Chapter 3

On Integrating Continuous Simulation* and Statistical Methods for Evaluating Urban Stormwater Systems

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The purpose of this chapter is to discuss various approaches for estimating the pollutant removal by urban stormwater detention systems. After a brief description of detention basins and their components, the characteristics of the inflow and its quality are described, including the effect of covariance between flow and concentration. Solids removal processes are discussed briefly.

Various modeling approaches for estimating pollutant removal effectiveness are compared, including single storm event simulation, continuous simulation of multiple storm events, statistical methods for evaluating pollutant removal effectiveness, and spreadsheet-based approaches which include Monte Carlo simulation. The pros and cons of the various approaches are described, and a simple example is used to illustrate the potential integration of these approaches. This chapter *reviews* the topic rather than develops a hard-and-fast methodology.

3.1 Performance of Detention Systems

A wide variety of methods exist for evaluating the effectiveness of detention systems for removing pollutants in urban runoff. These methods are described in contemporary textbooks, e.g. Wanielista and Yousef (1992), Debo and Reese (1995). Virtually all methods view the detention pond as a settling basin wherein the removal rate depends on the residence time in the basin and the reaction rate.

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* see *Editor's note at end of Chapter*

These processes occur in any storage device be it a small pond, large lake, primary clarifier, or stormwater detention pond. Detention systems can be classified based on detention time:

<i>Detention Time</i>	<i>Descriptor</i>
Few hours to few days	Detention
Weeks or months	Retention
Intermittent	Dry
Intermittent	Wetland

The theory for estimating the performance of detention basins is based on Stokes' law for discrete particle settling of suspended solids, or by reaction kinetics. These theories are described in Nix, Heaney, and Huber (1981), Nix (1982), Goforth, Heaney, and Huber (1983), Nix and Heaney (1984), Nix (1985), Nix and Heaney (1988), and Nix, Heaney, and Huber (1988). The mechanisms affecting removal in detention facilities are shown in Figure 3.1. For stormwater detention systems, the basins fill and empty at relatively short intervals such as every few hours, days or weeks. Thus, it is vital to properly characterize the process dynamics. Major components are discussed below.

Figure 3.1 Mechanisms affecting pollutant removal in detention facilities (Nix et al. 1981).

3.2 Inflow Characteristics

3.2.1 Inflow Quantity

The mass balance for the flow into and out of a detention system is:

$$\frac{dS}{dt} = \sum I - \sum O \tag{3.1}$$

where:

$$\begin{aligned} dS/dt &= \text{rate of change of volume in the detention system,} \\ I &= \text{inflow, and} \\ O &= \text{outflow.} \end{aligned}$$

Many of the results in the literature are for this simple steady-state case. For steady-state operation of detention systems, such as a typical primary clarifier in a wastewater treatment plant (WWTP), $dS/dt = 0$. However, stormwater systems are much more complex. The volume in the detention system and the inflows and outflows typically vary over time. Thus, it is essential to track the dynamics of the operation of stormwater detention systems. The accuracy of the depiction of the performance of the detention system depends upon the selected time step in Equation 3.1. Some of the criteria for selecting the appropriate time step are:

- Availability of data. Precipitation data may be available in time steps as short as five minutes; however, fifteen-minute to one-hour data are widely available.
- Average detention time of the basin. A simple definition of detention time is:

$$t = \frac{S}{Q} \quad (3.2)$$

where:

$$\begin{aligned} t &= \text{detention time,} \\ S &= \text{volume of the basin, and} \\ Q &= \text{average outflow rate.} \end{aligned}$$

- As mentioned above, the average detention time may vary from a few minutes to several months. Thus, methods of analysis vary accordingly. This is discussed in more detail later.
- Pollutant uptake rate. If the pollutant removal rate is very rapid, then a relatively small pond will suffice and vice versa.
- Purpose of the analysis. Very short time steps would be appropriate for real-time control and longer time steps may be used for preliminary planning.
- Computational considerations, e.g. need for numerical stability in solving the differential equations and the ease of computing using various time steps.

For urban stormwater analyses, the most popular time steps have been (i) five to fifteen minutes, (ii) one hour, or (iii) storm event. The five to fifteen minute time step is often used in detailed single-event simulations for evaluating the effect of surcharging in the pipe system. The one-hour time step is used in STORM and similar models to evaluate various storage-release strategies. Lastly, the hourly data may be aggregated into a “storm event” which is defined

as ending when a specified number of dry hours has elapsed. Storm events are used in statistical models of stormwater systems. The critical question in defining a storm event is to specify the appropriate number of dry hours which will terminate an event. Various event definitions have been used but there is no correct definition. It depends on the nature of the problem. Hourly precipitation data for Boulder, Colorado for the period from August 1948 to December 1993 were analyzed to determine the number of wet-weather events as a function of the definition of an event. The results are shown in Figure 3.2. If an event is assumed to end when no precipitation has occurred during the previous hour, then over 11,000 events would result. A two-hour event definition reduces this total to over 5,000 events. The so-called knee of the curve occurs at a three-hour definition with about 4,400 events. The number of events continues to decrease as the event definition increases to 24 hours when the number of events is about 2,500. Thus, the assumed event definition has a major impact on the results.

Figure 3.2 Number of events as a function of inter-event time, Boulder, Colorado, 8/48-12/93.

Traditionally, a major justification for using a longer time step is computational expediency or necessity. However, the economics of computing have changed radically since the introduction of PCs.

3.2.2 Inflow Quality

While the quantity of stormwater varies widely during a storm event, the quality varies even more widely. Depending on the nature of the storm and the sources of pollutants, the concentration of pollutants may exhibit a first flush, i.e.

concentration decreases as the flow duration increases. However, a first flush may not occur in all cases. Process-oriented models such as EPA SWMM provide various buildup-washoff relationships for estimating pollutant concentrations and loadings. However, these methods have only had limited success in depicting concentration variability.

A popular way to describe input quality to a detention system is to use the event mean concentration (EMC), the flow-weighted mean concentration:

$$EMC = \frac{L}{V} \quad (3.3)$$

where:

- L = total load during the storm event, and
- V = total runoff during the storm event.

The introduction of flow-weighted composite sampling devices made it easier to measure the EMC. However, the EMC is limited by the ambiguities of defining an “event” as described above. “Typical” stormwater pollutant EMCs may be found in textbooks, e.g. Debo and Reese (1995) and planning manuals, e.g. Schueler et al. (1992). The variance in EMCs has also been tabulated based on the results of the NURP studies (US EPA, 1983). Driscoll et al. (1990) summarize this data for highway runoff. A more accurate way to estimate pollutant input to a detention system is to use observed monitoring data. Unfortunately, such data tend to be scarce.

In order to gain a process-level understanding of urban runoff quality and to explain its variability and treatability, it is important to evaluate seasonal water quality changes. For example, Thomson et al. (1994) examined Minneapolis highway runoff consisting of 211 events, of which 47 are snow events. They divided the storm events into snow, rain, and mixed rain and snow. They show how the probability density functions (PDFs) of these events differ. One would expect strong seasonal variations in urban runoff quality, especially in areas like Minneapolis with strong influence of sanding and salting during the winter and spring, and the influence of fallen leaves in the fall.

Thomson et al. (1994) evaluated the impact of first flush for the Minneapolis database. Their results indicate a strong first flush effect for most suspended solids and chlorides. If a first flush exists, it can greatly benefit the design of detention basins because the design and operation can focus on the first flush.

A critical component of the inflow characterization is to accurately describe the particle size distribution of the influent. Pisano and Brombach (1996) summarize suspended solids characterizations in North America and Germany. Pisano and Brombach (1996) make several important points regarding the evaluation of “sewer solids”:

- The test method is critical and only recently have appropriate testing procedures been used.

- It is important to characterize the entire range of solids from very coarse to very fine material. If rapidly settling particles are excluded, then the results are skewed since the “removal efficiencies” are based on the final vs. the initial concentration. This has been a chronic problem in comparing the effectiveness of urban stormwater detention systems.
- The median settling velocities vary widely even for similar waste streams. For example, the median settling velocity for CSO solids ranges from about 8 cm/sec to 0.08 cm/sec., a difference of two orders of magnitude.
- The median settling velocities vary widely depending on the type of waste. A summary of the North American and German studies is shown in Table 3.1. The German data indicate higher settling velocities than the North American. However, Pisano and Brombach (1996) attribute much of this difference to different evaluation methods.

Table 3.1 Reported settling velocities in North America and Germany.

	Settling Velocities (cm/sec)					
	North America			Germany		
	Geometric	Medians		Geometric	Medians	
	Mean	Low	High	Mean	Low	High
Dry weather wastewater	0.045	0.03	0.066	0.32	0.1	0.8
Stormwater	0.011	0.0015	0.15			
CSO	0.217	0.01	5.45	0.42	0.12	1.4
Sediment	3.23	0.8	6.75	14	0.8	0.23
Slime				0.8	0.2	6

Reference: Pisano and Brombach (1996)

3.3 Covariance between Flow and Concentration

Figure 3.3 shows the daily influent biological oxygen demand (BOD) concentration to the Boulder WWTP during a wet period that extended over three months in Spring 1995. For normal flows into the WWTP, the average BOD concentration is about 250 mg/l. As the inflow increased to 45 mgd (2.0 m³/s), the corresponding concentration dropped to about 50 mg/l, 20% of its normal value. The correlation coefficient for this data set is -0.82, indicating a strong

negative correlation: as flow increased, concentration decreased. Accounting for covariance, when it exists, is critical. The load of BOD entering the WWTP is found using:

$$L = cQ \quad (3.4)$$

where:

L = load,
 c = concentration, and
 Q = flow rate.

Using the Boulder WWTP data, the total daily influent load, shown in

Figure 3.3 Effect of flow on influent BOD concentrations - Boulder, CO. WWTP.

Figure 3.4, indicates a constant or slightly decreasing total load as flow increases. In this case, the added infiltration to the sewer system is “clean water” which does not cause any increase in pollutant load.

Driscoll et al. (1990) evaluated the covariance between flow and concentration of highway runoff. They examined data for a given site and the aggregate database for all sites. This approach ignores the seasonal effects described above, e.g. the flow-concentration relationship would be expected to be different during early spring as opposed to midsummer. They concluded that significant correlation between flow and concentration occurs only about 25% to 35% of the time and that this covariance can be neglected. They also ignore the covariance among pollutants. By neglecting these covariances, the statistical approach proposed by Driscoll et al. (1990) is simplified.

Figure 3.4 Effect of flow on influent BOD load to Boulder WWTP.

3.3.1 Covariance between Wastewater and Receiving Water Flows

Another important source of covariance that should be checked is between the wastewater flow and the receiving water flow. If larger stormwater runoff flows occur when the receiving water is at low flow, then the “worst case” conditions would occur. For example, the concurrent Boulder WWTP influent flows and the Boulder Creek streamflows, shown in Figure 3.5, indicate a strong positive correlation ($r = +0.81$). There were at least 23 days during a five year

Figure 3.5 Boulder WWTP flow vs. Boulder Creek flow.

period when the flow in the WWTP was at least 40 cfs ($1.1 \text{ m}^3/\text{s}$). Because of the strong positive correlation, when the flow in the WWTP is 40 cfs, the flow in Boulder Creek would be expected to be over 500 cfs ($14.1 \text{ m}^3/\text{s}$), or a dilution ratio of over 14:1. At a WWTP influent of 70 cfs ($2.0 \text{ m}^3/\text{s}$), the expected flow in Boulder Creek would be over 1,600 cfs ($45.2 \text{ m}^3/\text{s}$), a dilution ratio of over 23:1. If the WWTP was forced to bypass during these high flow conditions, the bypass would be the flow in excess of the WWTP's capacity, or about 10 to 20 cfs (0.28 to $0.56 \text{ m}^3/\text{s}$). Thus, the joint probability of CSOs or sanitary sewer overflows (SSOs) and large flows in the receiving water is very high in this example. Accordingly, the overflows are less serious, due to the high dilution.

3.4 Basin Characteristics

3.4.1 Provision for Bypass

Referring to Figure 3.1, an important design consideration regarding the inflow is whether to include a bypass for high flows. If no bypass is included, then the deposited solids can be washed out at higher flows causing a major load to leave the detention basin in a short period of time. Because of the flashiness of urban runoff, high peak flows can occur, even for light or medium storms. It may be desirable to route as much flow through the detention system as possible because this water will receive some pollutant removal. There is also a regulatory issue: all bypasses may be counted as system "failures" if the regulations limit the number of overflows per year. A critical issue with regard to bypasses is determining the "capacity" of the detention system.

3.4.2 Basin Configuration and Volume

The size and geometry of the basin depend on many factors including: whether it is a single or multipurpose facility (e.g. stormwater quantity and quality control, wetland); its relation to the groundwater table; the estimated rate of solids accumulation and removal; the evaporation rate; ownership of the stormwater; efficient geometry and baffles to encourage settling; and efficient geometry for cleaning.

3.4.3 Removal Efficiencies of Detention Basins

Virtually all popular methods for evaluating the expected removal of pollutants from a detention basin are based on simplified representation of settling processes. For example, Brune's trap efficiency curves, shown in Figure 3.6, express removal efficiency as a function of the capacity-to-inflow ratio (a measure

of detention time) and the type of suspended solids. While the reservoir capacity is known, the inflow is an average for the year and may vary widely. Similarly, the nature of the suspended solids can vary widely. Brune's curves show the importance of properly estimating the nature of the suspended solids.

Figure 3.6 Brune's trap efficiency curves (Nix, Heaney, Huber 1981).

3.4.4 Reaction Rates

A popular approach to estimating removal efficiency is to parameterize the settling process as a first order reaction, i.e.

$$\frac{dc}{dt} = -kc$$

$$\frac{c}{c_0} = e^{-kt} \quad (3.5)$$

Equation 3.5 assumes that removal rates are *independent* of the initial concentration. Thus, we get the same removal rate independent of c_0 .

Taking the log of Equation 3.5 yields:

$$\ln\left(\frac{c}{c_0}\right) = -kt \quad (3.6)$$

A semi-log plot of the data should yield a straight line with a slope of k . Whipple and Hunter (1980) have analyzed the settleability of urban runoff. The settleability of hydrocarbons is shown in Figure 3.7. A semi-log plot of this data

shows that k is not constant but can be divided into three stages: an initial relatively rapid removal rate for the first several hours, and subsequent lower reaction rates for longer detention times as shown in Figure 3.7. Nix and Heaney (1984) provide a more general solution wherein the reaction order is included directly in the formulation, as shown in Equation 3.7. This improvement allows the dependency of k on concentration to be included. This is very important. If an “average” value of k is used, then the effectiveness of the detention system is underestimated for short detention times and overestimated for longer detention times (Goforth, Heaney, and Huber 1983).

Figure 3.7 Hydrocarbon data on semi-log scale (Whipple and Hunter 1980).

The equation expressing the change in concentration may better be described by a higher order reaction, i.e.

$$\frac{dc}{dt} = -kc^n$$

$$\frac{c}{c_0} = \left[\left(\frac{n-1}{c_0^{1-n}} \right) kt + 1 \right]^{\frac{1}{1-n}}, n \neq 1 \quad (3.7)$$

where:

- n = reaction order
- k = reaction rate constant, and
- c, c_0 = concentration

The reaction order, n , and rate constant, k , may be determined by transforming the differential equation by the natural logarithm; i.e.

$$\ln\left(-\frac{dc}{dt}\right) = n \ln(c) + \ln(k) \quad (3.8)$$

(Nix and Heaney 1984).

This method of analysis greatly improves the characterization of settling dynamics in a detention basin by using a higher order reaction equation to describe mass removal as a function of initial concentration.

3.5 Evaluation of Detention Systems Performance

3.5.1 Review of Evaluation Approaches

Early evaluations of the effectiveness of urban stormwater detention systems were done using the Storage/Treatment (S/T) block of the EPA SWMM (Heaney and Huber et al., 1975). These single-event methods proved to be inadequate because the regulatory agencies could not agree on the criteria for selecting the “design event”. Thus, these methods were extended to include continuous simulation. The first large-scale effort to evaluate the effectiveness of detention ponds was done in support of a national assessment of the cost of urban stormwater quality management (Heaney et al., 1977, 1979). In this study, cost estimates were prepared for every significant urbanized area in the United States. Detailed studies were done in five cities: Washington, D.C., Atlanta, Minneapolis, Denver, and San Francisco. The optimal mix of storage and treatment or release rate was found by running continuous simulations of hourly rainfall using the STORM model. The resulting storage-treatment isoquants and associated costs of storage and treatment were used to find the least costly mix of storage and treatment for a given level of pollution control. This assessment methodology is still used today.

The so-called statistical method was first introduced to the stormwater field by DiToro (1975), Howard (1976), and DiToro and Small (1979). Adams and his students at the University of Toronto have led the extension of this earlier work (Adams and Bontje 1984). Their work includes software to make these methods easier to use. The statistical method was used extensively to summarize the results of the EPA-sponsored Nationwide Urban Runoff Program (NURP) (US EPA 1983). Driscoll et al. (1990) have shown how these methods can be used for preliminary planning of highway stormwater detention systems. Loganathan and his students have also made recent contributions to this area, e.g. Seggara-Garcia and Loganathan (1994).

The early efforts to evaluate the effectiveness of storage-treatment systems revealed that the problem is more complex than meets the eye. Medina (1976), and Medina, Huber, and Heaney (1981a, 1981b) showed how to model the detailed process dynamics associated with storage-treatment systems. An improved storage-treatment block for the EPA SWMM model was developed that attempted to incorporate the dynamics of detention ponds to estimate their removal efficiencies (Nix 1994). The reaction rate is typically not constant. For example, the settling of suspended solids proceeds at different rates as a function of time. Thus, a more general formulation of removal rates is needed to capture these dynamics. A detailed description of these methods is given in Nix (1982, 1985), Nix, Heaney and Huber (1988), and Nix and Heaney (1988).

As part of the above work on stormwater detention ponds, the available data on pond removal efficiencies were reviewed. Virtually none of these studies measured pond removal efficiencies correctly: typically, no account was taken of the change in storage (all that was measured was the influent and effluent quality during a storm). The resulting estimates revealed wide ranges in performance.

3.5.2 Very Simple Approaches

Debo and Reese (1995) show that the expected effectiveness of wet detention systems is “high”. Similar descriptors are found in stormwater design manuals, e.g. for Washington, D.C. (Schueler et al. 1992) and Camp, Dresser and McKee (1993). Debo and Reese (1995) summarize the estimated annual pollutant removals of wet ponds as shown in Table 3.2.

In order to use Table 3.2, one only has to input the ratio between the basin volume and the mean storm event volume. However, the definition of mean storm volume depends on how storm events are defined. *The mean volume per event changes drastically as the definition of a storm event is varied from ending after one, two, or more dry hours.* For example, using precipitation statistics for Boulder, Colorado, the mean volume per event ranges from 0.17 inches (4.3 mm) for a two dry hour definition to 0.391 inches (9.93 mm) for a 24-hour dry hour definition. The proper definition of a storm event depends on the relative size of the detention pond. In the statistical method, the event is defined so that the coefficient of variation is about one, which is important for simplifying the statistical analysis. However, it is not better than other storm event definitions. Thus, the pond designer will find confusion using even this very simple ratio.

The expected performance of wet ponds based on interim Federal Highway Administration (FHWA) guidance for designing wet detention systems for highway runoff is shown in Figure 3.8 (Dorman et al., 1988). The expected TSS removal is plotted as a function of the basin surface area expressed as a percentage of the contributing catchment area. The database for this curve is

Table 3.2 Average annual pollutant removal capability of wet retention ponds (Debo and Reese 1995).

Pollutant	Wet Pond Design Type		
	0.5 in./ acre	$V_b/V_r = 2.5$	$V_b/V_r = 4.0$ Two week det.
TSS	60-80%	60-80%	80-100%
TP	40-60%	50-70%	60-80%
TN	20-40%	20-40%	40-60%
BOD	20-40%	20-40%	40-60%
Metals	20-40%	60-80%	60-80%

Data from Schueler (1987 1993).

V_b = volume of basin, and V_r = volume of runoff from the mean storm.

the results of eleven NURP studies in Michigan (6), New York (1), Washington, D.C. (2), and Illinois (2). Thus, extensive transposing was required to extend these results to the entire United States.

Lastly, Wanielista and Yousef (1992) present a performance curve for removal of suspended solids and total phosphorus as a function of the detention basin volume/runoff volume from the mean storm as shown in Figure 3.9. The database for these curves is from Denmark and the United States (the eight NURP sites mentioned above for the FHWA curves). The wide variance in the estimates is apparent. Also, the measure of performance, while related to detention time, does not accurately reflect components of detention time such as interevent time for storms.

Nix, Heaney, and Huber (1981) compared various methods of evaluating the effectiveness of detention systems. The simple methods were borrowed from earlier results on sediment control systems. For example, Brune's trap efficiency curves are based on the pond volume, the annual inflow to the pond, and the physical characteristics of the suspended solids as shown in Figure 3.2. The database consists of 44 normally ponded and semi-dry reservoirs located in twenty different states.

Interestingly, Brune's curves, developed many years ago, are more refined than contemporary performance curves for estimating the effectiveness of stormwater detention ponds. Brune's curves at least vary according to both hydraulic and suspended solids characteristics.

3.5.3 Statistical Methods

Statistical approaches emerged in the 1970's by which probability density functions (PDFs) were fitted to storm event data in order to predict the performance of detention systems based on the characteristics of the precipitation events, the

Figure 3.8 Basin surface area as a percent of contributing catchment area (Dorman et al.,1988).

Figure 3.9 Removal of suspended solids and total phosphorus in detention ponds (Wanielista and Yousef, 1992).

drainage area, and the detention system. This work was pioneered by Howard (1976), DiToro and Small (1979) and Small and DiToro (1979). The statistical method has been used as a preliminary screening tool in presenting the results of the NURP studies (US EPA 1983) and has been used to evaluate highway-related runoff (Driscoll et al. 1990). This method allows the PDF of the output to be derived directly. The same information can be obtained by running a continuous simulation model such as SWMM, STORM, or HSPF. Numerous simplifying assumptions must be made to use the statistical method including: restrictions on the type of PDF, ignoring the covariance between flow and concentration, a simple runoff coefficient, and simplistic treatment removal kinetics. The statistical method was originally designed to be a preliminary screening tool for planning purposes, and to be used as a way of efficiently summarizing the results of process-based continuous simulation models, e.g. Howard et al. (1979) compared their statistical results to the output from STORM runs.

Statistical methods are an improvement over simple empirical approaches because they incorporate the storm event statistics (Small and DiToro, 1979; DiToro and Small, 1979). They also incorporate the “average” removal rate coefficient. The resulting equation for estimating basin performance is:

$$R = a\{1 / [1 + (bQ_r) / kA]\}^{(k+1)} \quad (3.9)$$

where:

- R = percent removal,
- a = removal efficiency coefficient,
- b = kinetic coefficient,
- Q_r = average runoff rate,
- k = inverse of the coefficient of variation of the runoff rate,
and
- A = surface area of sedimentation tank.

A key assumption is that removal follows first order kinetics. As discussed earlier, this may be inaccurate.

Li and Adams (1994) cite two advantages of the statistical method for estimating the long-term pollution control performance of storage-treatment systems:

1. closed-form equations describing the relationships between input rainfall statistics and output control system performance statistics are available; and
2. preliminary cost optimization can be performed easily with knowledge of the cost functions of the control measures.

Segarra-Garcia and Loganathan (1994) also used the statistical approach for deriving estimates of the performance of stormwater systems. The assumptions and results of the Li and Adams (1994) approach are:

1. Rainfall event characteristics such as rainfall event volume (v), duration (t), and interevent time (b), can all be described by the single parameter exponential probability distribution:

$$f(w) = ze^{-\xi w} \quad (3.10)$$

where:

$z = 1/E(w)$, and the reciprocal of the average magnitude of v, b, t (ξ, λ, ψ),

$f(w)$ = the probability density function of w , and

w = the rainfall event characteristic (v, b, t);

2. Runoff can be estimated from rainfall using a simple coefficient:
3. Rainfall pulses can be divided into events using an event definition which provides the best fit for the exponential distribution. Thus, the criteria for the event definition is one of analytical convenience, rather than based on the expected response time of the control system.
4. Covariance between concentration and flow is ignored.
5. Treatment efficiencies are assumed to be constant and do not depend on residence time and reaction rates.
6. A constant pollutant concentration is assumed for all events.

Given these assumptions, the final equation for estimating the expected performance of the storage treatment system is a complex function of eight variables which describe the rainfall, catchment and drainage system characteristics and treatment efficiency.

3.5.4 Simulation Models

Early research on evaluating the effectiveness of detention systems for urban stormwater quality evaluations was done using the Storage-Treatment block of early versions of the EPA SWMM (Heaney et al., 1975). This initial effort estimated the removal efficiency of a storage-release system for a single design event. It was soon recognized that continuous simulation was needed to meaningfully characterize the overall performance of these systems. Concurrently, there was interest in getting planning level estimates of the performance of these systems. This interest was stimulated by the large 208 planning effort and our nationwide assessment of the cost of controlling stormwater pollution. Thus, the STORM model, with hourly rainfall data as input, was used to define the trade-offs between storage volume and treatment or release rate. These results are summarized in Heaney and Nix (1977), Heaney et al. (1977), Heaney et al. (1978), and Heaney et al. (1979). The continuing theme of this research was to obtain a *process-level* understanding of how real detention systems work, so that improved designs could be developed.

3.6 Comparison of Methods

The above methods range from very simple planning level estimates , e.g. Brune’s curve, to detailed process-oriented approaches, e.g. EPA SWMM S/T block. Nix, Heaney, and Huber (1981) compare all of the above approaches using a common example. Also, Goforth, Heaney, and Huber (1983) compare the statistical method to using continuous simulation using the Storage/Treatment block of SWMM. The results, shown in Figure 3.10, indicate that the statistical method does not perform well. The statistical method estimated the required basin size to be 2.28 times bigger than the simulator estimate. The associated cost for the statistical design was 1.87 times the cost of the S/T design. Li and Adams (1994) compare the results of their statistical approach to continuous simulation and feel that the results are close.

As seen from this comparative analysis, the statistical method is a very simplified characterization of the problem. In our opinion, it should only be used as a companion to process-oriented, continuous simulation models as a way of summarizing the findings from these studies. *It should not be used as the primary*

Figure 3.10 Determination of least cost combination of basin volume and drawdown rate (Goforth et al 1983).

tool for design-level evaluations. Driscoll and Strecker (1993) report wide variability in the performance of detention basins. It is essential to explain this variability using process-based approaches. Using a process-oriented simulator like the S/T block of SWMM, the engineer can explicitly incorporate:

1. a wide variety of detention facility geometries and outlet structures;
2. sludge accounting;
3. the capability for dry-weather drawdown;
4. the effect of various assumptions about buildup and washoff rates;
5. a variety of particle size/specific gravity distributions;
6. a wide variety of pollutant removal equations; and
7. multiple pollutants

3.7 Statistical Method

The statistical method described below is a form of risk or reliability analysis. As part of this risk analysis, continuous simulation and scenario analysis are used to evaluate how the proposed design performs for a variety of forcing functions. The U.S. Army Corps of Engineers has already moved strongly in this direction by developing guidelines and mandates to incorporate formal risk analysis into their evaluations (Greeley-Polhemus Group, 1992). The availability of @Risk, a spreadsheet add-in for Monte Carlo simulation, was critical in helping engineers understand and accept the risk-based approach. The US EPA has also embraced risk reduction as a priority-setting procedure (Finkel and Golding, 1994). The U.S. water supply industry is interested in developing and implementing formal approaches to evaluate risk and reliability.

Even though the background theory has been available for nearly half a century, systematic applications of risk and reliability have a very short history of the past few years. The main reason for this long gestation period is that the analytical methods are difficult to understand and require advanced knowledge of probability, statistics, and calculus. Even with the ability to use these advanced methods, closed-form solutions are available only for very simple, well-behaved systems. A major breakthrough in developing easy-to-understand-and-use methods for estimating risk and reliability was the introduction of Monte Carlo simulation software as an add-in for spreadsheets (Palisade Corp., 1994). Other risk analysis software is also available. However, state-of-the-art versions of spreadsheets allow simple risk and reliability analysis even without these add-ins.

Reliability is defined as: 1-risk. A large engineering literature exists on this subject, e.g. Pierucshka (1962), Hahn and Shapiro (1967), and Kapur and Lamberson (1977). The analytical techniques are very similar. Reliability engineering deals with “failures” of any type whereas the recent interest in risk analysis has been prompted by “failures” that cause public health problems.

Mays and Tung (1993) present a summary of risk analysis applications in water resources. Another major source of information on the use of risk analysis in water resources is the set of seven proceedings of Engineering Foundation Conferences on this subject which summarize developments in the field through the end of 1995, e.g. Haimes et al. (1994).

3.8 Computational Methods for Risk Analysis

3.8.1 Simple Sensitivity Analysis

Simple sensitivity or what-if analysis uses the output from a design event simulation and systematically varies the values of selected parameters to test the sensitivity of the solution to the assumed values of the parameters. This method can be done on spreadsheets using one, two, or three-way data tables which automate the sensitivity analysis process. Scenario analysis wherein a discrete number of alternatives are evaluated can also be done (a scenario is a vector of assumed values of the key parameters). Single or design event evaluation is very restrictive since a design can rarely be reduced to evaluating performance for a single future scenario.

3.8.2 Continuous Simulation

Continuous simulation models can track the status of the detention basin at all times. The summary output could include the cumulative density function (CDF) of how often the reservoir was at any given stage or spilling. Sensitivity analysis entails varying the values of key parameters and rerunning the simulation to evaluate the impact on the solution. In addition to older Fortran models, continuous simulation can be done on spreadsheets.

3.8.3 Monte Carlo Simulation

Monte Carlo simulation can be an efficient alternative to continuous simulation (Law and Kelton 1991). Probability density functions are fitted to the data and the distributions are sampled to estimate the variability of the solution. Monte Carlo simulation is now easier using spreadsheet add-ins. The CDF is determined directly. Using Monte Carlo simulation removes virtually all of the major objections against the current statistical method for stormwater analysis, e.g. the theory and derivation are hard to understand; only well-behaved distributions can be used; covariance is ignored; seasonality is ignored. Similar limitations have impeded the adoption of these methods in other areas of water resources engineering.

3.8.4 Advanced Continuous Simulation

A process-based continuous simulation is essential for understanding and properly designing detention basins. The EPA SWMM with the Storage/Treatment block simulates conventional treatment processes. However, the S/T block was written fifteen years ago and is not as user-friendly as engineers now expect from software. An excellent dynamic wastewater treatment simulator called GPS-X is available for Work Stations. It is being used to evaluate various wet-weather control options. [Editor's note: Several shells for SWMM also render SWMM S/T user-friendly.]

3.9 Towards More Robust Evaluation Methods

After more than twenty years experience in evaluating the effectiveness of stormwater detention systems using single event and continuous simulation and analytical statistical methods, there appears to be agreement on the following:

1. Evaluation of at least one year of precipitation data is essential in order to estimate the overall performance of stormwater detention systems. This requires the use of continuous simulation and/or statistical approaches.
2. The advent of the PC has made computing much easier than anticipated even a decade ago.
3. Widespread availability of databases for precipitation, water quality, etc. is permitting us to go from an *analytical* to an *information* based approach.

Because of the historical difficulty in dealing with information, we have been conditioned to replacing data by an approximating equation. Given such equations, we can conduct sophisticated analytical evaluations of the equations to find “optimal” solutions. A fundamental problem with replacing data by equations is that the equations may not accurately characterize the response surface. For example, Nix and Heaney (1988) could not find an accurate equation to describe the relatively simple production function of pollution control (y) as a function of storage volume (S) and release rate (T), or

$$y = f(S, T) \quad (3.11)$$

Thus, the production function was found by fitting cubic splines to the database and outputting the numerical result to a data table. Similarly, only a few probability distributions such as the exponential and log-normal have been used in the statistical method because they are “well-behaved” in the mathematical

sense. Thus, the analyst's choice of functional relationships is heavily influenced by analytical tractability. Fortunately, we are no longer bound by these restrictive approaches.

There is active discussion in the literature on the relative merits of continuous simulation vs. analytical statistical methods. The statistical methods purport to decrease computational time by reducing the need to run continuous simulations using models such as STORM. However, most of these debates predate the advent of personal computers. Our more recent excursions into evaluating these problems indicates that the economics of computing and database acquisition have resulted in a significant shift in strategy. One can now get hourly precipitation data directly off CD-ROMs. The statistics of this hourly data can be easily determined for an assumed precipitation event definition. With PCs, spreadsheet-based models can easily process the precipitation data and perform continuous simulations. With the introduction of risk analysis software such as @Risk, it is now possible to replace the relatively complex analytical statistical analysis with a much more robust Monte Carlo simulation. Given these improved methodologies, how do the continuous simulation and statistical methods compare? The following simple example, developed using Boulder, Colorado data, provides a preliminary evaluation of these two approaches.

3.10 Case Study of Boulder, Colorado

Given that we can analyze stormwater problems using spreadsheets with Monte Carlo simulations, which method or combination of methods seems to be most appropriate? First, consider event-based methods, be they continuous simulation or statistical.

3.10.1 Continuous Simulation using Precipitation Events

The required steps to perform a continuous simulation using precipitation events are:

1. Adopt a definition of precipitation events based on a maximum number of dry hours allowed within an event.
2. Aggregate the hourly precipitation data into storm event data based on the above definition.
3. Set up a storm event water budget for the period of investigation keeping track of the status of the detention pond during and between storms.
4. Perform the simulation and record the summary statistics on the performance of the storage-release system. Repeat this process by varying the assumed storage volume (S) and release rate (T).

Sensitivity analysis can be expedited using a spreadsheet feature called two-way data tables (the analyst creates a two dimensional matrix of assumed values of S and T). The two-way data table feature is invoked and the model runs for each assumed pair of S and T values. If more than three parameters are to be varied for each simulation, then the scenario analysis spreadsheet tool can be used. For example, we may wish to vary depression storage and the runoff coefficient in addition to varying S and T.

A sample calculation using this method is shown in Table 3.3. For an assumed event definition, 10 hours in this example, the precipitation events for June 1987 are listed. Knowing the ending hour of the event, its duration, the total precipitation, and the storage in the reservoir at the beginning of the simulation, it is straightforward to calculate the performance of the system as shown in Table 3.3.

Table 3.3 Event modeling: sample calculation for Boulder, Colorado.

Event Rule	= 10 hrs	Runoff Coefficient	= 0.5
Depression Storage (in)	= 0.05	Total Storage (in)	= 0.6
Drawdown Rate (in/hr)	= 0.004		

Date	Time	Rain Event Totals	Event Dura- tion	Inter- event time	Runoff (in)	Storage at start of event (in)	Storage at end of event (in)	Volume stored (in)	By-pass Volume (in)
6/7/87	2200	0.2	2		0.05	0.60	0.558	0.05	0.00
6/8/87	2400	2.9	5	26	1.4	0.60	0.000	0.60	0.80
6/10/87	1600	0.1	1	40	0	0.16	0.164	0.00	0.00
6/24/87	1800	0.1	1	338	0	0.60	0.604	0.00	0.00
6/29/87	2400	2.4	14	126	1.15	0.60	0.000	0.60	0.55
TOTAL		5.7			2.6			1.25	1.35
MEAN		1.14			0.52			0.25	0.27
% Stored = 48%									

3.10.2 Continuous Simulation using Hourly Precipitation Data

The procedure for continuous simulation using hourly precipitation data is a simplification of the storm event procedure described above. The major difference is that it is unnecessary to define a storm event since the hourly precipitation data are being used directly. The simpler procedure is described below.

1. Set up an hourly water budget for the period of investigation keeping track of the status of the detention pond during and between storms.
2. Perform the simulation and record the summary statistics on the performance of the storage-release system. Repeat this process by varying the assumed storage volume (S) and release rate (T).

An example of this simulation is shown in Table 3.4 for the same period of June 1987. The general calculations are the same as for the event simulation except that hourly accounting and intrastorm variability is incorporated. For this example, the number of calculations increases from five for the event analysis to 24 for the hourly analysis. Thus, the event analysis does save some computations. On the other hand, the event analysis aggregates the 6/29/87 event which actually goes from 7 am to midnight into a single event. Thus, the entire dynamics of the behavior of this storm are lost when the event simulation is done. This may introduce significant errors in calculating the performance of the detention pond. Major advantages of the hourly accounting include not having to select a storm event definition and the ability to calculate detention times more accurately. This avoids significant sources of error that can result from aggregation. With the current economics of computing, it is very easy to simply use hourly data. Thus, we recommend using the hourly data directly for continuous simulation and avoiding the use of storm events.

The recommended procedure for generating the final storage-treatment production function and the cost minimization is to follow the procedure described by Nix and Heaney (1988) wherein approximating splines are used to find the isoquants and the output is in the form of a tabular production function. This avoids the errors introduced by trying to fit equations to the data. Then the final cost analysis is done by simply multiplying the various S , T pairs by their respective unit costs in order to derive the optimal expansion path.

3.10.3 Statistical Method

An alternative to continuous simulation is to use the statistical method whereby PDFs are fitted to the hourly precipitation data. The monthly results for Boulder, Colorado are shown in Figure 3.11 for the number of events per month, the hours per event, the volume per event, and the volume per month. Similar statistics can be generated for other factors including the interevent time. Using the statistical method, one selects a period or periods for which PDFs will be developed. One option is to take all of the precipitation events in the period of record and develop the PDFs for all of the data. This approach can be inaccurate due to seasonal differences that clearly exist. Another option is to select a period of interest, e.g. the summer months, and generate the PDFs for the summer period only. Finally, some analysts derive PDFs for each month.

Table 3.4 Hourly simulation: example calculation for Boulder, Colorado.

Runoff Coefficient = 0.5

$$\text{Depression Storage (in)} = 0.05$$

Total Storage (in) = 0.6

$$\text{Drawdown Rate (in/hr)} = 0.004$$
[illegible]

Figure 3.11 Seasonal variability of rainfall for Boulder, Colorado.

3.10.4 Monte Carlo Simulation

A more robust approach is to use Monte Carlo simulation which is much less restrictive than analytical methods (types of distributions can be selected and the covariance among these distributions can easily be included in the simulation). The steps in the analysis are:

1. Define a precipitation event in terms of the maximum number of dry hours allowed within an event.
2. Given this event definition, generate the rainfall statistics for event volume, duration, and interevent time.
3. Find the best PDFs for the above distributions, e.g. using BestFit (Palisade Corp. 1994).
4. Upon completion of the Step 3, specify the three input distributions for volume, duration, and interevent time.
5. The covariance among these three distributions is calculated by the spreadsheet.
6. These three PDFs and their correlation matrix are entered into the spreadsheet, where storage and detention time characteristics are used to calculate performance.
7. The Monte Carlo software samples the input distributions, and after the spreadsheet calculates the basin performance, output distributions are developed, e.g. using @Risk (Palisade Corp. 1994).
8. The output CDF is used to estimate the statistics of the long-term performance of the system.

An example of the Monte Carlo approach is shown in Table 3.5. The spreadsheet calculation is very simple because the simulation proceeds from event to event as new estimates are generated by the Monte Carlo method. The major limitation of this approach is the inaccuracies introduced by converting the original hourly precipitation data into approximating PDFs and the associated covariance. Increased accuracy can be obtained by fitting PDFs for each month but that complicates the calculations from month to month. It is more accurate to work directly with the original hourly time series data.

3.11 Summary and Conclusions

A wide variety of methods exist for evaluating the effectiveness of detention systems for removing pollutants in urban runoff. The purpose of this chapter was to describe various approaches for estimating the pollutant removal capability of urban stormwater detention systems. Virtually all of the methods view the detention pond as a settling basin whose removal rate depends on the residence time in the basin and the reaction rate. These processes occur in any storage

Table 3.5 Example Monte-Carlo simulation for Boulder, Colorado.

Event Rule (10 hrs) = 1000 Runoff Coefficient = 0.5
 Depression Storage (in) = 0.05 Total Storage (in) = 0.6
 Drawdown Rate (in/hr) = 0.004

	Event Volume (in)	Event Duration (hr)	Inter-Event Time (hr)	Runoff Volume (in)	Storage at Start of Event (in)	Storage at End of Event (in)	By-Pass Volume (in)	% Stored
	0.06	1.42	136.97	0.00	0.60	0.61	0.00	
Input PDF's	Inverse Gaussian	Pearson Type VI	Truncated Lognormal					
Minimum	0.02	0.03	10.14	0.00	0.00	0.00	0.00	0.00
Mean	0.33	5.26	133.15	0.12	0.57	0.49	0.02	0.96
Maximum	2.33	89.15	2101.05	1.11	0.60	0.60	1.11	1.00

device be it a small pond, large lake, primary clarifier, or stormwater detention pond. The theory for estimating the performance of detention basins is based on either Stokes' law for discrete particle settling of suspended solids, or more complex reaction kinetics. For stormwater detention systems, the basins fill and empty at relatively short intervals such as every few hours, days or weeks. Thus it is important to properly characterize the process dynamics.

The mass balance for the flow into and out of a detention system is determined using a mass balance equation. The accuracy of the depiction of the performance of the detention system depends upon the selected time step in the mass balance equation. For urban stormwater analyses, the most popular time steps have been five to fifteen minutes, one hour or storm event. The five to fifteen minute time step is often used in detailed single event simulations such as those used to evaluate surcharging in the pipe system. The one hour time step is used in STORM and similar models to evaluate various storage-release strategies. Lastly, the hourly data may be aggregated into a "storm event" which is defined as ending when a specified number of dry hours has elapsed. Storm events are used in statistical models of stormwater systems. The critical question in defining a storm event is to specify the appropriate number of dry hours which will terminate an event. Various event definitions have been used but there is no correct definition. Traditionally, a major justification for using a longer time step is computational expediency or necessity. However, the economics of computing have changed radically since the introduction of PCs.

Virtually all popular methods for evaluating the expected removal of pollutants from a detention basin are based on simple removal kinetics. However, experimental work with urban runoff indicates that there are multiple stages of removal. Detention time is defined as the residence time of a parcel of water in a detention basin. Detention times vary widely during and immediately after a storm event due to the dynamics of the storm event. Existing simplified methods calculate an “average” detention time which may give a very inaccurate measure of real detention times because of the nonlinearities involved.

The earliest evaluations of the effectiveness of urban stormwater detention systems were done using early versions of the Storage/Treatment block of the EPA SWMM . [*Editor's note: EPA SWMM now runs S/T continuously.*] These single event methods proved to be inadequate because the regulatory agencies could not agree on the criteria for selecting the “design event”. Thus, these methods were extended to include continuous simulation. The optimal mix of storage and treatment or release rate was found by running continuous simulations of hourly rainfall using the STORM model. The resulting storage-treatment isoquants and associated costs of storage and treatment were used to find the least-costly mix of storage and treatment for a given level of pollution control. The so-called statistical method was first introduced to the stormwater field in the late 1970's.

Current practice includes very simple approaches which estimate pollutant removal as a simple function of the ratio of detention basin volume and the mean storm event volume. However, the definition of mean storm volume depends on how storm events are defined. The mean volume per event changes drastically as the definition of a storm event is varied from ending after one, two, or more dry hours.

Statistical approaches for evaluating stormwater detention systems were reviewed. They are an improvement over the simple empirical approaches because they incorporate storm event statistics. Two types of statistical approaches can be used. One option is to derive the performance of the system analytically. The other approach is to use Monte Carlo simulation. The major limitation of these approaches is the need to aggregate the hourly precipitation data into storm events. The results are very sensitive to how events are defined.

Single event and continuous simulation models have been used for many years to evaluate stormwater detention systems. The EPA SWMM and STORM have been the two most popular simulation models. With the advent of the PC, it is now possible to do many of these calculations with much easier to use software or to use spreadsheets.

We recommend using the statistical procedures as a companion to process-oriented continuous simulation models as a way of summarizing the findings from these simulation studies. However, they should not be used as the primary tool for design.

[Editor's note: In this chapter "continuous simulation" is evidently taken to mean preprocessing the rain record into a sequence of wet events which are then input to the model - as opposed to the usage in following chapters, wherein the long-term precipitation record is directly input to a model that includes all algorithms active for the complete record, independent of any definition of minimum interevent dry-weather period.]

References

- Adams, B.J. and J.B. Bontje. 1984. Microcomputer application of analytical models for urban stormwater management. in James, W.D. Ed. *Emerging Techniques in Stormwater and Flood Management*, ASCE New York, p. 138-162.
- Camp, Dresser, and McKee. 1993. *Best Management Practice Handbook-Vol. 1*, Municipal. California Stormwater Task Force.
- Debo, T.N. and A.J. Reese. 1995. *Municipal Storm Water Management*. Lewis Publishers, Boca Raton, FL
- DiToro, D.M. 1975. Statistical design of equalization basins. *Jour. of Env. Engg. Div., ASCE*, 101,EE6, p. 917-933.
- DiToro, D.M. and M.J. Small. 1979. Stormwater interception and storage. *Jour. of Env. Engg. Div., ASCE*, 105, EE1, p. 43-54.
- Dorman, M.E., Hartigan, J., Johnson, F. and B. Maestri. 1988. *Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff: Interim Guidelines for Management Measures*. FHWA/RD-87/056, Federal Highway Administration, McLean, VA
- Driscoll, E.D., Shelly, P.E. and E.W. Strecker. 1990. *Pollutant loadings and impacts from highway stormwater runoff*. Vol. I. Design Procedure (FHWA-RD-88006), Volume II. User's Guide for Interactive Computer Implementation of Design Procedure (FHWA-RD-88-007), Vol. III. Analytical Investigation and Research Report (FHWA-RD-99008), and Volume IV. Research Report Data Appendix (FHWA-RD-88-009). Federal Highway Administration, McLean, VA
- Driscoll, E.D. and E. Strecker. 1993. *Assessment of BMP's being used in the U.S. and Canada*. *Proc. 6th Int. Conf. on Urban Storm Drainage. Niagara Falls, NY*
- Field, R., Struzeski, E.J., Masters, H.E. and A.N. Tafuri. 1974. Water pollution and associated effects of from street salting. *Jour. Env. Engg. Div., ASCE*, 100 (EE2), p. 459-477.
- Finkel, A. and D. Golding. 1994. *Worst Things First? The Debate Over Risk-Based National Environmental Priorities*. Resources for the Future, Washington, D.C.
- Goforth, G.F.E., J.P. Heaney, and W.C. Huber. 1983. Comparison of basin performance modeling techniques. *J. of Environmental Engg. Div., ASCE*, 109, EE5, p. 1082-1098.
- Greeley-Polhemus Group, Inc. 1992. *Guidelines for Risk and Uncertainty Analysis in Water Resources Planning*. Report prepared for U.S. Army Corps of Engineers, Institute for Water Resources, Fort Belvoir, VA.
- Hahn, G.J. and S.S. Shapiro. 1967. *Statistical Models in Engineering*. J. Wiley and Sons, New York.

- Haimes, Y.Y., D.A. Moser, and E.Z. Stakhiv, Eds. 1994. Risk-Based Decision Making in Water Resources VI, ASCE, New York.
- Heaney, J.P., Huber, W.C., Sheikh, M., Medina, Jr., M.A., Doyle, J.R., Peltz, W.A., and J.E. Darling. 1975. Urban stormwater management modeling and decision making. EPA-670/2-75-022, Cincinnati, OH
- Heaney, J.P., and S.J. Nix. 1977. Storm Water Management Model: Level I-Comparative evaluation of storage-treatment and other management practices. EPA-600/2-77-083, Edison, NJ
- Heaney, J.P., Huber, W.C., Medina, Jr., M.A., Murphy, M.P., Nix, S.J., And S.M. Hasan. 1977. Nationwide evaluation of combined sewer overflows and urban stormwater discharges, Vol. II, Cost assessment and impacts. EPA-600/2-064b, Cincinnati, OH
- Heaney, J.P., Nix, S.J., and M.P. Murphy. 1978. Storage-treatment mixes for stormwater control. Jour. of Env. Engg. Div., Proc. ASCE, 104, EE4, p. 581-592.
- Heaney, J.P., W.C. Huber, R. Field, and R.H. Sullivan. 1979. Nationwide cost of wet-weather pollution control. Jour. Water Poll. Control Fed., Vol. 51, No. 8, pp. 2043-2053.
- Howard, C.D.D. 1976. Theory of storage and treatment plant overflows. Jour. Env. Engg. Div., Proc. ASCE, 102, EE4, p. 709-722.
- Howard, C.D.D., Flatt, P.E. and U. Shamir. 1979. Storm and combined sewer storage treatment theory compared to computer simulation. Grant No. R-805019, US EPA, Cincinnati, OH
- Kapur, K.C. and L.R. Lamberson. 1977. Reliability in Engineering Design. J. Wiley and Sons, New York.
- Law, A.M. and W.D. Kelton. 1991. Simulation Modeling and Analysis. 2nd Ed. McGraw Hill, NY, NY.
- Li, J.Y. and B.J. Adams. 1994. Statistical water quality modeling for urban runoff control planning. Water Science and Technology, Vol. 29, No. 1-2, p. 181-190.
- Mays, L.W. and Y-K. Tung. 1993. Hydrosystems Engineering and Management. McGraw-Hill, New York.
- Medina, M.A. 1976. Interaction of urban stormwater runoff, control measures, and receiving water responses. PhD Dissertation, U. of Florida, Gainesville, FL
- Medina, M. A., W.C. Huber, and J.P. Heaney. 1981a. Modeling stormwater storage/treatment transients: theory. Jour. of Environmental Engg. Div., ASCE, 107, EE4, p. 781-797.
- Medina, M., W.C. Huber, and J.P. Heaney. 1981b. Modeling stormwater storage/treatment transients: applications. Jour. of Environmental Engg., Div. ASCE, 107, EE4, p. 799-816.
- Nix, S.J., Heaney, J.P., and W.C. Huber. 1981. Water quality benefits of detention. Chapter 12 of Urban Stormwater Management, Special Report No. 49, American Public Works Assn., Chicago, IL
- Nix, S.J. 1982. Analysis of storage-release systems in urban stormwater quality management. PhD Dissertation, U. of Florida, Gainesville, FL
- Nix, S.J. and J.P. Heaney. 1984. Characterization of suspended solids settling. Proc. Int. Symposium on Stormwater Management. U. of Kentucky, Lexington.
- Nix, S.J. 1985. Residence time in stormwater detention basins. Jour. of Environmental Engg., 111, 1, p. 95-100.
- Nix, S.J. and J.P. Heaney. 1988. Optimization of storage-release strategies. Water

- Resources Research, 24, 11, p. 1831-1838.
- Nix, J., J.P. Heaney, and W.C. Huber. 1988. Suspended solids removal in detention basins. *J. of Environmental Engg., ASCE*, 114, 6, p. 1331-1343.
- Nix, S.J. 1994. *Urban Stormwater Modeling and Simulation*. Lewis Publishers, Boca Raton, FL
- Palisade Corp. 1994. *@Risk*, Newfield, NY.
- Palisade Corp. 1994. *BestFit!*, Newfield, NY.
- Pieruschka, E. 1962. *Principles of Reliability*. Prentice-Hall, Englewood Cliffs, NJ
- Pisano, W.C. and H. Brombach. 1996. Solids settling curves. *Water Environment and Technology*, Vol. 8, No. 4, p. 27-33.
- Schueler, T.R. 1987. *Controlling Urban Runoff-A Practical Manual for Planning and Designing Urban Best Management Practices*. Metropolitan Washington Council of Government, Washington, D.C., 202 p.
- Schueler, T. 1993. Performance of stormwater ponds and wetland systems. in *Engineering Hydrology*, C. Kuo, Ed., ASCE
- Schueler, T.R., Heraty, M. and P. Kumble. 1992. A current assessment of urban best management practices: Techniques for reducing nonpoint source pollution in the coastal zone. Metropolitan Washington Council of Governments, Washington, D.C.
- Segarra-Garcia, R. and G.V. Loganathan. 1994. A stochastic pollutant load model for the design of stormwater detention facilities. *Water Sci. Tech.*, Vol. 29, No. 1-2, p. 327-335.
- Small, M.J. and D.M. DiToro. 1979. Stormwater treatment systems. *Jour. of Environmental Eng. Div., ASCE*, 105, EE3, p. 557-569.
- Thomson, N., E. McBean, I.B. Mostrenko and W. Snodgrass. 1994. "Characterization of Stormwater Runoff from Highways." *Journal of Water Management Modeling* R176-09. doi: 10.14796/JWMM.R176-09.
- Urbonas, B. and P. Stahre. 1993. *Stormwater Best Management Practices and Detention*. Prentice-Hall, Englewood Cliffs, NJ.
- Wanielista, M.P. and Y.A. Yousef. 1992. *Stormwater Management*. J. Wiley and Sons, New York.
- Whipple, Jr., W. and J.V. Hunter. 1981. Settleability of Urban Runoff Pollution. *Jour. Water Pollution Control Federation*, Vol. 53, No. 12, p. 1726-1731.