo (Ventura County), California, Airport in 1997, a high efficiency oil-water separator was installed to treat the stormwater runoff from the area where the refueling trucks were filled (Mohr et al., 2001). The system included a precast concrete separator vessel with multiple-angle enhanced gravity separator plate packs. Performance tests were performed on the system as part of the acceptance procedure. The results were presented along with the results of three year’s operations and maintenance.

A variety of projects employed stormwater control as part of a larger environmental restoration effort. Aichertner (2000) reported on a stormwater BMP program that included the construction of three stormwater treatment basins, implementation of a watershed education program, and completion of an alum injection system for removal of phosphorus from stormwater. The application of alum treatment had several unique features: its design to address treatment of base stream flows, storm event flows, and seasonal changes in stormwater temperature and pH; its off-line
innovative aquifer storage and recharge technique. After pretreatment in wetlands, this water was stored in otherwise-

stormwater and treated sewerage effluent, previously regarded as waste, has begun in South Australia through the

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of the Santa Monica Urban Runoff Reclamation Facility (SMURRF). Perkins and Shapiro (2000) reported that the City of

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diverted its major dry-weather stormwater flows from the Pico-Kenter and Pier Storm Drains to the City of Los Angeles’

In connection with efforts to restore water quality in Santa Monica Bay, The City of Santa Monica, California has

hypothetical-case study illustrating the cost-effectiveness of reclaiming urban stormwater for complete industrial supply.

Treated stormwater has been suggested as a candidate for irrigation water or similar reuses. Heggen (2000) reviews the

challenges of rainwater catchment in sustainable development. Fan et al. (2000a) discussed current urban stormwater

control and treatment technologies, and the feasibility of reclaiming urban stormwater for various purposes, including a

hypothetical-case study illustrating the cost-effectiveness of reclaiming urban stormwater for complete industrial supply.

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flows could be treated and economically reused in place of potable irrigation water and has begun design and construction of the Santa Monica Urban Runoff Reclamation Facility (SMURRF). Perkins and Shapiro (2000) reported that the City of Santa Monica, California is using both a micro- and a macro-scale approach to watershed BMP implementation. Reuse of stormwater and treated sewerage effluent, previously regarded as waste, has begun in South Australia through the innovative aquifer storage and recharge technique. After pretreatment in wetlands, this water was stored in otherwise-
united States for summer irrigation of parklands. Barnett et al. (2000) presented several case studies where the
aquifer storage and recharge technique has been successful, with savings in water and infrastructure costs, as well as
providing environmental benefits. Domestic harvesting of rainwater as a source of water for flushing toilets and watering
gardens was assessed in Berlin, Germany. Rainwater harvesting relieved demand on potable water supplies and rainwater
drainage in Berlin’s urban districts (Koenig 2000).

Urban streams are often badly degraded from their pre-development, natural state. Restoration of these streams is
becoming a widespread practice, and is often done in conjunction with WWF control efforts. Athanasakes et al. (2000)
described the holistic stream restoration program which was developed by the Louisville and Jefferson County, Kentucky,
Metropolitan Sewer District. Their discussion focused on issues involved in developing and managing a streambank
stabilization/stream restoration program, such as getting a program started, a brief overview of stream restoration
techniques, items to consider during construction and a summary of items learned throughout the development of the
program. Stormwater management in an urbanized basin near Dallas, Texas included channelization of a creek which was
eroding private property (Amick 2000). Since the watershed was nearly fully developed, areas where mitigation could be
accomplished were limited. Mitigation was required - leading to some restoration of another urban stream that had
previously been channelized. The creeks in the Kelowna, British Columbia, Canada area, like those throughout North
America, have been impacted by human development. The City of Kelowna initiated the Lower Mill Creek Watershed
Program in 1997. Objectives of the program included (1) improvement of Mill Creek water quality by preventing
streambank erosion and creating riparian areas; (2) restoration and enhancement of instream and streamside habitat; and
(3) education of the public, private landowners and developers on the importance of Mill Creek (Gow and Kam 2000).
The U.S. EPA has allowed local governments to establish natural vegetative buffers (greenways) along stream corridors
in lieu of incurring other EPA enforcement actions associated with violations of the Clean Water Act. Kleckley and
Kung’u (2000) identified the role of greenways in protecting water quality and aquatic and stream corridor habitats, and
described an on-going greenways project in Jefferson County, Alabama. Rodriguez et al. (2000b) presented a pool-riffle
design for straight urban streams where existing infrastructure has prevented channel planform re-alignment. The
proposed structures fulfilled four main requirements: (1) increased flow variability during low and moderate flows; (2)
produced minimal increase in the water levels during high flows; (3) self-maintained in terms of bed erosion and sediment
deposition, and (4) provided in-stream habitat for fish. Von Euw and Boisvert (2000) presented two case studies that
focused on the partnership process, design and implementation, and lessons learned from the construction of two riffle
weirs in urbanized streams in Vancouver. Key conclusions were that partnerships are an effective tool for implementing
stream improvement projects in a cost-effective manner; and that riffle weirs can function effectively in an urban setting
to mimic natural stream morphology, thereby improving fish habitat and channel stability.

Urban watershed managers are increasingly investigating stormwater control programs as a whole, rather than focusing
on individual BMPs. Chocat et al. (2000) described the evolution of urban drainage, noting that even though urban
drainage has been practiced for more than 5000 years, many challenges arising from growing demands on drainage still
remain with respect to runoff quantity and quality, landscape aesthetics, ecology and beneficial uses, and operation of
existing urban wastewater systems. In Lulea, Northern Sweden, Backstrom and Viklander (2000) investigated which
integrated stormwater system components might be suitable in cold climate regions. The authors found that porous
pavement, grassed waterways (swales, ditches), wet pond, and percolation basin were the most suitable integrated
stormwater system components in cold regions whereas dry basin, stormwater infiltration surfaces, and stormwater reuse
seemed to be less suitable. The Delaware Canal, a unique, 60-mile long, 167-year-old man-made waterway, was built and
operated commercially to haul coal and other goods from Bristol, Pennsylvania to Easton, Pennsylvania. Environmental
Liability Management, Inc. prepared a map of the Delaware Canal Watershed, analyzed potential strategies to reduce
accelerated erosion and sedimentation in the canal watershed, and produced a report intended to educate local residents
and township and county officials on land use/management practices that could be incorporated into local ordinance to
reduce the excessive sedimentation in the canal (Brussock et al. 2000). Barrett (2000) discussed the potential for BMPs to
adequately address receiving water impairments in southern California. He concluded that pollutant removal rates for
conventional BMPs will not enable BMPs to reverse adverse receiving water impacts.

Several innovative watershed management approaches are attempting, in combination with a system of BMPs, to preserve
the natural runoff-controlling features of a site. Low Impact Development (LID) is rapidly being recognized as an
ecologically sustainable and cost effective strategy to protect receiving waters from the water quality, volume, magnitude,
and frequency effects of stormwater runoff. The LID strategy is based on creating hydrologically functional equivalent
design features that replicate the pre-development conditions through the use of pollution prevention, precision
engineering, and integrated micro-scale BMPs throughout a site. Coffman et al. (2000) presented the management
strategies, protocols, and technological approaches incorporated in the development of an LID management strategy for the control of WWF in urban areas. Two publications that describe LID are the *Low-Impact Development an Integrated Design Approach* and *Low-Impact Development Hydrologic Analysis* (obtainable from the National Service Center for Environmental Publications (NSCEP) 1-800/490-9198). Daniil et al. (2000) presented general design considerations and principles for flood protection and related stormwater design, based on an integrated environmental approach and involving less technical works and preservation of the physical condition of streams and creeks. The application of the above mentioned consideration was illustrated in two specific case studies from the suburbs of Athens, Greece. Hall and Scarbrough (2000) reviewed the development and implementation of new-development requirements aimed at watershed protection in Gwinnett County, Georgia, USA. The approach presented is simple to use and encourages site design that takes advantage of the natural site amenities and minimizes impervious surfaces. Kauffman and Brant (2000) advocated amending existing zoning codes to establish watershed-zoning districts based on percent impervious cover thresholds in the Christina River Basin of Delaware.

The Storm Water Phase II Rule, published in the Federal Register on December 8, 1999, will bring approximately 5,000 small municipal separate storm sewer systems (MS4s) and over 100,000 small construction sites into the National Pollutant Discharge Elimination System (NPDES) permitting program by 2003. USEPA is supporting implementation of this rule through the development of a ‘tool box.’ This tool box will consist of fact sheets, guidance, a menu of BMPs, an information clearinghouse, training and outreach efforts, technical research, support for demonstration projects, and compliance monitoring/assistance tools (Kosco 2000). The City of Portage, Michigan, pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The approach has served to define the application of the now elusive "Maximum Extent Practicable" (MEP). Breidenbach et al. (2000) presented the approach for selecting design parameters to define MEP and identified how the minimum control measures for Phase II regulations are incorporated into the passive storm water treatment system design.

Once a watershed management study has been conducted and a plan adopted, local planners and engineers are often faced with the questions of how to practically translate these recommended management strategies or best management practice recommendations into zoning and subdivision regulations, capital improvement plans, and assistance programs, how to encourage effective site design and also provide flexibility in meeting environmental objectives, and of finding a practical, economical way to track how the design and best management practices are performing. Brewer et al. (2000) documented Rockdale County’s innovative Development Performance Review, including its procedures, and program cost/staffing requirements. Fernando et al. (2000) described the development of effectiveness indicators for stormwater and watershed management programs and the development of a regional monitoring program. The study was conducted for the jurisdictions encompassed by the Hampton Roads Planning District Commission, with specific focus on the six cities that currently have Virginia Pollutant Discharge Elimination System stormwater permits. New Jersey developed a rule proposal to standardize its approach to the watershed planning process, and to goals and objectives for watershed planning. Van Abs (2000) proposed a conceptual basis for watershed planning objectives and thresholds, and then described how New Jersey’s planning and regulatory system currently and prospectively addressed the issues. As part of the stormwater planning process for the Greater Vancouver area, a watershed classification system was developed to help evaluate the current and future impacts of stormwater discharges on the receiving environment. The system was designed to easily communicate these impacts along with potential mitigation strategies to stakeholders and decision-makers. Woods et al. (2000) described the watershed classification system, presented the classification results for 1996 and 2036, and outlined some of the experiences with developing and using this watershed management tool.

The California Department of Transportation (Caltrans) constructs, operates, and maintains the state highway system in California; the runoff from which is subject to the federal Clean Water Act and its associated NPDES permit program. New permit requirements have required methods that achieve higher levels of pollutant control than conventional BMPs. As a result, Caltrans initiated an extensive research and pilot-testing program to identify new technologies that can be used to meet water quality standards (Krieger 2000). Prior designs assumed that street drainage was designed to collect stormwater as fast as possible, and therefore, the street stormwater capacity was defined as its hydraulic conveyance and was estimated by Manning’s formula. Guo (2000) found that the street stormwater capacity at a sump was actually dictated by the storage capacity rather than the conveyance capacity. A new design methodology was developed that considered the street depression storage as a criterion when sizing a sump inlet. In 1999, two oil-water separators at Mobil de Colombia’s terminal facilities in Cartagena, Colombia were replaced in order to bring the facility into compliance with environmental law. Using a proprietary computer program it was found that the existing pits were large enough to meet the national environmental regulations for effluent oil content if fitted with multiple-angle coalescing plates. Gutierrez et al. (2000) presented the legal requirements, operating conditions, the new internals, and a discussion of how the new
internals will affect the quality of the water exiting the facility. Patwardhan et al. (2000) briefly outlined the Best Management Practices (BMPs) and reporting modules of the Hydrological Simulation Program – FORTRAN (HSPF) model in relation to its application to the Camp Creek and Little River Watershed Assessment Project (Fulton County, Georgia).

Stovin and Saul (2000) described an extensive laboratory and computational fluid dynamics study into the hydraulic performance and sediment retention efficiency of tanks. The results showed that (1) using computational fluid dynamics, it was possible to predict the flow field that was measured in the laboratory, and (2) a critical bed shear stress could be used to determine the extent of sediment deposition. The study also showed that the length to breadth ratio of the chamber was the most important parameter to influence sediment deposition, and that changes to the benching and longitudinal gradient of the tank had minimal effect. Intensity/duration/frequency (IDF)-relationships of extreme precipitation have been widely used for design of stormwater facilities. Because the properties of extreme precipitation may be very different for different storm types and different seasons, IDF-relationships which permit decomposition into different components and scaling properties were established by Willems (2000). Hydrologically functional landscapes integrated principles of maximizing infiltration, contouring the landscape to encourage temporary detention, and the use of stormwater to reduce demand for irrigation water. Wright and Heaney (2000) reported on the design and monitoring of a hydrologically functional landscape in Boulder, Colorado, and presented a simulation that evaluated the performance of the system. Low Impact Development (LID), a micro-scale runoff control strategy for WWF, has been based on a combination of conservation to reduce hydrologic impacts and incorporation of distributed micro-scale BMPs throughout the subcatchment. LID has resulted in a need to develop new models or modify existing ones. Wright et al. (2000) explored the potential and limitations of existing models in order to evaluate the effectiveness of this design approach. An extensive review of some 50 designs for litter traps which are recommended for urban drainage designs indicated that only seven showed much promise for South African conditions. A preliminary assessment of the seven most promising trapping structures concluded that three designs - two utilizing declined self-cleaning screens and the other using suspended screens in tandem with a hydraulically actuated sluice gate - are likely to be the optimal choice in the majority of urban drainage situations in South Africa (Armitage and Rooseboom 2000a and 2000b).

According to Herr and Harper (2000), stormwater treatment using flow-weighted injections of alum achieved high removal rates of nutrients, heavy metals, and bacteria while proving to be an extremely cost-effective retrofit. Two case studies using alum injection in Florida were presented. A National Cooperative Highway Research Program-funded research project was described by Stein et al. (2000) and included both a synthesis of current information and a plan to guide future research on management of runoff from surface transportation facilities. The issues to be studied included regulations and permitting, runoff water quality characteristics, best management practices, receiving water impacts, and habitat impacts. Insufficient space, high land values, topography, maintenance, aesthetics and liability issues were given as reasons why underground detention has been considered more frequently. Finlay (2000) presented the development of a computer program for designing underground stormwater detention tanks. The program had four main functions: (1) develop or allow the direct input of an inflow hydrograph, (2) size the structure and develop a stage-storage relationship, (3) design the release structure and develop the stage-discharge relationship, and (4) route the inflow hydrograph through the structure. Boyd (2000) presents a collection of pre-programmed hydraulic and hydrology-related functions that have been compiled as an add-on module for use in computer spread sheets to aid in BMP and urban drainage design. Results from the modules are similar to results given by widely-used modeling software.

BMP performance can be verified only through expensive field testing, making published testing results a valuable resource for planners and engineers. Strecker et al. (2000) reported on a research program funded by USEPA and ASCE to develop a more useful set of data on the effectiveness of BMPs used to reduce pollutant discharges from urban development. They described some of the comparability problems encountered between different BMP effectiveness studies, considerations that affect data transferability, such as methods used for determining efficiency and statistical significance, efforts used to establish and analyze the currently available data and proposes protocols for future analyses. The authors recommend that efficient quality would likely be a much more robust measure of BMP effectiveness and performance than the currently used “percent removal” metrics. Ball et al. (2000) evaluated the effectiveness of stormwater treatment devices installed on a roadway in Australia, including detention tanks, a Continuous Deflective Separation (CDS) GPT, and a sand filter. It was concluded that the devices were improving the quality of stormwater flowing from the road drainage system into the general catchment stormwater system. Greb et al. (2000) evaluated the water-quality benefits of a new urban best management practice design called the multichambered treatment train. High reduction efficiencies were found for all particulate-associated constituents, such as total suspended solids (98%), total phosphorus (88%), and total recoverable zinc (91%). Dissolved fractions had substantial but somewhat lesser removal.
rates (dissolved phosphorus, 78%; dissolved zinc, 68%). The Washington State Department of Ecology's efforts to reduce the flow of pollution to Commencement Bay sediments, a federal Superfund site, caused metals concentrations in the bay to decrease by a factor of 10 between 1984 and 1997. This accomplishment demonstrated that major water quality improvements were possible in a heavily industrialized area (Smith et al. 2000c). Wang et al. (2000) sampled stream physical habitat, water temperature, and fish and macroinvertebrate communities at multiple paired watersheds in Wisconsin before and after BMP installation from 1993 to 1999 to examine the responses of stream quality to watershed-scale BMP implementation. Results clearly demonstrated that watershed and riparian BMP implementation improve overall stream quality. A CDS unit would be expected to separate the following pollutant loads from a stormwater system: suspended solids, bed loads, floating solids, free oil & grease. Field studies verified removal efficiencies for gross solids to be greater than 95%, with particulate phosphorous removal of greater than 30%, and TSS removals greater than 70% (Kohzad 2000).

Non-structural BMPs, such a reduction in the use of pesticides and fertilizers, often have been suggested for WWF control; however it is often difficult to assess the impact of such BMPs. A project in Sydney, Australia assessed the effectiveness of a directed community education program for non-structural management at stormwater sources through detailed monitoring of both the community and the stormwater volume and contamination. Ball et al. (2000) outlined how the community education program focused on issues of concern to the local community and how changing practices could impact the problem. Also outlined were the monitoring program developed to evaluate the effectiveness of the program and the availability of stormwater contaminants. Henning (2000) outlined the development and work of “WaterShed Partners,” a coalition of more than 40 public, private and non-profit organizations in the Minneapolis/St. Paul, Minnesota metropolitan area. “WaterShed Partners” developed and implemented a variety of public education programs to educate the public about changing household behaviors such as water usage, lawn care practices and proper disposal of household hazardous waste.

The pollutant loads conveyed by street cleaning waters, by street runoff and the maximum pollutant load removed by street washing were measured for three streets in central Paris, France. For suspended solids and organic matter, the pollutant load removed on a daily basis from street surfaces by street cleaning waters was found to be similar to that removed during one rainfall event. However, it was five times lower for heavy metals. It was also shown that the total mass of pollutants stored on the street surface is significant, and that the effects of street cleaning may be limited. An unexpected effect of street cleaning was found - it induces sediment erosion inside the sewer during dry weather periods, thus reducing the stock of pollutants available for wet weather flow (Gromaire et al. 2000).

Current turfgrass management practices in the U.S. have contributed to environmental problems, generated large amounts of solid and hazardous waste, and used large amounts of water during the summer months when fresh water supplies are lowest. These practices, including home lawn care, have included intensive use of water-soluble fertilizers, herbicides, insecticides, and fungicides, which may be harmful to human health and to aquatic ecosystems. McDonald (2000) presented an alternative approach based on observation of the entire soil and grass ecosystem, appreciation that turfgrasses are sustained by the activities of soil-dwelling organisms, and understanding that this grass community is a dynamic equilibrium among many plants, invertebrates, and microbial organisms. Pauleit and Duhme (2000) developed a method to delineate urban land cover units to establish the relationship between, on one hand, the socio-economic performance of the urban system and its different sub-units (i.e. housing schemes, commercial and industrial developments, services), and on the other, the environmental impacts of these sub-units. A case study on urban hydrology was presented to characterize aspects of the metabolism of the urban system. A multi-stakeholder group, was formed to address and to remediate nonpoint sources of bacteriological pollution threatening the economic and environmental health of Baynes Sound, Vancouver Island, Canada. This work demonstrated that partnerships among government, the shellfish industry, community groups, and citizens can create a powerful force for improving water quality (Pinho 2000). The University of Connecticut Nonpoint Education for Municipal Officials (NEMO) Project developed an educational program targeted at land use decision-makers. The program emphasized natural resource-based planning that prioritizes local natural resources and finds a rational balance between development and conservation. Four simple elements are shared by projects in the group: (1) an educational approach, (2) an emphasis on land use education, (3) a focus on land use decision makers as the target audience, and (4) the use of geospatial technology in the service of education (Rozum et al. 2000).

According to Strecker et al. (1999), the EPA cooperative research program with the American Society of Civil Engineers (ASCE) developed a more useful set of data on the performance and effectiveness of individual BMP and to assess the relationship between measures of efficiency and BMP design. BMP monitoring data should not only be useful for a
Ecotechnology was the use of technological methods for environmental management in a way to minimize the harm to the environment. Herein the primary contributors to NPS pollution were presented. Best management practices (BMP) for NPS pollution were reviewed, and ecological engineering measures for NPS control were described and evaluated (Dermissi et al., 1999). Stormwaters flow directly into the Matajoki River, which was situated in Southern Finland with a catchment area of 24.4 km², was monitored with a limnograph. Separate sewage systems were present throughout the catchment area; domestic sewage was directed to a sewage plant directly outside the catchment area. During the research period July 1, 1995 to June 30, 1996, water samples from the Matajoki were taken at least weekly (Olli, 1999).

According to Rushton (1999), an innovative parking lot design at the Florida Aquarium in Tampa, Florida, was being used as a research site and demonstration project to show how small alterations to parking lot designs can dramatically decrease runoff and pollutant loads. Three paving surfaces were compared as well as basins with and without swales to measure pollutant concentrations and infiltration. Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlack, 1999).

Prince George’s County, Maryland first introduced the bioretention device (commonly referred to as a “rain garden”) in 1990. Utilizing physical, chemical, and biological treatment processes within an aerobic soil media/vegetated filter system, bioretention has been shown to be highly effective in removing pollutants such as heavy metals and nutrients from urban runoff. By capturing, infiltrating or filtering stormwater runoff close to the source, the use of bioretention treatment can also restore hydrologic functions (Winogradoff and Coffman, 1999). Beginning in July 1997, the University of Virginia has been testing a vault/reservoir structure installed at a bus maintenance facility in Charlottesville, Virginia; two larger such structures were later installed in Warrenton, Virginia and were monitored between October 1997 and September 1998. Another ultra-urban BMP, a bioretention area, was installed at a high school site in 1998 and has been monitored since November 1998. A total of 22 storm events were sampled at the vault/reservoir structure sites, and 4 storms have been sampled at the bioretention site; water quality parameters examined included total suspended solids (TSS); total phosphorus (TP); chemical oxygen demand (COD), and oil and grease (OG) (Yu et al., 1999).

No single BMP will prevent all the effects of receiving waters caused by urban runoff, however, through a combination of source and treatment controls, the greatest benefits will be gained. Stormwater management objectives should focus on obvious localized problems for near-term goals and should establish an appropriate scientific and administrative structure for addressing long-term beneficial use protection in a cost-effective manner (Joint Task of WEF and ASCE, 1998). A BMP screening procedure was used to develop a watershed plan for the Bear Creek part of the Clinton River Watershed in southeast Mich. (Paluzzi and Ditschman, 1998). The screening procedure assessed water-quality sampling and habitat inventory, physical suitability, stormwater benefits, pollutant removal, environmental amenities, and institutional constraints and costs. A linear program, which was developed and run on commonly available spreadsheet software, optimized the selection of BMP for a watershed (Lewis, 1998). O’Leary and Clevenger (1998) reviewed the Maryland Department of the Environment’s past and present stormwater regulations and plans for a new design manual. De Hoop et al. (1998a) reported the results of a survey of log storage yards in La. that gathered information related to stormwater runoff such as storage practices, soil composition, materials stored, and runoff control practices.

Silt fences removed sediment from runoff at a construction site in Austin, Tex. by particle settling, not filtration and were ineffective in reducing turbidity (Barrett et al., 1998b). Mean sediment removal efficiencies in flume studies ranged from 68—90%, depending on detention time of the runoff, however, large quantities of construction sediment remained in the discharge because initial sediment concentrations were 3 000 mg/L or more. Dee et al. (1998) reported on efforts by the Virginia Department of Transportation to help protect the water quality of the reservoir before, during and after construction of a roadway project located within the Rivanna River Reservoir watershed. The benefits provided by porous and permeable pavements over the last 20 years included flow attenuation, aquifer recharge, pollution control and
Several sources addressed a “new technology” in BMP - Low Impact Development (LID). By reducing the change in curve number (CN), maintaining the pre-development time of concentration (Tc), incorporating distributed retention and then, if required, adding detention BMP to maintain the runoff volume and peak runoff rate, (Coffman et al., 1998a, 1998b, and 1998c) LID creates a “functional landscape” that incorporates design features that mimics pre-development, natural watershed hydrologic functions. Runoff may be reduced and controlled at the site by minimizing impacts to the extent practicable by reducing imperviousness, conserving natural resources, recreating detention and retention storage, maintaining pre-development Tc by strategically routing flows to maintain travel time, and implementing effective public education programs that encourage property owners to use pollution prevention measures. Net results for LID stormwater treatment and management mimic the water balance between runoff, infiltration, storage, groundwater recharge, and evapotranspiration (Dep. Environ. Resour., Prince George’s County Md., 1997). LID techniques integrate stormwater controls in small discrete units throughout the site. Distributed BMP reduce the need for a centralized BMP facility. Micro-management of stormwater, which has been used successfully in several communities, stores water temporarily at many locations on and off the street and below the surface and as close as possible to the precipitation source prior to entry into a combined, sanitary or storm sewer system (Carr and Walesh, 1998). Bioretention uses plants and soil to filter runoff from developed areas. Laboratory and field tests showed good removal of metals, P, and NH₃ with little or negative removal of nitrate. A significant mulch layer was found to be important for metals removal (Davis et al., 1998b).

Within the 16.2 ha (40 acre) festival grounds in downtown Milwaukee, Wis. a flow splitter diverted the first flush stormwater from a 1.2 ha (3 acre) area to a constructed landscaped island with a layer of peat over a layer of fine sand and at a hospital in Green Bay, Wis., a pressurized two stage filter system was designed to reduce pollution from a 2.6 ha (6.5 acre) parking lot (Bachhuber, 1998). A swale-infiltration trench system that combined three engineering techniques (infiltration, storage and throttled drainage) to manage rainfall runoff can be applied to new developments or as a retrofit (Sieker, 1998). Urban stormwater was treated by a combination of engineered and natural treatment systems comprised of a wetland perimeter swale and a berm which directed collected surface water runoff to a 30 m wide forested wetland filter strip (Berg, 1998). A sand-filter system and two grassy medians located on highways near Austin, Tex. were evaluated (Barrett et al., 1998c). The grassy areas reduced SS by 85% while the sand filter reduced pollutants by 90%, but was plagued with maintenance problems and detention times exceeded the 48 hour design. The capability of vegetated highway medians for treating stormwater runoff in the Austin, Tex. area was studied by examining pollutant removal efficiencies of two medians on major highways. Removal efficiencies at the two sites were remarkably similar despite being designed solely for stormwater conveyance and differed in slope and vegetation type and were comparable with those observed in structural controls such as sedimentation/filtration systems (Barrett et al., 1998d).

Washington, D.C. required that BMP be required for new and re-development projects to control urban-stormwater-runoff pollution. Dee (1997) retrofitted an existing drainage basin with a sand-filtration system that controlled the 2-yr and 15-yr rainfall events. An innovative BMP system for a recreational farm in Taiwan was evaluated by Wen and Yu (1997). The BMP system included a grassed strip, a swale, wetland vegetation, two check dams, a shallow lotus pond, and two wet-detention ponds. The results indicated that BMP put in series could provide high pollutant removal, especially for particulates. According to Pechacek et al. (1997), key components of BMP include good-housekeeping procedures; preventive-inspection and maintenance schedules; management strategies to prevent contamination of stormwater runoff; facilities that manage runoff to prevent contact between pollutants and runoff; and facilities that reduce pollutants in the runoff. U.S. EPA (1997d) addressed some of the unique challenges for designing BMP in cold climates.

Barrett et al. (1997) evaluated different types of structural BMP systems for treating highway-stormwater runoff, including grassy swales, extended detention ponds, and sedimentation-filtration systems. As a part of stormwater management BMP, the Maryland Department of Environment applied a groundwater-syphon system to mitigate wet-pond-outflow temperatures in order to comply with the State’s threshold criteria for stream-flow temperatures (O’Leary, 1997). A literature summary documented the benefits analysis associated with an alternative development approached for controlling stormwater runoff (U.S. EPA 1997e). The Baltimore County, Department of Environmental Protection and Resource Management developed a stormwater-management-water-quality-retrofit program to improve BMP performance in an urbanized environment. O’Leary et al. (1997) reported the program details, including assessment of water quality, BMP-retrofit options and prioritization, feasibility and cost effectiveness, and aesthetics and neighborhood acceptance.
Livingston et al. (1997a and 1997b) developed two separate reports to address institutional aspects of urban-stormwater-runoff management and the operation and maintenance of stormwater-management systems which included sample stormwater-management-inspection forms.

**General stormwater control objectives and sustainable drainage design.**

Braune and Wood (1999) described how South Africa currently has one of the highest rates of urbanization in the world, causing a significant increase in surface water runoff and attendant increases in flooding and significant decreases in water quality. They presented a method of how the existing problem areas can be identified and ranked, and how the use of BMP can be used to reduce the impacts associated with urbanization. Cutler and Eastman (1999) described two projects in Christchurch Cith, New Zealand. The first, Regents Park, was an urban subdivision in an area with springs, open drains and a high water table. The City Council worked with the developer to naturalize and enhance the open waterways so that they added value to the landscape, ecology, drainage, and value of the subdivision. The second area, the Tranz Rail transfer yards, was a multi-million dollar development involving extensive areas of roofing and paved surfaces. They developed an integrated stormwater design approach that includes a two-stage settling/treatment/filtration system that retains peak discharges, contains contaminated spills, and alleviates downstream flooding. Hottenroth et al. (1999) examined the effectiveness of integrated stormwater management in Portland, Oregon. The stormwater program encourages innovative, non-structural pollution reduction techniques such as native landscaping, grass swale drainages, ponds, and public involvement and education. The Parkrose Pilot Project was started in 1994 to test the effectiveness of a wide range of these BMP in a small watershed in north Portland.

The Auckland Regional Council (ARC), New Zealand published a manual for design of stormwater quality improvement devices (TP10). Within that manual a modified Rational Method was used for flood estimation. An improved method was developed for estimation of storm runoff to represent the effects of different approaches to land development, including the use of different types of land cover and drainage systems, which could significantly modify the volume, timing and peak rate of runoff (Levy and Papps, 1999). The ARC developed a manual “Low Impact Design for Stormwater Management” (Shaver, 1999). Schueler et al. (1999) described a series of 22 land development principles developed by a consortium of American planning, road, banking, engineering, development and public safety organizations. The environmental impact assessment database being developed for Project Storm consists of a ranking system to provide comparative data for aquatic resources in terms of existing natural environmental values and existing effects (Stevens et al., 1999).

Iwamoto et al. (1999) described the sequence of urbanization, and associated receiving water problems in Japan. River excavation and widening were first used in the suburbs, followed by the raising of levees and overflow spillway to let flood discharges flow into temporary storage areas near rice fields. In the most urbanized areas, drainage channels and pump stations were constructed to handle the increased flows. Contrary to these historical approaches, they feel that “soft” approaches should be tried to encourage the natural benefits associated with reforestation and land consolidation. Kobayashi (1999) described changes that have occurred with development in Nagoya City, Japan. Rapid rainwater conveyance was being achieved by expanding storm sewers and pumping stations, but they were also stressing the use of infiltration facilities throughout the city area. Private infiltration facilities have not been developed as much as they hoped. The authors described an approach to constructing porous pavements; managing the decreased infiltration capacity of the pavements with time; and the needed field inspection and recovery operations to restore the infiltration capacity.

Cutler and Simpson (1999) described the challenge facing the city of Christchurch (New Zealand) to develop sustainable, aesthetically pleasing waterway environments that were environmental assets for the adjacent landowners. Designers were expected to naturalize the artificial drainage channels, or create new realigned reaches in confined urban settings. A range of techniques were being applied to replace the existing drainage system with a sustainable naturalized waterway environment. Stahre (1999) reviewed ten years of different experiences pertaining to sustainable stormwater management in the city of Malmo, Sweden. A basic element in sustainable stormwater management in Malmo was the involvement of ecological processes in drainage and that the technical design, to a great extent, was adapted to the prevailing local conditions.

Zhang et al. (1999) stated that, although separate sewer systems usually were not designed to take full advantage of available NPS controls, a great improvement can be achieved by combining a number of separate control options. Thorolfsson and Sekse (1999) reports that the green trend in urban stormwater management, as demonstrated in the Birkeland test basin in Bergen, Norway, utilizes the capabilities of nature to store huge stormwater and snowmelt volumes and to reduce the pollution content in the receiving water. Thorolfsson (1999a) further described the Sandsli system (an
alternative drainage system demonstrated in Bergen, Norway) used for drainage management in the north Atlantic. The
goal was to manage the total urban runoff (wastewater, stormwater, and snowmelt) in a way that environmental damage
was avoided, and the goals for the receiving water were achieved at reasonable costs. Thorolfsson (1999b) described how
non-contaminated runoff was to be handled near the source by percolation and/or detention, while the polluted runoff will
be collected and conveyed to an appropriate site for treatment and discharge.

McAlister et al. (1999) found that the fine sediment in urban stormwater was a key cause to many receiving-water
impacts. As a consequence of these studies, a total catchment approach has been developed and applied to urban
stormwater quality management in Brisbane city (Australia). Mehler and Ostrowski (1999) found that an economically
and ecologically sound combination of centralized and source area control measures will be a concept of the future of
stormwater management in Germany and elsewhere. Holz (1999) described how engineering solutions have not been
effective at avoiding the degradation of receiving waters in the northwest of Washington’s Pacific coastal region. They
concluded that “hard” engineering methods have little chance of mimicking the stormwater runoff attenuation of forest
cover, regardless of storage provided, and that another paradigm for development must be adopted (in contrast to the
present “clear, grade, and pave” approach that has not been proven to be mitigatable).

**BMP effectiveness.**

Chocat et al. (2002) presented the current French and other western European approaches to stormwater management.
The paper reviewed BMP analysis, design and performance and was drawn from the available literature on the subject.
Stahre (2002) discussed the use of BMPs in Malmo, Sweden. All new developments in Malmo have been planned with
special consideration of the drainage of stormwater. Wherever possible, new developments will be built up along
constructed open drainage corridors, which are laid out at a very early stage in the planning process. Marsalek and Chocat
(2002) reported on an international survey of urban stormwater management practices that was conducted for IWA and
contained contributions from 18 countries. The main findings of the survey included clear indications of a widespread
interest in stormwater management and of the acceptance of a holistic approach to SWM promoting sustainable urban
drainage systems (SUDS). Specific implications of this philosophy included emphasis on source controls in SWM,
transition from traditional "hard" infrastructures (drain pipes) to green infrastructures, needs for infrastructure
maintenance and rehabilitation, formation of stormwater agencies (within larger integrated water agencies) with
participation of both public and private sectors, and sustainable funding through drainage fees rather than general taxe s.
Lawrence (2002) performed a strategic review of Australia’s urban water BMPs. The review indicated that while
substantial advances have occurred, a number of significant shortcomings in the selection and application of BMPs
remained.

Blaha et al. (2002) evaluated the effectiveness of the principal structural and non-structural BMPs used in the United
States – stormwater management facilities and forested riparian buffers. The results of the analysis showed that
stormwater management facilities do little to offset the effects of urbanization on aquatic communities, while natural
riparian buffers appear effective at low to moderate levels of urbanization. Macdonald and Jeffries (2002) summarized
monitoring results for BMP performance in Scotland. A porous pavement and two swales were monitored. The results
showed that these BMPs reduced pollution when compared to the traditional drainage design.

Cave (2002) reviewed an approach in the Rouge River, which links the performance of BMPs to receiving water impacts.
The approach considers the various stages of the ‘life cycle’ of the BMP design and implementation. Benefits have
included progress in restoration in the Rouge River watershed, and sharing of practical and transferable results with other
watersheds. Stribling et al. (2002) investigated the relationships between instream biological conditions to BMPs in the
watershed. The paper presented findings from two case studies where a "BMP-assemblage" was evaluated without the
benefit of calibrated biological reference conditions, and another where SW retention ponds, in isolation, were evaluated
with calibrated reference conditions. Strecker and Urbonas (2002) assessed the receiving water effects of urban
stormwater BMPs. The paper provided a framework to begin discussions regarding potential approaches and methods for
assessing the performance of urban stormwater BMPs in improving the health of aquatic ecosystems. It also presented
potential methods and study approaches along with potential individual physical, chemical, biological, and biochemical
measurements/indicators that employed in particular combinations may be useful in assessing downstream BMPs
performance.

Field surveys of structural best management practices (BMPs) in the Pacific Northwest found that, even with a relatively
high level of attention, a minority of the developed watershed area was typically served by these BMPs (May and Horner,
2002). Those BMPs installed are capable of mitigating an even smaller share of urban impacts, primarily because of
inadequacies in current design standards. Even with these shortcomings, though, results showed that structural BMPs help to sustain aquatic biological communities, especially at moderate-high urbanization levels, where space limits non-structural options. In addition, structural BMPs can be effective in water quality treatment of stormwater pollution "hot-spots" or in "ultra-urban" settings. The most promise appeared to be in the use of low-impact development (LID) concepts that incorporate conservation of native vegetation and soil, minimize imperviousness, and utilize integrated, on-site treatment of stormwater.

Horner et al. (2002) presented a study on structural and non-structural BMPs for protecting streams. Intensive study of structural best management practices (BMPs) in one location found that, even with a relatively high level of attention, a minority of the developed area is served by these BMPs. Those BMPs installed were capable of mitigating an even smaller share of urban impacts, primarily because of inadequacies in design standards. Even with these shortcomings, though, results showed that structural BMPs help to sustain aquatic biological communities, especially at moderately high urbanization levels, where space limits non-structural options.

Chavez and Cunningham (2002) described the use of sediment removal boxes (baffle boxes) as a retrofit technique in areas where sedimentation basins/detention ponds would not be possible. The performance of three different sustainable urban drainage systems (SUDS) (porous pavement, roadside filter drain, and regional SUDS) in East Scotland were presented by Schluter et al. (2002). The systems were found to perform well at both attenuating flows and pollutant peaks. Modeling of these systems is showing good agreement with field results.

Nandi et al. (2002) presented a spreadsheet-based tool for estimating pollutant load reductions (nutrients, sediments and organic compounds) due to BMP implementation at the watershed levels. The pollutant load and reduction results are presented in summary tables and graphs that are linked dynamically to the data sources. This tool would be expected to assist federal, state, and local organizations in implementing their point and nonpoint source programs, Farm Bill programs, TMDLs, and other water quality-related programs.

Freni et al. (2002) reviewed the catchment-wide efficiency of distributed stormwater management practices (DSMP) in Baerum, Norway. The paper proposed a methodology that allows evaluating the efficiency of complex DSMP packages through the application of detailed rainfall-runoff modeling and sensitivity analyses. In this methodology, variation of hydrological model parameters was used to simulate the presence of different DSMPs. The developed procedure allowed screening and pre-selection of DSMP alternatives, avoiding simulation of numerous alternatives.

O’Shea et al. (2002) studied the role of stormwater BMPs in mitigating the effects of nutrient over-enrichment in an urban watershed. Structural BMPs were found to attenuate stormwater flows and provide some removal for settleable solids and particulate-associated pollutants. The effect of detention and BMPs on flow frequency of runoff was investigated by Nehrke and Roesner (2002a). The study examined the effects of the state-of-practice in flow control on the peak flow frequency curve, and how well the postdevelopment flows were controlled to predevelopment levels. Continuous simulation was performed on two climatically diverse locales and detention ponds with a variety of flow control orifices were examined.

Mikkelsen et al. (2002) reviewed BMPs used in urban stormwater management in Denmark and Sweden and found that BMPs used included structural elements (infiltration, ponds and treatment, wetlands, and retrofitting of river reaches) and non-structural BMPs (chemical control, building materials, and street sweeping). The available knowledge of stormwater BMPs performance in pollution control was inconsistent and the effect of various BMPs on receiving water quality was either poorly understood, or not known. A review of recent experiences with selected stormwater BMPs in Denmark and Sweden was discussed with respect to the current issues related to legislation and the forces driving future development in stormwater management.

James (2002a) investigated removal of suspended material in stormwater runoff by BMP implementation. The USGS reported that the TSS method of analysis to determine concentrations of suspended sediments could result in unacceptably large errors and is fundamentally unreliable and use of TSS data could result in loading errors of several orders of magnitude. Research, development and standardization of new and improved sample collection and sample management techniques and additional analytical methods are needed to better characterize storm water pollutants. The Mass Balance Approach has been proposed to determine the effectiveness of suspended sediment-capture BMPs.

Pyke et al. (2002) used a loosely-coupled watershed-water treatment plant modeling technique to provide a screening-
level assessment of (1) the impacts of major point and nonpoint source pollutant loads on treatment plant operating costs; (2) the potential of agricultural and urban BMPs and best available technologies (BATs) to mitigate these impacts; and (3) the cost-effectiveness of BMPs and BATs versus increased treatment at the water treatment plant. The model was used to quantify changes in annual suspended solids and organic carbon loads exported under varying land use and BMP implementation scenarios, and a dynamic water treatment plant model was used to quantify the impact of associated changes in daily raw water quality profiles on water treatment plant operations and costs.

The two interrelated assessments conducted by EPA while developing effluent guidelines for stormwater from new construction and land development activities was presented by Clar et al. (2002). First EPA conducted an evaluation of the environmental impacts attributable to the land development industry. Second it conducted a related assessment of the effectiveness of erosion and sediment controls, post-construction stormwater BMPs and low-impact development practices to determine the ability of these practices to mitigate impacts attributable to construction and development activities which were identified in the first assessment. Schueller and Caraco (2002) reviewed the prospects for LID at watershed levels. Comparisons between baseline rural loads and loads from suburban developments with traditional stormwater treatment practices (STP) were made. Loads from suburban development with STP exceed the baseline rural loads for nitrogen, phosphorus and fecal coliform bacteria. Reininga and MacDonald (2002) presented a case study in simulating the effectiveness of LID techniques for protecting stream corridors. Supplemental management practices for the protection of stream corridors were also evaluated and applied in the case study in terms of costs.

Raghavan et al. (2002) presented the cost data and methods that would support the development of an Internet-based, interactive tool for estimating capital and O&M costs. The cost equations developed from actual cost data provided rough estimates of the actual best management practices (BMP) capital and operation and maintenance costs. Sample et al. (2002) presented new methods for evaluating stormwater controls and BMPs in a land-development context. Costs were developed using published literature and standard cost estimation guides. The method had stormwater control costs assigned at the parcel level. Hunt (2002) evaluated the cost-effectiveness of stormwater BMPs for North Carolina. A tool was presented that links the removal efficiencies of BMPs to their associated costs (land, maintenance, and construction). The analysis found that (1) bio-retention was most often the most cost-effective BMP for small mostly impermeable watersheds, (2) the cost-effectiveness of stormwater wetlands and wet ponds was comparable when including land and opportunity costs, and (3) economies of scale existed.

Li and Kyriopoulous (2002) evaluated stormwater retrofit management practices (RSWMPs) for Mimico Creek Watershed. Using a derived probabilistic rainfall-runoff model and a treatment train efficiency model, the cumulative reduction of runoff volume and solids loading of a series of appropriate RSWMPs are determined to be 7% and 18% respectively. In the Mimico Creek watershed, the descending order of cost-effectiveness is: (i) downspout disconnection; (ii) water quality ponds; (iii) stormwater exfiltration systems; and (iv) oil/grit separators. The recommended sequence of RSWMP implementation should follow the descending order of cost-effectiveness.

Leaf et al. (2002) reviewed the guide manual developed for “Heart of the City,” Burnsville, Minnesota. The Low-Impact Development (LID) manual was created based upon XP-SWMM2000 goals, BMPs and existing permeable soils. Clar and Rushton (2002) presented case studies on low-impact development (LID). This approach results in an ecologically based approach to stormwater management that is usually more aesthetically pleasing, precludes impacts to receiving waters, and is generally less costly to construct and maintain than conventional end of pipe systems. While the emphasis of these projects is the state of Maryland, projects and case studies from other regions of the Country were also included. Strecker (2002) reviewed the inadequacies of the hydrological design procedures used to substantiate the effectiveness of the techniques used in LID. The paper recommended that much more robust hydrological techniques be used to quantify the potential benefits of this development approach. Coffman (2002) reviewed the use of LID as a stormwater management technology. Despite the demonstrated environmental and economic advantages of LID over today's conventional approaches, numerous barriers to its widespread acceptance and utilization remain and they include issues related political agendas, institutional structure and philosophy, lack of professional education and training, competing and vested interests in maintaining the status-quo, regulatory conflicts and inflexibility, lack of funding for research and development and professional / personal beliefs, knowledge and preferences. Rushton (2002) demonstrated how a low impact (dispersed) design of parking lots could reduce runoff and pollutant loads. Storm runoff was treated as soon as rain hit the ground by incorporating a network of swales, strands and a small wet detention pond into the overall design. Calculations showed that almost all the runoff was retained on site. Basins paved with porous pavement had the best percent removal of pollution loads with many removal rates for metals greater than 75 percent in the basin with a smaller garden area and greater than 90 percent with larger gardens. More phosphorus loads were discharged from basins with vegetated swales.
than from basins with no swales. Metal and nutrient pollutants in the sediments were not found to be migrating to the deeper strata.

Roesner and Brashear (1999) reported that over the last ten years, a number of BMP manuals have been developed to address the control of urban runoff for receiving water quality protection. They concluded that there was a lot of ignorance in the scientific community about what constitutes a properly designed BMP and what it really achieves, with respect to environmental protection. They therefore recommend a design criteria development approach that can be applied over a wide variety of climatologic, topologic, and geologic conditions to protect receiving waters systems. Roesner (1999) further believes that the conflicting opinions on the effectiveness of various BMP result mostly from: 1) there was no accepted uniform design criteria for BMP; and 2) the objectives of the management practices differ between authors.

Buffer corridors. Crifasi (1999) gave a description of Boulder’s (Colorado) instream flow and riparian zone management program, where extensive, high-quality wetlands and riparian areas exist along south Boulder Creek. South Boulder Creek’s riparian corridor contains plains riparian cottonwood forests, willow shrublands, freshwater marshes, and alkali wetlands that provide refuge for two federally threatened species, plus other rare species of plants and animals. Haberstock (1999) presented a method used to determine optimal riparian buffer widths for Atlantic salmon habitat protection in Maine. Zone 1 (no-cut zone), closest to the stream, has a fixed width of 35 ft in which no disturbance to soils or vegetation should occur. Zone 2, landward from zone 1, was a variable width zone where only limited uses that do not compromise the desired functions of zone 2, such as light tree harvesting and light recreation, should occur. Resulting total optimal buffer widths (zone 1 plus zone 2) range from a minimum of 70 ft to a maximum of more than 350’. In rare cases (e.g., extensive slopes > 25%), optimal buffer widths can be 1,000 ft or more. The rehabilitation of urban stream channels to protect Pacific Northwest salmon runs were described by Henshaw (1999). In an effort to bolster the survival of salmon returning to the local streams to spawn, land managers have begun extensive programs to rebuild or rehabilitate appropriate habitat that has been lost or degraded due to urban development. Although rebuilt habitat in a stabilized urban stream may not provide the level of ecological integrity required to maintain endangered salmon and other stream biota, physical stability was likely one necessary component of a healthy stream. O’Neal et al. (1999) described hydraulic and biological effects of large woody debris (LWD) and an engineered wood alternative for stream channel rehabilitation projects in the state of Washington. The engineered structures consist of an interlocking complex of small diameter poles that can be carried by hand and assembled on site. The artificial structures have a high hydraulic and surface roughness to trap sediment and debris and caused variations in the pattern of water flow and resultant scour compared to natural LWD. No statistically significant differences were observed in the biological communities associated with these structures compared to LWD.

The city of Austin, Tex. Stormwater Monitoring Program (Glick et al., 1998) monitored various types and designs of BMP over a 15 year period and concluded that large regional water quality BMP tended to be more cost effective even if the treatment efficiencies are moderate because they can treat more runoff. The cost differential indicated that large systems (e.g., wet ponds) may be a more cost-effective option for areas being retrofit with BMP. Alum proved to be the most effective coagulant for stormwater runoff at Mosquito Lagoon located in New Smyrna Beach, Fla. when tested against ferric chloride which was not effective at enhancing settling (Escobar et al., 1998).

Stormwater reuse.

Argue and Pezzaniti (1999) investigated the harvesting of stormwater to replace water supply mains for the irrigation of areas landscaped with grass, flowerbeds, and shrubs in Adelaide, South Australia. Four categories of catchments were recognized according to their levels of pollution production - roof runoff and “low”, “medium” and “high” pollution runoff surfaces. Large roof areas draining to gravel-filled trenches provide passive irrigation for grassed surfaces, for example. Dillon et al. (1999) described the development of “new” water resources by using aquifer storage and recovery of stormwater. The reuse of reclaimed water through storage aquifers can lead to more environmentally sensitive design, with reduced requirements for imported water, reduced exports of sewage and stormwater, and lower water supply costs. Dixon et al. (1999) demonstrated the water saving potential of domestic water reuse systems using greywater and stormwater. Monte-Carlo modeling results show that changes in household occupancy, roof area, appliance type, and storage volume, affect the water saving efficiency of a reuse system. Fox (1999) also described a watershed approach for integrated water reuse. Zaizen et al. (1999) described roof-runoff reuse at domed stadiums in Japan, as part of a wider program for preserving hydrologic cycle characteristics in urban areas. Tada et al. (1999) investigated three alternative storage methods that can be used to assist stormwater reuse. The best method (Type-1) uses a small tank to separate “first-flush” runoff nonpoint pollution loads from the remaining discharges. Type-2 has an overflow weir to separate polluted
runoff stormwater, while type-3 has an orifice to separate un-polluted stormwater into the utilization tank. Pratt (1999) described the use of storage reservoirs under permeable pavements for stormwater treatment and reuse. Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas and undersealing them to enable them to retain stormwater for reuse for non-potable uses was feasible. However, the stormwater may be degraded where the pavement was used for car parking. Tredoux et al. (1999) described the Atlantis Water Resource Management Scheme that uses artificial recharge of urban stormwater and treated wastewater to augment natural groundwater. The important element was the separation of the stormwater into components of distinctly different quality. Residential and industrial urban runoff was separated into baseflow and stormwater components and utilized for various appropriate purposes.

**Public education.**

Mashiah et al. (1999) found that raising community awareness of stormwater impacts was a critical component of an effective stormwater management program. The campaign included television advertising, newspaper and radio advertisements, displays, free environmental audits for local businesses, and a stormwater ambassador program for local schoolchildren. Heremaia (1999) described the public stormwater education program used as part of the Christchurch (New Zealand) integrated environmental planning program. The successful pilot program included the development of a web site, audio conferences, a competition, and a drama production. Young and Collier (1999) described the research-based stormwater education of the New South Wales (Australia) Environment Protection Authority. This education program was unique in Australia by providing a comprehensive, integrated, and continuing research-based strategy for involving the community in preventing stormwater pollution.

The needs for linking local-economic and water-pollution problems were discussed from an urban perspective, including (1) access to information, (2) communication and outreach efforts, and (3) advocacy (Alex-Saunders, 1996). The EPA sponsored a number of local public-education programs for cities in abating WWF pollution (Austin et al., 1996; Feuka, 1996). A multimedia public-information campaign helped achieve a 40% reduction of nutrients entering Chesapeake Bay (Leffler and Flagle, 1996). A multilevel cooperative-extension program including workshops, volunteer lawn, and master gardener lawn demonstrations was developed for the education of control of residential-nonpoint-source pollution. A community-action guide on environmental-restoration projects addressing citizen-volunteer participation and methods on how to organize restoration events resulted in a 100% positive experience in Chesapeake Bay areas (LeCouteur and Greenfeld, 1996).

Two new publications that address the causes and problem areas of SSO were released by the EPA (1996a and 1996b) for public awareness.

**Public Works Practices**

A management study for the Bell Branch and Tarabusi Creek subwatershed of the Rouge River was presented by Sutherland et al. (2002). The goal of the study was to help public agencies develop appropriate management practices. The advisory group for the project recommended stormwater management practices that reduce or eliminate pollutants at their source, such as leaf collection, catchbasin cleaning and street sweeping.

O’Loughlin and Stack (2002) compared four algorithms for pit pressure changes and head losses in stormwater drainage systems. The results were inconclusive with no method being superior.

**Catchbasins/grit traps**

Memon and Butler (2002) used a dynamic model to assess the impact of a series of water management scenarios on the quality of runoff discharged through catchbasins/gully pots. The simulation showed that the catchbasins/gully pots were effective at retaining solids, but they had an almost neutral performance in terms of removing dissolved pollutants. Model predictions, as against common perception, showed that frequent pot cleaning does not significantly improve the runoff quality. However, considerably improved solid retention was possible if larger pots with modified geometry are introduced into the drainage system. Lau and Stenstrom (2002) investigated the ability of catchbasin inserts to determine their ability to remove particulate pollutants, litter and debris. Laboratory tests with used motor oil showed that the inserts could remove in excess of 80% of free oil and grease. Sand particles larger than the screen mesh were completely removed. Field tests showed that median oil and grease, turbidity and total suspended solids concentrations in stormwater were reduced by 30 to 50%. The inserts were more effective in reducing maximum concentrations than low or median concentrations. Some of the inserts plugged after usage and bypassed stormwater without creating ponding on the street or reducing flood protection.
Because more than 780,000 tonnes of solids washed is washed into the drainage system in South Africa, the Water Research Commission of South Africa and the Cape Metropolitan Council are funding a four year investigation into the reduction of urban litter in the drainage systems through the development of catchment specific litter management plans (Armitage et al., 2001). The results of the litter audits from eight catchments will measure the effectiveness of the various litter management strategies. The California Department of Transportation (Caltrans) conducted a 2-year litter management pilot study in the Los Angeles area to investigate the characteristics of highway litter and the effectiveness of BMPs for removing the litter (Lippner et al., 2001). Half the catchments were treated with one of five BMPs; the others were controls. The BMPs tested were increased street sweeping frequency, increased frequency of manual litter pickup, a modified drain inlet, a bicycle grate inlet, and a litter inlet deflector (LID). Roughly half the freeway storm water litter was paper, plastic, and Styrofoam. Except for cigarette butts, the origins of most litter could not be identified because of its small size. Of the five BMPs tested, only increased litter pickup and the modified drain inlet demonstrated some apparent reduction of litter in stormwater runoff, although the data were highly variable.

Some people have advocated annually removing sediment, vegetation and litter from drain inlet vaults as a best management practice to improve the quality of Caltrans run-off before it enters the receiving waters (Dammel et al., 2001). In response, Caltrans implemented an annual drain inlet inspection and cleaning program in selected urban areas, and conducted the Drain Inlet Cleaning Efficiency (DICE) Study to evaluate if this practice improved effluent water quality. Irgang et al. (2001) evaluated the effect of catch basin cleaning on stormwater quality. Catch basins within two of the four drainage areas were cleaned at the beginning of the study, while those within the other two areas were not cleaned. Pollutant concentrations and runoff loadings were compared between the two areas. It was observed that fine particle deposits remaining in catch basins after cleaning could cause higher pollutant concentrations and loadings for several months when compared to control areas where catch basins were not cleaned. Untreated stormwater runoff reaches Santa Monica Bay (Los Angeles, California) primarily through catch basins or inserts to storm drains that terminate at the beach or in shallow coastal areas (Lau et al., 2001). Commercially available drain inlet devices for pollutant capture exist but few have been evaluated by independent parties in full-scale applications. Laboratory- and full-scale tests of inserts were conducted to evaluate their ability to remove trash and debris, suspended solids and oil and grease in stormwaters, with the results providing a basis for future insert development and application. The performance of Drain Inlet Inserts (Fossil Filter and StreamGuard) and an oil/water separator in treating runoff from four California Department of Transportation (Caltrans) maintenance stations was evaluated (Othmer et al., 2001). Drain Inlet Insert results to date showed that reductions in metals, hydrocarbons, and solids were consistent with expectations; however, frequent flow bypass required more maintenance than anticipated. Oil/water separator results showed no discernable difference between influent and effluent hydrocarbon concentrations at the low levels measured.

Newman (2001) described an analytical framework for the design and/or analysis of baffles to reduce floatables discharges from CSOs. This simple analytical framework, which is supported with a spreadsheet model, was compared to its predecessors and its advantages illustrated. The advantages included ease of use, improved applicability to typical installation configurations, and refined analyses of floatables-removal mechanisms. Model results were compared to previous results and to available laboratory test data for four test cases.

Interest in urban stream restoration has grown (Hession 2001). However, a scientific basis for restoring urbanized streams currently does not exist, although it is known that riparian vegetation along streams significantly impacted stream channel morphology, which in turn influences aquatic ecosystem structure and function. Watershed urbanization also has a significant, but typically conflicting, influence on channel morphology and aquatic habitat.

Grey et al. (1999) summarized the role of catchbasins in the CSO floatables control program in New York City. There were approximately 130,000 catchbasins, distributed over 190,000 acres, in New York City. They found that catchbasins were simple and very effective in controlling floatable material at the source. The most important aspect of catchbasin designs for floatables removal was the presence of a hood that was hung over the basin’s outlet. Several studies conducted in the City have shown floatable retention efficiencies of 70 to 90%. Catchbasin hoods were also very cost-effective controls at a cost of about $100 per acre. The City implemented a catchbasin inspection, mapping, cleaning, and hooing program as part of its CSO control program. Siegel and Novak (1999) reported on the activity of the microbial larvicide VectoLex CG (R) (Bacillus sphaericus) for the control of mosquitoes in 346 tested Illinois catchbasins. The tests were deemed successful.

Washbusch (1999) reported on an extensive evaluation of a proprietary urban stormwater treatment unit (the Stormceptor)
in Madison, Wisconsin, conducted by the United States Geological Survey (USGS) and the Wisconsin Department of Natural Resources (WDNR). The evaluation was conducted on a 4.3 acre city maintenance yard site over 9 months and for 45 runoff events having rainfall depths ranging from 0.02 to 1.31 in., plus some snowmelt influence from imported snow to the maintenance yard. About 90% of the runoff was treated by the unit, and the remainder flows bypassed the unit during periods of high flows. The overall effectiveness of the unit was 33% for suspended solids, 17% for total phosphorus, 34% for total PAH, and from 20 to 30% for most heavy metals. In general, dissolved constituents were unaffected by the unit. Performance during the early spring events was degraded by high saline snowmelt water, which had elevated conductivity from on-site deicer storage, that significantly slowed particle settling.

Treatment of stormwater runoff from the recently constructed convention center on the shore of Lake Monona in Madison, WI, has recently been achieved with the installation of two vortex separators. The systems were designed to remove >80% of sediments and oils at flowrates of up to 0.48 m$^3$/sec (17 ft$^3$/sec), with peak 25-year flows of 1.27 m$^3$/sec (45 ft$^3$/sec) and 1.7 m$^3$/sec (60 ft$^3$/sec) anticipated at the two system locations (American City & County, 1996a and 1996b).

Litter/floatable control
Armitage and Rooseboom (1999) summarized the results of three years of laboratory investigations sponsored by the Water Research Commission of South Africa into the movement of urban litter through potential trapping structures. They found that once the litter has entered the drainage system it was difficult to remove. They concluded that declined self-cleaning screens showed the greatest promise for the removal of urban litter from most stormwater conduits and streams in the less developed countries. Newman et al. (1999) reported that the City of New York has improved its ability to control one source of floatables and possibly other pollutants to New York Harbor through its newly implemented “Illegal Dumping Notification Program.” This program takes advantage of one City Department’s field presence to gather and transmit valuable information to another City Department for enforcement and cleanup. They found that this program likely will reduce the number of illegal dumping sites by 15%. Phillips (1999) described how the State Government of Victoria (Australia) provided funding to develop a litter trap (the In-line Litter Separator, or ILLS). The ILLS can be retrofitted into the drainage system downstream of shopping areas.

Two proprietary stormwater control devices were placed at drainage inlets and their performance compared with that of a conventional catchbasin inlet (Pitt and Fie ld, 1998). No significant removals were found in the field tests of the proprietary devices, though large debris was trapped by one device, and a catchbasin retrofitted with a sump provided good removal of pollutants. A NYC study indicated street litter is a major contributor of floatables to N.Y. Harbor (Grey and Oliveri, 1998). Hooded catchbasins were 80—90% effective in retaining floatables and a city-wide program to inspect, map and hood all catchbasins was reviewed. Based upon a detailed examination of 18 facilities in Ger., Can., and U.S., Pisano et al. (1998) reported the performance of two widely used sewer and tank flushing technologies, i.e., the tipping flusher and the flushing gate.

Infiltration and Biofiltration, including Grass Swales and Grass Filter Strips
The use of porous bituminous pavement for infiltration as a method to reduce the peak discharge and runoff volume into a receiving water was examined by Adams et al. (2001). In addition, this paper reviews the literature for infiltration meadows, trenches, swales, porous concrete sidewalks, bioretention gardens, etc. The design, installation, and performance of these methods at actual sites, “lessons learned,” and the effectiveness of these infiltration methods were reviewed. Infiltration of stormwater in the southeast of France was studied by Bardin et al. (2001) at the Venissieux infiltration basin that drains a 380-ha industrial catchment. The study quantified the effects of the infiltration system in terms of pollutant transport in the groundwater system, including pollutant removal performance of the basin and the pretreatment devices. In-situ performance monitoring of an infiltration system that collected the runoff of a school roof and paved area was reported by Abbott and Comino-Mateos (2001). The resulting data was used to verify the typical design procedures for these infiltration systems. Govindaraju et al. (2001) investigated the difficulty of modeling infiltration through soils that had spatially varying saturated hydraulic conductivities, but which can be represented by a homogeneous correlated lognormal random field. The Green-Ampt equation described the infiltration at the local scale. Approximate expressions based on a series expansion and a parameterization of the local cumulative infiltration were also presented for describing the ensemble-averaged field-scale infiltration.

Gharabaghi et al. (2001) monitored the sediment removal efficiencies of vegetative filter strips. Fifty percent removal efficiencies were seen when the flow length was 2.44 m and were increased to 98% when the flowpath length was 20 m. However, small-sized particulates were not effectively removed in the grass strips. Improved removal efficiency of very-
fine sediments was achieved through the installation of a drainage system (e.g. a French drain) to increase infiltration. Reinforcement of vegetation with various geosynthetic products reduced flow channelization and short-circuiting. Yu et al. (2001a) field tested grass swales in Virginia and Taiwan. Average pollutant removal efficiencies varied from 14 to 99% for total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). Water and sediment transport in grass swales and filter strips were modeled by Deletic (2001). The one-dimensional model simulated runoff generation and sediment transport. The modified Green - Ampt model was used for infiltration assessment, while a kinematic wave model was used for overland-flow simulation.

Limitations to vegetation establishment and abundance in biofiltration swales and other vegetated storm-water facilities that treat runoff were studied through field monitoring and greenhouse experimentation (Mazer and Ewing 2001). With adequate light, vegetation and organic litter biomass was strongly inversely related to the proportion of time that the bioswales are inundated above 2.5-cm depth during the driest time of year. For most bioswales, both flow velocity and hydraulic loading were too large for sedimentation of silt and clay particles, even with dense vegetation and abundant organic litter. A lack of correlation between vegetation abundance and pollutant removal was seen.

Ellis (1999) described the benefits and problems associated with directing roadway runoff to a roadside swale/infiltration system. He summarized the range of pollutant removal efficiencies achieved by vegetative BMP and reviewed available design procedures for grass-lined swales and constructed wetlands for the United Kingdom. Gharabaghi et al. (1999) described how rolled erosion control products have proven to be successful in reinforcing vegetative channel lining systems and improving their performance in erosion and sediment control. Mendez et al. (1999) summarized the results from an 18-month field experiment that was conducted to evaluate the effectiveness of grass filter strips in removing sediment and various nitrogen species from runoff. They found that the grass filters reduced contaminant yields from 42 to 90% and concentrations from 20 to 83%, depending on length and nutrient specie. Boubakari and Morgan (1999) tested the effectiveness of growing Festuca ovina and Poa pratensis on contour grass strips for erodible sandy loam soil on steep slopes. The Poa pratensis was less rigid and became flattened under submergence in the later part of the storms and was therefore not very effective in controlling erosion on the steepest slope tested (29%).

The effectiveness of grass strips in controlling highway-runoff contaminants was studied by Newberry and Yonge (1996). The largest portion of metals was found to be retained within the first 1 m of grass strip and 10 mm of depth, with 84% of the applied Zn, 93% of Pb, and >99% of Cd and Cu being retained by the grass strip. Pratt (1996) described recent research into design approaches for sizing of infiltration areas, illustrated the seasonal variability and difficulties in determining soil infiltration rates, and assessed the cost implications of alternative designs.

**Infiltration**

Bardin et al. (2002) reviewed the performance assessment using multiple indicators of stormwater infiltration devices. The purpose of these reviews was to evaluate the relevance and sustainability of several infiltration strategies.

Schaffner and Ostrowski (2002) describe the application of a combination of a surface collector flume that is connected to a subsurface infiltration trench. Application areas include impervious yards of single family or semi-detached houses, roof runoff, drainage of sidewalks and bicycle lanes, school yards and other public less polluted areas, pedestrian zones, and parking areas with low or medium traffic frequencies in domestic or small to medium size industrial areas. An infiltration system (permeable connection box, permeable underground pipe, permeable U-shaped and permeable pavement) has been installed in Japan for more than 20 years (Imbe et al., 2002). The paper presents the flood control results of the infiltration system based on observed data and runoff analysis using SHER (Similar Hydrological Element Response) Model.

Pitt et al. (2002a and, 2002b) reported on testing performed on the impact of compaction in urban soils on infiltration and bioretention designs. The results of these tests showed that infiltration rates are significantly affected by infiltration, even 20 years later. For sandy soils, infiltration rates were impacted by compaction and antecedent moisture conditions, whereas for clay soils, both infiltration and moisture condition were important in determining infiltration rates. The paper by Raimbault et al. (2002) addressed the temporal infiltration variability found in urban soils and on the evaluating the effect of soil drainage on infiltration capacity and consequently, on sizing retention structures. Akan (2002) proposed a design procedure for appropriately sizing stormwater infiltration structures based on the hydrological storage equation for an infiltration structure coupled with the Green and Ampt infiltration equation.

The paper by Dechesne et al. (2002) defines context indicators for assessing the present state of selected stormwater infiltration basins: a clogging indicator and a contamination indicator. An analysis of metals removal found that the
metals were trapped in the top 30 cm of soil in the basin.

Ellis (2000b) addressed the potential conflict between the benefits of groundwater recharge of stormwater runoff versus the risks of long-term groundwater pollution in this paper. The long-term performance of a number of infiltration systems was reported in terms of their pollutant removal efficiencies, and the usefulness of an infiltration acceptability matrix approach was reviewed. Pitt et al. (2000a) presented a review of the literature available on the potential for groundwater contamination from the infiltration of stormwater runoff. The results on both the frequency and mobility of the potential contaminants was organized into a methodology that allowed evaluation of the potential contamination based on these two parameters. Part of this analysis included evaluation of the effects of infiltration on pollutant removal from the percolating water.

Nakazato (2000) presented a manual developed by the Japan Institute of Wastewater Engineering Technology on the technical issues faced by infiltration facilities. The objective of the manual was to clarify the definition of these facilities for stormwater management planning, and to promote the use of these facilities throughout Japan. The manual covers all phases of infiltration facilities through siting, design, installation and maintenance.

Morris and Stormont (2000) showed that near-surface processes such as precipitation, runoff, snowmelt and evapotranspiration have a significant impact on moisture movement in soils, and that models must include these near-surface processes. Pitt and Lantrip (2000) examined the effects of urbanization on soil compaction and resulting infiltration capacity through a series of double-ring infiltrometer tests. They found that sand was mostly affected by compaction, with little change due to soil-water content levels. However, the clay sites were affected by a strong interaction of compaction and soil-water content. The fit of the data to the Horton equation was inconclusive, indicating that when modeling runoff from most urban soils, assuming relatively constant infiltration rates throughout an event, and using Monte Carlo procedures to describe the observed random variations about the predicted mean value may provide the best results. Pitt, et al. (2000b) argued that if the traditional design equations were going to be used to predict infiltration, local data must be obtained and used.

Reemtsma et al. (2000a), in their study on the infiltration of combined sewer overflows versus tertiary-treated municipal wastewater, found that, when looking dissolved organic compounds, the groundwater quality that results from infiltration of CSOs is comparable to or better than the quality after infiltration of tertiary-treated municipal wastewater. However, the nutrient quality of the CSO water was worse compared to the tertiary-treated municipal wastewater after infiltration of both. Desorption of both nutrients and organics previously adsorbed was seen to be a potential problem of long-term infiltration. They also investigated the metals content of infiltration water from these two sources and the retention of these metals in the soil profile (Reemtsma et al. 2000b). They found that the metals were effectively retained during passage through the soil; however, additional alkalinity was needed to buffer the acidity caused by bacterial nitrification and mineralization, since soil acidification likely would result in both a reduction in efficiency of metals removal and a potential release of previously-trapped metals. Singh et al. (2000) investigated the potential for metals release from dredged-sediment-derived surface soils in the Netherlands. The authors found that runoff rates and sediment yields were highest for a silt loam sediment. The metals content of both the runoff and percolating water was greater than the standards for groundwater quality and very high metal fluxes were observed for the recently-oxidized dredged sediment. Metals transport per unit surface area was found to be two to twenty times greater for the percolating water when compared to the runoff water.

Backstrom and Bergstrom (2000) investigated the impact that snowmelt and temporary freezing conditions would have on the infiltration capacity of porous asphalts. Their results showed that alternate freezing and thawing conditions (similar to times of snowmelt) would reduce the infiltration capacity of the asphalt by 90% to a level of approximately 1 - 5 mm/min. Westerstrom and Singh (2000) investigated the infiltration of snowmelt runoff in Lulea, Sweden, and found that unlike rainfall infiltration, the snowmelt infiltration resembled a flow hydrograph, i.e., there was a distinctive rise, peak and recession to the graph. Unlike the relationship for rainfall and infiltration which is decidedly non-linear, a strong linear relationship between the snowmelt runoff hydrograph peak and the amount of snowmelt was found.

The use of filtration media for stormwater runoff treatment was investigated by several groups of authors. Brown (2000) investigated the potential for using kudzu to remove heavy metals from dilute aqueous streams, such as stormwater runoff. Kudzu was found to be an effective adsorber for heavy metals, and while its capacity was lower than that of commercial-grade resins, it was also cheaper than the resins. The application of kudzu to stormwater runoff was found to be particularly attractive both because of the cost and because of the potential problem of premature fouling of an
expensive resin. Clark et al. (2000) investigated the potential of using low-cost adsorbents, such as peat moss and municipal leaf compost, to treat dilute aqueous wastestreams of copper such as stormwater runoff. The capacity of these adsorbents was compared to the capacities of other well-known adsorbents, such as activated carbon, bone char and cation-exchange resins. The low-cost adsorbents had removal capacities of approximately 20 - 30 mg Cu/g media. While these capacities were less than those of the bone char and resin (approximately 90 mg Cu/g), their cost was significantly less, and they demonstrated a robustness for dealing with the intermittent flow and potential interferences of stormwater runoff.

The behavior of heavy metals (Cd, Cu, Zn, Cr, Pb), nutrients (organic C, P, and N parameters), and major ions were investigated during percolation of roof runoff water through an artificial infiltration site. The concentrations of various components were determined in rainwater, roof runoff, and infiltrating water at various depths in the soil (Mason et al., 1999). Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas. Such surfaces provide an alternative to impermeable concrete or tarmacadum surfaces which would otherwise produce rapid stormwater runoff leading to possible flooding and degeneration of receiving water quality through the uncontrolled discharge of polluted urban waters. A further advantage may be obtained from such constructions by undersealing them so as to retain stormwater for reuse for non-potable uses (Pratt, 1999).

Given the characteristics of urban surfaces, and notably the amounts of the different pollutants that stormwater was likely to contain, an experiment was carried out in Valence (France) on two infiltration facilities, in order to assess the impact of intentional stormwater infiltration systems on the soil, and on groundwater. Stormwater from impervious urban areas can adversely impact water quality and quantity. The PET was a control device designed to moderate both the quality and quantity of urban runoff (Li et al., 1999). Urban stormwater often contains high levels of traffic-generated metal elements and particulates. These constituents were transported by stormwater runoff to surficial soils, drainage systems and receiving waters; Sansalone (1999) summarized the in-situ field-scale performance of a passive treatment system called a PET for source control of these constituents. Two infiltration trenches were constructed in a densely built-up area in central Copenhagen and equipped with on-line sensors measuring rain, runoff flow from the connected surfaces and water level in the trenches. Warnaars et al. (1999) described the field site, the measuring system and the results from an initial soil survey. There were numerous reasons, such the saturation of the existing downstream sewer system or its concentrate discharge impact on the receiving water, for using stormwater infiltration systems. However, their feasibility within an urban development project depends on physical soil characteristics and contamination risk, and also on socio-economic considerations (Alfakih et al., 1999).

Sediment transport was studied in non-submerged overland flow over grass in a laboratory. Artificial turf (astro-turf) was used to simulate natural grass and no infiltration was allowed at this stage of the investigation. Experiments were conducted for different grass densities, flow rates, sediment inflows, and sediment types (Delectic 1999).

Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlock, 1999). Suarman et al. (1999) reported a laboratory simulation study, supplemented with information from field installations, in which four paving sub-structures were subjected to sediment loads equivalent to those which could be expected below porous car park surfaces in stable, fully-developed residential neighborhoods in Adelaide, South Australia. Brough (1999) outlined the development philosophy behind the use of ground soakage (construction of soil adsorption basins), and discusses the procedures that have been used in the design of the basins at residential, industrial sites.

Peak flow reduction and aquifer recharge. Infiltration devices were installed in existing housing areas as a means of reducing the peak flow in a combined sewer system. The resulting economic benefits of the retrofit, especially as compared to the installation of a new sewer, were discussed by Simon and Terfuchte (1999). Watts et al. (1999) reported on the utilization of infiltration and groundwater recharge as part of an overall management strategy for Christchurch, New Zealand’s waterways and wetlands. The infiltration devices used in the Upper Heathcote catchment included a separate infiltration system for roof drainage, grass swales for non-roof stormwater runoff, infiltration basins and storage of excess runoff for later infiltration. Flood control was also suggested as another benefit of planned infiltration. Yura et al. (1999) demonstrated the effects of a well-maintained infiltration facility on the volume of stormwater runoff from a large-scale housing site. In addition to flood control, the infiltration basin also had other positive effects: groundwater recharge, emergency water storage, and the control of pollutants in stormwater. Oka and Nakamura (1999) used a kinematic wave model in combination with GIS data to demonstrate basin scale effects of storm and infiltration on flood control. Rauch et al. (1999) evaluated an integrated drainage system and simple deterministic models for modeling this
The reservoir structure technique (used in streets and parking lots for infiltration) has been developed in France and is used in influent concentration ranged from 2 – 20 ppm. *Pseudomonas putida* of the heavy metal load from the stormwater. Hebrard and Delolme (1999) demonstrated that a biofilm of *Pseudomonas putida* of highway runoff. The tested prototype was able to infiltrate 10 to 30% of the highway runoff while removing at least 75% of the heavy metals. Hebrard and Delolme (1999) investigated the one-year performance of the partial exfiltration reactor (PER) in removing heavy metals from urban runoff. Sansalone (1999) proposed using an oxide-coated sand in a PER to treat urban runoff. Sansalone and Hird (1999) investigated the impacts of the pollutants contained in the runoff on the performance of these infiltration facilities as well as on the groundwater. A similar study on highway runoff was performed in Germany by Dierkes and Geiger (1999). They tested soil profiles and collected water samples at different soil depths for lead, zinc, copper, cadmium and PAH and found that the highest concentrations were found in the top 5 cm of soil and within two meters of the street.

Infiltration installations for pollutant removal. Pagotto et al. (1999) reviewed the information currently available regarding the ability of infiltration systems to remove pollutants from water, and including the various physical, chemical, biological and microbiological processes that occur in the unsaturated and saturated zones of the soil profile. Barraud et al. (1999) investigated the impacts of the pollutants contained in the runoff on the performance of these infiltration facilities as well as on the groundwater. A similar study on highway runoff was performed in Germany by Dierkes and Geiger (1999). They tested soil profiles and collected water samples at different soil depths for lead, zinc, copper, cadmium and PAH and found that the highest concentrations were found in the top 5 cm of soil and within two meters of the street.

Dupre et al. (1999) used ultrafiltration at different pHs to investigate the affinity of certain metal ions to form humate complexes in natural waters with a high dissolved organic carbon concentration. The log K constants for sorption to organic colloids (metal-humate complexes) were as follows: Al, Ga, Fe, Th, U, Y, Re (more than 7) >> Cr (5.5) >> Co (3) > Rb, Ba, Sr, Mn, Mg (approximately 2). The tendency of these metals to bind to organic colloids in water should be similar to their ability to bind to organic soils in the vadose zone during infiltration or to organic filtration media in a stormwater filter. Pitt et al. (1999) described adding compost to the natural soil in an infiltration system to improve both the flow and pollutant removal characteristics of the system. When compared to a natural soil infiltration area, the compost-amended soil system significantly increased the removal of both the quantity of surface runoff and the concentrations of many toxicants typically found in urban runoff. The drawback to the compost amendments was the increased nutrient loads in the system effluent. King and Baloph (1999) modeled the runoff losses of nitrates and pesticides from a golf course turfgrass using four irrigation schemes: normal and reduced water application using potable water and normal and reduced water application using reclaimed water. They showed that nitrate losses were significantly affected by the reduction in irrigation water volume, although the pesticide losses were not significantly different between irrigation strategies. Sansalone (1999) proposed using an oxide-coated sand in a PET to treat urban runoff. Sansalone and Hird (1999) investigated the one-year performance of the partial exfiltration reactor (PER) in removing heavy metals from highway runoff. The tested prototype was able to infiltrate 10 to 30% of the highway runoff while removing at least 75% of the heavy metal load from the stormwater. Hebrard and Delolme (1999) demonstrated that a biofilm of *Pseudomonas putida* on sand could significantly enhance zinc removal from runoff percolating through the vadose zone when the influent concentration ranged from 2 – 20 ppm.

The reservoir structure technique (used in streets and parking lots for infiltration) has been developed in France and is used in
Bordeaux to reduce flooding risks and to protect receiving water (Raimbault, 1998). The first function enables the construction of the structure to withstand various types of loads and the second temporarily retains rain, thereby reducing runoff and improving the quality of discharged water. The urban community of Lyons, Fr. uses infiltration facilities for urban drainage. Chocat et al. (1998) presented information on the rehabilitation of old infiltration pits and a study of an infiltration basin. ‘Ruwenbos’, a small housing estate in the western part of the city of Enschede in the eastern part of Neth., bounded by the German border, was the first project in Neth. where stormwater infiltration was applied on a large scale (Bruins, 1998). Stormwater of all the roofs and most of the streets is transported overland to wadis (‘Wadi’ is the Arabic word for dry riverbed) where it percolates through the soil. A case history described how stormwater management is carried out in Hilleœiö, Den. (Sulsbrück et al., 1998). The existing sewer system was enlarged with retention basins and detention ponds and urban storm infiltration has been expanded. The sizing and dimensions for the disconnection of sewered impervious areas to reduce the overflow frequency and hydraulic load of both combined and improved separate sewer systems was explained. The effect of a discharge drain at the bottom of a percolation trench was also investigated and it appeared that, compared to a facility without a drain, the required dimensions of a facility with a drain decrease significantly. (Leeflang et al., 1998).

Infiltrating stormwater locally into the ground instead of discharging to conventional sewers has been used increasingly as a means of controlling urban-stormwater runoff; however, much research is still required, including development of methodologies for determining the design parameters based on local conditions, technologies for soil-clogging prevention, and a simplistic model for assessing the impact on soil and groundwater in local areas (Mikkelsen et al., 1997).

Oka (1996) examined a gravel-storage infiltration method to control urban storm runoff. The gravel layer was inserted in the underground that had been covered with impervious faces, such as buildings and pavements. This method was shown to be more effective for decreasing flood discharges in the urbanized areas than the pipe infiltration method.

**Design and maintenance guidelines.** Hamacher and Haubmann (1999) compared infiltration as part of a decentral stormwater discharge program to the more traditional method of rapid removal of stormwater from an area through a planned drainage system. They provided information in the article about stormwater disposal through infiltration, including construction, maintenance and system costs. In Stockholm, infiltration was included as part of an overall stormwater drainage plan. Bennerstedt (1999) reported on the Stockholm plans, including the financing of the stormwater drainage system. Hasegawa et al. (1999) described the data collected during the installation of infiltration systems in Japan and that collected by seven governmental entities on the performance of existing infiltration systems. They also proposed a qualitative method for evaluating the applicability of infiltration for flood control and environmental protection. Argue (1999) described many of the misconceptions about stormwater infiltration systems and proposed design limits and practical advice for dealing with these concerns. Noki et al. (1999) outline some of the current research on infiltration and their application to establishing proper maintenance procedures.

Alfakih et al. (1999) described how siting of infiltration facilities was dependent on physical soil characteristics, groundwater contamination risk, and socio-economic considerations. Their paper provided an overview of feasibility and design criteria for infiltration systems, including a review of currently available models and approaches. Zimmer et al. (1999) argued for the use of physically based models to design infiltration systems, rather than the traditional approach of using a design storm to calculate the required storage volume. They developed diagrams which allowed the designer to read the necessary storage volume for the infiltration system once the soil’s hydraulic conductivity was known. Gautier et al. (1999) reported on the progressive clogging of three infiltration facilities and used the results to develop a model for predicting the effect of clogging on the hydraulic behavior and pollutant removal ability of the basins. Todorovic et al. (1999) also evaluated the impact of clogging on the hydraulic performance of infiltration basins over time. They successfully tested their methodology for sizing an infiltration trench/soakaway for the Miljakovac catchment in Belgrade. Laboratory testing using a simulated colloidal suspension was performed by Raimbault et al. (1999) and showed that clogging began with the application of only a small amount of clay. The wetting-drying cycle typically seen in infiltration basins increased the amount of clay retained in the upper layers of a soil and decreased its hydraulic conductivity.

**Porous pavement.** Knapton et al. (2002) reported on the design of permeable pavements surfaced with pavers as part of sustainable urban drainage systems (SUDs) planning. Hunt et al. (2002) tested two types of permeable pavements for runoff reduction. The block pavers (with an approximately 40% open space overlying a bedding layer of sand and washed marl) were found to
provide runoff coefficients of 0.2 to 0.5. A 150-mm thick porous concrete installation was just beginning testing. A new cleaning device for permeable pavements is reported on by Dierkes et al. (2002). The results of the testing of the device showed that cleaning of the pavements to recover infiltration capacity is possible, especially if they are designed, constructed and maintained carefully.

James and James (2000) advocated the use of permeable pavement to reduce the impacts of the thermal pollution of receiving waters associated with urban stormwater runoff. They discuss the required design criteria for an acceptable permeable pavement, including long-term performance. Laboratory studies indicated that infiltrating pavements reduced both the flow and contaminant load of runoff to the greatest degree, although asphalt provided the least buffering capacity for acid rainwater and also the least contaminant removal.

Conventional asphalt and porous asphalt were investigated by Pagotto et al. (2000) for their impacts on both runoff quantity and quality. It was found that, compared to the conventional asphalt, porous asphalt attenuated peak flow and mitigated splashing. The porous pavement also retained particulate pollutants by acting as a filter.

According to Anderson et al. (1999), permeable pavements and similar stormwater control devices have not been exploited in the United Kingdom, in part because their adoption has been hindered by a lack of detailed knowledge of their hydrological performance. A range of simulated rainfalls, which varied in intensity and duration, was applied to the permeable model car park surfaces and monitored over an 18-month period. Results demonstrated that evaporation, drainage and retention in the structures were strongly influenced by the particle size distribution of the bedding material and by water retention in the surface blocks.

In order to develop design guidelines for using permeable pavements in parking lots, Andersen et al. (1999) investigated the pavement’s hydrological/hydraulic behavior and its impact on evaporation and drainage during a range of simulated rain events and interevent periods. They determined that, for a one-hour, 15-mm simulated rainfall, an initially dry pavement could contain and infiltrate approximately 55% of the water, while an initially wet structure could retain approximately 30%. The ability to infiltrate significant quantities of runoff, especially as compared to asphalt, was confirmed by Booth and Leavitt (1999) in an experimental facility. Pratt (1999) reviewed existing information on water quantity and quality below porous pavement structures and suggested collecting the water that infiltrates through porous pavement structures for use in non-potable applications such as flushing toilets. The reuse of infiltration water below a porous pavement structure was applied at a Youth Hostel in the United Kingdom and details of the design were provided in the article.

Bond et al. (1999) reported on a 13-year study of permeable pavements in the United Kingdom. They found that microbial degradation of pollutants occurred in the pavement and that the addition of nutrients every three years was sufficient to support the microbial population. The retention ability of a 50-year old porous pavement structure and the soil below was investigated by Legret et al. (1999) and was modeled by LEACHM. Lead, copper, and zinc were not found in significant quantities in the soil below the pavement, i.e., surface retention of those metals, while cadmium was found to have migrated to a depth of 30 cm below the pavement.

Porous pavement was found to reduce storm-runoff-pollutant loadings significantly by Legret et al. (1996) at an experimental site that monitored about 30-rainfall events over four years. Influent-pollutant concentrations of SS were reduced by 64% and 79% for Pb.

Grass Swales.
Fletcher et al. (2002) reported on the results of controlled experiments on vegetated swales using in urban water design. Reductions in TSS concentration ranged from 73% to 94%, 44 to 57% reduction for TN and 58 to 72% for TP. Reductions in load ranged from 57 – 88% for TSS, 40 – 72% for TN and 12 – 67% for TP. Treatment performance decreased, especially for TSS, with an increased in flow rates. The k-C* model has been developed to mimic the swale performance using a first-order decay equation. Backstrom (2002) measured particle trapping in nine different grassed swales using a standardized runoff event simulation procedure and found that the removal percentage for total suspended solids ranged between 79 and 98%. High infiltration rates improved particle trapping and longer swales led to increased capture of smaller particles. Mean swale residence time was suggested as a design parameter for grass swales.

De Souza et al. (2002) presented an experimental and numerical study of infiltration trenches for urban runoff control. The Bouwer model was used to represent the hydraulic functioning of the trenches. Management tools for specification of
vegetative filter strips during site design is presented by Gharabaghi et al. (2002). These tools are based on site-specific soil, land use, land management and topography of the upland area. Performance of vegetative filter strips was also monitored under different flow conditions, pollutant loads and vegetation cover.

Hsieh and Davis (2002) investigated the use of engineered bioretention for urban stormwater runoff treatment. A variety of potential bioretention media were examined and the results showed that every media had excellent removal efficiencies (> 98%) for suspended solids, oil/grease, and lead. Total P removals ranged from 47 to 85%, increasing as the sand ratio in the media increased. Ammonia and nitrate removals ranged from 2 to 26% and 1 to 27%, respectively.

**Detention/Retention Ponds**

To reduce flooding, the City of Austin, Texas initiated a watershed-based program to use regional stormwater detention facilities (Altman and Nuccitelli, 2001). The new program provided an alternative to using only on-site detention facilities. In addition, the City wanted to develop multi-objective facilities for recreation, water quality, flood-tolerant commercial uses, and/or other benefits. Dechesne et al. (2001) evaluated the long-term performance of infiltration basins by modeling their structural and environmental evolution through a LCA (Life Cycle Assessment) point of view. Sustainable infiltration basins were found to have good economic performance. Alternative configurations of detention ponds and land management plans have been generated using a genetic algorithm (GA)-based method to meet target pollutant removal levels at a relatively low cost (Harrell 2001). The GA-based method has been extended to incorporate reliability estimation into the evaluation of solutions in order to determine cost-effective pond configurations and land management plans to achieve a specified reliability level.

Barbosa and Hvitved-Jacobsen (2001) suggested a method for design and evaluation of the design of infiltration ponds for treating highway runoff in semiarid climates. The design was based on capture and infiltration of the most polluted runoff and accounted for the rainfall and soil hydraulic characteristics in the determination of the design volume. Seasonal variations in rainfall and evaporation were considered. Soil characteristics (hydraulic conductivity, texture, pH, and cation exchange capacity), the infiltrated volume, and the infiltrated area were used to calculate the movement of the most mobile heavy metal, Zn, in the soil below the basin. In Dubai, United Arab Emirates, high groundwater levels restrict the amount of infiltration that is permissible and influence the design of the ponds (wet versus dry) (Darnell et al., 2001b). Design criteria specific to Dubai were established to maximize the efficiency of systems that incorporate the use of detention ponds. The criteria included minimum storage pond volumes, clear times, pond geometry, water depth, the use of linings, and alternative land uses. The first pond constructed using the design criteria is now in operation collecting runoff and excess groundwater flows.

For more than a decade, the Queen’s University/National Water Research Institute Stormwater Quality Enhancement Group studied stormwater ponds with a fully instrumented on-line system in Kingston, Ontario, Canada as a representative field installation (Anderson et al., 2001). The Group concluded that a number of identifiable factors will significantly influence the success, failure and sustainability of these ponds. These factors included initial design, operation and maintenance, performance and adaptive design. Guo and Hughes (2001) presented a risk-based approach for designing infiltration basins with design parameters of basin storage volume, drain time, and overflow risk. The risk-based approach provided an algorithm to calculate the long-term runoff capture percentage for a basin size. The diminishing return on runoff capture percentage would serve as a basis to select the proper basin storage volume at the site.

Cosgrove and Bergstrom (2001) reviewed the new policies and proposed regulations in New Jersey that require that no increase in stormwater pollutant loads from proposed residential and commercial developments. The authors reviewed the use of a bioretention basin as an advanced BMP that can achieve very high levels of pollutant removal. The bioretention basin would manage and treat stormwater runoff using a conditioned planting soil bed and planting materials to filter runoff captured by a collection system and transmitted to the basin. Fennessey et al. (2001) used a continuous simulation stormwater management model (with 33 years of historical precipitation) to determine how the design criteria from five different stormwater management pond ordinances changed the runoff from a 7.77 ha watershed after hypothetical development. All five ordinances required that the postdevelopment runoff rates be less than or equal to the predevelopment runoff rates for each return period. None of the five ordinances limited the increase in runoff peak rates for the 1- and 2-year return periods. This indicated that the lower frequency runoff events should always be analyzed for a basin's design.

The objective of the study by Jacopin et al. (2001) was to develop new operational management practices for detention
basins in order to limit flooding risk and to reduce pollutant discharges through optimizing the settling process. Current basin operation and “on/off” regulation studies were first carried out to quantify the freedom to act to change the control schemes. New operational rules were then elaborated and tested using a hydraulic model with their efficiency to protect against flooding and to reduce pollutant discharges being assessed.

A variety of pond-like BMPs are used to treat urban runoff, including permanently-filled ponds (wet ponds or retention basins) and ponds that are allowed to go dry between storms (dry ponds or detention basins). Detention basins may be lined or unlined, with unlined ponds usually being vegetated. Bhattarai and Griffin (2000) studied the pollutant removal performance of a concrete-lined detention basin that receives runoff from a highway bridge in Louisiana. The basin primarily acted as a settling basin and was most effective in terms of TSS removal. For other constituents, the basin exhibited a somewhat erratic range of removal efficiencies, but it was still able to reduce their concentrations in most cases. Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland, likely because of the inability of the pond system to retain the fine clay particles (< 2 um) to which the bacteria were predominantly adsorbed. The key to greater bacterial longevity in the pond sediments appeared to be the adsorption of bacteria to fine particles, which protected them from predators. Guo et al. (2000) experimented with modifications to the outlet structure of a dry detention basin to improve pollutant removal performance of the pond., and found no conclusive correlation between the pollutant removal efficiency and the detention time. Instead, pollutant removal efficiency in the field was strongly dependent on the inflow concentration.

Heitz et al. (2000) examined the precipitation and runoff patterns on Guam in order to: (1) characterize the hourly rainfall events for volume, frequency, duration, and time between storm events; (2) evaluate rainfall-runoff characteristics with respect to capture volume needed for water quality treatment; and (3) prepare criteria for sizing and designing of storm water quality management facilities. The resulting design curves should lead to a reduction of non-point source pollution to Guam's receiving waters. Marsalek et al. (2000) examined the hydrodynamics of a frozen in-stream stormwater management pond located in Kingston, Ontario, Canada. Measurements of the velocity field under the ice cover agreed well with that simulated by a CFD model (PHOENICS(TM)). During a snowmelt event, the near-bottom velocities reached up to 0.05 m/s(-1), but were not sufficient to scour the bottom sediment. Van Buren et al. (2000b) studied the thermal balance of an on-stream stormwater pond in Kingston, Ontario, Canada. During dry-weather periods, pond temperature increased as a result of solar heating, and thermal energy input exceeded output. Conversely, during wet-weather periods, pond temperature decreased as a result of limited solar radiation and replacement of warm pond water by cool inflow water from the upstream catchment, and thermal energy output exceeded input.

Newman et al. (2000b) described the application of the Storage-Treatment (S-T) Block of the EPA Storm Water Management Model (SWMM) to design and/or analyze extended-detention ponds (EDPs). The importance of this refined method for EDP design was emphasized with examples of how the use of rules-of-thumb or BMP-manual guidelines could result in unexpectedly poor EDP performance. Proctor et al. (2000) reported on Kentucky’s Sanitation District No. 1 working with a local elementary school to convert a badly eroding stormwater detention basin into an outdoor learning center for the school. The results were that the sewer district gained a corrected detention basin, the public gained an education in stormwater management, the students learned about water pollution, and the school gained an educational resource in the Outdoor Learning Center. Dewey et al. (2000) adapted a two-dimensional, vertically averaged hydrodynamic model to compute the circulation and sedimentation patterns in stormwater detention ponds or other water impoundment facilities. The Circulation and Water Quality Model (CWQM) identified areas in the pond where short-circuiting and dead zones occurred. Sedimentation, based on first-order decay, also could be predicted. Field testing verified that the predicted suspended solids (SS) concentration at the outlet and monitored outlet concentrations agreed.

The question has been raised as to whether stormwater ponds adequately protect downstream aquatic systems from the deleterious effects of stormwater runoff. Lieb and Carline (2000) examined the impact of runoff from a stormwater detention pond on the macroinvertebrate community in a small headwater stream downstream of the pond in central Pennsylvania, USA. Invertebrate communities 98 m and 351 m downstream of the pond were highly degraded, while a community 798 m downstream was markedly less degraded. Despite downstream improvement, all three sites were considered impaired relative to a reference community. These results were found to generally be in agreement with those of similar studies in other states and reinforced the need for land-use planning that considers the potential negative effects of urbanization on headwater streams. Based on an investigation into phytoplankton and periphyton algal communities of two recently constructed stormwater management ponds, Olding (2000) ponds suggested that stormwater impacts on
biological communities are reduced during passage through the ponds, providing a degree of protection for biological communities in receiving waters by reducing harmful toxins and nutrients. The taxonomic composition of the two sites provided an indication of the incoming stormwater quality. The lack of blue-green algae suggested that stormwater facilities may be engineered to inhibit undesirable algal communities. Turtle (2000) studied the impacts of road runoff on spotted salamanders breeding in roadside and woodland vernal pools in southeastern New Hampshire and found that Salamander embryonic survival was lower in roadside pools that received road deicing salt runoff.

Current stormwater quality control pond design in Ontario, Canada typically includes the specification of a uniform detention time for extended detention ponds to ensure water quality control. In reality, the pollution-control performance of such facilities was governed by two opposing forces: improved pollutant removal efficiency over longer detention times and the decreased volume of runoff captured and treated by the facility for longer detention times (Papa et al., 1999).

Three seasonal surveys of suspended solids were carried out in an on-stream stormwater management pond, by means of a submersible laser particle size analyser. Size distributions were measured at up to 17 points in the pond, and water samples collected at the same locations were analysed for primary particles aggregated in flocs. Using a relationship defining the flee density as a function of flee size and Stokes' equation for settling, an empirical relationship expressing the free fall velocity as a function of floc size was produced (Krishnappan et al., 1999). Jacopin et al. (1999) examined the new operational management practices for detention tanks, with grassed banks and bottom installed on a separate stormwater network, during rainfall events in order to limit flooding risk and, at the same time, to reduce pollutant discharges by optimising the settling process.

Use of stormwater retention and detention basins has become a popular method for managing urban and suburban stormwater runoff. Infiltration of stormwater through these basins, however, may increase the risk to ground-water quality, especially in areas like the Coastal Plain of southern New Jersey, where the soil was sandy and the water table shallow, and contaminants may not have a chance to degrade or sorb onto soil particles before reaching the saturated zone. Ground water from monitoring wells installed in basins in Camden and Gloucester Counties, New Jersey, was sampled and analyzed for volatile organic compounds (VOC), pesticides, nutrients, and major ions (Fischer, 1999). Crunkilton and Kron (1999) measured the toxicity of stormwater runoff before and after it had been allowed to flow through a pilot-scale wet-detention basin. Selected heavy metals and PAH compounds were measured in incoming and outgoing-settling basin water. Daphnia magna and Pimephales promelas (fathead minnow) were exposed to pre and post-settling basin treated stormwater runoff for three test periods of 14 days each in 1996 and 1997.

Stormwater reuse has been incorporated into the design of wet-detention systems constructed in Florida. Stormwater reuse reduces the volume of stormwater discharged downstream thereby decreasing the loss of potentially valuable freshwater resource. Additionally, by reusing the detained stormwater instead of discharging it, the treatment efficiency of the stormwater detention pond was increased thereby decreasing the pollutant load delivered downstream (Livingston, 1999). The suitability of treatment ponds for mitigation of chemical contaminant loads and toxicity was investigated under baseflow conditions in two systems serving urban and industrial catchments (Hickey, 1999).

Approximately 40x10^6 L (10 MG) of stormwater were managed at a hazardous spill site for the release of ethyl acetate (Buckles and Sanborn, 1998). Five earthen dams were constructed in series along a stormwater drainage ditch to contain the contaminated stormwater and were removed after the completion of the project.

Vignoles and Herremans (1996) studied pollutant loads (SS, COD, TKN [total Kjeldahl nitrogen]) in runoff waters from a highway to determine capacity of a settling tank for collecting adequate volume of runoff to mitigate the spread of pollutants.

Solids-settling characteristics of urban storm runoff have been addressed by Pisano (1996), due to their importance in designing CSO and stormwater high-rate treatment facilities. Solids settling curves and median settling velocities for different waste types have been presented. Settling column methods and solids settling curves for various wastes were presented by Pisano and Brombach (1996) along with global estimates of median settling velocities and results of recent German research.

Multiple drainage objectives and pond design conflicts.
Wada et al. (1999) investigated the possibility of using a storage tank or pond, for both flood control and stormwater
control. They found that the first flush could be directed into an initial storage area, while peak runoff flows could be directed to a secondary storage area. The suitable storage volume of the first pond would be 1-2 mm of runoff and the secondary pond volume would be 3-4 mm of runoff. Cabot et al. (1999) also described the dual use of ponds in Barcelona, Spain, where several detention facilities have been designed to simultaneously address both flooding and CSO. The design procedure has been validated with a detailed model, and a simplified rule has been developed stressing the use of the 10-year design storm. The 100-year design storm was then used to obtain the design capacity of the overflow structures of the facilities. Drainage objectives in Belgrade, Yugoslavia were to separate stormwater from wastewater in areas of existing combined systems and to limit peak discharges by means of detention ponds in the upstream part of the drainage areas for downstream flood prevention (Despotovic et al., 1999).

Henderson (1997), Sela and Chidananda (1997), Yeh and Labadie (1997), and Smith and Sila (1997) reported that stormwater-detention basins (ponds) in urbanized areas have been designed for many purposes, including flood and pollution control and recreation.

Gupta and Saul (1996) discussed use of storage tanks incorporated into the design of combined sewer systems at two sites in northwestern England for controlling discharges to receiving waters. The Regional Municipality of Hamilton-Wentworth operates a large combined-sewer system with 20 overflow structures that result in an average of 23 overflow events per year per outfall. Stirrup (1996) concluded that the only reasonable means of dealing with large volumes of CSO in Hamilton was to intercept it at the outfalls, detain it, and convey it to the wastewater treatment plant after the storm event ends. Target reductions of CSO to be achieved are 1 to 4 per year on the average.

Nix and Durrans (1996) analyzed offline-detention systems as a means of stormwater management and concluded that offline systems required considerably less storage than inline systems to achieve the same management goal.

**Pond sizing.**

Bertrand-Krajewski and Chebbo (2002) compared two types of stormwater treatment facilities – storage-settling tanks and on-line settlers) for event, annual and inter-annual time scales. Storage-settling tanks with specific volumes of 100 m³/active ha intercept approximately 80% of the annual TSS pollutant load, and on-line settlers designed for 8L/s/active ha can intercept 82 to 85% of this load. Differences exist between combined and separate systems but are usually less than 10-15%.

Bertrand-Krajewski and Bardin (2002) evaluated how the uncertainties in urban hydrology contribution to calculating storage/settling tanks volumes and pollutant loads. The example presented was a calculation of the uncertainties in some quantities describing the behavior of the Venissieux (France) storage and settling tank during one rainfall event. The quantities were the flow rates and the volumes entering into the tank, the inflow and outflow mean concentrations and masses of TSS (Total Suspended Solids), and the TSS removal rate. The results led to the following relative uncertainties: 8% for the total volume, 30% for the inflow concentration, 38% for the outflow concentration, 31% for the inflow mass, 39% for the outflow mass and 138% for the removal rate.

Guo (1999) described a simple method to size stormwater detention basins using a volume-based method such as provided by the Federal Aviation Administration that was applicable to small urban catchments. The average outflow from the detention basin (the most important aspect affecting reliability) was found to be related to the time of concentration of the catchment and the duration of the design storm. Guo and Adams (1999a) described how the flow-capture efficiency and average detention time (the performance measures commonly used in assessing the long-term pollutant removal effectiveness of stormwater detention ponds) can be statistically estimated. Guo and Adams (1999b) further described the analytical probabilistic approach that can be used for evaluating designs of detention facilities that was a computationally efficient alternative to continuous simulation. Papa et al. (1999) described how the pollution-prevention performance of detention facilities was governed by two opposing forces: improved pollutant-removal efficiency over longer detention times, and the decreased volume of runoff captured and treated by the facility for longer detention times. The combination of these effects produces a maximum attainable level of long-term pollution-control performance at an optimal detention time. Harston and Joliffe (1999) described the recent New South Wales (Australia) stormwater management manual which has identified three different classifications for sediment basins. Type F and Type D basins were designed for total containment of runoff and discharge after a predetermined time period to allow efficient containment and release after flocculation to settle the fine sediments.

Retention basins should be cost-effectively sized based on analysis of local-hydrological characteristics and their impact
on stormwater-runoff capture. Urbonas et al. (1996) suggested that fine-tuning to site characteristics and local conditions can save significant costs over recommending oversized ponds. Guo and Urbonas (1996) presented a strategy for estimating stormwater-detention volume to achieve quality control based on the fraction of storm runoff volume captured and the number of storm runoff events predicted to occur in a given time period.

Kachalsky et al. (1996), discussed an approach to optimal sizing of a CSO-retention facility that was used for a planned CSO facility in Jamaica Bay, New York, NY, by the New York City Department of Environmental Protection. In this approach, an evaluation of the impact to water quality improvement versus construction cost of the CSO-retention facility was considered. Kluck (1996) investigated performance of CSO-settling tanks for certain selected designs as result of time-varying flowrates and dimensional effects as well. This research evaluated the effectiveness of baffles and diffusers and confirmed the importance of the shape of the tanks.

Locating detention facilities in older areas.
Rivard and Dupuis (1999) described how older drainage systems, especially combined sewers, that frequently experience hydraulic surcharges can sometimes be improved by restricting the inflows at the inlets, causing a limited retention of stormwater on the streets. Scott et al. (1999) examined both onsite detention and on-site retention for a set of hypothetical urban catchments ranging in size from 14 ha to 210 ha. The objective was to achieve the same peak flow rate reduction at least cost. The onsite retention facilities was shown to out-perform the detention in most of the medium to large catchments.

Modeling pond performance.
The paper by Guo (2002) presented a design method by which the overflow risk associated with a basin storage volume could be evaluated for various drain times. The risk-based approach developed in this study provided a quantifiable basis for making the decision on the operation of a stormwater quality control basin. Krishnappan and Marsalek (2002) presented a new model to predict the transport characteristics of suspended sediment for an on-stream stormwater management pond. Simulated suspended concentrations vs. time and the size distribution of the flocculated sediment, produced with the calibrated model, agreed well with flume measurements.

Hollingwork et al. (1999) also presented an analytical probabilistic model (MTOPO) that used probability distribution functions of rainfall characteristics in order to develop closed form expressions for the long term pollutant removal efficiency of stormwater ponds. Operational management practices for detention facilities to limit flooding risks simultaneously with reduced pollutant discharges was possible by optimizing the settling process, as described by Jacopin et al. (1999a). They found that proper descriptions of the particle sizes were critical and that the particle size distribution in the surface sediments were close to those of the suspended solids in the stormwater. Jacopin et al. (1999b) further described the optimization process where the detention facilities were empty most of the time, offering a large safety margin to protect against flooding. The detention facilities store all of the runoff from light and medium rainfall events, consuming about half of the detention capacity. The probability of exceeding the tank capacity was small, even for the larger storms. Adamsson et al. (1999) found that computational fluid dynamics (CFD) was a good tool for studying the hydraulic properties of detention basins in urban drainage systems.

According to Greb and Bannerman (1997), the influent particle-size distribution affected the efficiency of an urban residential area stormwater wet pond’s performance on sediment and associated pollutant removal. Karounarenier and Sparling (1997) studied toxicity of stormwater-treatment-pond sediments. Guo (1997) measured the amount of heavy-metal content, organic content, and mass distribution of the bottom sediment in an 18-year-old-single-purpose-dry-stormwater-detention basin, assessed the effect of sedimentation on flood-control capacity, and determined values for predicting amounts of sediment and heavy-metal accumulation. Results of dye-tracing studies performed in a stormwater pond in Kingston Township, Ont., Can. demonstrated an increase in retention times with reduction in the velocity and volume of short-circuiting flow and a decrease in wind-generated-flow patterns due to the installation of retrofitted baffles (Matthews et al., 1997).

Yeh and Labadie (1997) applied successive-reaching-dynamic programming (SRDP) and a multiobjective-genetic algorithm (MOGA) to the design of a stormwater-detention-system in the Pazam watershed located in southern Taiwan. This study indicated the computational efficiency of the SRDP algorithm and the MOGA’s nondominated solutions for trade-off analysis. Lawrence et al. (1997) reported on the considerations involved in stormwater-hydrological and pollutant-mobilization processes and the selection of stormwater-detention and pollution control BMP. A summary of the major structural and nonstructural BMP commonly used including pollutant removal and flow attenuation capacities of
each BMP was provided.

**Observed pond performance.**

Yang et al. (2002) reported on the use of aerated wet ponds at CVG airport (Cincinnati/Northern Kentucky) to treat glycol-contaminated streams in cold temperatures. The operation of the pond resulted in a nearly 50% BODs removal and intermittent discharges that appear to have resulted in the reduction of nuisance growth in the once-polluted streams. Marsalek et al. (2002) reported on an assessment of the impacts of urban development on a small creek with an on-stream stormwater pond. The assessment included creek-pond system hydrology, water and sediment chemistry and toxicity, and benthic communities. The pond accumulated sediments and toxicants and thereby prevented further degradation of the creek condition downstream of the plaza drainage outfall.

German and Svensson (2002) explored the relationship between stormwater quality and sediment quality in stormwater ponds in Sweden. A correlation between the inflow EMCs and sediment concentrations of heavy metals was found. It was concluded that the pollutant load from a catchment could be characterized by analyzing the pond sediments. The pollutant removal efficiency of three wet detention ponds was investigated by Mallin et al. (2002). The results for solids removal were good for all ponds, but nutrient removal was variable. To achieve good reduction in a variety of pollutants, wet pond design should include maximizing the contact time of inflowing water with rooted vegetation and organic sediments. This could be achieved through a physical pond design that provides a high length to width ratio, and planting of native macrophyte species. Nehrke and Roesner (2002b) reviewed the influence of extended detention BMPs and traditional flood controls on the flow frequency curve of urban runoff (pre- and post-development). Detention ponds with a variety of flow control orifices sized using traditional and innovative methods were examined singularly and in conjunction with extended detention best management practices (BMPs). Shammaa et al. (2002) investigated the effectiveness of dry ponds for removal of TSS from stormwater. Detention time was the most important factor affecting TSS removal. Two-stage facilities and multi-level outlet design were important means of enhancing TSS removal in dry ponds. Two dry ponds within the city of Edmonton were selected to evaluate their TSS removal. Pettersson (2002) investigated the characteristics of suspended particles in a small stormwater pond. The results showed the particle volume in the stormwater (particle volume per stormwater volume) predominately consisted of very fine particles and that the smallest particles comprised most of the surface area. The stormwater pollutants exhibit strong correlation with particle characteristics. Scholz (2002) presented an overview of the pilot plant that will assist in developing design and management guidelines for operating stormwater pond systems. Sustainability analyses were also performed.

Konrad and Burges (2001) used a three-year rainfall record from a site in the Puget lowland, Washington in a mass-balance model to simulate outflow from single- and multiple- purpose detention systems, with the results compared to time series of measured runoff from Evans Creek. The discharge from a small on-site reservoir was sensitive to both the storage capacity and maximum controlled release rate for extreme high flows (those exceeded 1% of the time) and low flows (those exceeded 80% of the time). Using wetland filtration, the North Griffin Regional Detention Pond has proven to be an effective BMP for improving water quality to receiving waters and for reducing flooding (Feldner and Greuel 2001). The 30-year-old Expo Park regional stormwater detention facility in Aurora, Colorado needed renewal (Hamilton et al., 2001). Improvements to the multi-use 60-acre park facility were made to provide water quality, improve site drainage, increase flood control detention, improve recreational usefulness and aesthetics, and upgrade the facility to meet jurisdictional State dam safety requirements. Dam safety related improvements included new outlet works, spillway improvements, and acceptance by the Engineer’s Office for using irrigated turf grass as overtopping erosion protection for the emergency spillway.

Karouna-Renier and Sparling (2001) investigated the accumulation of Cu, Zn, and Pb by macroinvertebrates collected in Maryland stormwater treatment ponds serving commercial, highway, residential and open-space watersheds to determine if watershed land-use classification influenced metal concentrations in macroinvertebrates, sediments, and water. Composite Zn concentrations in odonates from ponds with commercial development (mean = 113.82 µg g⁻¹) were significantly higher than concentrations in the other land-use categories. Similarly, Cu levels in odonates from commercial ponds (mean = 27.12 µg g⁻¹) were significantly higher than from highway (mean = 20.23 µg g⁻¹) and open space (mean = 17.79 µg g⁻¹) ponds. However, metal concentrations in sediments and water did not differ significantly among land-uses. The levels of Cu, Zn, and Pb in invertebrates from all ponds were less than dietary concentrations considered toxic to fish. Caltrans initiated a study in two Districts (Los Angeles and San Diego, California) to examine the benefits, technical feasibility, costs and operation and maintenance requirements of retrofitting extended detention facilities into existing highway and related infrastructure (Taylor et al., 2001). Monitored constituents will include suspended solids, metals, nutrients, and organics (e.g., gasoline). Detailed records will also be kept for maintenance and
researching stormwater ponds for the past decade, using a fully instrumented on-line system in Kingston, Ontario, Canada.
The Queen's University/National Water Research Institute Stormwater Quality Enhancement Group has been actively addressing problems observed with stormwater ponds.

Martin (1996) in terms of reductions in discharges of BOD and selected metals. The benefit of constructed reed beds in treating stormwater overflows was evaluated by Green and Papa and Adams (1996) analyzed the implications of required detention times for retention basins with respect to their actual pollution control performance. It was found that pollution-control performance is maximized with typically short-detention times and diminishes monotonically with additional detention time thereafter.

Van Buren et al. (1996) assessed the pollution-control performance of a retention pond in Kingston, ON, Canada, and provided results on removal rates for SS, nutrients, metals, organic contaminants, and selected dissolved constituents. Internal pond baffles were evaluated, and it was found that extended hydraulic-residence times and prevention of flow short-circuiting result in increased particulate settling and associated contaminant removal. Stanley (1996) quantified removal efficiencies achieved by a retention pond in Greenville, NC for SS, N, P, TOC (total organic carbon), and selected metals. The benefit of constructed reed beds in treating stormwater overflows was evaluated by Green and Martin (1996) in terms of reductions in discharges of BOD$_5$, SS, NH$_4^+$, and TON (total organic nitrogen).

Problems observed with stormwater ponds. The Queen's University/National Water Research Institute Stormwater Quality Enhancement Group has been actively researching stormwater ponds for the past decade, using a fully instrumented on-line system in Kingston, Ontario, Canada.

Petterson et al. (1999) studied the pollutant-removal efficiency of two stormwater ponds in Sweden. Observed outflow pollutant conditions were independent of the influent conditions for the two ponds. They also found that pollutant removal efficiency increased for increasing values of ratio of the pond surface area to the watershed impervious area, up to about 250 m$^2$/ha, while the benefits of larger ponds were not as important. Bartone and Uchrin (1999) compared the performance of two dry-stormwater-detention facilities, one having a concrete low-flow channel, and the other with a vegetated low-flow channel during four events. As they expected, the detention pond having the concrete channel was ineffective for stormwater quality control. However, the basin with the vegetated channel was also found essentially ineffective for water quality improvement, with flushing of previously captured pollutants being the most likely reason for the poor performance. The retention of heavy metals in a wet reed-bed wetland were compared to retention in a dry-detention pond near London, United Kingdom, by Hares and Ward (1999). A higher percentage removal occurred in the monitored wetland facility than in the dry pond. Shatwell and Corderly (1999) examined nutrient removals in a pond in Sydney’s (Australia) Centennial Park that receives stormwater from a 120 ha catchment that was predominantly residential. They found significant amounts of phosphorus and sediment accumulating in the pond, especially during the small- to medium-sized rain events (approximately 60% phosphorous and 80% suspended sediment reductions).

Krishnappan et al. (1999) monitored in-pond particle sizes using a submersible laser particle size analyzer, reducing potential changes in particle characteristics that may occur during sampling. The suspended solids were mostly composed of flocs, and were about 30 µm in size during winter surveys and about 210 µm during the summer surveys. MacDonald et al. (1999) investigated the removal of heavy metals in a detention pond in Scotland. They found that the sediment in the pond may reach unacceptable concentrations of heavy metals within twenty years. Petterson (1999) examined the partitioning of heavy metals in particulate-bound and dissolved phases in a stormwater pond in Goteborg, Sweden. The results showed a clear variation in lead partitioning affected by specific conductivity.

A monitoring study in Kingston, Ont., Can. (Shaw et al., 1997) concluded that regardless of the magnitude of inflow, the length to width ratio (3:2) of the urban-stormwater-detention pond studied and inflow momentum promote short-circuiting of the flow and limit settling efficiency.

Maxted and Shaver (1966) studied the use of retention basins, constructed as the best management practices (BMPs) to mitigate stormwater impacts on aquatic life. Physical habitat and biological measurements were taken below eight stormwater basins (BMPs). Two of the sites were in commercial land use, while six were in residential areas. The results were compared to 38 sites with no BMPs that had been sampled in 1993. The BMPs did not prevent the almost complete loss of sensitive species. The BMPs did not attenuate the impacts of urbanization once the watershed reached 20% impervious cover. This study showed that the data set size used here was too small for a conclusive evaluation of the effectiveness of stormwater controls to protect stream biota and habitat. It is also possible that the stormwater facilities studied were not used long enough to achieve improvements in habitat and to repopulate the species.

Papa and Adams (1996) analyzed the implications of required detention times for retention basins with respect to their actual pollution control performance. It was found that pollution-control performance is maximized with typically short-detention times and diminishes monotonically with additional detention time thereafter.

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as a representative field installation of this group of stormwater best management practices (Anderson et al., 2002). The factors that were found to be crucial to the success or failure of stormwater ponds could be grouped into the following categories: initial design, operation and maintenance, performance and adaptive design.

Beyerlin (1999) described the short-comings of relying on stormwater-detention facilities for complete mitigation of urban runoff problems. Increased winter flood flows, decreased summer low flows, and a general degradation of the stream systems has occurred with development. It was concluded that these problems persisted because of the attempt of replacing the complex interactions of the hydrologic cycle with a pond, which was not possible. Brown et al. (1999) described the degradation in quality in Sydney (Australia) Centennial Park’s ponds over the past 150 years. Pond rehabilitation techniques have been developed and were being implemented, based on wetland principles.

**Wetlands**

It has been hypothesized that smaller lot sizes in a development need not seriously decrease quality of life but instead, may result in increased use of local open space (Syme et al., 2001). This hypothesis was investigated with matched small and larger blocks in four areas in Perth, Western Australia. Households with smaller lots had increased visitation to the wetlands. Wetlands, while improving stormwater management, also fulfilled demands caused by higher urban densities. The City of Edmonton, Alberta issued “Draft Guidelines for Constructed Stormwater Wetlands” to assist developers who use constructed wetlands for stormwater management (Lilley and Labattuk, 2001). Edmonton has accepted constructed wetlands as an alternative means of managing stormwater, while providing benefits of aesthetics, public enjoyment and wildlife habitat. The City’s draft guidelines are intended to optimize the design of constructed wetlands for water quality improvements including suspended solids removal, drainage area, soil permeability, vegetation, water depth, wetland area, wetland volume, length to width ratio, forebays, inlets and outlets, grading, floatables and oil and grease, maintenance, monitoring, signage, secondary uses, land ownership, access, fencing, wildlife and mosquitoes. The research presented by Fassman and Yu (2001) examined the relative pollutant removal capability for specific wetland vegetation. Results of water quality analysis show various trends with respect to pollutant removal and time. In general, export of TP was shown in all vegetated cells. Maximum export for vegetated cells was observed usually during the first week of a treatment, especially for *Typha* spp. and *Phragmites* spp. By the end of most treatments, TP removal was observed in all cells. COD removal was seen in all cells for all weeks of each treatment (average removal ranged from 54-78%). TSS results were inconsistent. Export of Cu was noted for *Scirpus* spp. whereas all other plants showed positive removal. TOC was removed by all plants (average removal 24 – 69%), with the exception of the *Scirpus* spp. cell.

Data from 35 studies on 49 stormwater treatment wetland systems were examined for obvious trends that may aid future design efforts (Carleton et al., 2001). Despite the intermittent nature of hydrologic and pollutant inputs from stormwater runoff, steady-state first-order plug-flow models commonly used to analyze wastewater treatment wetlands could be adapted for use with stormwater wetlands. First-order removal rate constants for TP, NH$_3$, and NO$_3$ for stormwater wetlands were similar to values reported in the literature for wastewater treatment wetlands. Constituent removals were demonstrated via regression analyses to be functions of the ratio of wetland area to watershed area. Goulet et al. (2001) tested a first-order removal model to predict metal retention in a young constructed wetland receiving agricultural and urban runoff. The wetland retained metals best during summer and fall. The first-order removal model predicted Fe and Mn retention in the spring and dissolved Zn retention from spring to fall in both years. However, first-order removal models failed to fit summer, fall and winter data for almost every metal under investigation (Fe, Mn, dissolved Cu, dissolved As) suggesting that HRTs (< 1-25 days) did not affect metal retention during these seasons. Therefore, the first-order removal model is inadequate to predict metal retention on a seasonal basis. Constructed wetlands design models for cold climates must consider seasonal changes that affect biological as well as hydrological variables. Wetland BMPs have focused on smaller storms, encouraging long retention times and vegetative contact for pollutant removal, design elements not typically considered for detention basins (Traver 2001). It was hypothesized that traditional storage - indication routing may not be appropriate for stormwater wetlands, especially for smaller water quality storms. To test this hypothesis, a recently constructed wetland was monitored for rainfall and flow. Sediment behavior in a stormwater wetland in Adelaide, Australia was studied using models that were based on solving hydrodynamic and transport equations, with the results compared to field-observed deposition patterns (Walker 2001). The long-term residence time distribution was useful in predicting overall sediment removal rates. Comparisons between the model and field observations indicated generally good agreement. The importance of the transient nature of the flow events was highlighted by the distribution of sediment throughout the wetland.

In the study by Kao and Wu (2001), a mountainous wetland located in McDowell County, North Carolina was selected to demonstrate the natural filtration and restoration system for maintaining surface water quality. Analytical results from the
summer of 1997 indicated that this wetland removed a significant amount of NPS pollutants [more than 80% N removal, 91% total suspended solid removal, 59% total phosphorus removal, and 66% COD removal]. In Taiwan, research on constructed wetlands was conducted as part of a project supported by National Science Council (Yang 2001). Different waters, including contaminated river water, aquaculturing pond water, sewage, industrial wastewater, and storm water, were tested by using microcosm or macrocosm constructed wetland systems. The results of this project showed that the wetlands’ effluents had a high potential for water reuse. Shutes (2001) illustrated the role of plants for treating water pollution in man-made wetlands in tropical and temperate climates. The design of the Putrajaya Lake and Wetland system in Malaysia was compared with an urban-runoff-treatment constructed wetland in a new residential development in the UK.

The ability of a wetland to mitigate highway-runoff pollutants, particularly metals, was investigated by Mitchell et al. (2001a). Fifty-seven rainfall-runoff events were monitored. Data collection included rainfall volume and frequency, conduit flow rate, and temperature, conductivity, pH and dissolved oxygen in the runoff. Metal concentrations were reduced via flow through the grassy median and then the wetland system. Average heavy metals removals were zinc (67%) and iron (67%), followed by lead (54%) and then nickel (45%). Metals were reduced some even during winter months and low temperatures. Wetland sediment analysis indicated a broad range of concentrations of metals. Rodgers et al. (2001) reported on the A-01 effluent outfall, which collected both normal daily process flow and stormwater runoff from a industrial park area and did not meet its South Carolina NPDES permit limits for metals, toxicity, and total residual chlorine at the outfall sampling point. Installation of a constructed wetland system including a basin to manage stormwater surges reduced the problematic constituent concentrations to below the NPDES permit limits before the sampling point. The constructed treatment wetland system proved its ability to treat industrial wastewaters containing metals with low O&M costs. With an anticipated life of over 50 years, the wetland system will be cost-effective.

The Greater Toronto Airports Authority (GTAA) constructed the first full-scale vertical-flow treatment wetland in Canada for reduction of ethylene glycol in stormwater (Flindall and Basran 2001). The two-cell treatment wetland was preceded by a sedimentation forebay. The wetland facility collected water discharged from terminal aprons, taxiways, and runways where aircraft receive de-icing compounds particularly glycol, are applied. The facility provided 24 to 48 h of retention to attenuate storm flows and remove suspended sediment. The selected vegetation was Phragmites australis reeds. This emergent hydrophyte should be able to withstand the periodic flooding conditions characteristic of a stormwater management system. The reeds will provide very little habitat benefit for gulls and waterfowl and will therefore not attract birds that may cause hazards for aircraft.

Constructed wetlands have been used to capture, detain, and treat stormwater runoff from urban areas because they have the potential to treat a variety of pollutants. Knight and Kadlec (2000) presented an overview of constructed wetlands used for water pollution control. Bachand and Horne (2000) examined the effect of vegetation type on nitrogen removal rate in wetlands used to treat wastewater, including urban runoff. Based on the study and a literature review, in organic carbon-limited free-surface wetlands, a mixture of labile (submergent, floating) and more recalcitrant (emergent, grasses) vegetation would be recommended for improving denitrification rates. Carleton et al. (2000) examined the pollutant removal performance of constructed wetlands treating stormwater runoff from a residential townhome complex in northern Virginia. Median load removals of all constituents were greater for a subset of storms that had inflow volumes less than the maximum volume of the marsh. Estimated removals were positive for most constituents and consistent with expectations based on the relative ratios of wetland area to drainage area at the two sites. Zhu and Ehrenfeld (2000) compared the ability of sediments from Atlantic cedar wetlands in suburban and undisturbed watersheds to remove added inorganic N in laboratory incubations. Results suggested that wetlands in suburban drainages may have limited ability to retain frequent, pulsed N inputs from runoff, and high intrinsic N mineralization in N-saturated sediments can become a cause of water quality degradation. Graham and Lei (2000) evaluated the effective long-term operation of stormwater management ponds/wetlands, including removal, methods of removal and disposal of removed sediments.

Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland. Quintero-Betancourt and Rose (2000) assessed the microbial quality of stormwater and/or reclaimed water in terms of bacterial indicators, coliphages, Cryptosporidium and Giardia in order to determine its suitability for use in recharging stressed wetlands overlying a public water supply wellfield. Preliminary data demonstrated that the level of bacterial indicators such as fecal coliforms and total coliforms in three of the lakes sampled were above the water quality standard established by the Florida Department of Environmental Protection for ambient waters, and other pathogens and indicators were detected.
Wetlands have been chosen for retrofitting existing developments or stormwater detention facilities to improve the treatment of stormwater pollutants. Kerr-Upal et al. (2000) presented a conceptual plan to retrofit a wetland component within the a stormwater management facility in Toronto, Canada, using three wetland design options. Traver (2000) converted an existing stormwater detention pond to an extended detention wetland at a site near Philadelphia, Pennsylvania. The project maintained the original storm water controls and provided proper hydrologic growth and non-point source pollution control. The City of Elkhart, Indiana has constructed an artificial wetland at a CSO outfall to capture and treat overflows prior to discharge into the Elkhart River. The treatment process consisted of (1) a bar screen/sedimentation basin to remove grit and flotables, (2) nearly 30 different species of native aquatic and transitional vegetation, and (3) a downflow drainage and collection system to enhance biological removal of dissolved organics and inorganics, dissolved metals, and suspended particulates (Umble et al. 2000). Davis et al. (2000) reported laboratory and field results of a study of bioretention for treating urban runoff. Kim et al. (2000) evaluated the capacity of bioretention to remove nitrate from urban runoff using a design modification to incorporate a continuously submerged anoxic zone with an overdrain. Work so far has focused on selecting an electron donor/carbon source that promotes significant denitrification and is stable for an extended time in the subsurface. Further studies will use the electron donor (newspapers, wood chips, small sulfur particles/limestone) with the best nitrate removal efficiency and effluent quality.

Since surface flow constructed wetlands (SFCW) are now often designed with low aspect ratios to circumvent surfacing problems, plug flow is not ensured; therefore, alternative models which more accurately describe the flow must be considered. However, to solve the alternative models, a value for dispersion is required. The fundamental variables affecting dispersion are the interstitial velocity (dependent on flow rate, porosity, and cross-sectional area) and the pore geometry (dependent on media characteristics such as average grain diameter and permeability). The dispersion number also will fluctuate with a series of uncontrollable variables specific to a particular SFCW situation. Cothren and Daly (2000) reported the results of their research to extend the results of an empirical relationship between the interstitial velocity as a function of flow rate and aspect ratio and the dispersion number developed using a bench-scale model to the field scale application. Larm (2000) presented a methodology for quantifying yearly and monthly material transport into and out of stormwater treatment facilities (STFs) and discussed problems related to monitoring and estimation of reduction efficiency. Standard values of runoff coefficients and pollutant concentrations together with precipitation data and estimated areas of different land uses within sub-watersheds were used to predict loadings to a multiple pond-wetland STF. A comparison of standard concentrations with measurements shows good correlation for nitrogen, but variable correlations for other pollutants. Tucker and Acreman (2000) described a user-friendly, physically-based model for the estimation of ditch water levels in wet grassland drainage ditches and thus assess the impacts of different water level management strategies on ecological communities and agricultural practices in wet grassland areas. Simulated rain events and runoff were found to produce a more realistic influent to a stormwater treatment wetland than do averaged inlet flow and concentration. Network flow models provided a more realistic prediction of a treatment wetland's internal flows than did plug flow or complete mixing estimation (Werner and Kadlec 2000). Moustafa (2000) extended empirical mixed-reactor models governing phosphorus (P) retention and nutrient assimilation in lakes and reservoirs to include free surface water wetland treatment systems. It was found that sedimentation rates, loading rates, and settling velocity in these wetlands, and their typology were comparable to their lake counterparts. Stormwater treatment areas (STAs) are extremely large-scale (several square miles) wetland BMPs being constructed on former agricultural areas of south Florida to provide total effective treatment of stormwater before discharge to the water conservation areas and Everglades National Park. Hyder and Hilton (2000) reported on the hydraulic design model that provides a technical basis for management of STAs. Neumeister et al. (2000) presented a modeling approach to evaluate design alternatives for STAs. The flexibility of their model allowed impacts from alternative design scenarios to be evaluated and incorporated.

Because vegetation is crucial in many wetland treatment processes, the establishment of vegetation in newly constructed wetlands is important. Fassman et al. (2000) examined strategies for planting constructed wetlands to enhance development and survival of constructed wetland systems used for stormwater management and mitigation credit. Galatowitsch et al. (2000) used wetland biomonitoring approaches to determine when changes in response to stressors were occurring and to predict the consequences of proposed land-use changes for 40 wet meadows in Minnesota. Site impacts (stormwater, cultivation) and landscape disturbance (agriculture and urbanization, combined), coincided with a reduction in native graminoid and herbaceous perennial abundance.

One often cited advantage of wetlands for stormwater treatment is the associated development of wildlife habitats. A study by Bishop et al. (2000a) of 15 stormwater pond wetlands and one natural wetland varying in age from 3 to 22 years in the Guelph and the Greater Toronto Area (GTA) in Ontario, Canada, showed that wildlife made use of the ponds, but
species richness at almost all sites was low to moderate, indicating that the ponds did not provide high quality habitat for wildlife. Due to concerns that wildlife would be attracted to stormwater detention ponds and be exposed to contaminants accumulating in these ponds, contaminant levels in ponds, sediments, and wildlife were also investigated (Bishop et al. 2000b). A variety of impacts detected in wildlife species including fish, songbirds, and amphibians led the authors to conclude that stormwater ponds did not offer clean ecosystems for wildlife and the monitoring of contamination and its effects within stormwater ponds was necessary. The Lake County Sanitation District has developed a program to recycle treated wastewater in Lake County, California. The plan included constructed wetlands to improve water quality, enhance wildlife habitat, offer evapotranspiration of excess water, and provide public benefits by creating settings for passive recreation and wildlife study. Kimmelshue et al. (2000) presented a paper which included results from a wetlands screening study, a preliminary design effort and the design and construction of an initial wetland.

According to Koob et al. (1999), the successful design of constructed wetlands required a continuous supply of water or vegetation that can withstand drought conditions. Detention structure designs should be based on times between events as well as on hydrologic return periods, since between events was when most evaporation and infiltration losses were likely to occur. Serrano et al. (1999) investigated phosphorus (P) concentrations in Donana seasonal wetlands in southwestern Spain as the wetlands started to fill following storm events after a drought. NPS N from riverine origin was a major water quality problem throughout the world. Hunt et al. (1999) reported that total annual N removal for the in stream wetland was approximately 3 kg/ha per day, which was about 37% of the inflow N. Removal of both NO$_3$-N and total N (NO$_3$-N + TKN) were positively correlated to temperature with r-values of 0.77 and 0.62, respectively. According to Zhu and Ehrenfeld (1999), the presence of urban and suburban lands adjacent to wetlands may cause changes in nutrient-cycling processes, due to changes in the quality of the ground and surface waters that drain from the developed uplands into the wetlands. The alternations in hydrology and the input of mineral-rich sediments, in addition to excess N from the septic drainage and road runoff, can apparently cause increases in N mineralization within the wetland sediments, thus exacerbating the direct deleterious effects of roads and housing on water quality. Quantitative estimates of denitrification were needed in designing artificial wetlands to optimize nitrate (NO$_3^-$) removal. Acetylene blockage and N-15-tracer methods were employed to quantify denitrification in constructed wetlands receiving agricultural tile drainage, using plastic tubes to enclose in situ mesocosms. Because water infiltration carries NO$_3^-$ through the anaerobic sediment/water interface for denitrification, a subsurface-flow wetland may denitrify more NO$_3^-$ than a surface-flow wetland (Xue et al., 1999).

According to Guardo, (1999) the Everglades Nutrient Removal (ENR) Project, a 1544-ha wetland, was designed and constructed as a pilot project to gain experience on design, construction, and operation of the stormwater treatment areas. For the 732 days analyzed (19 August 1994 through 19 August 1996), the average water inputs into the project were as follows: 86.2% from the inflow pumps, 11.2% from rainfall, and 2.6% as emerging measured and estimated seepage from an adjacent area with higher stages; the average water outputs from the project consisted of 85.1% from the outflow pumps, 8.9% as evapotranspiration, and 6.0% as a net seepage and groundwater component. The ENR Project’s purpose was the removing of nutrients (especially phosphorus) from agricultural drainage and stormwater runoff before entering the Everglades. The hydrology and water quality of an urban wetland receiving stormwater runoff from a municipal maintenance garage were measured during the summer of 1993 to evaluate the wetland’s water quality enhancement function. According to Thurston (1999), hydrologic and analytical data together suggest that sedimentation was the primary mechanism actively reducing water column concentrations of lead and petroleum hydrocarbons introduced to the wetland via stormwater runoff.

It was evident that existing designs for the control of highway discharges were primarily if not exclusively intended to control runoff volumes rather than as any complementary pollution treatment function. However, regulatory pressures on highway authorities and agencies were increasingly requiring that drainage controls should include reference to water quality treatment and the clear inadequacy of conventional drainage systems has stimulated interest in the design, implementation and operation of alternative vegetative systems, such as swales and wetlands (Ellis, 1999a and 1999b).

To address the unknowns and design concerns of a stormwater wetland system, a bench-scale vegetative-treatment-cell study has been conducted for the purpose of examining nutrient and metal dynamics and removal efficiencies of three individual plant species under various stormwater-pollutant loadings and detention times. The plant species being evaluated are: cattails (Typha latifolia), reeds (Phragmites sp.), and bulrushes (Scirpus sp.) (O’Shea et al., 1999). The design and pollutant removal performance of seven wetland mitigation sites and two detention basins with emergent vegetation in Virginia were examined over a three-year period to assess the effectiveness of mitigated wetlands for the control of NPS pollution and the influence of design on wetland performance as a BMP, in a study sponsored by the
Existing wetlands located in the future Rocky Ridge subdivision of Calgary, AB, Canada will be retained and maintain the hydraulic effectiveness and hydrologic regime of the wetland.

Outlet configurations for draining wetlands: an orifice, riser, and siphon. Each outlet type was evaluated for its ability to possible but also provide adequate wetland storage capacity for the next storm event. This study concentrated on three storage volume and outlet characteristics. The outlet of a wetland must retain the stormwater in the wetland as long as control involves consideration of the inherent variability of storm events and interevent dry periods to size the wetland.

Somes and Wong (1996) modeled a series of hypothetical wetland systems to determine the influence of different outlet types on their hydrologic regimes. It was concluded that the design of constructed wetlands for stormwater-pollution removal involved consideration of the inherent variability of storm events and interevent dry periods to size the wetland storage volume and outlet characteristics. The outlet of a wetland must retain the stormwater in the wetland as long as possible but also provide adequate wetland storage capacity for the next storm event. This study concentrated on three outlet configurations for draining wetlands: an orifice, riser, and siphon. Each outlet type was evaluated for its ability to maintain the hydraulic effectiveness and hydrologic regime of the wetland.

Environmental agency effluent quality data were given for 39 sites where reed beds either treated stormwater and secondary effluent together or have been installed as remedial treatment for works struggling to meet secondary treatment standards (Green et al., 1998). Brdjanovic et al. (1998) attributed deterioration of biological P removal (BPR) efficiency observed after heavy rainfall and weekends to excessive aeration. The lull in BPR performance was originally thought to be low plant loading that took place during such events. A quarry in Du Page County, Ill. currently used for temporary flood control storage was evaluated for treatment of stormwater and dry-weather flow in order to improve water quality to Salt Creek (Lampe et al., 1998).

As wetland ecosystems degrade due to human actions, restoration efforts have become more pronounced. Mass-balance models could provide valuable information about ecosystems with respect to input sources and the relative importance of each pollutant load, based on a study of P and SS loadings to Cootes Paradise Marsh in Hamilton Harbour, Lake Ontario, Can. (Prescott and Tsanis, 1997). Shutes et al. (1997a and 1997b) reported on the results of two case studies of the pollution-removal performance of constructed wetlands for urban-stormwater-runoff treatment. The design of constructed wetlands included primary-treatment components, substrate composition, and flowrate regulation. Two subsurface-flow-constructed wetlands were tested for pollutant-removal performance in conjunction with an online-stormwater-detention pond. The wetlands were able to maintain removal of SS (46%), dissolved metals (Cu 50%), and organic C (10%) (Rochfort et al., 1997). Stormwater-control basins can be easily and inexpensively modified to act as stormwater-treatment wetlands. Preliminary results indicated removal of 93% SS, a total P removal of up to 83%, and a minimal amount (22%) of total N removal (White et al., 1997).

Somes and Wong (1996) modeled a series of hypothetical wetland systems to determine the influence of different outlet types on their hydrologic regimes. It was concluded that the design of constructed wetlands for stormwater-pollution control involves consideration of the inherent variability of storm events and interevent dry periods to size the wetland storage volume and outlet characteristics. The outlet of a wetland must retain the stormwater in the wetland as long as possible but also provide adequate wetland storage capacity for the next storm event. This study concentrated on three outlet configurations for draining wetlands: an orifice, riser, and siphon. Each outlet type was evaluated for its ability to maintain the hydraulic effectiveness and hydrologic regime of the wetland.

Existing wetlands located in the future Rocky Ridge subdivision of Calgary, AB, Canada will be retained and
incorporated into an integrated-stormwater-management system for the subdivision. Van Duin et al. (1996) discussed measures taken to protect the integrity of these wetlands during and after construction of the subdivision including a multiyear-monitoring program. Werner and Kadlec (1996) evaluated the performance of constructed wetlands in terms of effluent concentrations resulting from impulse-tracer inputs to the systems.

**Design guidelines.**

Nirupama and Venema (2002) demonstrated how multi-criteria evaluation (MCE) decision-making tools which incorporate GIS can be used to manage wetlands. Remotely-sensed satellite data and GIS have excellent capabilities to study and analyze spatial issues regarding wetlands management.

Koop et al. (1999) stress that the successful design of constructed wetlands requires a continuous supply of water for vegetation to withstand drought conditions. They acknowledge that there were drought tolerant species of vegetation that can be used in constructed wetlands, however, it can take several days to re-establish the attached bacteria communities that were necessary for optimum pollutant removal. Lawrence and Breen (1999) described new design guidelines for constructed wetlands. They also highlighted some areas where further information was required to facilitate a more rigorous analysis of wetlands to optimize their selection, design, and assessment. Lawrence (1999) described a generic pond and wetland model that can provide water quality assessments for a range of geographic areas and information needs.

Persson et al. (1999) examined the hydraulic efficiency of constructed wetlands. They found that proper control of the hydrologic regime of the wetland and optimal flow hydrodynamics within the wetland were necessary for their sustainable operation. They concluded that many of the problems encountered in constructed wetlands can be minimized, or avoided, by good engineering design principles, including optimizing their shape and layout. Rash and Liehr (1999) also looked at the flow patterns within a constructed wetland near Wilmington, North Carolina, using lithium chloride tracers. Short-circuiting was common in subsurface-flow wetlands, while vegetated free water surface wetlands were well-mixed and not as subject to short-circuiting.

**Wetlands for CSO control.**

Liebig, et al, (1999) described the stochastic behavior of hydraulic and pollutant loadings of constructed wetlands for CSO and stormwater treatment. A comprehensive three-year monitoring program of a constructed CSO wetland in Kamen-Methler, Northrhine-Westfalia, Germany, was undertaken to monitor the pond’s effectiveness and to establish planning, design and operation guidelines. Wong et al. (1999) reported on the performance of the Braunebach research wetland in Germany and described the suitability of a two-parameter first-order-decay model for predicting the performance of the constructed wetlands for the treatment of CSO. A total of 30 CSO events were monitored and the results demonstrated the suitability and reliability of this model for SS, BOD$_5$, total phosphorus and soluble reactive phosphorus. The Fulda Fellenweg wetland system, also in Germany, was built in 1992, and consists of a 550 m$^2$ soil filter planted with reeds, and a basin with a detention volume of 786 m$^3$. Born (1999) described the performance of this system in treating CSO. The efficiency of the system was about 90% for COD, NH$_4$-N, SS and PO$_4$-P and the removal efficiencies were independent on the resident times in the system. The permeability did not decrease during the five-year monitoring period. The main design parameter for the system was the surface loading rate (usually about 0.011 L/m$^2$-s). Faster rates (up to 0.027 L/m$^2$-s) showed only a negligible decrease in performance.

**Observed wetland performance.**

The advances in Australian practice on the use of constructed wetlands for stormwater treatment were discussed by Wong and Breen (2002). The Australian design practices of constructed stormwater wetlands include the compartmentalization of constructed stormwater wetlands, testing of particle size distribution on suspended sediments conveyed by urban stormwater and the use of hydrologic effectiveness curves for selection of appropriate extended detention storage volume of constructed wetlands. The implementation of stormwater management practices, the Integrated Weed Management Program and the Blue-Green Algae Management strategy in the Botany wetlands resulted in reversing the decline of the wetland’s ecological aesthetic and recreational values (Sim, 2002). The analysis suggested the need of a comprehensive monitoring program to substantiate the success or failure of restoration projects.

Dennett and Spurkland (2002) investigated the performance of a constructed wetland along Steamboat Creek, a tributary to the Truckee River. Monitoring of the wetland for one year showed that total nitrogen was reduced by an average of 42 percent, and the inorganic forms of nitrogen were removed more efficiently. The stormwater management system, including wetlands, at Intel’s Ronler Acres Campus in Hillsboro, Oregon was described by Whitaker et al. (2002). The
project uses extended dry detention basins, spreader bars at the outlets, and pervious, vegetated spillways to maximize stormwater infiltration. Also, bio-retention planting strips are incorporated in the parking lot landscaping to encourage infiltration of stormwater flows and reduce the use of irrigation water. Integration of the stormwater facilities with the mitigated wetland benefits local wildlife by creating a larger habitat block. Nietch et al. (2002) compared ponds and constructed wetlands for stormwater treatment. Compared to wet ponds, wetlands tended to have higher constituent concentrations in an effluent, inefficient nitrogen removal and preferential retention of phosphorus. The reuse of stormwater collected in retention ponds by nurseries was investigated by Norman et al. (2002) because of the potential for concentrating plant pathogens. *Erwinia* soft-rot bacterial accumulation on plants watered with water from nursery retention showed that without treatment of the runoff prior to use, there was a potential for introducing concentrated *Erwinia* onto the plants.

The paper by Higgins and Maclean (2002) reviewed the feasibility study for a sub-surface flow constructed wetland to treat runoff water from the Edmonton International Airport. A comparison between the Edmonton facility and a similar facility at Heathrow Airport was also presented. Subsurface transport and commensurate water quality transformations in a combined wetland/recharge basin was studied using bromide and rhodamine dye (Fox et al., 2002). Vertical infiltration rates varied across the basin; however, the variation in infiltration rates did not affect water quality transformations since an excess of carbon has accumulated in the wetlands sediments.

Guardo (1999) examined the nutrient removal ability and the hydrologic balance of a wetland located in South Florida over a period of two years. A 1540 ha wetland was constructed as a pilot project as part of a major study investigating methods to reduce nutrient discharges into the Everglades. Hunt et al. (1999) studied nitrate removals in a wetland located in North Carolina. The average concentrations were reduced from 6.6 to 2.0 mg/L. Nitrate mass removals were highly correlated to inflow concentrations in the warmer months when biological processes were more active, while the ammonia mass removals were highly correlated to inflow ammonia concentrations during the cooler months. Moustafa (1999) described monitoring results from Boney Marsh, Florida. Water-loading rate, water depth, phosphorus-loading rate, and water-retention time were examined for their influence on phosphorus removals. A simple quantitative diagram was developed that related these factors to phosphorus removal. White (1999) described the performance of a small wetland, located near Mobile, Alabama, for reducing suspended solids and nutrients in stormwater. The wetland system was constructed in January 1996 and monitoring results have shown that suspended solids and total phosphorus removals were significant (up to 90%), but that nitrogen removals were much less (about 20%).

Bacteria removal rates in a marshland upwelling system were reported by Rusch et al. (1999). Fecal coliform (FC) bacteria analyses indicated reductions from an average influent value of about 1500 FC/100 mL to an average of 2 FC/100 mL in 5-foot deep monitoring wells. A filtration model predicted that the k value for the first order removal reaction was 0.40 – 0.56/d and that the predicted content of FC in the wetland surface was near zero.

Scholes et al. (1999) described the performance of two wetlands located near London, United Kingdom. Removal efficiencies were greater than 65% for Zn, Cd, Pb, and Cu, at one site, while they were only about one-half of these rates at the other site. They also investigated the role of microorganisms in removing the heavy metals and two metal tolerant strains were found to accumulate Pb and Zn. It was believed that this ability may prove to be an important year-round pollutant removal process. Lead and petroleum hydrocarbons (originating from a municipal public works yard) were monitored in an urban wetland by Thurston (1999). Levels of these compounds in the sediments were higher near the inlet than elsewhere. It was concluded that sedimentation was the primary mechanism responsible for reducing the concentrations. Dombeck et al. (1999) examined the assimilation of trace metals in wetland sediments at the Sacramento (California) Regional County Sanitation District’s Constructed Wetland Demonstration Project. Six metals (silver, cadmium, copper, mercury, lead and zinc) consistently exceed mass removal rates of 60%. Chromium and nickel were observed in concentrations approaching or exceeding the freshwater sediment Probable Effect Levels (PEL). It was expected that the nickel enters the wetland in a predominantly dissolved and strongly organic-complexed form.

**Problems in wetlands.**

An overview of natural and constructed wetlands in Canada was presented by Kennedy and Mayer (2002). They found that natural wetlands remain threatened by anthropogenic activities. They also found that the use of constructed wetlands is not as widespread as in the U.S. and that more research is needed before the technology will gain widespread acceptance (cold weather performance, more monitoring, design adaptation, and effects of constructed wetlands on wildlife).
Traver (2002) compared routing techniques in a stormwater-wetlands BMP and found that the traditional storage-indication routing likely is not appropriate for stormwater wetlands, especially for smaller, water-quality storms. This concern was tested using a retrofitted detention pond and the results showed that the concern was valid and more research was needed.

The aquatic plant community was found to dramatically degrade in an urbanizing wetland study area located in Portland, Oregon, during studies by Magee et al. (1999). They were concerned that current wetland management practices were replacing natural marshes and wet meadow systems with ponds, further resulting in changes in the composition of the plant species assemblages. Revitt et al. (1999) studied the pollutant removal at two constructed wetlands. The behavior of suspended solids was the greatest concern, as higher outlet concentrations were consistently discharged compared to inlet conditions, presumably due to re-suspension.

Russell (1999) was very concerned about artificial wetlands providing suitable habitats for mosquitoes in Australia. The Ross River virus, spread by mosquitoes, was of special concern as it was responsible for thousands of cases annually of a disease that was severely debilitating. It was suggested that mosquito control should not rely solely on chemical and biological agents, but that the design parameters of wetlands can also be important. Shallow water and dense vegetation promote mosquito production, while deeper habitats with cleaner steeper margins, and more open water, produce fewer mosquitoes. Aeration and fountains can reduce larval densities and vegetation thinning can assist mosquito predators.

**Critical Source Area Controls**

Bennett and Curtis (2001) tested a soil and vegetative contact treatment system (modified Howland Swale) for stormwater runoff from a fuel cell manufacturing facility. It was designed to remove copper and zinc (and thus overall effluent toxicity) to the point where the toxicity guidelines for the daphnid, *Daphnia pulex*, were met. The paper detailed the design and construction of the treatment system. To better understand the cost, maintenance requirements, and pollutant removal ability of sand filters, the California Department of Transportation retrofitted five Austin-style and one Delaware-style sand filters in the Los Angeles and San Diego metropolitan areas (Barrett and Borrone 2001) at their maintenance yards and park-and-ride facilities. Contributing areas averaged less than 0.7 ha. They had a relatively high cost of implementation, about $350,000/ha treated. Pollutant removal was comparable to the performance observed in various City of Austin studies. Average suspended solids removal was 85%, total metals removal varied between 51% and 85%, while dissolved metals removal varied between 19% and 77%. Poor removal occurred for nutrients, especially nitrate, which was generally negative. No major maintenance has been required, although evidence of clogging is beginning to appear.

Hird et al. (2001) tested a passive treatment system, called a sorptive buoyant media clarifier (SBMC), for highway-runoff treatment. Pollutant removal efficiencies approached 95% on a mass basis total suspended solids (TSS), turbidity and particulate-bound chemical oxygen demand (COD), with the efficiencies not being affected by highly variable influents or extended periods of non-operation between storms. Prototype treatment capacity, at breakthrough, was 1000 pore-volumes treated. Liu et al. (2001a) investigated the potential of manganese oxide coated polymeric media (MOPM) for urban stormwater runoff treatment. The adsorption onto the MOPM was shown to be very sensitive to the pH, with the order of adsorption affinity on MOPM for the four divalent heavy metals studied being Pb(II) > Cu(II) > Cd(II) > Zn(II).

MOPM was seen to be a viable alternative adsorption medium for heavy metal removal in upflow BMP filters, such as a SBMC. Further investigations of the surface of the MOPM (with a specific gravity of less than 1) showed that the surface area increased from 0.05 m$^2$/g (uncoated media) to 27 m$^2$/g for the same media after oxide coating (Liu et al., 2001b). The multiple-layer coatings enhanced filtration and adsorption of heavy metals. Investigation of materials (Liu et al., 2001c) with specific gravities greater than 1 demonstrated that cementitious materials could be coated effectively for use in stormwater treatment devices. The increase in surface area resulting from coating sand was not as significant as it was for the coating of the cementitious materials.

Pitt et al. (2001) reported on the results of laboratory-scale investigations into upflow filtration as a means of increasing the run times of traditional stormwater filters (which tend to clog rapidly due to the small size of particles in urban runoff). Using laboratory-scale columns (4.8-cm inner diameter (ID)), a power equation to model downflow filtration was demonstrated. However, the coefficients for the laboratory sand filter were significantly different from those of the Lakewood, CO sand filters reported by Urbonas. Testing with a larger diameter column has been performed. Comparison of the two clogging tests indicated that a significant scale-up effect exists. Clark et al. (2001b) investigated the ability of filter media to retain previously-trapped pollutants under aerobic conditions, as would be expected if the filters were operated in an upflow mode. Permanent retention of heavy metals occurred even in an anaerobic environment.
However, retention of nutrients did not occur. These results showed that aerobic conditions must be maintained in the media if nutrient removal and retention is important. The permanent retention of the heavy metals indicated that upflow filtration may be feasible where the primary stormwater pollutants are metals.

The use of jute and mulch as filtration media for stormwater runoff treatment was investigated by Wojtenkio et al. (2001b). The effectiveness depended on the physical characteristics of the media. Both the sand content and the particle size of the filter media affected stormwater flowrates and the media’s pollutant removal capacities. Removals as high as 100% of copper (Cu) were observed for both mulch or jute. The removal of benzo(a)pyrene (B(a)P) depended on the media-to-sand ratios and ranged from 68 to 94%. Brown et al. (2001) assessed the use of kudzu (*Pueraria lobata* ohwi) as a medium for of copper, cadmium, and zinc removal from low concentration waters. Kudzu was an effective adsorbent for heavy metals. Although its capacity for metals removal is less than commercial-grade ion-exchange resins, kudzu could be used at much lower cost, and may be useful in treating dilute mixed-matrix metal wastestreams, such as urban runoff, where the application of resins is not practical. Davis et al. (2001b) investigated laboratory-scale bioretention facilities to treat urban runoff. The roles of the soil, mulch, and plants for the removal of heavy metals and nutrients were evaluated. Reductions of specific metal removals ranged from 15 to 145 mg/m² per event. Moderate reductions of TKN, ammonium, and phosphorus levels were found (60 to 80%). Little nitrate was removed, with nitrate production noted in several cases. The mulch to later in metal removal was found to be important.

Five sets of field test results of the Storm and Groundwater Enhancement System (SAGES) device were presented by Koustas and VanEgmond (2001). The SAGES device, a three-stage filtering system designed to be retrofitted to existing catchbasins/stormwater inlets, consisted of three separate filtering sacks consisting of gravel on top, sand in the middle, and granulated activated carbon on the bottom. The testing showed that the highest removal efficiencies occurred in conjunction with elevated influent suspended solids concentrations. Washout from the modified catchbasin appeared to contribute to increased effluent suspended solids concentrations that clogged the SAGES filter sacks.

In their paper, Cairo and Pujol (2000) advocated the use of membranes and biofilters for urban wastewater treatment. They demonstrated that the membrane and bio-filters produce a high quality effluent during both dry- and wet-weather flows. Lau et al. (2000) demonstrated that biofilters, even with a biofilm as young as three days, is capable of providing good removal efficiencies for both dissolved and sediment-adsorbed metals. During the nine-week operating of a laboratory-scale biofilter, 90% of the total Cu and Zn were removed. Field-testing of a submerged, aerobic biofilter for the treatment of stormwater runoff was reported by Mothersill et al. (2000). They found that the biofilter removed 97% of the suspended solids in the runoff; however, the suspended solids accumulation interfered with the nutrient removal through bacterial assimilation. Removal efficiencies of 64% for ammonia nitrogen were seen throughout the life of the filter. Backwashing to remove sediment was found not to be sufficient to maintain optimal biological filtration conditions.

Stormwater runoff contains a greater variety of pollutants than sanitary wastewater including such priority pollutants as benzene, PAH, pesticides and toxic heavy metals (Fan et al., 1998). These pollutants are usually associated with particles < 50 µm which are difficult to remove using standard WWF sedimentation technologies, however, advanced sedimentation systems have shown effectiveness for removing such particles. Biological leaching was proposed as a method to treat urban stormwater sediments contaminated with trace metals. An iron oxidizing bacteria indigenous to the sediment removed soluble Cu (64% solubilization) and Zn (98% solubilization) in laboratory and pilot-scale experiments (Anderson et al., 1998). Lainé et al. (1998) provide a treatment system for urban stormwater designed to meet treated water standards suitable for bathing.

**Filtration/sorption**

Ray et al. (2002) evaluated the treatment of stormwater by filtering the runoff through natural organic materials. The results demonstrated that the fluxes through pure media were higher than through a traditional sand bed, and that mixtures of the media with sand had fluxes that decreased as the sand quantity increased. Clark et al. (2002a). performed an initial evaluation on the effectiveness of upflow filtration to treat stormwater runoff. The results demonstrated that upflow filtration likely would provide longer filter run times. A concurrent study by Clark et al. (2002b) evaluated the effect on pollutant retention if stormwater filters of peat moss, activated carbon, sand, or a municipal leaf compost go anaerobic. Permanent retention of heavy metals, but not nutrients, was found during the studies.

Ellard et al. (2002) evaluated the potential of using direct filtration for wet-weather flows at sewage treatment plants or for SSO and CSO treatment. The filters were able to achieve near secondary effluent quality on suspended solids, CBOD and other contaminants and an innovative rapid backwashing technique was developed to clean the filters in order to
handle the peak flows. Kang et al. (2002) presented a unique design for a municipal wastewater treatment plant equipped to deal with wet-weather flows (and operating data for 2000) where sand filters were used to filter an enhanced primary effluent and an activated carbon adsorber was used to polish the filter effluent prior to chlorination.

Treatment of runoff containing copper from roads and roofs by a special adsorber made from granulate iron-hydroxide and calcium carbonate was proposed by Boller and Steiner (2002). The results of testing of this adsorption trench showed average copper reductions of 96 – 99%. Tramonte et al. (2002) studied the transport and treatability of entrained particulate matter from elevated transportation infrastructure by rainfall-runoff. The passive treatment device of interest was adopted from in-situ adsorptive-filtration systems that had been installed to treat storm water from an elevated section of Interstate 10 in Baton Rouge, Louisiana. Results indicate pollutant removal efficiencies of greater than 90% could be realized for total suspended solids (TSS), turbidity and total chemical oxygen demand (COD). Removal efficiencies were not affected by a highly variable influent composition or extended periods of non-operation between storms. Approximately 1000 pore-volumes were treated and breakthrough of TSS and COD mass in the clarifier effluent nor excessive head loss across the adsorptive-filter media clarifier was observed, indicating treatment capacity has not been exceeded.

Sansalone (1999) conducted detailed tests of a partial exfiltration trench (PET) for passively treating highway runoff at a test site in Cincinnati, Ohio. Runoff treatment in the PET occurred primarily by sorption and filtration. Media in the PET was expected to last more than 10 years. The mass pollutant removal efficiency generally exceeded 80% during the one year of tests. Exfiltration from the PET to clayey glacial till soils also exceeded 30% for some runoff events. Stephenson et al. (1999) also described a pilot-scale stormwater runoff treatment system for highway runoff that used peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption. Field-testing sites were located in Knoxville, Tennessee, and Frederick, Maryland. The primary goal of this investigation was the development and evaluation of practical remedial measures for treating highway runoff draining into sinkholes, where very rapid movement of surface runoff to the groundwater can occur. Urbonas (1999) presented a detailed description of the design approaches needed for effective sand filtration of stormwater. The approach uses the unit processes known to exist in urban stormwater runoff and within filter devices. The suggested design was based on hydraulic capacity of the filter media, which, in turn, was a...
function of the total suspended solids removed by the filter. Shibata (1999) reported on the performance characteristics of pipe installations with replaceable filters. The data collected included information on the quantity of sand and gravel trapped in the filter section, as well as the ability of the filter to concentrate pollutants from stormwater runoff.

A system that included settling tanks, sand and carbon filters, and an ion exchange unit treated stormwater runoff from an airport prior to infiltration (Vivona et al., 1998). A laboratory and parking lot investigation showed that porous pavements significantly reduced the volume of stormwater runoff, as well as the concentrations of undesirable constituents in stormwater. Asphalt pavement had increased petroleum products (e.g., phenols) possibly due to the interaction of acid rain with the asphalt pavement (James and Shahin, 1998). Laboratory experiments conducted over the past three years showed that activated carbon, peat moss, zeolite, and compost were efficient at removing toxicants such as organics and metals from the stormwater runoff and retaining them during subsequent flushings with distilled water (Clark et al., 1998a). Sand was found to effectively remove toxicants from runoff, but then released them in subsequent flushings. Field experiments evaluated several filtration media for stormwater infiltration and treatment potential (Clark et al., 1998b). An activated carbon and sand mixture showed the best overall removal, though a recommendation for settling of runoff prior to filtration is given. A two-dimensional model was developed to assist in the design of infiltration systems for stormwater management (Guo, 1998). The model revised the Federal Aviation Administration method to predict the detention storage volume by maximizing the volume difference between the design storm runoff and the basin infiltration rate.

A filter with humic media was discussed for the treatment for stormwater runoff (Kratch, 1997b). The media, which contains a processed leaf compost, removes 90% of SS, 85% of oils and grease, and 98% of metals.

**Treatment train systems**

Annadurai et al. (2002) presented the factorial design analysis for turbidity and humic acid removal from stormwater using polyaluminum chloride (PACl) as a coagulant. The response surface method along with the Box-Behnken design of experiments was adopted to investigate the effects of pH, turbidity, and alkalinity of the suspension, the PACl dosage, and the dosed amount of humic acid. The PACl dosage was the most significant variable for turbidity removal, while that for humic acid removal was the suspension pH. A compromise will be needed to produce both large and loose flocs.

Greenway et al. (2002) monitored the spatial and temporal changes in stormwater quality through a series of treatment trains. The case study evaluated the performance of several devices in a ‘treatment train,’ including a sediment basin, constructed wetland, pond, CDS unit, ECOSOL unit, natural riparian wetland and a 600 m length of natural stream channel. The study showed that during a storm event there was little reduction in the concentration of total suspended solids throughout the treatment train due to limited detention time, however there was a decrease in soluble nutrients. The sediment basin, wetland, pond and riparian vegetation were all effective in removing these nutrients. The existing 600 m natural stream, lagoons and associated vegetation were effective at removing sediment and nutrients to achieve Water Quality Objectives of 15 mg/L TSS, 0.65 mg/L TN and 0.07 mg/L TP, at the end of the treatment train.

Pitt (1996) discussed the utility of the SLAMM stormwater quality model in designing watershed-scale pollution reductions and evaluated technologies for control of stormwater, such as catchbasin retrofit devices, a multichambered treatment train (MCTT) for critical source areas, and different filtration media. The Multi-Chambered Treatment Train (MCTT) was developed for removal of stormwater toxicants from critical source controls (Pitt et al., 1999). The MCTT was an underground device that has three main chambers: an initial grit chamber for trapping of the largest sediment and release of most volatile compounds; a main settling chamber (providing initial aeration and sorbent pillows) for the trapping of fine sediment and associated toxicants and floating hydrocarbons; and a sand and peat mixed media “filter” (sorption-ion exchange) unit for the reduction of filterable toxicants. A typical MCTT requires between 0.5 and 1.5% of the paved drainage area, which was about one-third of the area required for a well-designed wet detention pond. The research report described extensive development of the MCTT, including much stormwater treatability information that can be used by others who want to enhance performance of conventional stormwater control devices. A pilot-scale unit was tested in Birmingham, Alabama, at a large parking lot. During monitoring of 13 storms, the MCTT was found to have the following overall median reduction rates: 96% for total toxicity, 98% for filtered toxicity, 83% for SS, 60% for COD, 40% for turbidity, 100% for lead, 91% for zinc, 100% for n-Nitro-di-n-proplamine, 100% for pyrene, and 99% for bis (2-ethyl hexyl) phthalate (Pitt et al., 1999b). Corsi et al. (1999) reported the results of a full-scale test of the MCTT at a public works yard in Mileaukee, WI, conducted by the USGS and the WDNR. Monitoring of 68 common and toxic constituents was conducted during 15 storms having rain depths ranging from 0.17 to 1.4 inches in depth, over a five-month period. Very high reductions were found for all particulate-associated pollutants (reductions of 98% for SS, 88% for total phosphorus, and 91% for total ZN, for example), and somewhat less reductions for dissolved pollutant fractions.
(13% TDS, 78% dissolved phosphorus, and 68% for dissolved ZN, for example). The WI DNR also conducted a full-scale test of an MCTT at a 4-acre municipal parking lot at Minocqua, in northern Wisconsin, with similar high level removals noted.

**Airport Deicer Control**

Revitt et al. (2002) investigated the biodegradability of glycol- and acetate-based aircraft de-icing fluids on airport surfaces at three temperatures below 8oC, because the high solubilities of these substances results in high BOD loadings in runoff and pose a serious toxicity problem in receiving waters. The reductions that could be expected in ethylene/diethylene glycol-, propylene glycol- and potassium acetate-based deicing fluids by bacteria, actinomycetes and fungi on airport surfaces would be 33.6, 30.6 and 15.2%, respectively. Rusten et al. (2002) investigated the potential co-treatment of spent airport deicing chemicals and municipal wastewater in Oslo. The deicing runoff was mixed with primary-treated municipal wastewater and treated using a moving bed biofilm reactor, coagulated and then treated by DAF separation. With that treatment, the mixed wastewater was suitable for discharge to the biological treatment stage at the municipal wastewater treatment plant. Results were better when treatment temperatures remained high.

The paper by Switzenbaum et al. (2001) provided a theoretical assessment of the potential environmental impact of airport stormwater runoff. It also described in detail current information on alternative deicing fluid application methods and materials, collection and treatment practices.

Periello et al. (1999) described a biological treatment system for treating stormwater runoff that was contaminated with de-icing fluid at the Syracuse (New York) airport. During winter deicing operations, spent deicing fluid, combined with storm runoff, was collected and held in large treatment lagoons. When warmer weather arrives and deicing operations cease, the collected deicing fluid and combined stormwater runoff (deicing runoff) were treated in aerobic lagoons to reduce the BOD in the deicing runoff to levels suitable for discharge to the local receiving waters. Safferman et al. (1999) studied the treatment of stormwater contaminated with ethylene glycol originating from airport deicing operations using a bench-scale subsurface microbiological contactor. Zitomoer et al. (1999) discussed the use of anaerobic co-digestion of aircraft deicing runoff and municipal wastewater sludge. The high COD runoff can lend organics for increased methane production and the oxygen demanding constituents in propylene glycol deicing fluid were found to be readily converted to methane, with neither effluent BOD$_5$ nor TKN concentrations higher in co-digestion systems as compared to a conventional digester. They concluded that existing municipal digesters could be employed to convert the seasonally-generated deicing fluid organics to methane that could be used to run equipment or generate electricity.

**Combined Sewer Overflow/Sanitary Sewer Overflow Control**

Combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) continue to be an important source of water pollution throughout the world. The analysis of CSO abatement alternatives often proceeds in an evolving manner. Landside models are generally used to determine which outfalls need CSO abatement, sometimes in conjunction with receiving water quality models. Once CSO outfalls needing abatement are identified, an optimal level of abatement needed to achieve water quality standards can be determined. With the required abatement level determined, various methods of achieving that level can be explored. Many small- to-medium-sized communities with combined sewer systems are faced with regulatory mandates to prepare long-term CSO control plans.

Dwyer (2002) reviewed the 2001 Combined Sewer Overflow Report to Congress. The report benchmarked the status of CSO permitting and enforcement activities and the implementation of CSO controls in accordance with EPA’s 1994 CSO Control Policy. It also identified key program challenges and next steps to be taken by EPA. The paper addressed the activities that EPA has taken and plans to take in response to the Consolidated Appropriations Act for 2001, and in meeting a requirement to prepare the second Report to Congress that is due in December 2003.

The paper by Siddique (2002) described the District of Columbia Water and Sewer Authority’s proposed approach for incorporating wet-weather provisions and CSOs into the water quality standards. The Large Diameter Sewer Assessment Program (LDSAP) of Sanitation District No. 1 in Kentucky and the James Avenue Pilot Project was reviewed by Cantrell and FitzGerald (2002). The program was developed to prioritize the District’s collection system using a customized criticality analysis procedure and then to set priorities for detailed structural inspection and grading. Walker et al. (2002) presented an overview of the Massachusetts Water Resources Authority Long-Term Control Plan (LTCP) for CSO control. The plan used a watershed approach to assess CSO impacts in the context of other pollution sources in the watershed and resulted in the decision to eliminate CSOs in critical use areas and cost-effectively minimize them in non-critical use areas. Adoption of the plan was contingent on changing existing water quality standards in areas where CSO
would remain, which was accepted provided that certain specific conditions were met. Doshi et al. (2002) provided an overview of the key elements of the regional SSO control program contained in the City of Detroit’s long-term wastewater master plan. Examples were also provided of how the seven key elements have been applied in the service area and the corresponding results. The paper by Bouchard (2002) focused on the how the planning components of infrastructure management were used in long-term infrastructure management in Champaign/Urbana (Illinois). The process exposed the need for expansion of one treatment plant and rehabilitation at both plants.

Godsey (2002) presented the engineering toolkit used by the Central Contra Costa Sanitary District to effectively determine the most effective method/technology for improving the performance of the sewer system. The paper by Marcotte et al. (2002) described the selection of Washington, D.C.’s CSO Draft Long-Term Control Plan, and the difficulties encountered in balancing costs, water quality benefits and public expectations. Hassey et al. (2002) provided an overview of Sacramento’s CMOM project for SSO control, which contained an extensive audit of the system and identified necessary improvements. Short-term and long-term improvements were identified in three key areas: (1) SSO reduction; (2) asset management; and (3) improvement of information management. Smith et al. (2002) reviewed the second phase of the long-term control plan for CSO abatement in Augusta, Maine. The program focused on the West Side Consolidation Conduit and the design challenges it faced: narrow project corridor, active railroad, steep and unstable banks, and coordination with a rails-to-rail project. Walker and Donahue (2002) reviewed the CSO long-term control plan for Alewife Brook in the Boston, MA suburbs and the problems that arose when the investigation showed that the brook’s dry-weather bacteria levels did not meet standards and that elimination of CSOs by sewer separation would increase flooding in the Brook. These problems are currently being addressed in the plan development.

Geiger and Schuster (2002) reviewed the City of Concord’s (NC) CMOM program and its sanitary sewer evaluation study. The city has replaced 20,000 feet of pipe a year since 1994 to reduce SSOs. Ablin and Kinshella (2002) provided an overview of Phoenix’s Lower Buckeye sewer emergency repair, rehabilitation, and replacement project. The project included sewer investigations, pipeline collapse, installation of 790 feet of 84-in diameter sewer in an area with utility conflicts; and bypass pumping of 150 MGD. Allen and Yee (2002) reviewed the collaborative service lateral rehabilitation program in Sacramento County. The program is a joint effort of the following two work groups in the District: the Design and Rehabilitation Engineering section and the Special Projects section. Fee and Ramirez (2002) reviewed an emergency project that included the cured-in-place lining of approximately 1,200 linear feet of 30- and 36-inch interceptor sewer and the implementation of a 30-MGD bypass pumping system. Davis et al. (2002) reviewed Onondaga County’s (Syracuse, New York) CSO program and the technologies that are incorporated into it: Vortex treatment, storage, sewer separation, netbags, floatables boom, screening and disinfection. Giguere et al. (2002) presented the City of San Diego’s five-year program to inspect and assess the condition of 1,000 miles of its 3,000-mile sewer system. The paper discussed the key challenges and benefits achieved through the development and implementation of GIS-based computer software system to store and evaluate the data and video collected in the inspection program.

The paper by Brombach (2002) provided an overview of the European history of urban stormwater practice, specifically focusing on Germany and discussed the latest trends in technical equipment to reduce the impacts of CSOs. Fujita (2002) studied the improvements in the combined sewer and flood control systems in Japan, including the recent changes in technology. Chan et al. (2002) presented the City of Edmonton’s Interconnection Control Strategy, which has been designed to eliminate or minimize the discharge of sanitary and combined sewerage to the storm sewer system and the North Saskatchewan River. The focus of the Strategy has been on monitoring the sanitary sewer to storm sewer interconnection activity and fixing dry-weather interconnections.

Oldenburg et al. (2002) reviewed the separation of wastewater streams in Luebeck Flintebreite. The analysis showed that the separation of wastewater into blackwater, graywater, and stormwater was more cost effective than other systems. O’Neill (2002) discussed the Topeka, Kansas best management practices for reducing CSOs. The recommendations from a workshop were sewer separation and diversion of stormwater into a construction wetlands system. Frehmann et al. (2002a) investigated stormwater management in an urban catchment through simulation of the system. It was shown that the management measures, especially source control measures, could significantly reduce the CSO volume and pollutant discharge load, resulting in a positive impact on receiving water quality. Pond et al. (2002) presented the use of stormwater micromanagement systems (temporarily storing stormwater in many varied locations on the surface and, as needed below the land surface, near to where it falls as a method of preventing persistent basement flooding. The goal is not to prevent the volume from entering the system but to delay the entry of the runoff to the hydraulic capacity of the sewer system.
Hollenbeck (2002) reviewed 100 projects performed by RJN Group, Inc., throughout the U.S. in the last 25 years, for lessons learned in terms of investigating sewer systems and determining rehabilitation needs. The key variables in these programs included: inflow source distribution/flow meter spacing; rainfall/inflow design storms; private/public sector source distribution; system rehabilitation procedures; and rehabilitation costs. Olthof et al. (2002) reviewed the ongoing initiatives of the City of San Diego in reducing SSO occurrences. These initiatives include an accelerated cleaning program for all 3,000 miles of pipe, a CCTV inspection program and a capital program, which are coordinated with a GIS implementation. Rietsch et al. (2002) presented a new concept for evaluating all relevant processes occurring in stormwater structures, including combined sewers, and especially focusing on sedimentation processes. The possibility of enhanced retention of pollutants by using lamella separators was also discussed.

Agbodo et al. (2002b) introduced the use of gage-adjusted radar data to estimate precipitation volumes for wastewater and water resources planning studies for either sanitary or combined sewer systems; the methods to estimate the optimum number of rain gages for precipitation-volume measurement; the advantages and disadvantages of alternative measurement approaches; and the use of radar precipitation data for enhancing collection systems planning, development, and operations and maintenance. The paper reviewed the data collected in South Florida and contained a cost comparison of gage-adjusted radar and rain gage methods for precipitation measurement. Boccado et al. (2002) reviewed the methodology used in the Stony Brook Illegal Connection Investigation in Boston, Massachusetts, to identify wastewater discharges in Boston’s storm drainage system. Water-quality investigations during dry weather flow for pH, conductivity, temperature, ammonia and surfactants was followed by placing sandbag barriers in the pipe to confirm no dry-weather flow and the use of dye testing where dry-weather flow was found.

Keefer and Gilbert (2002) reviewed the North Central Sewer Separation project in the Columbus, Ohio downtown area. The paper included a discussion of the problems that were encountered by working in a historical area and the solutions that were developed with federal, state and local concerns in mind.

Brilhante et al. (2000) described the use of USEPA’s Storm Water Management Model (SWMM) in CSO analysis. As a project proceeds through planning and design of CSO abatement, the model would be refined to test alternatives and set the detailed specifications. Lyon (2000) advocated a systematic approach to CSO control systems. The first step would be to examine wastewater treatment plant flows during dry and wet weather periods to determine the effectiveness of the CSO control system in capturing base sanitary flows. Second, all available data should be examined to determine how the system is affected by wet weather events and the probable relative magnitudes of CSO loadings to area receiving streams. This approach was successfully used in Charleston, West Virginia, to identify a low-cost solution to minimize CSO loadings to the Kanawha River. The City of Niagara Falls, New York, also used a step-wise approach in dealing with levels of infiltration and inflow in its collection system, which are creating service problems for residents and impacting the City’s ability to redevelop its eastern portion. The City sought the cooperation of state officials when addressing the problem which seemed to keep from imposing undue financial hardships on the ratepayers and residents (Roll and Benson 2000).

Gomis et al. (2000) analyzed the factors involved in the response of an urbanized drainage basin with a combined sewer system to a rainfall event. In the case of moderate and heavy rainfall, the coefficient of flow was independent of the rain characteristics and was close to the imperviousness coefficient. For lighter rainfall, flow was determined by the initial surface state of the drainage basin. Lindholm and Nordeide (2000) evaluated the relevance of different methods and criteria for choosing the best system to solve a CSO problem in Oslo, Norway. A simple EIA analysis with a pragmatic choice of criteria was found most suitable for choosing between conventional or nature-based solution. Marsalek and Giulianelli (2000) presented a comparative analysis of urban drainage challenges in Italy and Canada. Canada offered stormwater management practices and satellite CSO treatment; Italian contributions included effective layouts of distributed CSO storage and operation of such systems in real time. The City of Livonia, Michigan used Geographic Information Systems (GIS) technology to enhance the implementation of its illicit discharge elimination program. As a result, record keeping was improved, problem areas identified earlier, and joint efforts with surrounding communities and agencies in Livonia simplified (Rohrer and Beckley 2000). Smith et al. (2000d) presented observations and determined causes of increased odor production and release in recently separated collection systems. The authors also presented the corrective actions which have been shown to reduce these odor effects. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/relocation project in South Boston. The SWMM model was used for design, facilities planning. The model was refined and recalibrated as needed to provide greater confidence in the design flows. A 50-year storm that occurred during the flow monitoring period provided confidence that the recalibrated flows were appropriate for use as design criteria for the CSO consolidation/relocation
Buchholz et al. (2000) used a computer model to evaluate the performance of a CSO retention treatment facility in Michigan. To comply with the requirements of the Federal Clean Water Act, improvements to the system were accomplished by additional storage of CSO, removal of storm water inputs to the treatment facility, and maximization of the use of the existing interceptor system. The regulatory impetus for this work was Michigan’s CSO Policy, which states that CSOs must be eliminated or controlled to protect designated uses at times of discharge. The level of control may be determined either by a water-quality based demonstration or by accepting a presumptive level of treatment described in terms of a retention/treatment structure (Cowles 2000). Six years after the EPA’s 1994 CSO Policy was issued, only two of the 30 States with CSO municipalities have taken actions to implement the water quality provision of the federal CSO policy. Conditions in urban areas and other point and non-point sources of pollution may make current water quality standards in some urban waters no longer appropriate or unable to be met, regardless of CSO controls that are implemented. Dwyer and Huang (2000) have advocated a review and revision of existing water quality standards in order to save unnecessary expenditures, ensure that proper water uses are maintained, and significantly improve the implementation of the water quality-based provisions. The expectation of the CSO Control Policy was that long-term control plans (LTCPs) would be developed to meet water quality standards (WQS) and, where appropriate, states would revise their WQS to reflect the difficulty in achieving compliance with current bacterial standards in urban areas during wet weather events. Slack and Nemura (2000) discussed the difficulties CSO communities face in obtaining revisions to WQS as part of developing LTCPs that are cost-effective and protective of water quality and human health.

Rowe (2000) presented an overview of SSO control strategies to management and engineering staff who represent a National Pollution Discharge Elimination System (NPDES) permittee. The U.S. EPA’s Environmental Technology Verification (ETV) Program was established to overcome the numerous impediments to commercialization of innovative environmental technologies, particularly the lack of credible performance data. Stevens and Frederick (2000) described the ETV approach and two recently initiated pilot programs for verification testing of source water protection technologies and wet-weather flow technologies. USEPA is currently completing the issuing of a SSO Rule that will add control of SSO to the NPDES permit requirements. Lai et al. (2000) provided a preview of the rule and described the advantages of employing a collection system modeling approach for capacity analysis and development of the SSO mitigation plan. Historically, EPA and the States have allowed municipal facilities to bypass peak wet weather flows around the secondary treatment process, to disinfect the rerouted flows, and then blend the peak flow with the other, more highly treated, effluent. A reinterpretation of the federal “bypass” rule by some regulators includes the position that if rerouting causes any of the waste stream to skip a treatment process, bypassing is illegal (Hall et al. 2000).

Many large-scale SSO, CSO and WWF control programs are underway worldwide. The city of Evanston, Illinois, successfully undertook a large-scale project to control basement flooding from combined sewer backups by limiting the entry of wastewater to the sewer system to exactly the quantity that matches the conveyance capacity. Figurelli et al. (2000) evaluated the performance of the program against the following criteria: technical hydraulic performance (basement backup and street ponding performance), citizen perception of performance, maintenance concerns and costs, capital costs, level of construction disruption, and public acceptance. The City of Saginaw, Michigan completed the second phase of a comprehensive CSO control project that was required to meet NPDES Permit requirements. Hubbell and Phillips (2000) have provided information on the historical background of the existing Saginaw sewer system, NPDES permit issues, project planning requirements, design considerations, construction, operations, and performance. A multifaceted project including highway improvements, development of waterfront parks, and water quality improvements resulting from CSO abatement was begun in New York, New York. According to Kloman et al. (2000), the New York City project has served as an example of inter-agency cooperation to benefit the community and environment.

Kok et al. (2000) reviewed the work of Canada’s Great Lakes 2000 Cleanup Fund, which is administered by Environment Canada, in supporting the development and implementation of cleanup technologies to control municipal pollution sources, to clean up contaminated sediments, and to rehabilitate fish and wildlife habitats. The Urban Drainage Program has been instrumental in advancing the state of the art in CSO and stormwater management in Ontario (Kok et al. 2000). The Philadelphia Water Department’s (PWD’s) CSO program goal is to improve and preserve the water environment in the Philadelphia area and to fulfill PWD’s obligations by implementing technically viable, cost-effective improvements. The PWD’s strategy to attain these goals has three primary phases (currently being implemented): (1) continued implementation of a Nine Minimum Controls comprehensive program; (2) planning, design, and construction of 17 capital projects to reduce CSO volume and frequency; and (3) a commitment to complete comprehensive watershed-based

conduit (Walker et al. 2000b). A detailed hydraulic model was used to simulate alternative flows scenarios to and through the treatment plant as part of a city-wide CSO Strategy in Edmonton, Alberta, Canada (Ward et al. 2000).
planning and analyses to identify the actions needed to further improve water quality and quantity dynamics in local water bodies (Marengo 2000). In 1998 the City of Rockland, Maine, began a major capital improvement program of its wastewater collection and treatment system and included provisions for high-rate treatment of CSO flows (Freedman et al. 2000). Clifferde (2000) reviewed efforts by the English and Welsh water industry to solve urban CSO pollution problems and to develop guidance for integrated stormwater management. The Northeast Ohio Regional Sewer District has undertaken the lead role in CSO management in the metropolitan Cleveland area and has recommended a CSO control plan. This plan includes several technologies that will maximize use of the existing system, as well as new facilities for CSO control (Matthews et al. 2000). Various public utilities in Broward County, Florida have implemented sanitary sewer rehabilitation programs which are expected to include a minimum of at least 7,796 repairs (Larsen and Garcia-Marquez 2000). Seigle et al. (2000) reported on the negotiated long-term CSO control plan for Manchester, NH. An inventory and structural evaluation of CSOs in towns (greater than 30,000 inhabitants) in Slovakia was carried out during a three-year joint research project of the Water Research Institute and the Department of Sanitary Engineering of the Slovak Technical University in Bratislava (Szuhehr et al. 2000).

Riverine litter occupies a spatial and temporal position in any systematic analysis of river systems and was a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly two - sewage inputs through CSO and fly tipping. Whilst sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). If the storage in the rain water tanks can be used to flatten the rain water runoff, rain water tanks can have an additional benefit. The effect of rain water tanks on the CSO emissions was therefore investigated with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rain water tanks will be more efficient in reducing the overflow emissions (Vaes and Berlamont, 1999). Milina et al. (1999) described the results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. Major model development needs concern the integration of sewage production, transport and treatment simulation, the interface with existing databases and the possibility of simulating processes that were controlled in real time. The developed integrated model has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system.

The use of sand and other media filters was gaining acceptance in the held of urban stormwater structural best management practice. Much work has been done to develop local design guidance, such as in the State of Delaware and in Austin, Texas. The suggested design of the media filters for stormwater runoff treatment was based on hydraulic capacity of the filter media, which, in turn, was a function of the total suspended solids removed by the filter (Urbonas, 1999). Walesh et al. (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff. It focuses on the success achieved by using street storage in two communities in Illinois and includes a description and evaluation of how this technology eliminated surcharging and basement flooding, complied with regulations and proved to be a cost-effective solution which earned public support.

As a demonstration project, the Auckland Regional Council had designed and constructed a filter device to treat stormwater from a 3000 m² carpark. Eight sand filters were installed in 1993 to provide stormwater treatment at a new Alaska Marine Lines, Inc. barge loading terminal along the Duwamish River in Seattle, Washington (U.S.A.). Constructed according to the “Devalence” design, each consists of a settling chamber where relatively large solids can settle before the flow passes over the weir onto the sand for filtering. A performance study monitored the flow rate through two sand filters and the water quality of inflow and outflow (Horner and Horner, 1999). Because the Urban Community of Bordeaux had been hit by important floods in 1982, it was decided to set an efficient management system to control stormwater flows. Studies have showed the significant impact of discharged effluents on the environment, especially with regard to the contribution from CSO. Therefore, it was of importance to improve the management of the sewer system during rain weather and to foresee the design of new storage structures and new treatment plants to integrate the environmental protection target (Briat et al., 1999).

Overviews of WWF controls were provided by two papers. Buriclan et al. (1999) summarized a comprehensive historical literature review, highlighting the development of WWF management from ancient times to the present. The relationship between past developments, the current state, and the future of WWF management were addressed by identifying several lessons learned. Barner (1999) discussed the problems associated with stormwater management in a karst terrain in Springfield, Missouri. The lack of recognition of sinkholes as integral parts of dynamic hydrologic systems may result in problems with on-site/off-site drainage.
CSO control planning. Bontus et al. (1999) described Edmonton’s proactive long-term CSO control plan, which brought the opinions of stakeholders, including Alberta Environmental Protection, river user interest groups, the local health authority and a representative of the University of Alberta, to the technical process, and ensured that their input was considered in developing the plan. Newhouse et al. (1999a) described the development of a long-term CSO abatement plan by the City of Richmond, Virginia. The protection of recreational uses of the James River was a priority for the city. City officials at Richmond, Virginia, agreed to a joint venture with the Richmond Riverfront Development Corporation that would eliminate CSO and restore the Haxall/Kanawha canal system. Engineers not only had to ensure that each project's requirements and objectives were met, but also address technical and environmental issues without compromising the area's recreational and commercial needs or diminishing its aesthetic appeal or historic character (Newhouse et al. 1999b). Based on interviews conducted during 1998, Slack and Freedman (1999) compared and contrasted current state-to-state and community-to-community differences in efforts to control SSO. The variability in abatement efforts were tied into the proposed language for EPA’s forthcoming Federal Register notice that will clarify NPDES requirements for municipal sanitary sewer collection systems and SSO.

Other authors addressed the steps taken to achieve CSO and SSO control. In the early 1990s, the City of Auburn, New York, was faced with the challenge of achieving CSO abatement and sanitary and interceptor sewer overflow (SSO) elimination in its extensive, aged sewer system and achieved their overflow abatement goals by: (1) quantifying and characterizing sewer overflows to provide a basis of design for abatement-related system improvements; (2) selecting a principal approach of conveyance of excess WWF to a centralized high-rate treatment facility for a majority of the sewer system; and (3) re-evaluating and applying alternative technologies to select portions of the sewer system to minimize project costs. Li and Banting (1999) presented a case study using a GIS planning tool for stormwater quality management in urbanized areas. The planning tool comprised five steps: (1) definition of stormwater retrofit goals and objectives; (2) identification of appropriate retrofit stormwater management practices; (3) formulation of stormwater retrofit strategies; (4) evaluation of Strategies with respect to retrofit goals and objectives; and (5) selection of stormwater retrofit strategies.

Markowitz et al. (1999) described the conceptual ideas, cost analysis and other issues that effect implementation of watershed controls within the scope of a CSO control plan. Osaka City’s (Japan) major measures for improving CSO include: (1) leading as great a volume of pollutants as possible to WWTP in dry weather to avoid the pollutant accumulation in sewers; (2) storing first flush, which contains a large volume of pollutants, for treatment at WWTP after rainfall; and (3) treating WWF directly. Shiomi (1999) discussed the methods used to achieve these measures and reports the conclusions drawn from the cost-benefit analyses. A 5-year cooperative study of the Cumberland River at Nashville (Tennessee) allowed Nashville to alter its CSO control plan, eliminate two major detention tanks, and save $106,000,000. The study showed that neither DO depletion nor toxic material discharges were a problem, and that a fecal coliform bacteria problem would not be solved by planned detention tanks, or even by eliminating all CSO (Thackston and Murr, 1999). Today conventional planning and reconstruction of both the drainage network and the treatment plant for the same urban catchment was usually subdivided into two nearly independent parts. Walther and Rohlfing (1999) demonstrated optimal design of a combined sewer system and sewage treatment plant for a German city with 500,000 inhabitants by simulating the operation of both systems simultaneously, and costing each system based on a variety of possible configurations of the other.

Additional published accounts of the experiences of various municipalities in controlling CSO and SSO provide guidance for those beginning a WWF control program. The City of Auburn’s (New York) sewer overflow abatement program summarized by Gorthey et al. (1999) can serve as a guide and source of information for other municipalities faced with achieving sewer overflow abatement. Igwe et al. (1999) focused on design and operational issues encountered during the evaluation of the Rouge River National Wet Weather Demonstration Program, which includes the construction of nine CSO detention basins of varying sizes and design. The City of Akron (Ohio) has successfully implemented the demonstration approach to CSO control and has supported controls that will result in measurable improvement of recreational use, aquatic life use and aesthetics of the receiving streams, including concepts other than traditional collection system alternatives. These include riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration. Merritt and Wilkinson (1999) presented studies on wastewater collection systems, including: collection system design and construction; wet weather control; infiltration and inflow; SSO; innovations in sewers and collection systems; infrastructure modeling; sewer pipe maintenance and rehabilitation; sediment transport, deposition and erosion in collection systems; and sustainable development. Protopapas (1999) reported the methodology used by New York City to abate pollution from CSO in the receiving harbor waters based on a case study for the East River facility planning. The approach integrates water quality studies, facility planning, environmental assessment and public participation. Wong et al. (1999) presented a case study that covers the planning.
design and operation aspects of implementing a pumping drainage system into the existing drainage system at the Pasir Baru residential area in Kuala Lumpur (Malaysia) city. Zettler et al. (1999) discussed how the City of Fort Wayne, Indiana has successfully applied a consistent set of GIS-based information management tools to support both their CSO planning efforts and preliminary design process.

Both typical and non-traditional areas must be considered in order to eliminate SSO and prevent future, potential overflows from occurring. Community and wastewater leaders must change the influences which allowed SSO in the first place — insufficient funding, short term thinking, inadequate maintenance, insufficient inspection, lack of widespread understanding of the issues and other such factors (Jurgens, 1998). The town of Smithville, Tex. (Myers, 1998) demonstrated how a small city with a population under 5,000 can address and implement sound water-quality practices as an integral part of handling stormwater runoff and implementation of an overall drainage plan. A case study in the Great Lakes region of Can. illustrated the planning process for development of stormwater retrofit strategies for existing urbanized areas using downspout disconnection, oil/grit separators, exfiltration systems, and stormwater ponds (Li et al., 1998). Through a $1 billion wastewater improvement program the Miami-Dade Water and Sewer Department (Fla.) achieved a 56% reduction in the occurrence of SSO over a three year period and a 66% reduction in the total volume of SSO (Cardozo et al., 1998). The department also met 800 other milestones, some of which carried stipulated penalties of up to $10,000 per day for noncompliance.

To meet a 2001 deadline to eliminate SSO, Fort Worth, Tex. commenced a tunneling project to redesign its sewer system in 1995 (Sahu et al., 1998). The tunnel would result in a shorter, more direct route for the sewer and offered a potential savings of $4.5 million over feasible open-cut routes. Richmond Va., which was required to control two CSO points by retention storage for one month design storms by the Va. Water Control Board, chose to install tunnels because of the minimal disruption during construction and their low environmental impact (Harksen et al., 1998). The 3.960 m long and 3.35 m diameter North Dorchester Bay consolidation conduit will provide complete capture and relocation of discharges from seven CSO outfalls tributary to Dorchester Bay and the bathing beaches of South Boston, Mass. (Heath et al., 1998b, and 1998c). Columbus, Ohio implemented the minimum control of maximizing collection system storage as part of the CSO Operation Plan (El-Hosseiny et al., 1998b). Investigations of the Chestnut St. Regulator indicated that a system separation may not reduce the number and duration of overflows from the combined system and that separation may have a negative impact on the receiving stream.

The MWRA’s recent CSO facilities plan provided that floatables control technologies be applied to 48 CSO outfalls (Walker et al., 1998). After testing several floatable control mechanisms, the authority found baffles most cost effective, though little data was available about baffle performance or maintenance. The Boston Water and Sewer Commission undertook a study of alternatives to the MWRA’s proposal of a screening and disinfection facility to deal with CSO and recommended all of the combined sewers along the Stony Brook Conduit be separated (Keohan, 1998). The MWRA accepted this alternative and revised its CSO plan. A cooperative project with the U.S. EPA and the Association of Metropolitan Sewerage Agencies to track improvements and benefits associated with CSO control involving “stakeholders” interested in CSO control identified the use and benefits of performance measures and recommended a process for selecting among 24 practical and useful performance measures (Sullivan et al., 1998). Turner and Reindel (1998) proposed the establishment of a national database on CSO outfalls.

The U.S. EPA and Tex. Natural Resource Conservation Commission mandated that Houston, Tex. control wet-weather overflows caused by excessive I/I during rainfall events by December 1997. A long-term simulation model was used for the construction of wet-weather facilities as part of the SSO control strategy for three service area collection systems (Maa et al., 1998a). Relief of Houston’s collection system bottle necks for the short duration, high intensity thunder storms of the Gulf Coast Region was found to be a more cost-effective alternative than rehabilitation (Maa et al., 1998b). Based on 91 sewersheds worldwide the average reported I/I reductions were 49% of peak I/I rate with a standard deviation of 25%. Twelve projects reported reductions greater than 75% (Keefe, 1998). Racine, Wis. (Marman et al., 1998) constructed diversion facilities with storage and partial treatment. The facilities prevented a cumulative SSO discharge volume of 3 million $m^3$ (783 MG) between 1993 and 1998 and actual SSO discharge was limited to 0.05 million $m^3$ (14 MG). A study to set up a long-term wet-weather control plan by the NORSID in the Westerly District of Cleveland, Ohio discovered problems with manhole invert plates, system blockages, and located sources of dry-weather flow (Bingham et al., 1998).

A five-year study confirmed the benefits of the original automation of the Lima, Ohio combined sewerage system by maximizing their CSO system storage and minimizing the impact of storm overflows on receiving waters. An upgrade
provided additional benefits including decentralized communication, data accessability, and additional control capabilities (Nye et al., 1998). Applications in the U.S., Can., and Fr. of Global Predictive Real Time Control (GPRTC) which can optimize and aid design of more efficient CSO control were described by Villeneuve and Pleau (1998). Perdek et al. (1998) discussed both international and national state-of-the-art technologies related to storage and sedimentation treatment for CSO. Harold et al. (1998) provided guidelines for accurate data from SSO and CSO monitoring based on the experience of major SSO and CSO monitoring projects conducted.

Gaffoglio et al. (1998b) used NYC’s Inner Harbor CSO Facility Planning Project to demonstrate the cost effectiveness of maximizing WWF to the WPCP. This strategy has led from 74 to 88% capture of CSO. The East Bay Municipal Utility District and local communities eliminated sewer overflows to San Francisco Bay, Calif. by increasing capacity to its treatment plant, installing seven miles of large-diameter sewer interceptors, and increasing storage among other techniques (Housen and McCormick, 1998). The city and county of San Francisco, Calif. has, since the completion of the combined sewer system control structures, achieved a reduction in the number of overflows to the shoreline, and an associated reduction in the elevated bacteria counts and days of beach postings for public health concerns (Foree and McGregor, 1998). The WPCP of combined sewer systems are designed to operate satisfactorily for the design case and consequently all plants maintain reserve capacities for most of the time, even during high stormwater inflows. Muller and Krauth (1998) reported of the development of an automatic control strategy to manage the wastewater flow to a WPCP according to its actual treatment capacity. Winnipeg, Can. initiated a CSO management study in 1994 to establish a cost-effective prioritized implementation plan for remedial works (Rempel et al., 1998). The study indicated that the use of inline storage in 43 individual combined sewer districts covering roughly 10 000 ha is the most effective first step in the wet-weather pollution control plan. The database MED-MEASURE was used for in-sewer and CSO online monitoring in the city of Paris (Fr.) where more than 100 points were monitored simultaneously for COD, BOD, and SS (Tremblay et al., 1998).

Schaefer (1997) discussed that the challenge of stormwater management will be an environmental challenge in the 21th Century. New partnerships between environmental engineers and other professional groups have to be established to minimize diffuse long-term deposition of hazardous substances (Boller 1997). In Wayne County, Mich., animation was used effectively as a public information/presentation tool on the Rouge River Watershed National Wet Weather Demonstration Project to illustrate CSO and water-quality impacts (Shaw and Murray 1997).

A fast-track approach was taken in the construction of a 60-ft high surge well around an existing 108 in. outfall downstream of the effluent pump station in response to Tropical Storm Gordon in the City of Miami, Fla. (Chorlog et al., 1997). Guderian et al. (1997) showed that rigid flow management for a sewer and treatment plant did not always fulfill the total emissions reduction goals for CSS. Sanders (1997) reviewed results of a detailed study of six WWTP facilities in Missouri that were impacted by the Great Flood of 1993 and concluded design engineers could probably have prevented many of the negative impacts.

The cities of St. Paul, South St. Paul, and Minneapolis, MN recently completed their 10-year, $331-million sewer-separation program for CSO control (Water Environ. & Technol., 1996b). Included in this program were the installation of 189 mi of storm sewers, 11.9 mi of sanitary sewers, paving of 168 mi of oiled streets, and disconnection of roof leaders at 21,900 residential properties.

**Innovative CSO controls - source controls.**

The methodologies used by several sewerage agencies to control combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) were presented/reviewed during 2001. Jewell (2001) outlined the methodology used by the Boston Water and Sewer Commission to identify and correct illicit connections to the storm drain system, as detailed in the Massachusetts Water Resources Authority’s Combined Sewer Overflow Facilities Plan. The Plan proposed improvements to the system infrastructure to reduce the frequency and duration of CSOs. The CSO control plan proposed by the City of Springfield, Massachusetts to meet EPA and Massachusetts DEP requirements was reviewed by Heath and Donahue (2001). The cost for the various alternatives ranged from $144 million (reduce discharges to 12 per year) to $525 million (complete sewer separation to eliminate CSOs). Economic analyses were coupled with a regional water quality model to evaluate the benefits of various proposed alternatives for CSO control. Lai et al. (2001) reviewed the SSO Control Plan developed for Henrico County, Virginia. The paper discussed the following components: (1) dry-weather wastewater flow projections using GIS, water consumption records, and flow monitoring; (2) rainfall-dependent infiltration/inflow predictions; (3) capacity analysis (present and future conditions) using the SWMM EXTRAN model; (4) hydraulic and process capacity analysis of the wastewater treatment facility, including expansion requirements; and (5) implementation
of a capital improvement program for additional facilities (sewers, storage tanks, pump stations, force mains, and wastewater treatment plant expansion or process retrofitting). O’Rourke et al. (2001) presented the Northeast Ohio Regional Sewer District’s long-term control plan (LTCP) for bringing the District into compliance with EPA’s CSO control policy. This approach included traditional and non-traditional cost issues, including non-cost issues that were deemed important by the public. The paper presented by Stupar and Dierksheide (2001) reviewed the new integrated maintenance, inventory and purchasing system implemented by the Ocean County Utilities Authority. The goal of integrating the system was to not only ensure that high quality WWTP effluent is discharged but also to reduce the probability of sanitary sewer overflows. Scott et al. (2001) reported on the Emergency Response Plan implemented by the City of Baltimore, Maryland as a response to the EPA’s guidelines for developing a CMOM program. In this Plan, critical facilities (pumping stations, pipelines, valves, and other components with a high risk of failure) were identified and their impact on public health and the environment was ranked. This Plan is guiding the implementation of recommended mitigation measures.

The use of analyzing utility data relative to sanitary sewer overflows was presented by Nelson et al. (2001). The purpose was to establish protocols for identifying SSOs through data already collected by utilities. Turner et al. (2001b) reported on Columbus, Georgia’s development of plans for managing CSOs and SSOs. The strategy was based on the “further-reasonable-progress” approach to attaining water quality standards. The keys to success have been the demonstration of sustainable watershed solutions and the results from continued receiving water monitoring. The EPA BASINS model, with field-data calibration, was used to digitally represent the watershed and evaluate potential improvements. According to McConico et al. (2001a), in 2000, the City of Richmond, Virginia conducted a bacteriological monitoring. The purpose of this data collection was to monitor the effectiveness of the City’s long-term CSO control program through comparing the new data to data collected in the 1980s and 1990s. The data was also used in the combined sewer system and James River tidal models that predicted for the effectiveness of long-range CSO planning. Carr (2001) reviewed the concept of micromanagement of stormwater flows to reduce SSOs and CSOs. Micromanagement of stormwater advocates temporarily storing stormwater in many and varied locations on the surface (off-street and on-street) and, as needed, below the land surface, near to the source. The paper reviewed the application of stormwater micromanagement in Skokie, Illinois and the lessons learned from the implementation.

CSOs often have been treated at the overflow point. Overall, the operating experience of the nine CSO control facilities on the Rouge River (Detroit, Michigan) has provided valuable information for designing future phases of CSO control on the river and for communities engaged in CSO control in other watersheds (Johnson et al. 2000). Andoh and Saul (2000) outlined recent developments in CSO technologies, particularly screening devices, and described the characteristics of the ideal intermittent wet-weather screening system. The authors then describe the development and evaluation of a novel self-cleansing CSO device - The Hydro-Jet Screen™. Averill and Gall (2000) examined the implications of intermittent loadings on operation of treatment systems and outlined a strategy for the planning and design of CSO, SSO or stormwater treatment systems. In the City of Niagara Falls, New York, options other storage for CSO control were evaluated because of the high cost of constructing a storage facility. High rate treatment by means of vortex separators was considered an attractive option after preliminary settling column tests showed that the settling characteristics of the CSO were amenable to this treatment (Cheung et al. 2000). Underflow baffles have become popular for intercepting flotables in CSOs, but largely have been untested. Cigana et al. (2000) reported the results of a study of flotables capture by 17- meter-long basin at various flowrates. Their data suggested that capture efficiency of existing underflow baffles in an overflow chamber will be very low whenever the horizontal velocity is greater than 0.30 m/s or 1ft/s. Inappropriate operation of a partly -lowered gate in a new overflow structure caused the interruption of a 100-year old brick interceptor sewer in the Sea Cliff area of San Francisco during an intense, but not extraordinary, rainstorm (Medley 2000).

Clegg et al. (2000) presented projects for removal of rainwater inflow sources on private property from combined and sanitary sewer systems in Lansing and Port Huron, Michigan. Keys to success for these projects included property owner understanding, city identification of inflow sources, free advice and site visits, tracking and follow-up, flexibility on removal method, and ordinances to help enforce inflow removal on all private properties. Detroit, Michigan planned the Conner Creek Pilot CSO Control Facility to provide skimming, settling, and disinfection to meet the daily and monthly fecal coliform limits of 400 and 200 colony forming units (cfu) per 100 milliliters (ml), respectively (Fujita et al. 2000a). If this 30-million gallon “pilot facility” can meet the fecal coliform limits, it likely would provide significant cost savings in CSO treatment (Fujita et al. 2000b). The CDS method performs a liquid/solid separation and consists of a stainless steel perforated and deformed separation plate placed in a hydraulically balanced separation chamber. Louisville and Jefferson County MSD (Kentucky) have been a demonstration site for one of the first CSO applications of CDS technology (Gratzer 2000). The Detroit (Michigan) Water and Sewerage Department, in developing the Long Term CSO
Control Plan, has recommended an innovative screening and disinfection approach to reduce CSO impacts on the Detroit River. Underground structures were designed for two pilot facilities to convey the flows through 4mm raked bar screens, and then direct the solids to the wastewater treatment plant through a side stream, thus eliminating the need for residuals to be collected and transported from remote facilities (Rabbaig and Neibert 2000). Zaccagnino et al. (2000) reported on several end-of-pipe CSO controls implemented by the New York City Department of Environmental Protection to reduce CSO impacts on Flushing Bay.

Sanitary-sewer flows and wastewater-treatment-cost effectiveness were compared five years before a downspout-diversion program and 15 months after the program. The diversion program yielded a 25% reduction in mean-flow volumes and a significant reduction in wastewater-treatment costs (Kaufman and Wurtz, 1997).

Innovative WWF control strategies include using rainwater and runoff for potable uses and controlling gaseous emissions from combined sewer systems. Herrmann et al. (1999) reported on a four-story apartment building which was renovated using an innovative water concept. Roof runoff used stored for use in flushing toilet, and excess runoff was infiltrated, allowing the building to be completely unconnected from the stormwater sewer. The authors showed that independent from the soil and the available space it was possible to restore the natural water balance again by combination of rainfall use and subsurface infiltration. Lausten et al. (1999) described the use of a biofilter to capture and control hydrocarbon odors including VOCs from a combined sewer and an interceptor sewer in Philadelphia, Pennsylvania. The biofilter has proven to be a successful process application for treating VOC compounds from the air stream. Lim and Lim (1999) described a unique scheme to implement urban stormwater pond collection systems for potable water use in Singapore. Close monitoring and control of pollution through the adoption of stringent anti-pollution measures and enforcement actions have resulted in the collection of generally good quality raw water from these urbanized catchments with very low levels of heavy metals and low coliform counts as compared to raw water from largely forested catchments.

Source control of WWF aims to reduce overflows by reducing inputs to the system. Schmitt et al. (1999b) described the correct procedures for inclusion of source control measures in urban stormwater management into the German design procedure A 128. Results obtained by long term pollution load simulations emphasized the need to review existing guidelines. Williams et al. (1999) reviewed a partnership between the Louisville and Jefferson County Metropolitan Sewer District (MSD), the Louisville Education and Employment Partnership (LEEP), and the Jefferson County Public Schools (JCPS) designed to provide an opportunity for students and teachers to work in a paid summer internship with consulting engineering firms that contract with MSD, and assist MSD in collecting information regarding wet weather issues such as misconnected downspouts, sump pumps, and leaky sanitary sewers. The program, which has been successful for five years, provides a quick and cost effective investigation that identifies inflow source reduction opportunities for mitigation of property damage and SSO.

Walesh et al. (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff and CSO in two communities in Illinois. This technology eliminated surcharging and basement flooding, complied with regulations, and proved to be a cost-effective solution which earned public support. Lachmayr and Schofield (1999) focused on the fieldwork techniques used to identify specific inflow sources from large buildings in the area served by the Boston Water and Sewer Commission, Massachusetts. Vaes and Berlamont (1999) examined the effect of rainwater tanks on CSO with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rainwater tanks will be more efficient in reducing the CSO discharges (Vaes and Berlamont, 1999).

Sewerage repairs and I/I control.

Weiss et al. (2002) performed a long-term analysis of infiltration and inflow in 34 combined sewer systems in Germany. The results showed that significant control of pollution can occur by reducing I/I. Schultz et al. (2002) presented an overview of the provisions and programs that the Milwaukee MSD has developed to more effectively control infiltration and inflow into the interceptors and community sewers. The presentation emphasized those provisions where the rules,
Lukas et al. (2001) reviewed the WERF project to identify and develop Predictive Methodologies for Determining Peak

storm separation, pipe joint grouting and lining. The results showed that building a new treatment plant may be more cost-effective over the life of the plant and system than rehabilitation; however, rehabilitation may be a good investment so capacity is available for future growth and development.

TenBroek et al. (2002) reviewed the use of footing drain connections to correct basement backups in Ann Arbor, Michigan. A review of the system concluded that 70% to 90% of the wet-weather flows in residential areas were from connected foundation footing drains that convey drainage from around most homes into the collection system. Sherman et al. (2002) reviewed the City of Ann Arbor, Michigan’s program on footing drain disconnection (FDD) program. The initial phase of the project included a footing drain flow monitoring program in an area of the city with capacity problems, and the prioritization of future disconnect areas. The results of the program to date were presented in terms of financial costs, treatment cost savings, and the construction requirements. Salim et al. (2002) reviewed the effectiveness of downspout disconnection in Detroit after implementing downspout disconnection in side by side test pilot sites. The cost of disconnection was $243 to $278 per downspout and 50 to 83% of the downspouts were disconnected. The Continuous Greater Detroit Regional Sewer System Model showed an annual reduction in CSO volume of 2 billion gallons.

Keefe and Kimbrough (2002) discussed how to measure successful rehabilitation of sewer systems. Success has typically been measured as I/I removal and the paper presented a rigorous method for calculating the I/I removed from a system. As reported by Lai and Field (2001), the USEPA has conducted a series of research, development and demonstration projects on the characterization, cause, consequence, and control of infiltration/inflow (I/I) in both sanitary and combined sewers. The research addressed (1) state-of-the-art problem assessment; (2) pressure sewer systems; (3) polymers to increase sewer carrying capacity; (4) sealing methods and materials for sewer rehabilitation; (5) demonstration and evaluation of Instiufom; (6) trenchless sewer installation by “plowing in;” (7) house lateral rehabilitation; and (8) impregnated concrete pipe to increase corrosion resistance and strength. This review was designed to assist communities that will be implementing the soon-to-be-issued SSO Rule. Moisio and Barton (2001) reviewed the design standards for sewers used by the Metropolitan Sewer District of Greater Cincinnati (MSDGC). The MSDGC maintenance program was designed to avoid SSOs due to poor maintenance. What had been documented was that replacement pipes were designed to the standard of new sewers and therefore I/I for the older sewer system was not accounted for in the calculations. The new revisions to the design standards will incorporate I/I contributions for older areas, thus allowing the installation of replacement pipes that can carry the flows from older areas. O’Sullivan et al. (2001) reviewed the implementation of a private sanitary sewer lateral replacement program (SSLRP) in Mobile, Alabama. The SSLRP performed in two distinct processes that used separate contractors – the testing and identification of defective private sanitary sewer laterals (PSSLs) and the replacement of defective PSSLs essentially at the cost of the property owner. A detailed program methodology, consistent penalty system, and close coordination between Water and Sewer System, the engineer, and the contractors were the keys to the program’s success.

Hilderhoff and Wendle (2001) recommended a mini-basin or mini-watershed approach to sewer rehabilitation, as was used by Susquehanna and Lower Paxton Townships. Total rehabilitation by mini-basin means that all sewer system components including mainline, manholes, service laterals and building sewers located in one mini-basin were repaired to meet the same acceptance testing standards as new sewers. This work was completed at the expense of each Authority and not the property owner. Blakley and Summers (2001) reviewed the approach taken by the McCandless (Pennsylvania) Township Sanitary Authority for I/I control and recommended this synergistic approach to other communities. The approach combined strengths of five different strategies (dye testing, line replacement, pipe relining, line grouting and manhole rehabilitation), creating a synergistic effect, that balanced cost with gain. Field and O’Connor (2001) recommended communities develop a strategy for SSO pollution abatement because extensive sanitary sewer rehabilitation without planning is (1) relatively costly, (2) time-consuming, and (3) extremely disruptive to traffic, property owners, etc. I/I control studies have demonstrated that just correcting I/I in street sewers will not necessarily correct the problem because building connections contribute as much as 60% of the infiltration load. Building connection rehabilitation may be unfeasible economically. Inflow elimination or reduction, cost-effective sewer rehabilitation, and collection system inspection with associated clean out and repair must be performed in all cases, and must be part of an integrated economic and feasibility analysis.

Lukas et al. (2001) reviewed the WERF project to identify and develop Predictive Methodologies for Determining Peak
Flows after Sanitary Sewer Rehabilitation Projects. The first result of the municipal surveys was the lack of documentation on rehabilitation projects and particularly, their effectiveness. The paper by Watts and Forbes (2001) analyzed the procedures used to rate I/I defects located during the recent Sanitary Sewer Evaluation Studies (SSES) conducted in Carolina and Luquillo, Puerto Rico. The methods used to prioritize appropriate rehabilitation methods were presented. Kurz et al. (2001) reviewed the City of Chattanooga’s permanent network of flow meters for monitoring sewer flows as part of their billing. In addition, the flow meter data assisted the city in its CMSM program by locating capacity problems. Nashville’s flow metering system identified over 10 million m$^3$ of I/I removal after rehabilitation. Jackson, Tennessee’s flow meters demonstrated that I/I rehabilitation solved what appeared to be a capacity problem in a major trunk line. Hollenbeck and Rieger (2001) outlined the Rock River Water Reclamation District program that was designed to mitigate basement backups in the District. This program identified and rehabilitated both public and private sources of infiltration in the study area. Post rehabilitation flow monitoring confirmed that 10-year storm protection from overflows and basement backups was achieved.

The condition of a combined or sanitary sewer influences overflows from the system, and sewer inspection and prioritization of repair efforts are important parts of overflow control. Continual improvement and streamlining of an inspection and evaluation program for the condition of a system of interceptor sewers and CSO facilities in the Cleveland (Ohio) metropolitan area resulted in an innovative and widely applicable approach to locating, identifying, and inspecting interceptor and CSO facilities. This approach significantly reduced field time and greatly increased the accuracy of the data collected (Krizmanich et al. 2000). Hahn et al. (2000) described an expert system, Sewer Cataloging, Retrieval and Prioritization System (SCRAPS), that prioritizes sewer inspections to target information collection from critical portions of the network. Kelly et al. (2000) reported on a process successfully used in New Orleans (Louisiana) to quickly and effectively address manhole rehabilitation needs. This process consisted of standardized data collection, computerized decision-making and implementation of appropriate rehabilitation methods. Merrill et al. (2000a) presented a tool to help utilities prioritize inspection of sanitary sewers to overcome problems/limits of available data and the limited ability to inspect and repair or replace sewer infrastructure. In validation exercises using case studies supplied by the experts, the tool was shown to outperform a group of experts in quantifying the need to inspect (Merrill et al. 2000b). In 1995, the Washington Suburban Sanitary Commission, which is located in Montgomery County and Prince George’s County, Maryland launched a 4.5-year, multimillion-dollar I/I analysis and sewer system evaluation survey. The paper by Nguyen et al. (2000b) summarized the results of the Rock Creek I/I Analysis project, described the tools developed to analyze the voluminous amount of data, and discussed the method used to prioritize the repairs of the identified defective manholes and pipelines. Pomroy et al. (2000) reported on a statistical condition model that was used to forecast the future condition of selected small-diameter (4-inch to 10-inch) sewer pipes and to estimate necessary rehabilitation capital costs in the Central Contra Costa (California) Sanitary District. The authors reported that condition modeling provided an efficient means to plan future expenditures and staffing requirements. A highly-accurate dye dilution testing protocol was developed and used by Stonehouse et al. (2000) to quantify flow meter accuracy in the Greater Detroit Regional Sewer System. Many meters typically considered to be accurate had errors of more than 30%, with some meters having errors exceeding 70%. Overall, the average initial system accuracy for system meters was observed to be ±15.0% of measurement with an overall bias of 6.1% (under-predicting flow). It was concluded that (1) there were observable accuracy differences between flow meter technologies; (2) objective standards like dye dilution testing were critical to good metering; (3) verifying installed accuracy was important, even for technologies considered to be highly accurate; and (4) the simplest technology that can be used often was the best.

Forbes (2000) examined the causes, diagnosis, impacts, and treatments for excessive infiltration/inflow (I/I), a significant cause of sanitary sewer problems, including SSO. Kurz et al. (2000) reported on a program in Nashville, Tennessee to improve system characteristics, recapture capacity, and reduce I/I so the sewers can carry the peak flow from their design storm without overflows. Accordingly, the authors recommended that sewer rehabilitation programs should include procedures to measure I/I removal effectiveness as a program progresses. A geographic information system (GIS) based system was developed to manage both sewer maintenance and I/I reduction programs. The system was designed to be used primarily for issuing work orders and responding to customer complaints, but it could also be utilized by engineers in conjunction with sewer line modeling needs (Shaffer and Greiner 2000). In 1992, Springfield, Missouri, began a long-term program of I/I reduction which included a comprehensive sanitary sewer evaluation, development of a hydraulic model, various manhole and pipeline renewal projects, and the addition of strategic relief sewers (Wade 2000). In Beverly Hills, Michigan, I/I into the sanitary system from public and private sources overloaded the sewer system and caused basement flooding and SSOs to local surface waters during large rain events. Sump pumps from residences were connected to the sanitary sewer system, so a project was undertaken investigate the effectiveness of removing sump pump connections to the sanitary sewer system in an effort to correct this I/I source. The results showed that sump pump
removal would produce a quantifiable decrease in inflow (McCormack et al. 2000). Rehabilitation of two basins in the City of Olympia, Washington allowed direct comparison of the effectiveness of rehabilitation of the upper lateral versus the public sewer and lower laterals in order to reduce I/I, as well as the total removal that can be achieved when the entire system is rehabilitated (Merrill et al. 2000b). Trenchless technologies are often used for I/I control in sewers because they can be implemented with less traffic control, minimum conflict with other utilities, increased workers and community safety, and minimum dust and noise generation (Garcia-Marquez et al. 2000). The City of North Miami Beach, Florida initiated a system-wide I/I reduction program and selected formed-in-place liner installation for rehabilitation of damaged gravity mains. Through 1999, the City has installed 27,500 feet of liner, and a nearly 48 percent reduction in average daily flow has been seen to date (Rothman and Heijn 2000).

Public education.
The paper by Chapman et al. (2002) described the processes and projects in Milwaukee that have been designed to overcome the older view that urban streams are an environmental nuisance and hazard. In this spirit the District has three completed or are implementing ongoing urban channel rehabilitation projects and several programs are underway to reduce flooding while supporting environmentally sustainable development. The paper focused on the evaluation and selection of a monitoring tool for benchmarking their progress.

White (2001) reviewed the joint agency program of King County and the City of Seattle (in conjunction with the Seattle-King County Health Department) for public notification of combined sewer overflows. The program included posting warning signs at over 100 CSO locations, developing a website, information line, brochure, fact sheet and other materials. According to the review of Rozelman and Loncar (2001), the 1995 New York State Discharge Notification Act (DNA) (aka “Fisherman’s Right to Know Act”) caused the New York City Department of Environmental Protection to enhance their public education program regarding CSOs and encouraged the public to provide the City with early notification of sewer problems such as dry-weather discharges.

Public involvement and education play a role in WWF control programs. Barger (2000) reviewed Little Rock (Arkansas) Wastewater Utility’s Captain Sewer Water Conservation Education Program. The program has focused on water conservation and Captain Sewer now visits at least twenty-four schools each year and has appeared in 24 states and two foreign countries. A campaign to involve the public in developing a control plan for CSOs in Edmonton (Alberta, Canada) has evolved into a significantly broader program. “Towards a Cleaner River” has raised public awareness of the condition of the North Saskatchewan River, the functioning of the drainage and sewerage systems, and how people can help improve the river’s water quality (Barth et al. 2000a). The Project Working Committee, the City and their consultant team developed a long term CSO Control Strategy to mitigate the environmental impacts of Edmonton’s combined sewer system (Barth et al. 2000b). To address the problems facing Pogues Run and the West Fork River (Indianapolis, Indiana) from 23 CSO outfalls, a multi-million dollar comprehensive plan was formulated. Due to the multiobjective nature of the project and its funding needs, many agencies and neighborhood groups were involved to help resolve issues such as short-term funding, handling special waste, compensatory wetland creation, allowance for dam overtopping, and even the project’s name and purpose (Kirk and Beik 2000).

Tunnels and interceptors.
Bate and Plaumann (2002) reviewed the Milwaukee (Wisconsin) Central Metropolitan Interceptor Sewer (MIS) System Improvement Project and was designed to clean, inspect and repair nearly 50 miles of the District’s oldest interceptors, siphons and flow control structures, with the ultimate goal of achieving an additional 50 years of service life. Much of the rehabilitation was to be accomplished by trenchless technologies (large diameter cured-in-place lining, slip lining, segmental lining, cementitious and epoxy coatings). Muindi et al. (2002) discussed the variable soil and groundwater conditions encountered during design of near-surface CSO facilities in Providence, RI. It also reviewed the geotechnical-related construction issues and geotechnical instrumentation program implemented to mitigate the potential for damage of constructed facilities. Jones and Robinson (2002) reviewed the Chattahoochee Tunnel installed in suburban Atlanta to increase conveyance and reduce the number of SSOs into the Chattahoochee River. The five key features in the tunnel design included ideal tunneling rock; the lack of a need for tunnel supports in most of the length; fractured rock supports included rock bolts or steel ribs; low groundwater flow; and linings of cast-in-place concrete only in areas of fractured rock or significant groundwater flow.

Larsen and Garcia-Marquez (2002) reviewed trenchless technology application failures. After a review of failures experienced in South Florida, they proposed that the most common defects and failures are due to: sanitary sewer problem misdiagnosis, inadequate technology selection, poor design and inadequate specifications, improper installation, and/or
inadequate inspection.

Gibbons et al. (2002) reviewed a case study of the Grant Street Pump Station flood mitigation in a West Allis, Wisconsin neighborhood. The paper presented the process for alternatives identification, stakeholder involvement, evaluation, and remedy selection and a description of the selected alternative for mitigation of localized flooding in the city of West Allis, Wisconsin. The constraints of the urban setting, and the need to consider environmentally sound remedies that will not degrade the existing watercourse, required a new look for an approach to meeting the objective.

Three major tunnel construction projects were presented during WEFTEC 2001. Jones and Robison (2001) reviewed the history, the design, and the construction of the Chattahoochee Tunnel in Metropolitan Atlanta. This tunnel was designed to accomplish two purposes: relieve the existing Chattahoochee Interceptor and provide flow equalization for the existing water reclamation facility. Wood et al. (2001) presented an overview of the decisions that went into the design of the interconnected Westside and Eastside CSO tunnels in the City of Portland. The analyses included comprehensive hydrologic and hydraulic modeling of the combined sewer drainage system and the tunnel system, RTC simulation of gates, weirs, and pumping facilities, and planning for instrumentation, monitoring, operation, control, and maintenance. Roll and Lannon (2001) reviewed the repair of the Falls Street Tunnel in Niagara Falls, New York. The repair was designed to reduce the 6-MGD of groundwater infiltration into the tunnel. The contractor payment for the project was based on the infiltration reduction, which was estimated to be approximately 4 MGD.

Ab Razak and Christensen (2001) investigated the benefits of the Milwaukee deep tunnel for temporary storage of storm water and sewage, on the water quality of the Milwaukee, Menomonee, and Kinnickinnic Rivers. Statistical analysis of BOD, phosphorus, suspended solids, fecal coliforms, zinc, and chloride indicated that the Menomonee River benefited the most from the deep tunnel since 1994 when the tunnel came on line. Fecal coliforms inside the CSO area, and to a certain extent BOD and zinc levels, exhibited the most significant decline.

Other research investigated various aspects of sanitary sewer systems that impact SSO and CSO control efforts. Spurred by the increased scrutiny by EPA and other regulatory agencies on SSO prevention, Jones and Schneider (2000) reviewed the elements that compose a pumping station design, including the results of client-consultant interaction that has resulted in exceptional reliability and reduced operational costs. The Western Carolina Regional Sewer Authority is completing construction of the largest sewer project in South Carolina to reduce SSOs and to protect water quality - 10 miles of deep trunk sewer up to 96 inches in diameter, located 20 to 45 feet deep along the fully developed Reedy River valley (Hildebrand et al. 2000). The North Central Sewer Separation Project will separate storm water and wastewater pipes in a section of downtown Columbus, Ohio, USA (Keefer and Chase 2000). The Milwaukee Metropolitan Sewerage District authorized an emergency project to design and construct a new CSO pump station using a fast-track approach, as discussed by Maurer and Bush (2000). This discussion reviewed the use of large submersible pumps for CSO service, design considerations, procurement methods, and the challenges of fast-track design and construction.

The Vortex Drop Structure has been shown to be an effective energy dissipater and aerator. It is designed to dissipate the flow energy and aerate the wastewater, preventing emission of odorous gases, oxidizing the hydrogen sulfides, and protecting the drop structure from corrosion and abrasive wear. The analysis of multiple wastewater samples taken simultaneously upstream and downstream of the Vortex Drop Structures shows a significant decrease of dissolved hydrogen sulfides and a sharp rise in the dissolved oxygen concentrations downstream of the structures (Moeller 2000). Private pump stations (commercial, industrial, institutional, etc.) typically have been constructed as an immediate fix when no nearby wastewater facilities exist or to overcome sewer elevation differences. However, in many cases, insufficient documentation and coordination between the developer, engineer, permitting agency, and sewer system operator has rendered this component of the collection system seemingly non-existent (Huerkamp et al. 2000). Street storage refers to the temporarily storing stormwater in urban areas on the surface (off-street and on-street) and, as needed, below the surface close to the source. A case study approach, based on two largely implemented street storage systems, was used to explain the concept of construction and operation of street storage systems (Walesh 2000). Huisman et al. (2000) studied the propagation of surface waves on the operation of a urine separation system. The authors showed that the wave phenomenon had no adverse effects on the utility of the urine separation system, but could lead to the release of undiluted wastewater during a rain event.

Tunneling and interceptors play a role in WWF. The Columbia Slough Consolidation Conduit tunnel was a key element in alleviating CSO in Portland, Oregon. Rippe et al. (1999) described the design and construction of this soft ground tunnel project, with shallow ground cover and close proximity to an existing old concrete sewer, as well as the means of
Litter, floatables, and settled solids.
Fischer and Turner (2002) reviewed the North Bergen, NJ Solids and Floatables Control facility, which uses a system of nine Netting TrashTrap® system and one mechanical screen and which cost 300% less than the next least expensive technology evaluated. Operations and maintenance costs on the facility have been approximately $57,000 per year. Irvine (2002) discussed the Buffalo River (NY) Floatables control using a floatables trap and the continuous water quality monitoring. Mean accumulations rates in the trap were significantly greater for CSO periods than for dry weather and the distributions in the traps had more wood and less plastic than floatables traps in New Jersey. The average mass trapped per unit volume was also less for the Buffalo watershed than for the two New Jersey watersheds monitored, possibly due to the sewer hoods installed in the Buffalo watershed.

Dettmar et al. (2002) investigated the performance and operation of flushing devices in both a German field and laboratory study. The results showed that the generated flushing wave shear stresses of investigated gates surpass 14 N/m². The performance of the cleaning amounts to 0.5 kg sediment per m³ of flushing water.

Fan and Field (2002) provided an overview of the causes of combined-sewer deterioration and the heavy pollutant discharges, along with a discussion of their control methods. Their results indicated that both the tipping flusher and the flushing gate technologies appear to be cost-effective for flushing solids and debris from CSO storage tanks, while the flushing gate appears to be the most efficient method for controlling combined-sewer sediment. The use of slotted invert traps for managing sewer sediments was reviewed by Buxton et al. (2002). The paper presented the results from a laboratory investigation that compared the trapping performance of three slot-size configurations of a laboratory-scale invert trap and from 2-D modeling of stochastic particle tracking. The comparison of the two procedures showed that the modeling consistently overpredicted retention efficiencies observed in the laboratory model. The effect of a manhole drop on the hydraulics of combined sewer flow was investigated by De Martino et al. (2002). The main wave features were analyzed to give expressions that contain both the upstream filling ratio and the Froude number of the approach flow. The discharge capacity was also investigated and photographs were presented to show typical drop flow in combined sewer manholes.

The paper by Fan et al. (2001a) reviewed the causes of sewer deterioration and the control methods that can be used to prevent or postpone this deterioration. The remedy reviewed in the paper was inline and combined sewer overflow tank flushing systems to remove sediments and thus minimize hydrogen sulfide production in the sewer system. The two technologies reviewed were the tipping flusher and the flushing gate, both of whom have been demonstrated to perform well in facilities in Germany, Canada and the United States.

Sewer solids which are deposited in combined and sanitary sewers during dry weather make up a significant component of CSO and SSO pollution. Detailed research investigating all aspects of solids in sewer systems has been underway in Europe for nearly two decades. Recent research has characterized the nature of the solids getting into sewer systems, how they behave in terms of transport, and some of the main aspects of their effects. Ashley et al. (2000) has demonstrated that in a number of catchments, the majority of pollutants found in suspension during storms, and likely to be discharged from overflows, originate from the predominantly organic 'near bed solids' which accumulate in systems during dry weather. This knowledge has been used to improve the modeling of sewer solids behavior. The USEPA has also investigated the causes of sewer solids deposition and the development/evaluation of control methods to prevent sediment accumulation. Control of sewer sediment not only protects urban receiving water quality but also protects sewer structural integrity (Fan et al. 2000b). Chen and Leung (2000) demonstrated that the sediment phase played a key role in oxygen utilization in a sanitary gravity sewer. Their study indicated that the sediment phase contained more active biomass than the sewage phase. Del Giudice et al. (2000) examined supercritical flow in a bend manhole used in sanitary sewers, and introduced
the bend cover, which allows air entrainment into the downstream sewer. The bend cover may significantly increase the performance and capacity of bend flow and may easily be added to existing manholes. A three-dimensional particle settling model was used to predict the benthic exposure zone to sewage solids for a large marine outfall and diffuser serving Nanaimo, Canada. The predicted exposure zone was determined largely by horizontal advection, and to a lesser extent by the relative amounts of floc and non-floc solids settling at two different rates (Hodgins et al. 2000).

Riverine litter and floatables occupy a spatial and temporal position in any systematic analysis of river systems and represent a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly sewage inputs through CSO and fly tipping. Sewage-derived material constituted approximately 23% of all items on the river, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). Burgess et al. (1999) reported that the City of Indianapolis developed five CSO control facilities as "pilot" facilities, for the purpose of establishing and demonstrating the local suitability and effectiveness of the various technologies that they employ. Preliminary results, with emphasis on the capture characteristics of the floatable debris netting trap facilities, were presented. Bridgeport's (Connecticut) Water Pollution Control Authority has recently faced the problem of floating debris and the sound's high tide. These drainage problems have been successfully solved by building new flow-control regulators with integrated automatic radio (wireless) and telephone-modem (wired) control, water-flow, and instrumentation technologies (Morrill and Sound, 1999).

Arthur and Ashley (1998) examined near-bed solids transport in combined sewers, developed a method to estimate the rate of sediment transport near the bed in sewers and concluded that near-bed transport of sediment may contribute to the first foul flush phenomenon in sewers. A study to quantify the first flush phenomenon in stormwater runoff failed to identify any consistent, strong indication that the first flush runoff from a storm contains higher concentrations of pollutants than the event average. Analysis of SS in the River Seine (Paris, Fr.) both upstream and downstream of major CSO showed that SS from wet-weather events settled rapidly, after which they are gradually mobilized from the river bed during dry weather (Estèbe et al., 1998). Dimensionless mass versus volume curves for 197 runoff events in 12 separate and combined sewer systems depended on the pollutant, the site, the rainfall event and the workings of the sewer system. No general relationships was established because of the complexity of the phenomena involved and the multiplicity of influencing factors (Bertrand-Krajewski et al., 1998). Only slight first flush effects for SS and conductivity of storm runoff were observed at single road inlets for two catchments in Yug. and Swed. and no first flush effect was recorded for pH or temperature. After a year of study, conclusions were that the first flush, if strongly present at the end of a drainage system, is not generated by the first flush of pollution input and that regression curves are not very reliable for prediction of the first flush load of pollution input into drainage systems (Deletic, 1998).

**Real-time control (RTC).**

Nielsen and Nielsen (2002) evaluated the integrated real-time control system for the wastewater treatment plant and sewer system. The system was capable of adjusting the plant’s hydraulic capacity based on loads as monitored by the real-time control system. The effects of real time control of sewer systems were evaluated by Frehmann et al. (2002b) using an integrated model with four submodels (surface runoff, sewer flow, wastewater treatment plant, and receiving water). The results showed that the effect of a control measure may be ambivalent in an existing system but that drainage system can be optimized toward environmental protection using real time control on the catchment scale. Klepiszewski and Schmitt (2002) compared a conventional, rule-based control of a combined sewer with a fuzzy-logic control through the use of hydrodynamic simulation of optimizing storage capacities of four combined sewer overflow tanks. The results indicated that both control systems were able to reach the objective and the use of the fuzzy-logic-based system provided no additional benefits, in spite of its additional costs. Sugita et al. (2002) performed a feasibility study on the real-time control of pumps for the reduction of CSOs. The use of RTC control made it possible to reduce CSO by roughly 50% for small rainfalls (total precipitation of < 20mm) by storing rainwater in the pipes and rainfall forecasting led to a CSO reduction of 80%.

O’Connor and Field (2001) reviewed the USEPA Capstone Report on control system optimization, including a management strategy that will maximize the use of the existing system. This will postpone construction of new facilities and will size storage volumes in concert with the treatment rate to obtain the lowest-cost storage-treatment system. The components, hardware, and strategies to create such a system were described. An RTC methodology was used to measure the discharge problem from an urban area (Yamada et al., 2001b), and was used in conjunction with a stormwater tank to retain flows. The results showed that COD in the stormwater runoff was reduced to approximately 0.45 mg/L.
The sewer system evaluation by the Milwaukee Metropolitan Sewer District (MMSD) proposed that flow regulation in the system be controlled not by specific flow rate from the tributaries but instead by maintaining a constant hydraulic grade line in the system, i.e., the flow allowed in the system will be determined by the available capacity of the downstream pipes (Bate 2001). The paper by Schultz et al. (2001a) explained how controlling the interceptor system, rather than just relieving it, enabled the Milwaukee MSD to achieve far more than merely reducing bypass and overflow frequency. The collection systems controls allow the MMSD to meet tight overflow restrictions in a manner flexible to variable precipitation patterns, growth patterns, and lake and groundwater levels. In addition to more efficient use of intercepting sewer capacity, the regulation strategy also provided a significant cost savings when compared to conventional flowrate regulation. The Louisville and Jefferson County Metropolitan Sewer District (MSD) is considering Real Time Control as a possible alternative in the Combined Sewer Overflow (CSO) Long Term Control Plan (LTCP) (Charron et al., 2001). Two successive studies have produced very promising results – the first implying an overall reduction of 64% in annual overflow, and the second currently showing similar results to the first.

Chowdhury et al. (2001) reviewed the RTC control model developed for the District of Columbia. The model was applied to evaluate existing and potential improvements to the system, and also used to evaluate the effectiveness of previously-installed controls. The model results indicated that significant reductions in overflows had been achieved through the controls installed in the past. Real-time control (RTC) operations strategies for the Quebec Urban Community (QUC) were discussed by Colas et al. (2001). Simulation of each RTC strategy using 32 real back-to-back rainfalls showed that the existing system performs better under RTC than with conventional control. Efficient in-system storage and treatment capacities and the elimination of flood risks were the main benefits of this type of real-time management. The results of the first year of operation of the optimized real-time control system for the QUC were presented by Lavallee et al. (2001). These results confirmed the model results for the benefits of the QUC RTC. RTC use in Philadelphia was reviewed by Marengo et al. (2001). The implemented RTC system provides the capability to prioritize capture of combined flow in the collection system, to minimize overflows to sensitive receiving streams, and to optimize the use of available interceptor sewer-system storage during wet weather. SWMM model simulations were performed to quantify the benefits of RTC implementation in PWD's SWDD.

Real Time Control (RTC) of wastewater systems involves using automatically adjusting weirs, flow separators, and similar devices to divert flow to unfilled portions of the collection system before overflow occurs. One of the more frequently applied RTC techniques in combined sewer systems (CSS) is the activation of in-line storage capacities by positioning regulators such as moveable weirs and gates into the collectors. Campisano et al. (2000) presented the results of RTC application to the Roma Cecchignola CSS through the use of an advanced hydraulic model. Comparison of the results obtained with the tested strategies showed that a global control strategy reduced overflows considerably more than a local control strategy. Charron et al. (2000) presented the results of a study of RTC to reduce CSO in and around Louisville, Kentucky, which showed a global RTC strategy would enable a more efficient use of the existing system capacity and reduce the overall cost of the CSO control. Cigana (2000b) introduced the use of linear overflow devices to help municipal managers achieve increased retention of sewage in a sewer while protecting against flooding. Cigana’s examples demonstrated that the required water head was reduced by 50% for the same overflow rate. Jain (2000) summarized the hydraulic characteristics of a two-ramp drop structure used for diverting flows from near-surface storm-sewer systems to underground storage tunnels. The construction of this structure may be more suitable in urban areas where an open-cut construction is not feasible. Lavallée et al. (2000) reviewed the RTC system installed for the Quebec Urban Community (QUC), Canada. The results showed that a Global Predictive Real Time Control (GP-RTC) strategy on the Westerly Sewer Network was successful in terms of proven efficiency. GP-RTC meant that only 4 storage facilities would be required instead of the 7 needed without GP-RTC, a 22% savings (Pleau et al. 2000). Pollution-based RTC, or PBRTC, is designed to reduce the potential pollutant load on receiving waters during wet weather without expansion of transport or storage capacity. In branched interceptor systems PBRTC reduced CSO pollutant loads by more than 20% compared to volume-based RTC (Risholt 2000). Stinson et al. (2000) presented results of two case studies of RTC on portions of sewerage systems near Paris, France and in Quebec City, Canada. Villeneuve et al. (2000) compared three RTC strategies used in a collection system in terms of optimization of the use of the system capacity and the cost of long-term CSO control. The Philadelphia Water Department used the SWMM EXTRAN and SewerCAT models investigate RTC in its Southwest Drainage District (Vitasovic et al. 2000). Schutze et al. (2000) reviewed RTC for an integrated system that included the collection system, the treatment plant and the river. The results of their work was the development of an algorithm for the complete urban wastewater system and the methodology for parameter optimization.

RTC of combined and sanitary sewer systems aims to reduce overflows by better utilizing the existing storage in a systems using real-time data such as rainfall and water level data to control adjustable weirs or pumps. Gonzalez et al.
(1999) worked on the development and simulation of RTC systems for urban or metropolitan drainage systems with CSO or flood problems. They reported some conclusions and encourage the use of RTC systems on sewer systems. In response to floods in 1982, the Urban Community of Bordeaux decided to make improvements in their stormwater management system. Studies indicated that CSO have a significant effect on the environment. Therefore, emphasis will be placed on improving the management of the sewer system during rains and on the design of new storage structures and new treatment plants (Briat et al., 1999).

Artina et al. (1999) presented an evaluation of the benefits given by different configurations of storage tanks in a virtual but likely urban pilot site. The study showed that RTC, even if always useful for the reduction of overflow volume and frequency, in some cases can increase the discharged loads, under the hypothesis of complete mixing without settling in tanks. Fuchs et al. (1999) described the results of a study of the potential of real-time control of CSO for the combined sewer system of the city of Dresden. The results showed a significant 5% to 90% (mean more than 35%) reduction of the overflow volumes and loads for the controlled state compared to the uncontrolled one.

To address the problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events, Marinaki et al. (1999) proposed a linear multivariable feedback regulator that was developed via a systematic design procedure, including a simplified model, a quadratic minimization criterion, and subsequent application of the linear-quadratic optimization method. Simulation tests for a particular large network and various inflow scenarios indicate that significant overflow reductions were achieved by the application of the linear-quadratic regulator. Pfister and Cassar (1999) described measurement and modeling techniques developed for using X-band radar estimates of precipitation for RTC in a combined sewer system.

Villeneuve et al. (1999) presented a study of three types of RTC alternatives and conventional static control, applied to the Western section of the Quebec (Canada) Urban Community (QUC) sewer system. At the end of the long term CSO control plan it was projected that the QUC will control more than 85% of the CSO, for a total cost of US $107,000,000 which was 37% less than what had been estimated before the introduction of RTC. Risholt et al. (1999) reported on a project to document current discharges of pollutants and to find potential reduction by implementing RTC of the wastewater system in Fredrikstad, Norway.

Offline simulations carried out with a variety of control conditions suggest that great benefits were to be expected using global control with precise forecast information compared to a static system with local control only. Quirmbach et al. (1999) presented an approach to joint operation of an urban drainage system and the corresponding sewage treatment plant. This operation was based on real-time flood forecasts, which were computed with the aid of radar rainfall measurements to minimize the combined negative effects of the hydraulic load (water quantity) and the pollution load (water quality) in the receiving waters during floods. Schmitt et al. (1999a) developed a new management strategy of the City of Nancy’s sewage system (Lorraine, France) in order to reduce rainwater pollution overflows using a model which simulated flows in interceptors, transport of dissolved and solid pollutants, and precipitation, flocculation and sedimentation in WWTP. This new management strategy, optimizing the use of existing infrastructures, aims to conciliate flood risk management and the reduction of pollution overflows into the Meurthe River (France). Soeda et al. (1999) presented a case study of proposed improvements to combined sewer systems with no construction of new facilities and effective utilization of existing facilities through various modifications of stormwater pump operations. This system proved an effective means of reducing overflows and reducing pollutant loads from combined sewer systems.

Web and Brombach (1999) examined the application, advantages, and hydraulic performance of devices for water level control like movable weirs (self-regulating or auxiliary powered) or siphons which were frequently used at overflow structures in urban drainage. Special focus was given to possible critical points and limits of application. Yagi and Sheba (1999) applied fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. It was found that current pump operations can be improved by adding the sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters.

**CSO storage tanks and structures.**

Ashley et al. (2002) analyzed the effects of introducing extended in-sewer storage at CSOs on downstream sewerage and treatment. The study combined the Hydroworks model and a new model developed at Aalborg University to describe the range of conditions, including flow, odor generation and nutrient removal, that can be found in the collection system. Lau et al. (2002a) reviewed the use of optimizing storage volumes in sewer systems to control the concentration of specific
pollutants in receiving water bodies. An integrated simulation tool (SYNOPSIS) was used to determine the specific storage volume needed, with the results showing that an optimal solution can only be achieved sometimes and there are times that compliance with the standards will not be achieved, regardless of the storage volume provided.

Baki et al. (2002) reviewed the design and operation of the O’Hare Chicagoland Underflow Plan (CUP) Reservoir in the Greater Chicago area. The purpose of this underground 343 million-gallon reservoir was to collect and retain combined sewer flows until they can be pumped to water reclamation plants for treatment. Ridgway and Rabbaig (2002) reviewed the use of inflatable dams to provide in-system storage devices to reduce CSOs. A second important design criterion was to minimize the number of level sensors required since the sensors require frequent maintenance. Bate et al. (2002a) provided an overview of the inspection of the mainline storage tunnels that comprise Milwaukee’s Inline Storage System, while Bate et al. (2002b) reviewed the flow-regulation evaluation of Milwaukee’s Central Metropolitan Interceptor Sewer with the goal of optimizing the flow through the conveyance system while preventing overflows.

Ashley and Jack (2002) investigated the impact of retaining CSO flows in the sewer system on an activated-sludge treatment plant. It was concluded that the storage caused little or no benefit with respect to ammonia emissions from the plant but there was an overall benefit with respect to BOD total emissions.

The paper by Sonderup et al. (2002) compared rainwater tanks and detention basins for CSO abatement in Denmark. The result was that rainwater tanks were found to be less efficient and the tank volume would need to be 3 – 40 times larger than a downstream detention basin to obtain the same reduction of mean annual CSO volumes due to the fact that rainwater tanks are often partially full and cannot hold the complete peak flow. Rabbaig et al. (2002) presented an overview of Detroit’s three CSO treatment basins that discharge to the Rouge River, including ramifications of in-system storage provided by the facility, quantification of “sanitary trash,” facility operation and maintenance staffing recommendations. Rickard and Darter (2002) reviewed the selection of rectangular basins over vortex separators for CSO treatment in West Lafayette, Indiana. The comparative benefits of the rectangular basins were 20 minutes of chlorine contact time, greater solids removal and the ability to store larger volumes of water at the same capital costs as the vortex separators. Bode and Weyand (2002) reviewed the installation of about 500 stormwater/CSO detention facilities in the Ruhr river basins and the significant drop in pollution from stormwater runoff after the basins were installed. The tank volume for stormwater could be minimized by using real-time control for dynamic operation of all detention facilities.

Carr et al. (2001) reviewed the use of street-storage systems to prevent combined sewer overflows and mitigate basement flooding, based on the idea of accepting the complete volume of water but reducing the inflow rate of the stormwater to the sewer system. System components included street berms, flow regulators and surface and sub-surface storage facilities. Charlotte-Mecklenberg Utilities also found that they were able to service new development without creating overflows by storing peak flows upstream (Crowley and Howard 2001), thus delaying a system-wide expansion. Carter et al. (2001) reported on the evaluation of inflatable dams for use in Philadelphia as part of its Long Term Combined Sewer Overflow Control Plan (LTCP). These dams were operated under real-time controls to storage and treat flows upstream, thus reducing the frequency and volume of CSOs. Based on model results (using EXTRAN) with three inflatable dams operated by RTC, a 70% (50-million gallon) reduction in average annual CSO volumes to the Schuylkill River would be expected.

Murphy and Ring (2001) reviewed the use of pre-cast concrete box sections to create CSO storage facilities. The savings from using pre-cast versus cast-in-place boxes was estimated at $3.1 million dollars for the 1.2-million gallon Kenduskeag East CSO Storage Facility. The Pollution Control Plan (PCP) for Hamilton-Wentworth recommended the construction of 10 – 12 underground storage tanks to intercept CSO waters for subsequent conveyance to the treatment plant (Stirrup 2001). The sizing of the tanks was performed using SWMM. The premise was that continuous modeling would be the only reliable way to ensure that the tank performs to those control criteria under real operating conditions for long periods of time. Freedmand et al. (2001) reported on the use of unused aeration basins for receiving and equalizing industrial and CSO flows to the treatment plants in Rockland, Maine.

Temporary storage at CSO and SSO outfalls, with effluent returned to the system for treatment when system loading subsides, was a widely practiced method of WWF control. Some authors focused on modeling and design of storage structures. Harwood and Saul (1999) described how the computational fluid dynamics software Fluent was used to simulate the hydraulic and particle retention efficiency performance of three extended stilling pond CSO chambers in the United Kingdom. It was concluded that where the effective retention of neutrally buoyant particles was a design criterion, increasing the size of the chamber may not be the most appropriate solution. Hobbs et al. (1999) discussed the use of flow
equalization basins (FEB) for control of SSO and CSO. FEB increases systems capacity dramatically by retaining excessive flows until the collection system was better able to handle them and cost considerably less than more traditional methods. Maglione (1999) proposes a methodology for the design of CSO tanks aimed to control first foul flush in sewer networks, based on a five years period of field continuous measurements carried out on rainfall, discharge and water quality in an experimental catchment near Bologna (Italy). Stovin et al. (1999) compared the results of simulated flow patterns and gross solids separation predictions with field measurements made in a full size storage chamber within an urban drainage system. Although estimates of total efficiency based on the observed settling velocity distribution differed from the measured values by an average of ±17%, the simulated efficiencies agreed with the field observations in identifying the most efficient configuration. Van Mameren (1999) presented a method of using the results of rain series calculations as a design tool for stormwater sedimentation tanks, and demonstrated the method with an example.

Other papers presented case studies of CSO and SSO storage. For a better understanding of the spill over into the receiving waters, recorded data from 90 CSO tanks with a collective monitoring time of more than 300 years were compiled and analyzed by Brombach et al. (1999). A ranking procedure was proposed for an easy to handle evaluation of the overflow activity of CSO tanks. Hartshorne and Cadman (1999) described the design and construction of a 12,500 m³ capacity stormwater storage tank in Westbourne Avenue, Rhyl (United Kingdom). The finished structure was completely buried and incorporates new pumping plant to pump dry-weather and storm flows. Kearney and Schoettle (1999) described methods of cleaning dewatered CSO-storage basins at the Spring Creek Auxiliary Water Pollution Control Plant, which was used for temporary storage and treatment of CSO in New York City. Murphy et al. (1999) report on an in-line CSO storage facility constructed of bolted together precast box culvert sections that was designed and built by local engineers and contractors in the City of Bangor, Maine. This inexpensive CSO storage option has numerous advantages over the alternatives. A cost-effectiveness analysis conducted by the City of Slidell, Louisiana demonstrated that an offline storage facility would produce a substantial capital cost savings over multiple, decentralized line repair projects to achieve the same level of SSO control. The completed project applies commonly accepted technology to produce a system that worked within the funding constraints, was acceptable to the general public, and was easy to maintain for the operators (Prellop, 1999). Wada and Miura (1999) attempted to reduce CSO using a large-scale storage pipe, which was constructed for flood control. Using a movable diversion structure permitted use of the storage pipe for both flood control and CSO control.

The influence of the experimental procedure for separating a sample by settling-velocity fractions was demonstrated. This not only takes into account the settling-velocity characteristics of wastewater and stormwater SS but also considers SS which influence settling velocities, ultimately impacting the design and management of sewer networks (Lucas-Aigui et al., 1997). The settleable and nonsetturable SS concentrations were measured during a storm event at a combined WWTP in Sacramento, Calif. (Whalberg et al., 1997). While influent settleable and nonsetturable SS concentrations varied throughout the storms, the primary-sedimentation tanks were 100% efficient in removing the settleable solids the tanks were designed to remove.

CSO treatment.

The paper by Andoh (2002) reviewed the evolution of Hydrodynamic Vortex Separators in the context of their use as high rate rotary flow separators for achieving water quality improvements. The applications reviewed included treatment of CSOs, SSOs, stormwater and wastewater, and misconceptions about their use were addressed.

Heath et al. (2002a) reviewed the challenges associated with the design of the MWRA Union Park detention/treatment facility, which will provide treatment for wet weather flow discharged from the Boston Union Park Pumping Station (UPPS). Some of the more significant challenges include: siting the facility in a densely developed, urban setting; institutional challenges associated with a facility to be jointly owned and operated by two public agencies; maintaining the flood control function provided by the existing UPPS; and other technical challenges. This paper presented the design features and approaches developed to address project challenges, many of which may be faced by others tasked with implementing similar wet weather pollution control projects in urban areas.

Matson (2002) presented the results of a pilot study on the City of Salem’s (Oregon) high rate process train that treats SSO wastewater. The results from the pilot programs showed that the effluent produced by a peak excess flow treatment facility would be equivalent to the effluent from conventional secondary processes treating similar flow (> 85% removal of TSS and 60% removal of BOD was consistently achieved). Dorsch (2002) described the Muddy Creek-Westbourne high rate treatment facility in Cincinnati and discussed ways to reduce or eliminate CSOs. The structure was designed to blend into its environment and was designed to separate flow from the trunk line at a diversion chamber and run it
through a coarse screen and over a grit pit. Excess flow is retained in a detention tank. Yoshida and Tomita (2002) discussed the development of a high-speed combined sewerage stormwater treatment system. The new system was capable of effectively removing the high pollutant concentrations in the first-flush and that O&M was inexpensive. Hunt and Eckley (2002) presented the City of Salem’s (Oregon) peak excess flow treatment facility consisting of preliminary treatment, high-rate clarification and UV disinfection. This project has been designed and constructed to take the load off the City’s wastewater treatment plant and to reduce the number of annual SSO discharges into the Willamette River.

Schafer and Gray (2002) reviewed the proposed chemically enhanced high rate separation system to be added to the Sycamore Wastewater Treatment Plant in Cincinnati, Ohio. The addition would allow for treatment of peak wet-weather flows of up to 50 MGD total and should provide treatment sufficient to ensure that the discharge does not degrade the Little Miami River, a State and National Resource Water for Primary Contact Recreation. Sampley and Sullivan (2002) reviewed the CSO facility in East Bremerton. The facility uses the ACTIFLO ballasted clarification processes that combines conventional water clarification with microsand. Jacobsen and Hong (2002) reviewed the use of microsand ballasted flocculation and clarification for high-rate treatment of stormwaters and sewer overflows.

Andoh et al. (2002) reviewed the use of screening for treating CSOs in the UK through the short-term testing of CSO screen and chamber configurations. The system, including a novel non-powered self-cleansing screening system with no moving parts, provided robust, reliable, flexible and effective screening of CSO wastewater. Ungar and Schnipke (2002) reviewed fine screening for CSO control in Lima, Ohio for 90% treatment of the four-month storm. The fine screening equipment has 4-mm openings that will not only trap floatables but also provide CSO treatment by acting as a barrier to solids. Takasou et al. (2002a) performed a study on the control of CSOs by a fine CSO screen. This review included investigating their performance, structure, application, installation, maintenance, head loss coefficient and filtration rate. Takasou et al. (2002b) researched the potential use of a high-speed, space-saving fiber filter to reduce the discharge load of CSOs in Japan and evaluated its practical performance and applicability. The results showed that a high-speed fiber filter can be used to decrease the amount of primary treatment wastewater overflow on rainy days.

An evaluation of the effectiveness of UV disinfection of CSO processed through Continuous Deflective Separation (CDS) devices was reported on by Akridge et al. (2002). The combination of treatments was found to provide a three-log reduction of fecal coliforms in a preliminary study. Boner et al. (2002) evaluated the use of bromine disinfection for wet-weather flows at the Uptown Park CSO facility in Columbus, Georgia. Disinfection capabilities of BCDMH (1-bromo, 3-chloro, 5,5-dimethylhydantoin), in a suspension form manufactured by BioLab, Inc were examined on a bench-scale level along side of other chemical disinfectants to quantify disinfection performance at different CSO strengths. BCDMH dosing system set-up, tests and calibrations were performed.

Turner et al. (2002) reviewed the steady-state bacteria delisting approach in Georgia. Study conclusions and recommendations called for a full-scale demonstration to provide embankment stabilization, peak flow attenuation, flushed pollutant removal and disinfection. Stormwater treatment facilities will attenuate wet weather flows in the upstream channelized-reaches; remove pollutants from impervious area flushes and disinfect dry weather as well as a portion of the wet weather flow using ultraviolet light (UV disinfection).

Wojtenko et al. (2001a) reviewed the chapter of the EPA Capstone Report on control and treatment of CSOs, SSOs, and stormwater runoff. The paper discussed inline and offline storage systems as well as in-receiving water storage systems. Three major types of treatment systems and their associated costs were also discussed: (1) physical (screening and sedimentation), including comparing high-rate vs. conventional processes; (2) physical/chemical (filtration and high-rate sedimentation); and (3) biological (trickling filters, activated sludge, aerated lagoons, and rotating biological contactors).

Gaffoglio et al. (2001) reviewed the City of New York’s $1.8 billion Citywide CSO Program that addressed CSO discharges from the more than 450 CSO locations within the City. Four open water projects (East River, Jamaica Bay, Inner Harbor and Outer Harbor), and four tributary projects (Flushing Bay, Paerdegat Basin, Newtown Creek, and Jamaica Tributaries) were included in the program. The paper described the CSO facilities NYC is building and planning under this major capital planning and construction effort, and it discussed the challenges faced by the City in implementing the program. Mynhier et al. (2001) summarized the City of Atlanta’s recommendations for their Long-Term Control Plan for CSOs. The City proposed three options ranging from separating about 80 percent of the CSO service area ($1.25 billion) to solely adding large consolidated storage and treatment facilities ($710 million). The preferred option was between the two extremes, with some separation and consolidated storage and treatment facilities...
capable of treating all storm water runoff from the CSO area ($950 million). Turner et al. (2001a) reviewed the CSO technology-testing program implemented in Columbus, Georgia. Results included protocols for characterization, model calibration and watershed yield quantification. Overall program findings included load generation rates and yields for aquatic biology indices. CSO treatment demonstrations indicate high-rate compressed media filtration as a cost-effective technology that may also be applied to stormwater as an impervious area flush-control. Schenk et al. (2001b) presented an overview of the EPA’s Environmental Technology Verification (ETV) Program, with a focus on two areas of technology: flow meters and stormwater source-control devices. The Wet Weather Flow Technologies Pilot (WWF Pilot) program balances the desire for comprehensive testing (full characterization of equipment performance under a variety of water quality and facility conditions) against the need to keep testing costs reasonable.

**Disinfection.** Atasi et al. (2001c) presented the work performed by the City of Detroit Water and Sewerage Department (DWSD) that evaluated chemical disinfectants for the Baby Creek CSO water. EPA’s ETV Program developed generic protocols for the testing of mixing needs in high-rate disinfection, such as that needed for CSO treatment (Moffa et al., 2001). The ETV program is also investigating alternative disinfectants. The New York City pilot study addressed, and an ongoing WERF project is addressing, alternative technologies. As part of the ETV Program, the WWF Pilot investigated the potential of high-rate disinfection technologies for wet-weather flow applications (Schenk et al., 2001a). The benefits of using simulated flows were described, as were the potential limitations associated with applying the data to actual wet weather collection systems. Wojtenko et al. (2001c) presented the results of several major pilot-scale studies to evaluate the effectiveness of UV light to disinfect CSO flows. UV light irradiation, when correctly applied, was found to be an effective alternative to chlorination for CSO disinfection. However, the success of disinfecting with UV light seemed to be strongly dependent on water quality. Wojtenko et al. (2001d) reviewed the chapter of the EPA Capstone Report on disinfection. Locating effective alternate disinfectants has proved to be very difficult.

**High-rate clarification (including ballasted flocculation).** Jolis and Ahmad (2001) reviewed the use of high-rate clarification at the wet-weather treatment plants in San Francisco. The process was found to be highly effective for CSO pollutant removal. Suspended solids removal in excess of 80% of influent concentrations were achieved consistently. COD and BOD₅ removal exceeded 60%. Keller et al. (2001) reviewed the design of a ballasted flocculation system for the Lawrence (Kansas) WWTP. The ballasted flocculation system was used to treat excess flows from wet-weather events. The paper reviewed the jar test results, the performance of liquid versus dry polymers, and other design issues. The City of Rocky River, Ohio reduced their SSOs through expansion of the WWTP’s primary treatment capacity (Leffler and Harrington 2001). The primary-treated effluent in excess of what the secondary treatment could handle was then blended with fully-treated effluent waters prior to discharge to the receiving water. This blending allowed the overall plant effluent to meet regulatory standards with the concurrent elimination of headworks bypassing. Ballasted flocculation to improve WWTP performance during wet-weather flow periods was reviewed by Scruggs and Wallis-Lage (2001). Based on pilot and bench scale testing performed at three facilities, the ballasted flocculation technology was found to be compatible with client needs. In all cases, the ballasted flocculation system removed 75 to 95% of influent storm flow TSS at hydraulic loading rates varying from 60 to 80 gpm/sf when ferric chloride was used as the coagulant. The use of ballasted flocculation was also cost-effective at the three plants.

**Filtration.** Three western New York State treatment plants have retrofitted their existing sand filters to a coarse monomedia (Bentivogli and Smith 2001). The new media filters use less peak backwash water, have increased filter run times and have maintained the same effluent quality as the older sand filters with the smaller diameter media. Testing is ongoing for CSO treatment. The Niagara County Sewer District No. 1 Water Pollution Control Center installed monomedia filtration to increase capacity in order to treat additional flows during wet-weather events. The result is that the Sewer District has met their goal of increasing filtrating capacity and filter run times, while eliminating filter bypassing.

**Flow control in WWTP.** In Flanders, Belgium, the potential to treat additional flow in the biological system of a WWTP was investigated by Carrette et al. (2001). The concept was that higher hydraulic loadings could be treated within the biological treatment area if additional secondary clarifier volume was supplied. This operation scenario was successful and the overall pollutant discharge was significantly reduced. Chen and Beck (2001) also reported on using practical controllers to maximize the flow through the biological treatment system of a WWTP, with the result being the minimization of bypass flows. The results of the tests illustrated that the tested controllers could regulate the flows through activated sludge process sufficiently to maximize the treatment plant performance. Niemann and Orth (2001) modeled three modifications to traditional WWTPs in order to maintain a high efficiency of treatment during wet-weather flows. The three measures were increasing the nitrification volume, bypassing the primary sedimentation, and adding flocculants before secondary sedimentation. All three measures were effective.
Another approach to CSO and SSO control was to treat the effluent before it enters a receiving water. One widely-used approach to CSO and SSO control is to improve the ability of wastewater treatment plants (WWTP) to adequately treat high volume wet weather flows. The Binghamton-Johnson City Joint Sewage Treatment Plant, New York, is expanding its wastewater treatment facilities for three purposes: (1) to meet effluent limits for discharge to the Susquehanna River; (2) to increase the primary treatment capacity to treat peak storm weather flows up to 60 MGD; and (3) to increase the secondary treatment capacity to a minimum of 35 MGD. Ardigides et al. (2000) conducted a pilot-scale evaluation of biological filters that would fit within the existing site limits and allow elimination of the peak wet weather bypassing. In order to minimize CSOs to local receiving waters, the Philadelphia Water Department began a program to maximize flow treated by the existing WWTPs during periods of wet weather. As part of this effort, Ferguson et al. (2000) documented the effect of variations in influent characteristics, operational procedures, and minor physical modifications on clarifier performance. In the City of Edmonton, Alberta, Canada’s CSO Strategy, a preferred method of control was to convey more flow to the WWTP for treatment and expand treatment capacity. In order to understand and evaluate the hydraulic relationship between the upstream collection system and the WWTP, a detailed hydraulic model was developed as part of the collection system hydraulic model (Gray et al. 2000).

Kurtz et al. (2000) presented the results of pilot testing of high rate physical chemical treatment technologies in a New York City WWTP. All units performed well when operating correctly, removing between 69% and 84% of TSS on average. King County, Washington modified their continuously-operated Alki Treatment Plant to an intermittently-operated wet weather facility, and they successfully demonstrated that treatment of wet weather flows was possible after modifications to the existing primary treatment facilities (Maday et al. 2000). An analysis by Moffa et al. (2000) demonstrated that retrofitting existing wet-weather flow facilities was technically feasible in most cases (a function of site-specific conditions and treatment requirements) and may be more cost effective than construction of new conventional control and treatment facilities. A related paper by O’Connor and Goebel (2000) indicated that retrofitting processes better enabled communities to meet the U.S. EPA’s National CSO Policy and stormwater permitting program requirements. The Arlington County (Virginia) WWTP underwent a retrofit to meet a proposed mandatory ammonia and voluntary total nitrogen standard and to reduce wet-weather plant bypasses. The main components of the wet weather management plan were the new flow equalization basin, the operational flexibility in terms of the feed to the individual aeration tank passes, the flexible aerobic/anoxic swing zones and the retrofitting of the secondary clarifiers (Pitt et al. 2000c). Camp Dresser & McKee Inc. used microsand-ballasted high-rate clarification in WWF treatment for a wastewater collection and treatment system (Vick 2000). Chemically enhanced high rate separation has been shown to offer a robust treatment alternative for CSO, SSO and excess WWF at WWTPs, and will be evaluated by USEPA’s ETV Program (Zukovs et al. 2000).

Hufnagel et al. (1999) reported on the collection and analysis of data from six CSO demonstration facilities in the Rouge River watershed (Michigan) from June 1997 through September 1998, and discuss performance, operational experience, and insight gained on design of facilities from an operational perspective. Andoh et al. (1999) presented the results of testing of a novel self-cleaning CSO device at the United Kingdom National CSO Test Facility at Hoscar WWTP, Wigan, and concluded that CSO screening systems offering 4 mm two directional screening standard were significantly more efficient than 6 mm screens and might not entail any additional cost. Averill et al. (1999) described pilot-scale process development and full-scale demonstration work, and discussed considerations for the implementation of a high-rate physical-chemical treatment process that has been developed for use in satellite treatment systems to control CSO in Ontario, Canada.

The HydroSwitch consists of a control structure on a storm sewer, a diverting pipe to a receptor sewer system, a special slow control gate enclosed within a baffled inner compartment and a hinged boom trap to collect floatables. An installation in the District of Karlsruhe, Germany, moved 48% of SS and 32% of COD (Pisano, 1998). The Hiawatha CSO regional Treatment Facility in Syracuse, N.Y. demonstrated and tested vortex and storage abatement strategies with high-rate disinfection. The estimated construction cost for the 1.84 m$^3$/s (65 ft$^3$/s) CSO facility is $3.5 million or about $1.9 million/m$^3$/s ($50,000/ft$^3$/s) (Miller et al., 1998). A pilot-scale study for CSO treatment was conducted in Toronto, Ont., Can. with a CSO which had highly variable SS that settled poorly. Polymer coagulants improved solid/liquid separation efficiency and provided an effluent suspension amenable to ultraviolet (UV) disinfection (Averill and Cairns, 1998).

The NORSO operates three WPCP capable of handling 5.167 million m$^3$/d (1.365 MGD) of WWF (Debevec, 1998). An extensive flow monitoring and sampling study, including analysis of the influent and effluent BOD, SS, bacteria, NH$_3$, and seven metals at the NORSD’s Westerly CSO Treatment Facility indicated improvements are needed for inlet
hydraulic conditions and peak design loading rates should be reduced (McMasters et al., 1998).

Field and O’Connor (1997a) presented a strategy for the abatement of pollution from storm-generated SSO by maximizing flow to the WWTP, maximizing treatment capacity, and using CSO-control technology methods in addition to inflow reduction, cost-effective-sewer rehabilitation, and sewer-system inspection and associated cleanout and repair. Field and O’Connor (1997b) described a strategy to optimize CSO-control systems maximizing the use of existing system before new construction and sizing the storage volume in concert with the WWTP capacity to obtain the lowest-cost storage-treatment system.

The Actiflo® method is a compact physical-chemical water-treatment system that is being used increasingly for treating wastewater and CSO. The method uses weighted settling combined with lamella settling and typical efficiencies are: SS-85%, COD-60%, TKN-18%, total P-85% and also removes heavy metals efficiently (Plum et al., 1997). An urban stormwater-treatment system has been designed in order to obtain treated effluent satisfactory for bathing. This process combines air flotation, sand filtration, and UV disinfection (Laine et al., 1997). An alternative BMP, biodetention system was proposed and consists of a rock berm and alternating strips of native grasses and stiff grass hedges for control of stormwater quality in Austin, Tex. (Murfee et al., 1997). Treatment of urban-stormwater runoff was studied using a field-scale submerged aerobic-biological filter (SABF) system. The study showed that a SABF system may be suitable for stormwater treatment (Anderson et al., 1997).

Field et al. (1997b) discussed the application of swirl and vortex separators for the control of pollution from CSO and stormwater discharge. Design, application, and performance were presented for the U.S. EPA swirl concentrator, Storm King®, and Fluidstep™ technologies. Smith and Andoh (1997) discussed a new generation of hydrodynamic separators with an integral self-cleaning-screening system termed the Hydro Swirl-Cleanse™. This system ensures the removal of all material larger than a specified aperture size, e.g., 4 mm — 6 mm. A scaling protocol describing the residence-time characteristics of hydrodynamic separators, was discussed in terms of its importance for the removal of pollution from wastewater (Tyack and Fenner, 1997). A study evaluated various CSO-treatment technologies, e.g., vortex separator, circular clarifier, horizontal-flow-plate clarifier, and an inclined-rotary-drum screen and indicated that the vortex separator and plate clarifier are capable of 50% SS removal and 30% BOD removal (Schmidt et al., 1997).

Daligault et al. (1999) reported on two settling devices treating rainwater from urban drainage areas and equipped with secondary sludge treatment, which were monitored over a period exceeding one year. From analyses of the settled or extracted sludge it was possible to characterize the pollutants retained in the lamella settlers. To estimate the effect of enhancing settling in CSO storage basins by flocculation, a free growth and break-up model was developed and implemented by de Cock et al. (1999). Del Giudice and Hager (1999) discussed design and performance parameters for sewer sideweirs, which in a combined sewer system were used for diversion of excess discharge during rainfalls. Also discussed was the throttling pipe, which was a simple device to limit the discharge to treatment facilities. Dormoy et al. (1999) reported the results of a simulation of a WWTP with activated sludge, and concluded that it was advisable to allow for increased sludge production, O₂ requirements and also sludge quality (fermentability) when stormwater was treated. Faram and Andoh (1999) described the results of a program of numerical studies that were undertaken in order to assess and optimize the fluid-dynamic performance of a novel non-powered self-cleansing CSO screening system, the Hydro-Jet Screen™. Observations of the operation of both model and prototype scale units have indicated good qualitative correspondence with the predictions in terms of overall flow patterns, and have confirmed the superiority of the recommended design in terms of its self-flushing capabilities.

Green et al. (1999) examined the performance of constructed reed beds from a WWTP with storm treatment reed beds and another site with a combined storm and tertiary treatment reed bed. The results illustrated that sites with combined storm and tertiary treatment reed beds experienced a level of performance matching that of sites with tertiary treatment systems, with averages of 2.2 mg/L BOD₅, 3.0 mg/L TSS, 1.25 mg/L NH₄-N and 12.2 mg/L TON. Luyckx et al. (1999) compared the separating efficiency of an improved high-side weir overflow and a hydrodynamic Storm King™ separator. They show that when higher removal efficiencies were wanted, the hydrodynamic separator can technically as well as economically compete with simpler structures. The District of Columbia CSO Abatement Program included construction of a 400-MGD swirl concentrator at the outfall of the District’s Northeast Boundary combined sewer; an outfall responsible for approximately 50% of the total CSO from the District. Extensive pre- and post-construction monitoring of instream DO concentrations up and downstream of the outfall indicate that the separator has had a dramatic impact on DO concentrations downstream of the outfall; cumulative frequency analyses indicate virtually no difference in DO concentrations between the upstream and downstream meters since the swirl concentrator went online (Murphy et al., 1999).
Schindewolf et al. (1997) reported on the construction of Houston, Tex.‘s wet-weather-control facilities. The 1.2-billion dollar project includes unique wet-weather facilities that have storage, treatment, and discharge functions. Stirrup et al. (1997) of Hamilton-Wentworth, Ont., Can. plan to reduce pollution caused by CSO into Hamilton Harbor through construction of several offline detention-storage facilities and the implementation of a RTC system. Sherrill et al. (1997) presented the methodologies and results of the rating of the Detroit, Mich. collection system to both transport and store combined, which are general enough to have widespread application throughout the CSO community. The optimization of the insystem storage within the collection system, including the impact of maintenance considerations is also discussed. Portland, Oreg. began an extensive CSO program in order to meet requirements of the Oregon Department of Environmental Quality regarding the reduction of CSO. A new pipeline will convey wet-weather CSO to the City’s 300 mgd WWTP to store flows exceeding the treatment capacity during the peak wet-weather event (Williams et al., 1997). The process and monitoring for bypassing during storm events was found to be inadequate at a small WWTP in Ontario, Can. Modifications were made to the bypass lines and to other areas of the plant and the staff was trained on these modifications. Consequently, BOD loadings were reduced by 89%, SS loadings by 83% and NH₃ loadings by 93% (Hegg et al., 1997).

A CSO with a perforated screen (6mm aperture), which prevents passage of large solids, was evaluated at a WWTP with flows up to 180 L/s. Both raw and treated wastewater were used to simulate CSO at different strengths and the system was found to operate satisfactorily with no moving components (Jeffries et al., 1997). Wong (1997) described the fundamental mechanism behind continuous deflective separation (CDS) technology and outlined the potential application of the technology for pollution abatement in stormwater systems and other WWF applications.

Field and O'Connor (1996a and 1996b) discussed the design, evaluation, and application practice enhancements for swirl and vortex technologies in their dual use for flow regulation and reduction of settleable solids, as part of a CSO- and stormwater-pollution-control system. Wong et al. (1996) described development of an innovative solids filtration system from stormwater, which shows advantages over traditional gross pollutant traps and over some vortex separators as well. By utilizing the circular flow action, this system prevents the filtration screen from blockage and, unlike vortex separators, maintains its effectiveness with increasing flowrates. The system is based on a continuous deflective separation (CDS) mechanism developed by Pollutec Ltd. (now CDS, Inc.). Application of this technology can be also extended to CSO management. Advantages of a plate settler versus a conventional settling tank for management of CSO in Osaka City, Japan, were evaluated by Takayanagi et al. (1996). The plate settler achieved desired removal of SS at influent quality fluctuations, was easy to maintain, and required one-third of space required for a conventional settling tank.

A pilot study conducted by Columbus Water Works using the Storm King vortex separator projected annual SS reductions of 80% and COD of 70% at a hydraulic loading of 0.23 m³/m²/min (5.7 gal/ft²/min). At higher hydraulic loading of 0.73 m³/m²/min (18 gal/ft²/min) SS reductions of 50% were observed (Water Eng. & Mgmt., 1996).

Based on pilot test results, Briat and Delporte (1996) discussed the Densadeg lamellar separator from the Degremont Company for treatment of WWF. The Densadeg separator accomplishes optimized flocculation with the contact mass and effective lamellar settling. It is compact, flexible, and efficient and can be used either alone or in connection with a storage basin.

Averill et al.(1996) discussed interim results of a Canadian multi-agency initiative to test technologies for the treatment of CSO under realistic field conditions. A modular, automated pilot plant, composed of an elevated tank, interchangeable CSO treatment technologies, and a conventional clarifier, is located in the City of Scarborough, near Toronto, ON, Canada. The Storm King™, a vortex separator, has been the first CSO technology tested and has shown promising results to date. The data collected in this study will add to the knowledge of vortex field performance that is otherwise limited.
but necessary for a design of a full-scale facility.

Pfister (1996) discussed a laboratory study on the use of Fenton’s Reagent, which is hydrogen peroxide coupled with divalent iron salts, for treatment of CSO in existing overflow tanks. Addition of the Fenton’s Reagent to the CSO tank combines physico-chemical processes with chemical oxidation and can reduce COD by 30-50% and the bacterial content as well. Studies with real CSO are planned.

Herviou et al. (1996) presented results of a pilot-plant study with dissolved-air flotation for treatment of stormwater runoff. Dissolved-air flotation was shown to be effective for removal of SS, COD, and total hydrocarbons. This technology seems to be particularly suitable for hydrocarbon-contaminated stormwater. Also, this technology tolerates variations in the pollutant concentrations in the influent and can be used as a component of a treatment train (air flotation + filtration + UV disinfection) for the complete treatment of stormwater.

Brombach and Pisano (1996) presented results of a four-year performance evaluation of a rotary-drum-sieve filter for removal of floatables from CSO. The sieve, activated during storm events, treats the overflow of a CSO tank that serves a community of 3,000 in Birkenfeld, Germany. In four years, the sieve treated 97% of the overflow, which was 110,000 m³ of CSO, and removed gross solids effectively. Sieve maintenance was also discussed.

The use of magnetite assisted sedimentation and high-rate filtration, which combine the advantages of chemical coagulation with high-rate separation of flocculated solids, for treatment of storm-induced-sewer overflows was discussed by Booker et al. (1996).

Field and O’Connor (1996c and 1996d) presented an overview of SSO control as part of the EPA WWF research program. It was concluded that CSO technology should be considered for SSO control in addition to inflow reduction, cost-effective sewer rehabilitation, and sewer-system inspection and associated cleanout and repair.

Pujol et al. (1996) presented test results conducted in the Summer of 1995 on the Biofor® prototype (from Degremont) at the Acheres wastewater treatment plant of the Paris, France, metropolitan area. The prototype, an upflow biofiltration facility with heavy granular material, showed ability to treat high ammonia loading rates at high water velocities and to accept wet-weather conditions while maintaining good WWF performance. This process can be used in plants that accept periodic WWF.

Disinfection. Disinfection of CSO and SSO was practiced in many places. Disinfection of overflows is used to attempt to minimize the human health risks of CSO and SSO. The New York City Department of Environmental Protection performed a pilot study to evaluate the acute toxicity of CSO treated via ultraviolet irradiation (UV), chlorination/dechlorination, and chlorine dioxide. Toxicity effects observed in the treated effluents were associated with the untreated wastewater rather than the disinfection processes. Poor correlation was seen between field Microtox analyses and the off-site laboratory WET analyses (Santos et al. 2000). The Uptown Park CSO facility in Columbus, Georgia is the home of a national demonstration program for technology testing with peer review by a team of experts coordinated by the Water Environment Research Foundation (WERF). Four disinfection technologies have been examined in full-scale side-by-side comparisons to evaluate performance and operation criteria under similar CSO quality conditions. Vortex separators were used as contact chambers for three types of chemical disinfection, including sodium hypochlorite (with and without sodium bisulfite dechlorination), chlorine dioxide and peracetic acid. A compressed media filter followed by UV disinfection was also evaluated at various vortex pre-treatment levels in order to provide high quality control for the more frequent, more concentrated events. Turner et al. (2000) described methods for quantifying the statistical distribution loading on the receiving waters for a given solids removal and disinfection control scheme, and for operation of disinfection process control.

Wojtenko and Stinson (2000) provided a state-of-the-art review of the performance and effectiveness of ultraviolet (UV) light disinfection for CSO applications, and concluded that UV irradiation has potential for use in high-rate processes. As part of the expansion of 100-MGD WWTP in Wayne County, Michigan, a UV disinfection system design was provided—the largest of its type in the US. The UV system was designed to disinfect (measured using fecal coliforms) the “blended flow” from the primary and secondary treatment processes, and would be expected to provide disinfection that meets permit requirements for wet weather flows up to 175 MGD (Christeson and Fath-Azam 2000). Safety concerns and more stringent regulations regarding gaseous chlorine use have forced reconsideration of disinfection practices, with UV seen as an attractive alternative. However, varying flows pose a challenge for UV systems. Faisst et al. (2000) reported on the
implementation of UV disinfection at two coastal communities carried out in response to these challenges. Wojtenko et al. (2000) presented a state-of-the-art review of chlorine dioxide (ClO₂) for high-rate CSO disinfection. In general, ClO₂ appeared to be effective for high-rate disinfection and a suitable Cl₂ replacement. The New Orleans Sewerage and Water Board has attempted to control the odor and disinfection problems common to SSOs through the use of Nok-Out, a blend of oxidative chlorine compounds and non-charged amines. Since its inception, the use of this blend has effectively controlled both odor and disinfection problems (Austin et al. 2000). The City of Atlanta’s four westside, high-rate CSO facilities used coarse and fine screening followed by sodium hypochlorite disinfection. Disinfection optimization studies found that the CSOs exhibit a first flush, that the water quality varies throughout an event and between events, and that the CSOs are currently contact-time limited during the first flush in regards to disinfection (Richards and Gurney 2000).

One concern with using the standard methods for measuring microbial indicator concentrations in sewage before and after disinfection is that they fail to measure particle-associated microorganisms, thus underestimating the total concentrations present. A related concern is that particles and other matter in the water interfere with a disinfectant’s ability to contact and, therefore, inactivate microbes. EPA researchers presented the results of two projects which examine the effects of particle association on measurements of microbial indicator concentrations in CSOs, and determine the effectiveness of four treatment trains for CSO disinfection and the effects of removing solids on the disinfection effectiveness of chlorination and ultraviolet (UV) light irradiation (Perdek and Borst 2000a and 2000b). The USEPA has begun advocating that beach managers monitor marine water quality at bathing beaches using enterococcus, rather than the present approach which is usually use of a coliform indicator. Rex (2000) explored the potential impacts of changing from the fecal coliform indicator to the enterococcus indicator in three areas: (1) monitoring disinfection of wastewater, including CSO; (2) monitoring receiving water quality for the relationship between fecal coliform and enterococcus; and (3) monitoring changes in receiving water over time as improvements in CSO infrastructure are made. The analyses suggest that there is a potential impact on the ability of CSO facilities and wastewater treatment plants to meet new water quality standards.

Stinson et al. (1999) discussed high-rate disinfection technologies for CSO, including ultraviolet light irradiation, ozone, chlorination/dechlorination, chlorine dioxide, peracetic acid, and high-voltage electron beam irradiation. Discussions of the technologies included commercial availability and extent of use, state-of-development when not commercial, and where available, performance data and cost of either full-scale or pilot-scale installation. Also discussed was utility of increased mixing in concert with any disinfection technology. In 1996, the Vallejo Sanitation and Flood Control District (California) replaced an outdated chlorine gas disinfection system with a state-of-the-art medium pressure UV system, in combination with a liquid chemical system for use as backup during wet weather periods. Tekippe et al. (1999) reviewed VSFCD’s three-year operating history, and presented a summary of startup and post-startup problems and their resulting solutions.

Four pilot units representing three different technologies were investigated at the Hartford, Conn. WPCP to determine the disinfection ability of UV on secondary effluent, CSO flows and combined secondary and CSO flows. Based on technical, operational and cost comparison of the pilot study, the disinfection of the secondary effluent using UV radiation and sodium hypochlorite (NaOCl) for CSO was recommended (Amirhor and Roach, 1998). Four alternative disinfection technologies pilots (UV, ozone, chlorine dioxide and chlorination/dechlorination) were evaluated for the Spring Creek Auxiliary Wastewater Pollution Control Plant in NYC. All technologies provided three to four log bacterial reductions and chlorine dioxide and chlorination/dechlorination were determined to be the most cost-effective technologies for the facility (Smith et al., 1998). A full-scale CSO demonstration in Columbus, Ga. evaluated side-by-side treatment methods for removing wet-weather contaminants and disinfection by sodium hypochlorite, chlorine dioxide, peracetic acid, and medium pressure UV (Boner et al., 1998). Stinson et al. (1998) presented the applicability of four high-rate disinfection technologies for treating CSO and SSO including ozone, UV, chlorine dioxide and high-voltage electron beam irradiation.

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