Report as of FY2006 for 2006DC78B: "Wet-Weather Flow Characterization for the Rock Creek through Monitoring and Modeling"

Publications

Project 2006DC78B has resulted in no reported publications as of FY2006.

Report Follows

Wet-Weather Flow Characterization for the Rock Creek through Monitoring and Modeling

Progress Report

Prepared for
DC Water Resources Research Institute
University of the District of Columbia
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Introduction

In spite of massive public investments in sewage and drainage infrastructure, pollution loading from wet-weather flows continues to have significant impacts on receiving waters. Trends in urbanizations, increased quantities of urban wet-weather flows and corresponding increase in pollution loadings discharged to receiving waters demand that wet-weather flow control systems be planned and engineered to effect higher levels of water quality control. For future investments in drainage infrastructure to be cost-effective, decisions in wet-weather flow control systems planning must be made within a rigorous, comprehensive and systematic framework.

Similar to many older cities in the nation, the sewer system in the District of Columbia is comprised of both combined and separate sewer systems. It has recognized that these systems contribute significant pollution to the Anacostia and Potomac Rivers and Rock Creek through Combined Sewer Overflows (CSOs) and Storm Sewer discharges during wet-weather (i.e., rainfall and snowmelt) events. These overflows and associated pollutant loads can adversely impact the quality of the receiving waters. As per the District of Columbia water quality standards, the designated use of the Anacostia River, Potomac River and Rock Creek is Class A or suitable for primary contact recreation. Because the water quality in the receiving waters currently does not meet these standards much of the time, the actual use of the water body is Class B or suitable for secondary contact recreation and aquatic enjoyment. As a result, the District law prohibits primary contact recreation such as swimming in each of the receiving waters (DC WASA, 2002). To address these problems, the District of Columbia Water and Sewer Authority (WASA) has developed a Long Term Control Plan (LTCP) that provides the alternative solutions and their implementation costs.

In order to support LTCP a continuous monitoring and modeling of the watershed and drainage system is necessary not only to provide technical assessment but also to develop a cost-effective solution. In this regard, a long-term research program has been proposed at the University of the District of Columbia. The research program include capacity building for environmental research such as development of environmental simulation and modeling laboratory and water quality testing laboratory and student training in the field of environmental science and engineering. As a part of this program, it is envisioned that envisioned that a number of water quality parameters that include suspended solids, nutrients, heavy metals and other toxins, will be monitored and monitored data will be used for the development of models which ultimately support in developing effective solutions. The purpose of the proposed study is to collect information on the District drainage system, characterize runoff quality constituents, and field monitoring of runoff quality parameters and development of urban stormwater modeling systems. The modeling of urban stormwater system is developed using analytical probabilistic approach.

District of Columbia Drainage System

The sewerage system of the District of Columbia is the result of both random growth and planned development. Starting about 1810, sewer and culverts were built to drain streets and these scattered sewers gradually become linked together to form a system intended to carry storm and ground water (ASCE, 1982). Currently, the District of Columbia sewer system comprised of both combined and separate sanitary sewers. A combined sewer carries both sanitary sewage and runoff from wet weather events (i.e., rainfall and snowmelt). The combined system was built early 1900's exists in the oldest part of the city and modern practice is to build separate sewers for sewage and stormwater. Approximately one-third of the District (12,478 acres) is served by combined sewers (DCWASA, 2002).

In the combined sewer system, sewage from residential, institutional and commercial areas during dry weather conditions is conveyed to the District of Columbia Wastewater Treatment Plant at the Blue Plains, which is located in the southwestern part of the District on the east bank of Potomac River. The Blue Plain treatment plant was put into operation in 1938. At the treatment plant, the wastewater is treated to removed harmful pollutants before being discharged to the Potomac River. During wet weather events, when the capacity of combined sewer is exceeded, the excess flow, which is mixture of runoff and sewage, is discharged to the Anacostia and Potomac Rivers, Rock Creek and tributary waters through the sewer outfalls. The excess flow is called as Combined Sewer Overflow (CSOs). There are a total of 60 CSO outfalls in the combined sewer system listed in the National Pollutant Discharge Elimination System (NPDES) permit issued by the Environmental Protection Agency to WASA. The discharges from the separated storm sewer system generally directs to the river systems without any treatments. The CSOs and stomwater discharges known as urban wet weather flow or urban runoff can adversely impact the quality of the receiving waters. The pollutants in urban runoff include visible matter, suspended solids, oxygen demanding materials, nutrients, pathogenic microorganisms and toxicants such as heavy metals, pesticides and hydrocarbons. These pollutants impose considerable physical, chemical and biological stresses on the receiving waters that affect aquatic life and human health [Field et al., 1998] and impair the designated uses of water resources. Typical urban stormwater-related receiving water quality problems include the degradation of aquatic habitats, degradation in water quality during and after wet weather events, beach closures, and accelerated rates of eutrophication in lakes and estuaries, and thermal pollution [WEF, 1998].

The primary purpose of the LTCP is to control CSOs such that water quality standards are met. In order to assess the existing condition, WASA conducted study that developed the computer model of combined sewer systems, separate storm water systems. The computer models were calibrated based on the historical data and 9 to 12 months of monitored data collected in the receiving waters, combined and separated sewer systems. Table 1 presents annual CSO overflow predictions for existing conditions (WASA, 2002).

Table 1: Existing Condition Annual Average CSO Overflow Volume and Overflows

Description	*Anacostia River*	*Potomac River*	*Rock Creek*	*Total System*
CSO Overflow Volume (million gallons/yr)	2,142	1,063	48	3,254
No Phase I Controls (prior to 1991)	1,485	953	52	2,490
With Phase I Control (after 1991)				
Number of Overflow/yr	82	74	30	
No Phase I Controls (prior to 1991)	75	74	30	
With Phase I Control (after 1991)				

Characterization of Urban Runoff Quality

Assessments of urban runoff pollution problems are rarely well prescribed. Stormwater runoff from urban watersheds contains constituents that can, in some cases, occur with damaging pollutant levels. These situations and the urban areas that produce such runoff quality levels need to be identified. While information from the literature might be adequate to understand certain general issues, site-related data are often collected and analyzed to characterize the runoff pollution problem.

Urban stormwater management from a runoff quality perspective is generally related to the magnitude and frequency of pollutant mass discharges from combined sewer overflows (CSOs), stormwater discharges and runoff-induced sanitary sewer overflows to receiving waters. These discharges are intermittent in nature and often difficult to quantify. Nonetheless, documentation and characterization of site-specific runoff quality are important in developing effective stormwater management programs for the urban areas. Such a characterization includes assessment of the existing runoff pollution condition and its contribution to local water quality problems, and is followed by an analysis of future pollution conditions and the development of management options. In addition, characterization is required by many jurisdictions in the U.S. for compliance of new regulatory requirements (WEF, 1998). Therefore, most North American cities are investing significant resources in assembling and analyzing information on urban runoff in an effort to develop plans to meet the new regulatory requirements.

Runoff quality data collection and analysis are the most expensive component of an urban stormwater management study. Thus, there is a need to maximize the use of existing data so that the need for new runoff quality data can be minimized. In such cases, the information derived from the existing data is relatively more important. In many instances, the availability of continuous runoff quality data (e.g., on an event basis) is not long enough to perform reasonable statistical evaluations. Therefore, whenever a continuous data set of longer period is available, the statistical characteristics should be obtained which is useful for modeling and management of urban runoff pollution.

To assess and address urban runoff pollution problems, the characterization of runoff quality is necessary. The term characterization refers to the evaluation of statistical characteristics of measurable pollution causing variables (i.e., pollutant concentrations). From the quality perspective, urban runoff pollution is primarily influenced by the type of sewer system (i.e., separated stormwater and combined sewer systems). Accordingly, the characterization of runoff quality developed in this chapter is based on types of catchments, separated and combined systems.

Sources of Pollutants

Numerous studies on urban runoff quality conducted in different parts of the world over recent decades have proved that runoff carries relatively high concentrations of a variety of pollutants. These pollutants originate from diverse sources, both natural and anthropogenic, categorized by various boundary inputs, pollution processes and human activities that occur on the urban catchment. In addition, pollutant-generating activities are considered to be more prevalent on impervious areas than on pervious areas. The understanding of pollution sources is important for both the prediction and the control of pollutant loads. Common sources of urban runoff pollution include dry and wet atmospheric deposition; accumulation of street refuse including litter, street dirt, and organic residues, vehicular traffic emissions; vegetation; accidental spills; urban area erosion; and road deicing chemicals. One of the principal sources of pollutant accumulation in urban areas is dry and wet atmospheric deposition, which is considered as a boundary input caused by local or distant air pollution sources. In most cities, the deposition rate of atmospheric particulate matter is higher in the congested downtown core and industrial areas than rates in residential and suburban areas. Wet and dry fallout rates range from 7 to more than 30 tonnes/km^2-month (Novotny and Olem, 1994).

Dry deposition results from the turbulent and gravitational transfer of pollutants from the air to the underlying surface, unaccompanied by atmospheric precipitation (Hicks, 1997). A study of the chemical composition of particulate matter and aerosols over Edmonton, Alberta (Klemm and Grey, 1982) concluded that industrial emissions and transport are the major sources of dry deposition from the atmosphere. Atmospheric particulate matter is composed of aerosols and larger particles in the form of dust, soot, ash, fiber and pollen. The Edmonton study reported that the water soluble portion of collected urban air samples of total suspended particulates contained pollutants such as lead, nickel, chromium, cadmium, zinc, sulfate, nitrate and ammonium. The origin of atmospheric pollutants is attributed to sources such as construction sites, paved and unpaved areas, roads, landfills, tailing piles, industrial sources, fuel combustion from stationary and transportation sources, waste incineration, etc. A study (Hilborn and Still, 1990) of U.S. data indicated that the amounts and sources of toxic air pollutants can vary geographically from city to city and from neighborhood to neighborhood. Moreover, toxic air pollution is strongly influenced by local widespread sources, such as motor vehicles, wood stoves, combustion of oil and gas, metallurgical industries, chemical production and manufacturing, gasoline marketing, solvent use and waste oil disposal.

Wet deposition is a result of cloud processes that scavenge pollutants from the air at cloud altitudes and deposit them in falling rain, snow, and so on (Hicks, 1997). Studies on pollutant mass loading in precipitation and runoff have concluded that most of the atmospheric contaminants are washed out during the early stages of a rainfall event (Randall et al., 1982). Furthermore, the washout of atmospheric pollutants by rainfall droplets is effective and may contribute to a first-flush effect, indicating that pollutant concentrations in the earlier part of a precipitation event are higher than in the latter rainfall (Novotny et al., 1985). Urban rainfall is generally acidic in nature with pH values less than 5, which can cause damage to structures such as pavements, sewers and buildings. The atmospheric deposition of nitrogen compounds, trace metals, and organic compounds has caused substantial effects on water quality in the Chespeake Bay area (Hicks, 1997). An example of typical atmospheric loadings in urban catchments is presented in Table 1 in the form of reported mean values.

Table 1: Atmospheric loading in urban catchments

Pollutant	Total Deposition Rate (g / m^2-yr)	Wet Deposition Concentration (mg/L)	Snowmelt Concentration (mg/L)	Contribution to Runoff (%)
Total suspended solids	8.4 - 36.2	5 – 70	263 – 690	10 - 25
Chemical oxygen demand	0.44 - 31.6	8 – 27	15 – 25	15 – 30
Sulfates	6 – 15	4.8 - 46.1		31 – 100
Phosphorus	0.021 - 0.20	0.02 - 0.37		17 – 140 (sic)
Nitrate-nitrogen	1.8 - 8.2	0.5 - 4.4	4.1 - 5.7	30 - 94
Lead	0.04 - 4.0	0.03 - 0.12	0.3 - 0.12	15 - 54
Zinc	0.1 - 1.3	0.05 - 0.38	0.35 - 0.41	20 - 62

Source: After Ellis (1986)

Street refuse accumulation is characterized by locally generated particles of various sizes on the street surfaces. Typically, the fraction of street refuse passing a 3mm (1/8-inch) sieve is referred as ‘dust and dirt’. In general, most of the accumulation of street refuse occurs within one meter of the curb, and hence the accumulation is often expressed as mass per unit of curb length. Particle sizes greater than dust and dirt are considered as litter deposits. The general litter deposits in urban areas include debris, solid wastes deposited on surfaces, paper and plastic products, building materials, vegetation, dead animals, and animal excreta, so on. The street dirt particles include disintegrated parts of larger litter particles, pavement deterioration particles, soil particles and small organisms.

Vegetation inputs including fallen leaves, seeds, grass clippings, and other vegetation residues contribute significant quantities of dust and dirt in urban areas. The rate of vegetation input increases substantially during the fall season depending on the density of vegetation. A study conducted in Etobicoke, in the Greater Toronto Area (GTA), showed that a significant amount of organic load originates from autumn leaves in an urban area (James and Boregowda, 1986). The presence of phosphorus in runoff is commonly attributed to its leaching from vegetation in addition to plant fertilizers. For example, the potential phosphorus content of tree leaves and seeds is reported to range from 1.6 to 11 mg/g (Waller and Hart, 1986).

Vehicular traffic constitutes a major source of pollutants in urban areas. It contributes to solids (including fine particles) and many chemicals including heavy metals, polycyclic aromatic hydrocarbons (PAHs) and deicing salts (Thomson et al., 1997). These pollutants originate from vehicle exhaust pipe emissions, vehicle operation, tire wear, solids carried on tires and vehicle bodies, and the abrasion and corrosion of highway structures. The more important sources of PAHs are from oil leakage of vehicle crankcases and exhaust pipe emissions. Furthermore, pavement conditions also have an effect on pollutant loads. Sartor et al. (1974), reported that streets paved with asphalt could have a loading about 80% higher than streets paved with concrete. A study (Berbee et al., 1999) on the characterization of highway runoff in the Netherlands indicated that the concentration of pollutants in runoff from impervious asphalt is significantly higher than in runoff from pervious asphalt.

In snow-belt areas, deicing salts and sand are applied to road surfaces and side walks to provide safe driving and walking conditions during the winter season. The applied salt potentially increases the chloride content of the runoff. As an example, the citywide salt application rates in Halifax, Nova Scotia contribute to an annual average chloride loading in runoff at the order of 3,000 kg/ha-yr. The median chloride concentration in winter grab samples of runoff increased to as much as 786 mg/L, while the mean summer concentration in runoff is reported at 14 mg/L, which is higher than the concentration of 4.6 mg/L recorded in total atmospheric deposition at Halifax (Waller and Hart, 1986).

Pervious urban areas are generally considered to be well protected by vegetation and they contribute pollutants such as pesticides and herbicides during larger rainfall events. However, erosion of soil from construction sites, vacant lands and suburban agricultural lands may contribute significant amount of solids and sediments, which further degrade the runoff quality.

Urban Runoff Quality Constituents

The quality constituents of typical concern in urban runoff are visible matter, suspended solids, oxygen-demanding materials, nutrients, pathogenic microorganisms, and toxicants such as heavy metals, pesticides, and petroleum hydrocarbons (Field et al., 1998). These constituents can cause substantial impacts in terms of physical, chemical and biological stresses on receiving waters, resulting in ecological and environmental imbalance (Ellis and Hvitved-Jacobsen, 1996; Field et al., 1998; and Marsalek, 1998). Moreover, these impacts depend on the characteristics of both the catchment producing such discharges (in terms of runoff quantity and quality) and those of receiving waters. Hence, to protect the receiving water, the actual impacts should be evaluated in terms of specific characteristics of each site, including physical habitat alternation (e.g., change in morphology), water quality changes (e.g., dissolved oxygen depletion, and eutrophication), sediment and toxic pollutant impacts, impacts on biological communities, and ground water impacts (Ellis and Hvitved-Jacobsen, 1996).

To assess these impacts of stormwater discharges on receiving water quality, it is necessary to understand the effects of classes of pollutants independently as well as the combined effects of various pollutants. In the former case, the effects are understood to a reasonable extent; however, in the latter case, the combined effect of the entire range of different classes of pollutants is not well understood. To restore, maintain and enhance the physical, chemical and biological quality of receiving waters, the premise of urban runoff quality control analysis should focus on understanding the sources, types of pollutants from stormwater discharges and combined sewer overflows, their potential effects on receiving water bodies, and their control alternatives. The sources or origins of various pollutants found in urban runoff are described in the previous section, while the following section focuses on the types of pollutants and their effect on receiving water bodies.

Solids

The most common pollutants in stormwater are organic and inorganic solids in the form of particulate or colloidal matter. These solids are either eroded from pervious surfaces or washed off the paved surfaces by stormwater. In addition, drainage systems supply a significant amount of solids, which are accumulated on the bottom of sewers, and from the slime growth on the walls of the sewers during dry periods (Novotny and Olem, 1994). The solids content in runoff is measured as total solids, suspended solids, dissolved solids, and volatile solids as well as by turbidity [definitions of which may be found in Standard Methods, (Clesceri, et al., 1998)].

Suspended solids cause a number of direct and indirect environmental impacts such as increased turbidity, abrasion of fish gills and other sensitive tissues, reduction of visibility, transport of pollutants, loss of riparian vegetation with the concomitant loss of shade and refuge, decrease in sunlight penetration (interference with photosynthesis), and degradation of spawning areas. Suspended solids usually carry considerable quantities of other pollutants sorbed to their surfaces (Randall et al., 1986). Pollutants that are believed to have a particularly high affinity of adsorption on suspended solids include phosphorus, metals, and petroleum based organics. The effective means of removing suspended solids from stormwater are sedimentation and other forms of physical separation. In addition, the removal of suspended solids from stormwater may significantly improve the water quality because of simultaneous removal of the other pollutants with suspended solids. Typically, combined sewer overflows contain a higher suspended solids concentration than stormwater discharges (Moffa, 1990).

Nutrients

Urban runoff may contain significant concentrations of nitrogen, phosphorus and carbon compounds which accelerate the nutrient enrichment and eutrophication of receiving waters. These substances are essential for the growth of aquatic plants and are regarded as biostimulants. The source of nutrients is attributed to leaching of vegetation, agricultural fertilizers in runoff and municipal wastewater discharges. Nitrogen in the form of ammonia and nitrates and phosphorus occurring as orthophosphates are readily available for plant growth, possibly leading to algal blooms and excessive macrophytic growth and causing depletion of dissolved oxygen upon death and decay. Common measures of nutrients are total nitrogen, nitrates, ammonia, total Kjeldahl nitrogen (TKN), total phosphorus, total organic carbon, and indirectly, alga mass and chlorophyll a. (Wanielista and Yousef, 1993).

Oxygen Demanding Matter

Sufficient levels of dissolved oxygen (DO) in the water column are necessary to maintain aerobic conditions to support aquatic life. The influx of stormwater containing organic and other oxidizable matter may exert substantial oxygen demand on the water column impairing the water quality by depleting DO level. These impacts are estimated either by direct measurement of DO or by the indirect measures of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC). Typically CSOs contain higher levels of oxygen demanding substances relative to storm discharges.

Microbiological Pollutants

Both CSOs and stormwater discharges can be significant sources of microbiological pollution in receiving waters. Microbiological pollutants are typically described by organism counts per unit volume of water and include indicator bacteria, such as Escherichia coli, fecal coliforms, fecal streptococci and specific pathogens such as Shigella, Salmonella and Clostridium. These pollutants enter the drainage system from the washoff of animal feces and organic matter from catchment surfaces. Bacteria may also enter the drainage system through illegal sanitary sewer connections. Concentrations of indicator bacteria, such as E. coli and fecal coliforms, in CSOs and stormwater are often found in magnitudes well exceeding recreational water quality guidelines. Thus, recreational beaches in urban areas are frequently closed during and immediately after rainfall events because of fecal bacteria contamination caused by stormwater and CSOs. By definition, pathogenic bacteria and viruses may seriously affect human health. The removal of such microbiological pollutants is achieved primarily through the processes of biological decay, ultraviolet radiation and artificial disinfection where practiced.

Toxic Constituents and Priority Pollutants

Studies in the United States, Canada and Europe indicate that heavy metals are the most prevalent toxic contaminant found in urban runoff (U.S. EPA, 1983a, Marsalek et al., 1997). Commonly found heavy metals are arsenic, cadmium, copper, iron, mercury, lead, selenium and zinc. The primary sources of heavy metals are traffic-related activities and atmospheric fall out. Unlike some organic compounds, heavy metals are not degraded in the environment and are toxic when present beyond a threshold concentration.

Deterioration of receiving water quality is also caused by the presence of elevated levels of toxic constituents in urban runoff commonly known as priority pollutants. The priority pollutants are a group of 129 toxic chemicals or classes of chemicals identified as substances of serious concern in the Clean Water Act of U.S. (Terstriep et al., 1986). The pollutants fall into ten groups: pesticides, metals and inorganic, PCBs (polychlorinated biphenyls), halogeneted aliphatics, ethers, monocyclic aromatics, phenols and creosols, phthalate esters, PAHs, nitrosamines and nitrogen-containing compounds. Comprehensive investigations of toxic constituents and priority pollutants were conducted under the U.S. Nationwide Urban Runoff Program (NURP) (U.S. EPA, 1983a). Further studies conducted in the U.S. and Canada indicate that these priority pollutants are frequently detected in highway runoff (Sansalone and Buchberger, 1997; Marsalek et al., 1997).

The impacts of priority pollutants are evaluated on the basis of toxicity effects. Toxic pollutants have been characterized by acute or chronic effects on the environment (U.S. EPA, 1983b; Harremoes, 1988). Acute effects are characterized by relatively high concentrations of pollutants within a relatively short time causing immediate physiological impacts such as in the ingestion of heavy metal laden water, while chronic effects are characterized by the cumulative impact of gradual exposure to relatively low concentrations of pollutants that accumulate in the tissues of organisms over long periods of time.

To evaluate the ecological impacts of these constituents in stormwater, water quality standards are defined in terms of their degree of toxicity. The permissible frequency and duration of exposure to conventional and priority pollutants (water quality standards) as suggested by the U.S. EPA are (Novotny, 1997):

- Acute toxicity criteria: 1-h average concentration (essentially a daily grab sample) not to be exceeded more than once in three years on an average.
- Chronic toxicity criteria: 4-day average concentration, not to be exceeded more than once in three years on an average.

It is generally recognized that a large percentage of heavy metals and toxic contaminants have a high affinity for the suspended sediments present in runoff. This association is fortuitous in terms of control and treatment of runoff since it is relatively easy to separate suspended solids and the pollutants attached to them.

Other Parameters

In listing the runoff quality parameters of concern, physical parameters such as gross solids, turbidity, temperature, pH and electrical conductivity are also considered. The presence of dispersed and floatable materials along the shores of beaches or embankments deteriorates the aesthetic value of water bodies.

Temperature is an important parameter because urban surfaces may increase the temperature of runoff by as much as 100C compared to runoff from undeveloped areas (Marsalek, 1998). This thermal enrichment can influence the physiological processes of aquatic organisms such that original cold-water fisheries may become warm-water fisheries over time. The increase in temperature also decreases the water's capacity to dissolve oxygen. In addition, the rise in temperature increases the rate at which nutrients attached to solid particles are converted into readily available soluble forms (Hall, 1984). Urban runoff also conveys large amounts of chlorides originating from road salting during winter. The primary physical environmental effects of elevated chlorides are high discharges of dissolved solids and the establishment of density gradients in receiving waters, especially lakes (Waller and Hart, 1986). The presence and amount of chloride ions is measured by the electrical conductivity of the sample.

Characteristics of Runoff Quality Constituents

The analysis of urban stormwater quality problems requires an understanding of the characteristics of runoff pollutants and the nature of receiving waters. As described in the previous section, different types of pollutants have different types of impacts on receiving waters, and they operate on different temporal and spatial scales. The time scale of the pollutant effects on the receiving water is influenced by the characteristics of various pollutants.

The time scale of concern ranges from a few hours to a few years. Figure 1 illustrates the time scale of different categories of runoff pollutants. For example, water-borne pathogens may die away relatively quickly in receiving waters; thus, the time scale of interest in this case is relatively short (e.g., on the order of several hours or days). In this case, interest would lie in the low frequency overflow events, causing high concentrations of pathogens. Short-term effects are associated with bacteria, biodegradable organic matter and hydraulic effects. In contrast, plant nutrients such as phosphorus influence long-term effects related to eutrophication, causing interest in relatively long time scales (e.g., on the order of several years). Interest would lie more in the average annual mass discharges to the receiver. Long-term effects tend to be associated with suspended solids, nutrients and heavy metals. In still other cases, such as certain type of hazardous contaminants, both the long and short time scales would be of concern. Typically, the short time scale problem of acute toxicity and long time scale problem of toxic contaminant accumulation and chronic toxicity would cause interest in both the low frequency, high concentration overflow events and the average annual mass discharges to the receiving waters.

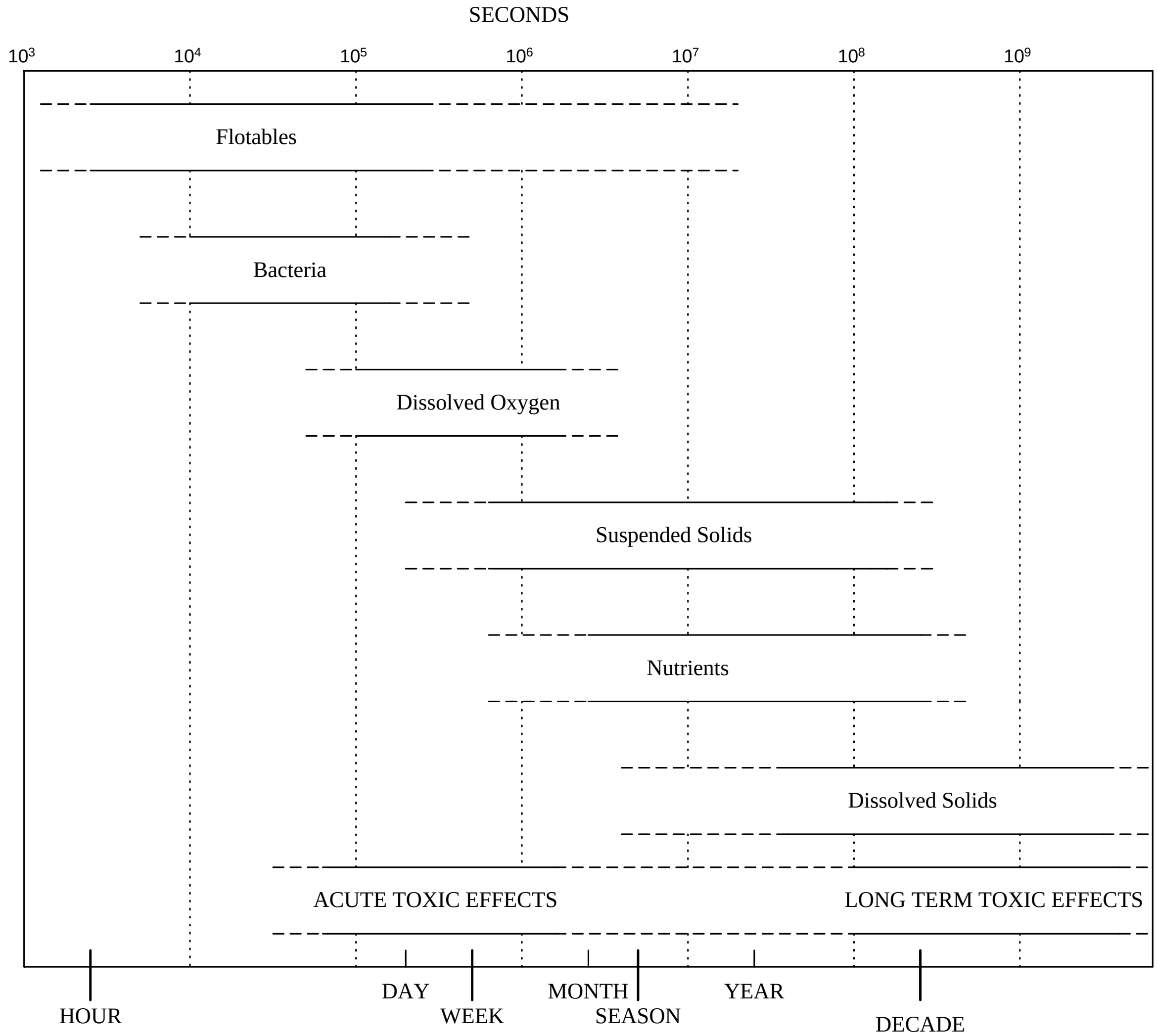

Figure 1: Time scale effects of runoff quality constituents (after U.S. EPA, 1979)

The spatial scale ranges from the localized receiving water to waters that are hundreds of kilometers from the sources. For instance, bacterial contamination generally occurs in a localized area (e.g., beach closures), while some toxic substances such as pesticides, persistent organics and heavy metals, which are viewed on the longer time scale, tend to be persistent (i.e., they do not readily decay in environment) over hundred of miles (U.S. EPA, 1979). The relevancy of characteristics of pollutants found in urban runoff is an important consideration in receiving water analysis.

To effectively address the water quality problems arising from urban runoff, the quantitative aspects of runoff quality, in particular the acquisition of data and analysis of data is important. Recent advances in water quantity and quality monitoring technologies gradually provide cost-effective means of collecting large amounts of information for complex water quality problems. Technological advances in water quality data analysis, however, have lagged, particularly for converting raw data into information, which can support decision-making on a regular basis (Hughes and Kummler, 1998). Therefore, intelligent decisions about the runoff quality management can be made easier when the appropriate data analysis methodologies are developed to derive information in suitable forms that would be useful.

Monitoring Runoff Quality at the Rock Creek

Monitoring and modeling are two essential components of implementing CSO Control policy (EPA, 1999). A planned development and implementation of a monitoring and modeling effort will support the selection and implementation of cost-effective CSO controls and an assessment of their improvements on receiving water quality.

Rock Creek, a tributary of the Potomac River is primarily an urban stream. The watershed for the creek covers part of Montgomery County (approximately 60 mi^2) and part of the District of Columbia (approximately 16 mi^2). The total length of the Rock Creek (in Maryland and Washington DC) is approximately 33 mi of meandering stream. The Creek flows from its source near Laytonsville, Maryland to the Potomac River in Washington DC. Water quality in Rock Creek is important to biotic life in and near the creek, and in the Potomac River Basin and the Chesapeake Bay (USGS, 2000). The water quality of the Rock Creek has been affected by urbanization and agricultural growth in the watershed.

In the long-term monitoring program, it is envisioned that a number of water quality parameters that include suspended solids, nutrients, heavy metals and other toxins, will be monitored. Total Suspended Solids (TSS) has been considered as an indicator pollutant and typically used for stormwater modeling. It is also envisioned that TSS will be continuously monitored at various representative sites of Anacostia and Potomac Rivers and Rock Creek and the monitored data will be used for the development of integrated drainage system and receiving water system models. The monitored data will be analyzed in the environmental laboratory of the University.

The scope of this present research is limited to field monitoring of Dissolved Oxygen at several locations within the Rock Creek nearer to University of the District of Columbia. The data presented in this report were collected from three locations along the Rock Creek in the fall and spring season of 2006-2007. The monitoring was conducted in November 2006 to represent fall season and in March 2007 to represent spring season.

Figures 2 presents the location of three sampling stations along the Rock Creek within the Washing DC.

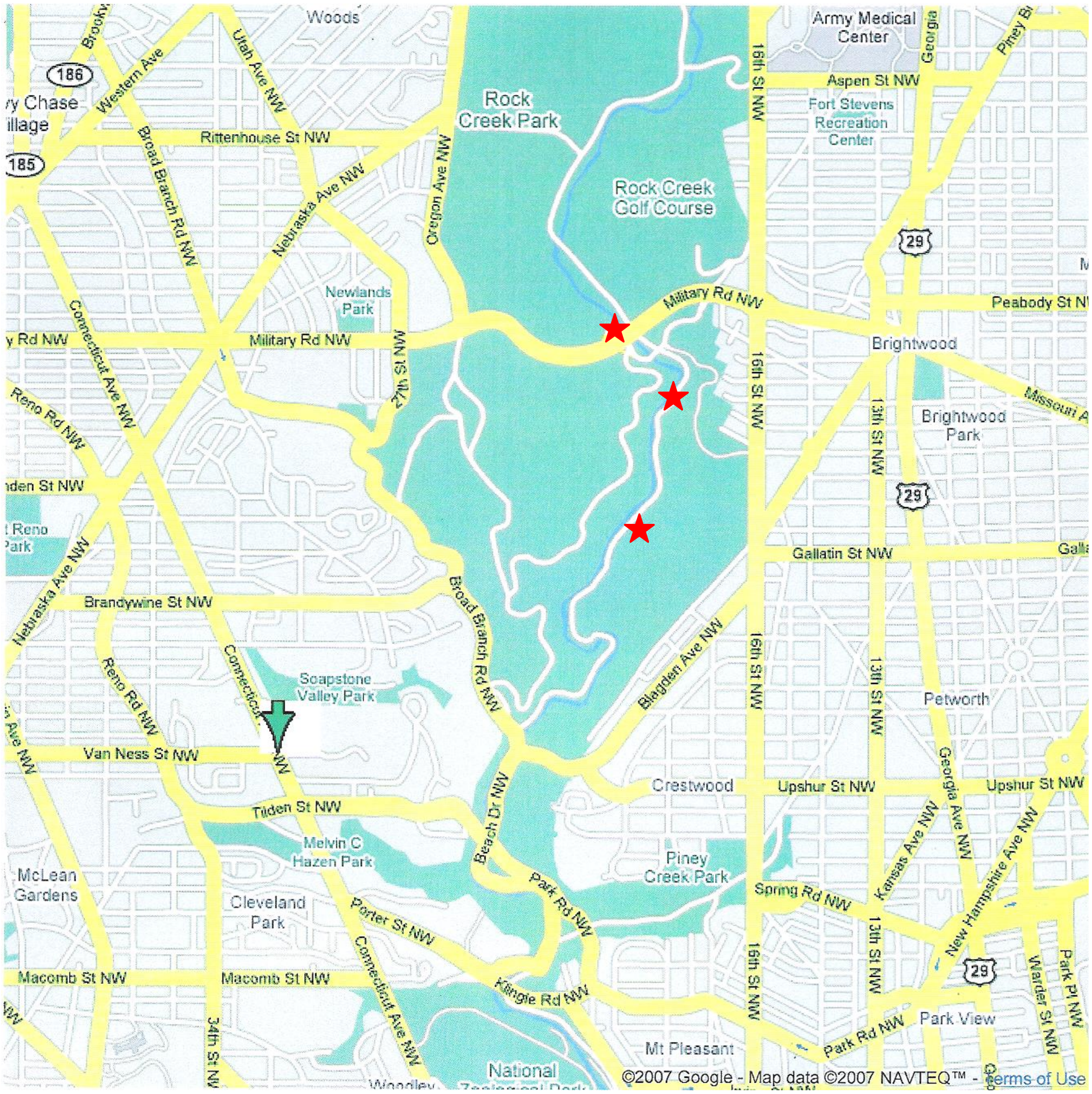

Figure 2: Locations of DO sampling stations

Dissolved Oxygen was measured at the three locations using a calibrated Oakton RS232 Dissolved Oxygen meter. Two undergraduate engineering student interns were trained to take the field measurements. The three locations include at the upstream of Military Road bridge crossing, nearer to police head quarter and third location is 0.5 miles south of Military Road bridge crossing.

Figures 2 to 4 presents the location of three sampling stations.

Figure 2: Station 1 – Located near to Police Head Quarter

Figure 3: Station 2 – Located upstream of a Military Road bridge crossing

Figure 4: Station 3 – Located south of Military Road bridge crossing

Table 2 through 4 present the measured DO data for three locations for fall and spring seasons.

Table 2 - Station 1: Near Police Head Quarter

Season	Date	Temperature (^oC)	Dissolved Oxygen (mg/L)
Fall	11/1/2006	13.7	16.2
	11/13/2006	14.5	9.8
	11/15/2006	12.8	11.2
	11/20/2006	7.8	13.1
	11/27/2006	11.5	11.6
Spring	3/1/2007	5.9	16.2
	3/5/2007	9.2	13.7
	3/6/2007	3.3	17.2
	3/9/2007	9.9	14.0
	3/12/2007	11.8	14.1
	3/13/2007	12.6	14.8
	3/15/2007	16.0	13.4
	3/19/2007	12.4	13.0
	3/20/2007	15.4	12.8
	3/23/2007	18.5	13.6
	3/26/2007	15.5	16.3
	3/27/2007	19.1	16.0
	3/29/2007	15.8	16.9

Table 2 - Station 2: Upstream of a Military Road bridge crossing

Season	Date	Temperature (^{o}C)	Dissolved Oxygen (mg/L)
Fall	11/1/2006	18.2	11.4
	11/13/2006	10.9	10.3
	11/20/2006	8.3	12.7
	11/27/2006	8.2	13.2
Spring	3/1/2007	5.2	15.8
	3/5/2007	7.4	14.8
	3/6/2007	4.7	16.5
	3/9/2007	4.7	14.0
	3/12/2007	9.6	15.2
	3/13/2007	12.4	15.2
	3/15/2007	14.2	14.3
	3/19/2007	8.6	14.9
	3/20/2007	12.8	14.1
	3/23/2007	17.1	13.5
	3/26/2007	14.4	17.0
	3/27/2007	19.1	16.0
	3/29/2007	16.0	17.6

Table 3 - Station 1: 0.5 mile south of Military Road bridge crossing

Season	Date	Temperature (^{o}C)	Dissolved Oxygen (mg/L)
Fall	11/1/2006	10.7	12.4
	11/13/2006	14.3	10.6
	11/20/2006	7.9	14.2
	11/27/2006	9.7	13.3
Spring	3/1/2007	5.2	16.4
	3/5/2007	7.8	14.9
	3/6/2007	3.1	17.8
	3/9/2007	9.9	14.0
	3/12/2007	10.7	15.4
	3/13/2007	13.1	14.7
	3/15/2007	14.4	14.6
	3/19/2007	7.9	15.6
	3/20/2007	12.9	14.1
	3/23/2007	16.8	13.3
	3/26/2007	13.9	15.9
	3/27/2007	19.6	14.6
	3/29/2007	15.8	16.9

The average temperature for the fall 2006 was 11.4 ^{o}C and for the spring 2007 was 12 ^{o}C. Table 5 presents the mean and standard deviation of DO at the three locations.

Table 5: Mean and Standard Deviation of DO at three locations

Season	Station 1		Station 2		Station 3	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Fall 2006	12.4	2.43	11.9	1.31	12.6	1.54
Spring 2007	14.6	1.55	15.3	1.24	15.2	1.26

The measurement of Dissolved Oxygen at the Rock Creek reveals that there is no evidence of low dissolved oxygen problems around the measured locations. The stream is naturally aerated by turbulence as it flows over the irregular channel bottom. It is free-flowing stream which provides relatively short residence time to wet weather pollution.

Modeling of Urban Stormwater Management

The analysis of urban catchment systems is prerequisite to the planning and design of stormwater management, which not only allows the assessment of existing conditions but also helps to understand the behavior of the system under various design conditions. In addition, the analysis with economic functions assists in determining appropriate cost-effective control measures.

Urban catchment systems are subjected to rainfall input - a random phenomenon. Therefore, the hydrologic, hydraulic and pollutant processes that govern the system are complex in nature. The system variables and process parameters also vary temporally and spatially and, as a result, the analysis of such systems is generally performed on simplified representations based on various assumptions that may or may not sufficiently represent the underlying processes for planning purposes. Often these representations use mathematical relationships intended to imitate the pertinent processes. Because these representations are not perfect, verification and validation is required for their regular use in similar situations. Verification is the adjustment of model parameters to replicate the measured condition and validation is confirmation of verification for a wide range of conditions. The model can be used to understand the system behavior (i.e., how the model output changes realistically as input to the model is varied).

A range of stormwater models, from simple to comprehensive, exists for the analysis of urban catchment systems. Models that provide greater levels of accuracy are complex, comprehensive models and include a heavy computational burden. Therefore, while selecting a model for the analysis, a balance must be struck between the accuracy and simplicity of the model, wherein this balance is dependent on the analysis objectives of the required model (Adams and Papa, 2000).

As is noted, the models are based on simplifications, and cannot provide a precise representation of physical reality under all conditions; however, they should provide reasonable solutions for the intended problems. Therefore, the system analyst should be aware of the assumptions on which the model is formulated and the limitations of the modeling exercise. Beyond these limitations, models provide the analyst an economical advantage over their prototypes because models render performance analysis of the system for the full range of conditions to which the prototype might be subjected.

In urban stormwater quantity and quality analysis, only monitoring theoretically can provide the ideal long-term information required for planning and design of systems (Nix et al., 1983). But, being cost prohibitive, monitoring over a realistic limited time frame cannot directly provide, a priori, the information needed to characterize the long-term behavior of a wide range of future designs. Therefore, it is essential to have properly formulated and validated models which can predict system behavior for analysis and design.

Urban stormwater models are developed in a mathematically descriptive mode to simulate the system or in a predictive mode to evaluate control performance before implementing the expensive measures in the field. These models and their mathematical equations - are defined by:

- System input such as rainfall and temperature;
- System output such as runoff volume, infiltration, runoff rate and pollutant load;
- System parameters of the urban catchment system such as runoff coefficient, depression storage, pollutant buildup and washoff coefficients;
- The control or decision variables such as design storage volumes and outflow rates.

Models describing stormwater management systems are classified in many ways, including the level of detail they provide, the type of approach they adopt and the time frame of analysis. Generally, based on their analysis timeframe, models fall into two categories: (i) event-based models and (ii) continuous simulation models. Each type of model has advantages and disadvantages.

Traditionally, runoff quantity control problems have been dominant in the urban stormwater management, and the design of quantity control systems was accomplished with event-based models. In this approach, an analysis is performed to select a design storm of a specified duration and frequency from a historical rainfall record or from synthetically generated rainfall patterns, and used to estimate runoff peaks and volumes. A commonly used event-based model is, for instance, the “rational method”. This approach ignores the effects of successive events on the analysis; therefore, it is not suitable for estimating the average long-term performance of the system. This approach is not suitable for runoff quality analysis, which is strongly influenced by more frequent and smaller rainfall events and which requires long-term analysis. In addition, a fundamental assumption of assigning a unique frequency to a natural hydrologic event and assigning this same frequency to both input and system output are questionable (Adams and Papa, 2000). Although event-based approaches have been employed in urban runoff control planning for many years, the current direction is towards the application of continuous simulation and probabilistic models for the long-term performance analysis of urban systems.

Continuous simulation modeling is currently considered to be the most sophisticated approach to stormwater modeling. It is a form of deterministic modeling of the physical system that not only considers the properties of a storm but also evaluates the impacts of closely-spaced successive storms. This approach is considered continuous because it uses long-term rainfall records as inputs to produce a continuous time series of output variables and continuously updates soil moisture etc. The statistics of the time series of output variables are then used for predicting the performance of the system. Continuous simulation can provide additional information such as the quality of runoff and pollutant loads as they can track the antecedent conditions, preceding pollutant buildup and storage conditions. However, these models are both data computation, and resource intensive and require elaborate calibrations. They are usually preferred in the detailed design analysis phase of engineering studies. In terms of rigor of the modeling approach, some are less intensive, such as STORM (U.S. Army Corps of Engineers, 1974) and the HSPF (Hydrologic Simulation Program- FORTRAN) (Johanson et al., 1984). The more rigorous and comprehensive continuous simulation models include the U.S. EPA's Storm Water Management Model, SWMM (Huber and Dickinson, 1988), and the Quantity-Quality Simulator, or QQS, (Geiger and Dorsch, 1980).

An alternative to continuous simulation is to model the system by the analytical probabilistic modeling approach. The basic premise for both the continuous simulation and analytical modeling approach remains same - long-term meteorology is the input to the model. Continuous simulation attempts to predict the system response of the output variable (i.e., dependent variable) time series in the sequence that would occur from the input time series (historical or synthetically derived rainfall), and post-processed statistical analysis provides the average, and/or long-term performance of an output variable. The analytical probabilistic approach fits probability distributions to the rainfall characteristics (e.g., rainfall event volume, durations, intensity and interevent times) determined from the same rainfall record otherwise used for continuous simulation. These fitted probability distribution functions (PDFs) are used to represent the independent variables and the parameters of the PDFs constitute the input to the model. The deterministic functional relationships (e.g., hydrologic and hydraulic processes) between the independent and dependent variables of continuous simulation models constitute the transformation function of the analytical probabilistic models, albeit, in a simplified manner. Using derived probability distribution theory (Benjamin and Cornell, 1970), the PDFs of the dependent variables are derived from those of the independent variables and the transformation functions. Often closed-form solutions of the dependent variable PDFs, which depict the system performance measures in terms of the independent variables, are obtained. The relative modeling agreement between the analytical and the continuous simulation approaches may be attributed to how well the PDFs of the input variables are hypothesized and the transformation functions are simplified and other things.

Since the PDFs of meteorological inputs are derived from the statistical analysis of long-term rainfall records, the mathematically derived PDFs of system outputs reflect the long-term performance of the drainage system under analysis (Papa et al., 1998). This method is intended to approximate continuous simulation modeling and is recommended for preliminary planning and design because of its computational efficiency. Furthermore, the closed-form mathematical equations can be easily incorporated into an optimization framework for system analysis. A recognized limitation of this approach is the simplified representation of urban drainage systems.

In the last decade, researchers have been developing a family of analytical probabilistic models and planning methodologies for analyzing the various aspects of urban stormwater management planning. These models are based on different hydrological representations, which range from simple such as STORM-type hydrology to complex such as SWMM-type hydrology. As an added contribution, analytical probabilistic models and planning methodologies developed in this thesis are intended for analyzing and controlling runoff pollution in urban catchments. The models proposed in this research are intended to be used for screening and planning level analysis to provide immediate insight into the magnitude of stormwater quality problems and to provide preliminary cost-effective designs of quality control alternatives. In the following section, a brief review of existing analytical probabilistic urban stormwater models is presented.

Analytical Probabilistic Stormwater Models

Benjamin and Cornell (1970) outlined the derived distribution theory and its applications to civil engineering problems in their classic textbook Probability, Statistics and Decisions for Civil Engineers. The theory permits the derivation of the probabilistic characteristics of a system output from the probabilistic characteristics of system input(s) and the knowledge of relationship between system input and output. As described in the previous section, the application of this theory to hydrological and urban water resources problems has culminated with the development of a set of analytical probabilistic models for urban stormwater management planning which can be used either as a parallel approach to continuous simulation modeling, or as a complementary aid to continuous simulation. In this research, the models developed on the basis of the derived probability distribution approach are referred as analytical probabilistic models, or analytical models, or derived probability models. The remainder of this section briefly reviews the development and application of analytical models in urban stormwater analyses.

Eagleson (1972) first applied the derived probability distribution theory to water resources engineering through hydrological problems. Eagleson (1972) derived the frequency of peak streamflow rates from a catchment from the exponential PDFs of climatic variables that included rainfall event average intensity, event duration and interevent time. The derived relationship between dependent and independent variables established the theoretical basis for estimating peak flood flow frequency in the absence of streamflow records and provided the insight of the effects of land use and climatic changes on flood frequency.

Howard (1976) applied the derived probability distribution theory to analyze the control performance of storage-treatment systems; which not only introduced the theory of storage in the analysis of urban drainage systems but also paved the way for further research. The probability distribution of spill volumes from a storage reservoir was derived from the joint PDFs of rainfall event volume and interevent time assuming that the reservoir is full at the end of the previous rainfall event. In the derivation, it is assumed that the rainfall events occur instantaneously. Following the pioneering work of Howard, a number of research studies were conducted at the University of Toronto, which improved substantially on the initial development.

Smith (1980) improved the Howard model by incorporating the steady-state probability distribution of reservoir contents at the end of the last storm. The derivation was based on the joint PDFs of three rainfall characteristics - event volume, duration and interevent time. The PDFs of rainfall characteristics were assumed to be independent and exponentially distributed and the joint PDFs were formulated as a product of their marginal distributions. The probability distribution of storage level after a storm event was determined numerically using a transitional matrix. The analysis of a single catchment with a storage reservoir by Howard's and Smith's method was extended to a series of catchments in cascade by Schwarz (1980) and Schwarz and Adams (1981). Each catchment was described by a catchment area, hydrological and meteorological parameters, a reservoir storage volume and a controlled outflow rate. Models were developed for both conditions of spill routed to downstream catchments and spills routed out of the system to a receiving water.

Adams and Bontje (1984) simplified Howard's single catchment model by considering the two extremities of reservoir conditions such as reservoir full and reservoir empty at the end of the last rainfall event and also derived many other performance characteristics which include annual number of spills and average annual runoff volume control. These theoretical developments were incorporated into a software package called the Statistical Urban Drainage Simulator (SUDS) by Bontje et al. (1984).

In order to relax and/or verify the assumption of statistical independence of rainfall characteristics, Seto (1984) explored several alternative derivations of Howard's model incorporating the statistical dependence between rainfall characteristics. The derived models were compared to that of Howard (1976) and to STORM simulations. The closed-form analytical probabilistic models that were developed on the basis of statistical independence of rainfall characteristics compared favorably with continuous simulation models; however, the Howard model maintained the closest agreement to the simulation model.

Water quality aspects of stormwater drainage were addressed by Flatt and Howard (1978). They initiated the investigation of pollution control effectiveness of storage-treatment systems assuming constant, uniform pollutant concentrations in runoff and uniform treatment efficiencies. Zukovs (1983) developed a methodology to predict the quality behavior of urban runoff. The models were developed to predict runoff volume and pollutant loads from urban catchments, to evaluate the effectiveness of source control measures and to evaluate the pollution control effectiveness of downstream storage-treatment systems. Derivation of analytical models was based on linear pollutant buildup and washoff processes. Storage analysis considered both batch and detention mode operation and pollutant removal was described by either first order decay or sedimentation. Although the mathematical formulations of the above were developed, their closed-form solutions were not obtained. In addition, the models were compared neither with simulation models nor with field data.

DiToro and Small (1979) derived probability distributions of stormwater overflows to evaluate the performance analysis of storage-interceptor treatment devices. They assumed a gamma distribution of runoff characteristics such as runoff flow, duration, and interevent time as opposed to rainfall characteristics, and the flow was assumed to be uniform over the duration. Several of the derived expressions did not have analytical solutions and required numerical evaluation. The analytical control isoquants, which could achieve the same fraction of runoff load control by different combinations of storage-interceptor devices, were compared with those predicted by continuous simulation STORM model. It was found that these control isoquants were in good agreement with those simulated by STORM model. Employing log-normal probability distributions of stormwater overflows and those of upstream flow rates and pollutant concentration, DiToro (1984) derived the probability distribution of in-stream pollutant concentration. This methodology was successfully applied to several water pollutants for several rivers in the U.S. Loganathan and Delleur (1984) and Loganathan et al.

(1985) employed an exponential probability distribution of runoff characteristics such as volume, duration, and interevent time to derive probability distributions for overflow volume from a runoff control reservoir. The overflow volume and pollutant concentrations were used to calculate the in-stream water quality concentration after mixing during critical periods.

The application of derived analytical probabilistic models to various practical problems have been demonstrated through real-world problems and hypothesized examples. Adams and Zukovs (1986, 1987) applied the models of Adams and Bontje (1984) to evaluate several rehabilitation alternatives for combined sewer systems including source controls, downstream storage, interceptor capacity, outfall treatment and sewer separation. The methodology was applied to a single combined sewer catchment in the City of York, Ontario. Zourntos (1987) extended the work of Adams and Zukovs (1986, 1987) by applying the models of Schwarz (1980) to combined sewer overflow analysis for a series of catchments in the City of York, Ontario.

Furthermore, analytical probabilistic models have been compared to both simulation model results and field measurements in many of the above studies. A very comprehensive comparison between analytical and simulation model results was undertaken by Kauffman (1987). In general, the agreement between the two modeling approaches is favorable, which is surprisingly considering the reduced level of effort required to produce the analytical model results.

As the analytical modeling approaches primarily depends on the input of meteorological statistics, extensive studies have been performed on long-term meteorological data to establish the functional forms and parameters of PDFs of rainfall characteristics. These studies include Adams et al. (1986), Walkovich and Adams, (1991).

In order to cater to the current emphasis on runoff quality control of urban drainage systems, many developments have been made, especially with respect to the long-term pollution control performance of stormwater management practices (SWMPs) or best management practices (BMPs). Research efforts include Li (1991), Segarra-Garcia and Loganathan (1992), Guo and Adams (1994), and Papa and Adams (1996).

Many analytical system performance models of urban drainage systems are closed-form expressions. Therefore, they offer two major advantages compared to continuous simulation counterparts in the screening and planning level analysis. First, not only is it easy to generate the results for obtaining runoff control tradeoffs among available alternatives, but it is also possible to perform sensitivity analysis, an approach that helps to gain an understanding of the system behavior. Second, various techniques of system analysis can easily be applied to formulate methodologies, which incorporate economic and performance functions for developing cost-effective design alternatives.

In summary, as an alternative approach to continuous simulations the above analytical models provide not only a computational competitive method but also provide enhanced insight into system behavior for screening and planning level analysis of urban drainage systems. The theoretical developments and the models developed at the University of Toronto are presented in Adams and Papa (2000). As urban runoff quality problems are emerging as major issues of urban stormwater management, models of runoff quality and methodologies that incorporate quality and quantity control simultaneously are warranted.

Modeling Approach

In this research, an analytical probabilistic modeling approach is employed as an alternative to continuous simulation. The basic premise for both the continuous simulation and analytical modeling approaches remains same – long-term meteorology is the input to the model. Continuous simulation attempts to predict the system response of the output variable (i.e., dependent variable) time series in the exact sequence that would occur from the input time series (historical or synthetically derived rainfall), and post-processed statistical analysis provides the average, and/or long-term performance of the output variable. The analytical probabilistic approach fits probability distributions to the rainfall event characteristics (e.g., rainfall event volume, duration, intensity, interevent time) determined from the same rainfall record otherwise used for continuous simulation. These fitted probability density functions (PDFs) are used to represent the independent variables and the parameters of the PDFs constitute the input to the model. The deterministic functional relationships (e.g., hydrologic and pollutant buildup and washoff processes) between the independent and dependent variables of continuous simulation models constitute the transformation function of the analytical probabilistic models, albeit in a simplified manner. Using derived probability distribution theory [Benjamin and Cornell, 1970], the PDFs of the dependent variables are derived from those of the independent variables and the transformation functions. Often closed-form solutions of the dependent variable PDFs, which depict the system performance measures in terms of the independent variables, are obtained [Adams and Papa, 2000]. The modeling performance of the analytical approach relative to continuous simulation is determined by how well the PDFs of the input variables are formulated and the transformation functions are simplified. Since the PDFs of meteorological inputs are derived from the statistical analysis of long-term rainfall records, the mathematically derived PDFs of system outputs reflect the long-term performance of the drainage system under analysis. This approach is intended to approximate continuous simulation modeling and is recommended for the preliminary planning and design stage because of its computational efficiency.

The advantage of such analytical methods is their generality; however, closed-form solutions generally require simplified system representations. Such methodologies have been applied in previous research to develop models for urban hydrology and storm water runoff control analysis [e.g., Eagleson, 1972; Howard, 1976; Adams and Bontje, 1984; Loganathan and Delleur, 1984; Guo and Adams, 1998]. A systematic application of such techniques to the development of analytical models for stormwater management analysis can be found elsewhere [Adams and Papa, 2000].

Example - Development of an Analytical Probabilistic Model

Rainfall Data Analysis

The development of analytical runoff quality models begins with a probabilistic representation of rainfall characteristics, through a statistical analysis of the long-term historical rainfall record. The available continuous chronological rainfall record is first discretized into individual rainfall events separated by a minimum period without rainfall – termed the interevent time definition (IETD). If the time interval between two consecutive rainfalls is greater than the IETD, the rainfall events are considered as two separate events. Once this criterion is established, the rainfall record is transformed into a time series of individual rainfall events and each rainfall event can be characterized by its volume (v), duration (t), interevent time (b) and average intensity (i). Next, a frequency analysis is conducted on the magnitudes of the time series of rainfall event characteristics, from which histograms are developed. Probability density functions are then fitted to these histograms. Although gamma distributions may better represent some climates, exponential probability distribution functions often fit such histograms satisfactorily for many climatic regions [e.g., Eagleson, 1972; Howard, 1976; Adams et al., 1986; Guo and Adams, 1998]. Moreover, the exponential distribution has the advantage of easer mathematical manipulation. An average annual number of events can also be obtained from the statistical calculations. In the development of the analytical runoff quality model proposed herein, the exponential PDFs of event rainfall volume and interevent time are utilized. Parameters of the exponential PDFs of rainfall volume and interevent time are denoted by and , and the values of these parameters can be obtained by taking the inverse of the average event volume, , and average interevent time, , respectively. The selection of the IETD is governed by the intended application. An IETD of six to twelve hours is used for the analysis of urban runoff quality in this research.

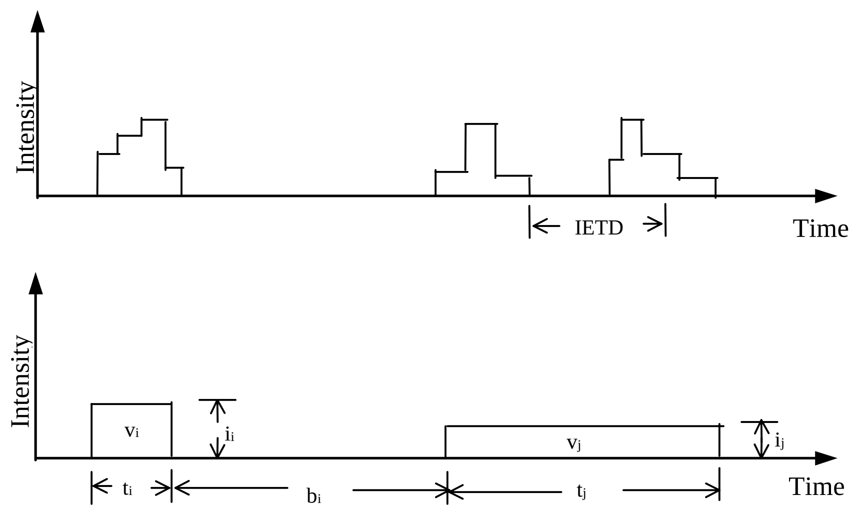

Figure 5: Discretization of long-term rainfall recod

Development of analytical expression for annual average runoff volume

The analytical probabilistic models are intended for screening and planning level analysis of urban stormwater management systems. Accordingly, the models are developed based on simplified system representations. Generally an analytical model employs a single urban catchment as the system. The urban catchment is characterized by its hydrologic parameters such as depression storage and runoff coefficient. Most of the models are developed on a per unit catchment area basis from which the performance measures for the entire catchment can be calculated.

The estimation of runoff quantity and quality by analytical probabilistic models is primarily based on the PDFs of rainfall characteristics and a rainfall-runoff transformation function employed in the model derivation. From modeling perspective, when rain falls on a catchment, it must satisfy the hydrologic losses including interception, depression storage and infiltration losses, before runoff occurs. If the volume of the rainfall event is sufficient to satisfy these hydrologic losses, then the resulting runoff from various pervious and impervious surfaces makes its way to the catchment outlet either through a drainage system or through natural channels. Processes that transform rainfall to runoff are many and they vary spatially and temporally. It is difficult to accommodate all of them in deterministic models and even more so in analytical probabilistic models.

The estimation of runoff quantity is a prerequisite for the estimation of runoff quality. The rainfall-runoff model used in this study follows the system representation presented by *Adams and Bontje* [1984], which employs a depression storage volume and a runoff coefficient to evaluate the resulting event runoff volume. The continuous simulation model STORM uses the same representation for runoff generation. This linear hydrologic model of the rainfall-runoff transformation employed herein is as follows:

$$v_r = \begin{cases} 0 & v \le S_d \\ \phi(v - S_d) & v > S_d \end{cases} \qquad (1)$$

where v_r is the runoff volume (mm), and the rainfall volume, v (mm) must satisfy the volume of depression storage, S_d (mm), before any runoff can be generated. For rainfall volumes greater than S_d, the runoff volume is determined by the product of a dimensionless runoff coefficient, ϕ, and the excess of rainfall over depression storage.

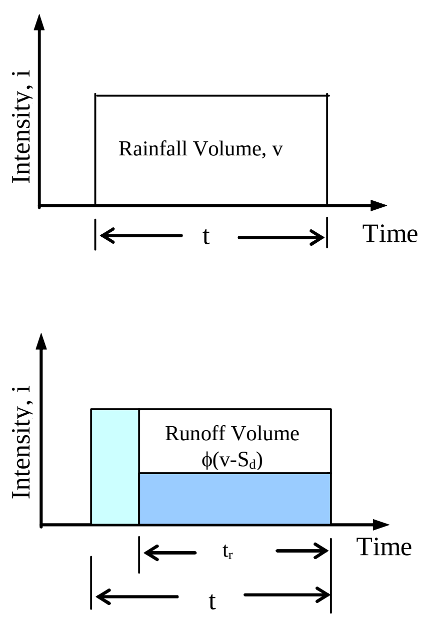

Figure 6: Rainfall-runoff Transformation

The runoff coefficient is a spatially and temporally average constant that is selected based on land use and is typically estimated from the percentage of impervious area. It is noted that the volumes are normalized by the catchment area and are expressed in terms of a uniform depth across the entire catchment.

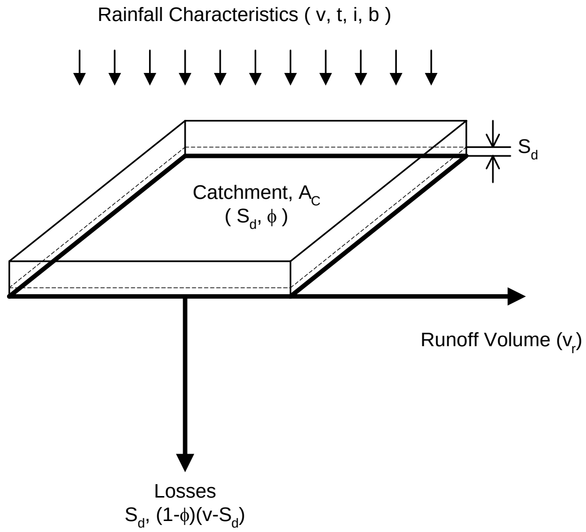

Figure 7: Schematic Representation of Rainfall and Runoff Process in a Urban Catchment

In this system representation, it is assumed that the duration of the runoff event is equal to the duration of the rainfall event. The event rainfall volume can be described by an exponential PDF as follows:

$$f_V(v) = \zeta e^{-\zeta v}, \quad \zeta = 1/\bar{v} \tag{2}$$

where $\bar{v}$ is the mean rainfall event volume (mm). Given the marginal PDF of event rainfall volume and the rainfall-runoff transformation function (1), the cumulative distribution function (CDF) of event runoff volume, $F_{V_r}(v_r)$, can be obtained using derived probability distribution theory as follows:

$$\begin{aligned} F_{V_r}(v_r) &= \Pr[V_r \le v_r] = \Pr[v_r = 0] + \Pr\left[S_d < V \le \frac{v_r}{\phi} + S_d\right] \\ &= \int_{v=0}^{S_d} f_V(v)\,dv + \int_{v=S_d}^{\frac{v_r}{\phi}+S_d} f_V(v)\,dv = 1 - e^{-\zeta\left(\frac{v_r}{\phi}+S_d\right)} \end{aligned} \tag{3}$$

The PDF of the event runoff volume, $f_{V_r}(v_r)$, can be obtained by taking the derivative of $F_{V_r}(v_r)$ as follows:

$$f_{V_r}(v_r) = \frac{d}{dv_r} F_{V_r}(v_r) = \frac{d}{dv_r}\left[1 - e^{-\zeta\left(\frac{v_r}{\phi} + S_d\right)}\right] = \frac{\zeta}{\phi} e^{-\zeta\left(\frac{v_r}{\phi} + S_d\right)}, \qquad v_r > 0 \tag{4}$$

The expected value of the event runoff volume, $E[V_r]$ is obtained as follows:

$$E[V_r] = 0 \cdot p_{V_r}(0) + \int_0^{\infty} v_r \, f_{V_r}(v_r) dv_r = \int_{v_r=0}^{\infty} v_r \cdot \frac{\zeta}{\phi} e^{-\zeta\left(\frac{v_r}{\phi} + S_d\right)} dv_r = \frac{\phi}{\zeta} e^{-\zeta S_d} \tag{5}$$

Equation (5) represents the model for expected runoff volume per event from urban catchments which is a function of the rainfall volume PDF parameter (ζ) and catchment characteristics parameters ϕ and S_d. From the expected event runoff volume, the average annual runoff volume, R, can be obtained as

$$R = \theta \cdot E[V_r] = \theta \frac{\zeta}{\phi} e^{-\zeta S_d} \tag{6}$$

where θ is the average annual number of rainfall events.

Using the equation (6), the average annual runoff volume can be obtained for an urban catchment. Utilizing the derived distribution approach, analytical expressions for average annual spill volume from a storage reservoir, number of spill volumes and average annual pollutant load can be derived.

Conclusions

Combined Sewer Overflows and stormwater runoff are a major source of water pollution problem for the District of Columbia. In order to address the problem, long-term monitoring of runoff quality and modeling of drainage system is necessary. As an initial attempt, Dissolved Oxygen was measured at three locations at the Rock Creek during Fall 2006 and Spring 2007. From the measurement, it is found that there is no evidence of low dissolved oxygen at the measured location of the Rock Creek. As an alternative to continuous simulation and/or to complement continuous simulation, analytical probabilistic models of urban storm water management systems can be developed using derived distribution theory. This is a promising approach to develop analytical expression which can be easily used for solving runoff quantity and quality problems in urban areas.

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