Extended Stormwater Detention Basin Design
for
Pollutant Removal

by

Edwin Wilson Watkins

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APPROVED:

_____   _____
G. V. Loganathan, Chairman   David F. Kibler

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Theo A. Dillaha

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(ABSTRACT)

A statistical formulation for estimating the average time of detention within a pond for a captured runoff volume is presented. It is assumed that mixing takes place during an event and that settling occurs over the period required empty the captured volume or the time between successive events, whichever is smaller. This analytical detention time is used in conjunction with a pollutant settling efficiency-detention time curve to estimate the settling efficiency. This curve is generated from Storm Water Management Model (SWMM) simulations and shown to be independent of runoff statistics, pond configuration, and arbitrary but constant influent concentration under complete mixing. The analytical detention time estimate, in combination with the settling efficiency curve and an expression for the capture efficiency of the pond provides a valuable desk top method for the planning level design of detention basins for pollutant removal. The method performs quite well when compared to the results obtained from long-term SWMM simulation runs.

ACKNOWLEDGEMENTS

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a	=	withdrawal rate (in./hr.);
b	=	detention storage capacity (in.);
c	=	given storage level due to previous event $(n - 1)$;
C	=	effluent and reservoir pollutant concentration (SWMM);
C^I	=	influent pollutant concentration (SWMM);
C_{eff}	=	downstream weighted pollutant concentration;
C_{BMP}	=	pollutant concentration leaving the pond;
D	=	detention time;
E( )	=	expected value of random variable;
I	=	inflow rate (SWMM);
k	=	$\beta\gamma/[(\alpha a + \beta)(\alpha a + \gamma)]$;
m	=	$\alpha\gamma a/[(\alpha a + \beta)(\gamma - \beta)]$;
n	=	index for current event;
O	=	outflow rate (SWMM);
R	=	removal fraction (SWMM);
R_{max}	=	maximum removal fraction (SWMM);
S	=	empty space in detention pond;
T	=	min $[c + aX_3, b]$;
t	=	time (SWMM);
V	=	volume of interest (SWMM);
V_E	=	effective volume;
X_1	=	runoff volume (in);
X_2	=	duration of runoff event (hrs.);
X_3	=	interevent time (hrs.);
Y	=	overflow volume (in.);
α	=	$1/E(X_1)$;
β	=	$1/E(X_2)$;
γ	=	$1/E(X_3)$;
η	=	overall efficiency;
η_{BMP}	=	settling efficiency (efficiency in the pond);
η_{FL}	=	capture efficiency;
θ	=	first order decay coefficient (SWMM);
Θ	=	$R/\Delta t$ (SWMM);
λ	=	Rainfall-Runoff Conversion Factor;

CHAPTER 1

INTRODUCTION

1.1 Motivation

The water quality impacts of stormwater discharges on receiving lakes and rivers are quite significant, as indicated by the Environmental Protection Agency's (EPA) recently drafted guidelines for stormwater discharge permits in the National Pollutant Discharge Elimination System (NPDES) program. Civil action may now be brought by the EPA against large municipalities which do not comply with the permit requirements. The EPA nationwide urban runoff program identified nonpoint pollution from urban areas as a major water quality problem [USEPA, 1983]. The primary carrier of areawide (nonpoint) pollutants is surface runoff from agricultural and urbanizing watersheds. In Virginia, several studies have pointed out the detrimental impact of nonpoint pollution on the Chesapeake Bay.

Because of the importance of nonpoint source (NPS) pollution control, municipalities in northern Virginia develop and maintain NPS pollution management programs. A major component of these programs is the utilization of Best Management Practices (BMP's) to control NPS pollution. A BMP being promoted by local regulatory

officials is to utilize stormwater detention basins as pollutant trapping units, by enhancing the detention time for pollutant settling ["BMP handbook ...," 1987]. Stormwater detention basins have long been utilized for reducing peak flows and monitoring studies reveal that stormwater detention basins provide effective pollutant removal, as well, provided sufficient size and settling time are available [Randall et al., 1983; Grizzard et al., 1986].

1.2 Objective

For detention ponds to work as Best Management Practices (BMPs) and prevent pollutant loads from being transported downstream, two goals must be accomplished: (1) capture of the runoff pollutant load by the pond; and (2) prevent the pollutant load from leaving the pond. The first goal is accomplished by providing sufficient volume within the pond to capture the runoff carrying the pollutant load. The second goal is accomplished by detaining the runoff in the pond for an extended time to allow the pollutant load to settle within the basin. These two goals are inseparable and in direct conflict.

This research focuses on detention basin design based on pollutant removal efficiency rather than traditional peak flow control. A planning level detention basin design methodology is presented that incorporates the two goals stated above for effective BMP detention pond design. A closed form analytical solution for the expected detention

time is presented. Coupled with an appropriate relationship between detention time and pollutant removal capability and an expression for the capture efficiency of the pond, the overall pollutant removal efficiency can be estimated. The design parameters for the detention pond, namely the storage capacity, b, and the withdrawal rate, a, can be determined based on the desired pollutant removal efficiency.

1.3 Organization of the Thesis

The thesis is organized as follows. Chapter 2 presents the runoff/storage process and a review of design methodologies for stormwater ponds. The probability distribution function for the random detention time is derived in Chapter 3. Using this probability distribution, the expression for the expected detention time, in terms of the design parameters and runoff statistics, is obtained. The expected detention time is then related to pollutant removal within the pond with the aid of the completely mixed concept for pollutant routing in Chapter 4. While the pollutant removal within the pond considers only the captured volume, the by-pass volume must be accounted for to define an overall efficiency of the pond. This overall efficiency equation is formulated in Chapter 5. The theoretical equations for expected detention time, device efficiency and overall efficiency are verified and illustrated through numerical examples in Chapter 6. Chapter 7 is a summary of the work presented.

CHAPTER 2

RUNOFF/STORAGE PROCESS

2.1 Background

Detention ponds were first used to reduce the peak flow from a developed area
to pre-development levels or other acceptable levels. The recognition of stormwater
runoff as a transporting process for NPS pollutants has brought about the use of these
ponds as BMPs. While the design methodologies used for quantity control are well
understood, design procedures for quality control are not, even though the use of extended
detention ponds for pollutant control is widespread. The methods of designing detention
ponds generally fall into three categories: (1) design storm approach; (2) continuous
simulation modeling; and (3) statistical methods which incorporate interevent times.

The design storm approach uses a single extreme event to size the basin to meet
either a peak reduction or satisfying a drawdown time (i.e. time to drain the entire pond)
requirement. Nix et al. (1988) observe that the variable nature of stormwater runoff
prevents a design storm approach from predicting the long-term performance of extended
detention ponds. Delleur and Padmanabhan (1981) and Goforth et al. (1983) point out
that, due to the sequential occurrence of runoff events, the available volume (empty

space) for capturing an event is random and single storm approaches do not account for it in the design. Despite the shortcomings of this type of design procedure, the design storm approach is commonly used.

The second approach involving continuous simulation essentially duplicates the natural occurrence of runoff events and is very useful for analyzing the long-term performance of a given basin configuration. By considering various alternative configurations, the engineer can select an appropriate design. Goforth et al. (1983) carry out an extensive performance analysis of a detention basin using the USEPA Storm Water Management Model [SWMM, Huber et al., 1980]. They consider the aforementioned goals of capturing and detaining the pollutant and point out the inseparable nature. Nix et al. (1988) also made the same observations from a set of SWMM simulations. Continuous simulations provide comprehensive evaluations of pollutant removal performance within detention basins. However, continuous simulation can be time-consuming and data-intensive and for planning stage calculations a simplified procedure may be sufficient.

The third approach involving statistical methods also considers interevent times and accounts for the net empty space available between events. Because they are aimed towards developing simplified probability-based equations, statistical methods often incorporate certain assumptions. As a result, statistical methods are considered to be planning level tools. Previous statistical planning methodologies by Howard (1976), Di

Toro and Small (1979), Loganathan et al. (1985) and Etoh and Kurita (1992) concentrate on the fraction of untreated runoff volumes leaving a detention basin. USEPA (1986) and Driscoll (1989) interpret the results of Di Toro and Small for pollutant settling within a wetpond. The fraction of untreated by-pass is interpreted as the fraction of pollutant that has not settled (Dorman, 1991).

This research differs significantly from the previous works in that it provides an explicit, closed form solution for the expected detention time E(D) under a random sequence of runoff events. A statistical methodology is presented that combines an estimate for flow capture efficiency with an estimate for removal in the pond based on E(D). This methodology is compared to the more rigorous results obtained from continuous simulation using the USEPA SWMM [Huber and Dickinson, 1988] model.

2.2 Problem Description

Traditionally, for the design of BMP ponds, many local governments use a drawdown time of 24-48 hours. Unfortunately drawdown time over-estimates the actual detention time. The importance of an average detention time is clear when one considers the variable nature of the runoff events arriving at a detention unit. The runoff volume may not be sufficient to fill the pond to capacity. In this case the full drawdown time is not realized. This points out a clear distinction between drawdown time and detention time. The drawdown time is the upper limit for the detention time. From a practical

standpoint, the detention time will always be less than the drawdown time.

Because of the sequential nature of runoff events, it is very likely that the detention unit will only be part empty when a new event arrives. The greatest opportunity to empty the detention unit (so that a large amount of the next runoff event's volume can be captured) is during the interevent time. However, if the next event arrives too quickly the desired settling may not be realized for the present event. The amount of empty volume at the onset of a new event is important in capturing the first flush, which is usually the most significant part of the storm in terms of pollutant inflow.

The following conceptualization is used in obtaining an estimator for the detention time (see Figure 2-1). A sequence of runoff events, each with volume X_1 (inches), event duration X_2 (hours), and interevent time, X_3 (hours), arrives at the detention storage unit. During a runoff event, the empty space of a detention storage unit is being filled by incoming runoff. At the same time, the stormwater is withdrawn from the unit with storage capacity, b (inches), at a rate, a (inches/hour), creating empty space for the progressing runoff. A by-pass occurs when the incoming runoff volume exceeds the sum of the initially available empty space and the volume made available by the withdrawal (outflow) during the event. If no by-pass occurs, then all the hydraulic load, and hence the pollutant load is captured by the unit.

If a by-pass does occur, then only that part of the load corresponding to the intercepted runoff volume is captured and only a part of this captured load will settle due
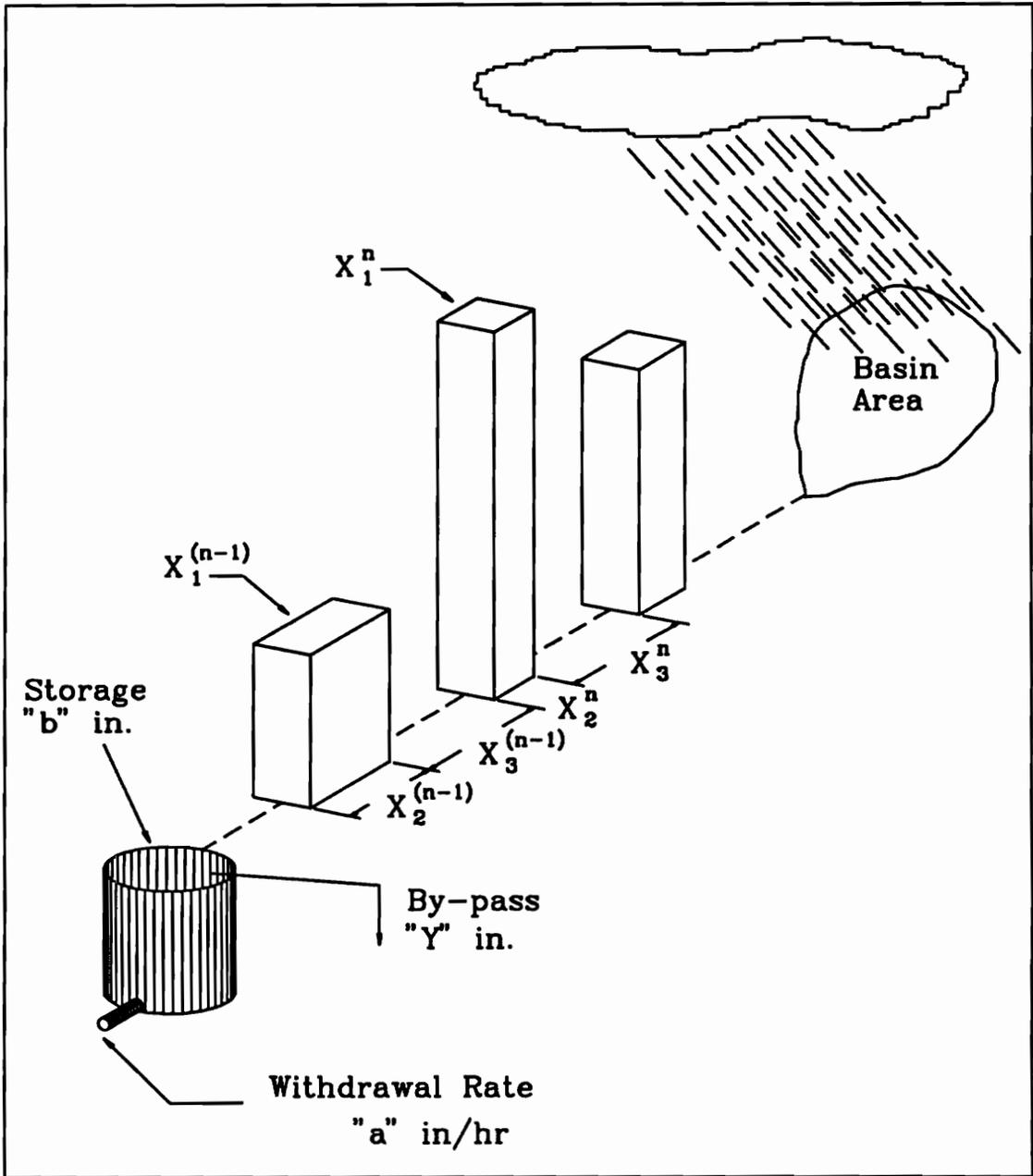
FIGURE 2-1. Runoff/Storage Process

to the available detention time. If the detention time is not sufficient, the next event may simply push out whatever is remaining from the previously intercepted pollutant load. As more stormwater is retained by enhancing the detention time the arrival of the next event is more likely to cause a by-pass. Therefore, the efficiency of the unit depends on two factors, namely: (1) how much stormwater is intercepted to minimize by-pass; and (2) how long the intercepted water is detained in order to improve pollutant removal. The second point is in conflict with the first because extending detention time reduces the available empty space.

The following notation is applied to the nth runoff cycle, as described in Figure 2-2: $X_1(n)$ = volume of the nth event; $X_2(n)$ = duration of nth event; $X_3(n)$ = time between nth and (n+1)th event; $Y(n)$ = by-pass volume at the end of the nth event; $S(n)$ = available storage (empty space) at the end of the nth runoff event; and $T(n)$ = storage available at the beginning of the nth event. The amount of empty space available at the beginning of the nth cycle, $T(n)$, is the sum of the empty space at the end of the previous cycle, $S(n-1)$, plus the empty space created by withdrawal during the interevent period $X_3(n-1)$ given by

$$T(n) = \min \left\{ S(n-1) + aX_3(n-1), b \right\} \tag{2-1}$$

$T(n)$ will equal b if the interevent duration is sufficient to empty the volume of water in the pond at the end of event n-1. If event n arrives before the pond is empty, the available storage will be a fraction of b. The available storage at the end of the nth event
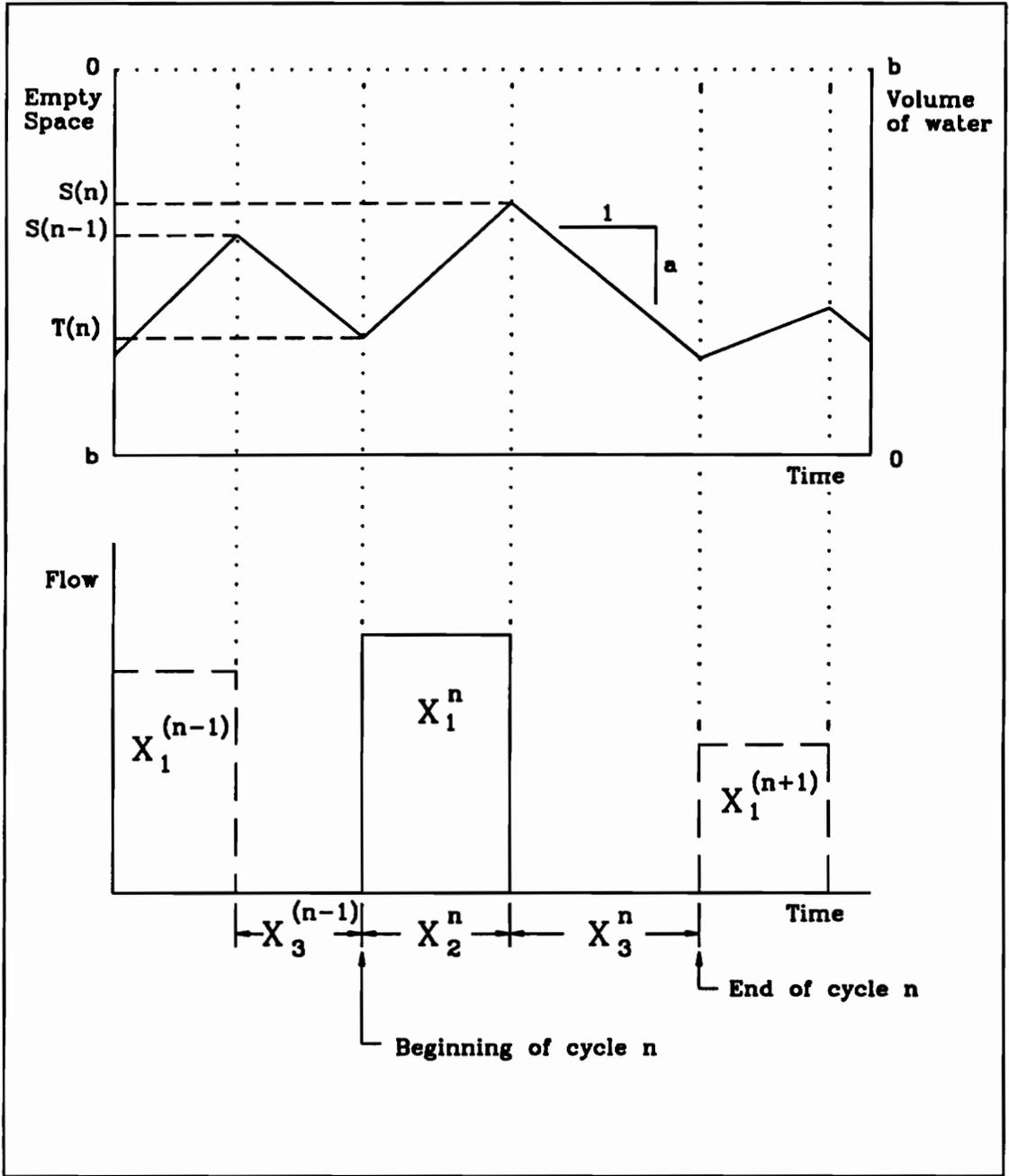
FIGURE 2-2. Runoff/Storage Cycle

which equals the available storage at the beginning of the event, $T(n)$, minus the empty space lost during an event, $X_1(n) - aX_2(n)$, is written as:

$$S(n) = \min\left\{ \max\left[T(n) - (X_1(n) - aX_2(n)), 0 \right], b \right\} . \tag{2-2}$$

It should also be noted that $S(n)$ has a lower bound of zero. If the available storage is less than the difference between the incoming volume and the volume withdrawn during an event, a by-pass will take place. A by-pass will take place whenever:

$$T(n) < X_1(n) - aX_2(n) \tag{2-3}$$

and the by-pass volume is:

$$Y(n) = X_1(n) - aX_2(n) - T(n) \qquad \text{for } Y(n) > 0 . \tag{2-4}$$

These definitions and assumptions are used in the derivation of the expected detention time in Chapter 3.

CHAPTER 3

ESTIMATING DETENTION TIME

3.1 Residence Time Theory

The following description is due to Levenspiel (1972), Nauman and Buffham (1983) and Fogler (1992). Particles enter the detention pond with the inflow. These particles have zero age as they first enter the pond and start aging as long as they are within the pond. Aging stops whenever a particle leaves the pond. The age of a particle when it departs from the pond is called the 'residence time' or 'detention time' for that particle. If the system is a pipe instead of a pond the residence time is nearly equal for all particles and is the travel time within the system. In ponds, such a uniform travel time for the particles is not possible. In a pond, particles carried by the influent stay mixed within the pond volume for a certain amount of time before joining the outflow. Pond systems exhibit dead zones (stagnant regions) which do not exchange material with well mixed regions. Some particles may also be short circuited in that they may be discharged before they mix well within the pond volume [See Figure 3.1].

The aforementioned phenomena also imply that different particles stay for different time periods within the pond before they settle to the bottom or are discharged through
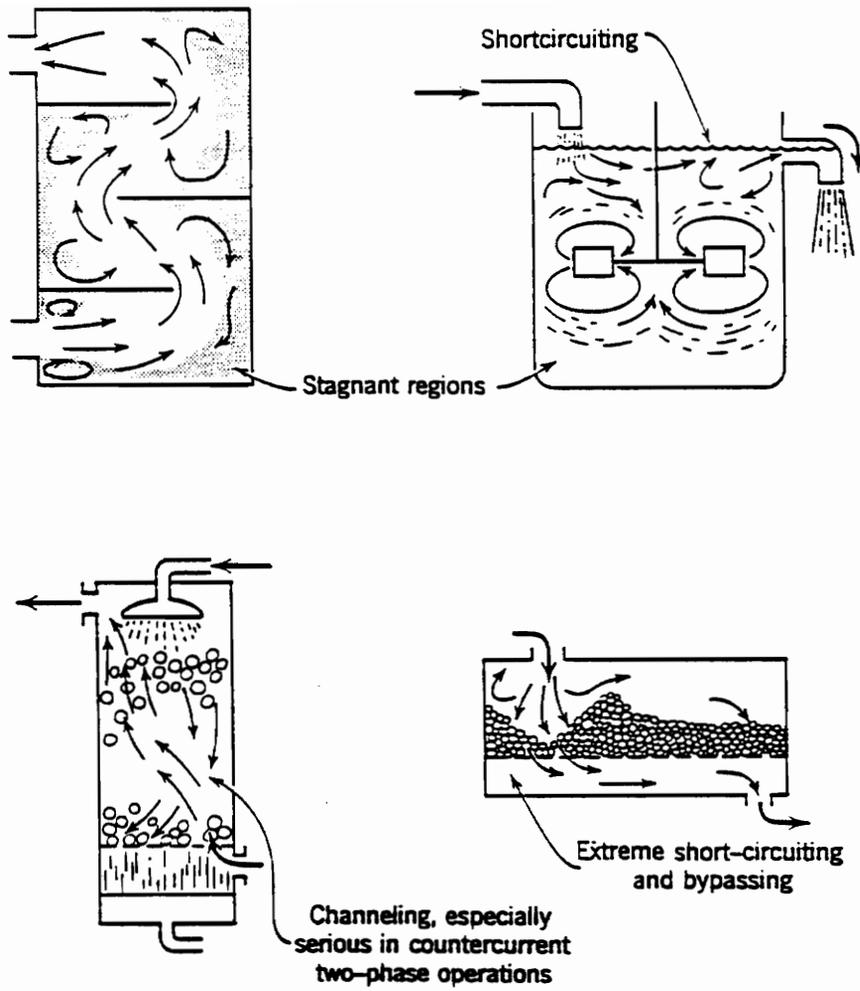
FIGURE 3-1. Nonideal flow patterns which may exist in process equipment [Levenspiel, 1972].

the orifice. Therefore, for N number of particles carried by the influent which take different routes to the outlet one may denote $t_1, t_2, .. t_N$ be the periods of stay or residence times of these particles. In general, one may denote R_T to be the random residence time of a particle. In this section we are interested in deriving an expression for the residence time, $E(R_T)$.

To begin, let us assume that the detention pond contains certain particles in its contents. Following Fogler (1992) the volume of particles carried away by the water at flow rate, a, during an interval dt is given by

$$dV = [a\,dt][1 - F_R(t)] \tag{3-1}$$

in which: $F_R(t) = P(R_T \leq t)$ = probability that the residence time is less that or equal to t. The third term on the right hand side of Eq.(3-1) indicates that for particles to be carried away by time t, they must have existed within the pond for at least time t. One may also claim that from an initial volume, V, the volume of particles removed during dt around time t is

$$dV = V [F_R(t + dt) - F_R(t)] \tag{3-2}$$

in which: $F_R(t+dt)-F_R(t)$= proportion of particles with ages between t and t+dt. That is, all particles with ages between t and t+dt are removed. Equating Eqs. (3-1) and (3-2) we obtain

$$a\,dt[1 - F_R(t)] = V f_R(t)\,dt \tag{3-3}$$

and

$$\int_0^\infty f_R(t)\,dt = 1 = \frac{a}{V}\int_0^\infty [1 - F_R(t)]\,dt \ . \tag{3-4}$$

For a nonnegative random variable [See Appendix A; Taylor and Karlin, 1984]

$$E[R_T] = \int_0^\infty [1 - F_R(t)]\,dt \ . \tag{3-5}$$

Therefore we obtain

$$E[R_T] = \frac{V}{a} \tag{3-6}$$

which is the hydraulic detention time.

3.2 Defining Detention Time

As shown in the previous section, if the detention pond is considered to be a completely mixed tank, the detention time or residence time for the nth event, $D(n)$, can be defined as the time it takes to empty the volume of water present in the pond at the end of the nth runoff event. In this study, the detention time is assumed to begin at the end of runoff event n and the event duration is not included. The event duration is considered to be a mixing period. The detention time for the nth event will be:

$$D(n) = \frac{V(n)}{a} \qquad \text{for} \quad 0 \le V(n) \le b \qquad (3\text{-}7)$$

where: $D(n)$ = the detention time for the nth event; $V(n)$ = the volume of water in the pond at the end of runoff event n; a = withdrawal rate from the pond (in/hr); and b = the maximum available storage for extended detention.

However, Eq.(3-7) is not appropriate if $D(n) > X_3(n)$. The motivation for defining detention time is to evaluate the pollutant removal efficiency of a given pond based on the time given for pollutants to settle. The composition of runoff event n+1 will have a different composition from event n and so forth. Following the assumption that the pond is a completely mixed tank, the composition of the pond will change if event n+1 arrives before the pond is empty. Consequently, the definition of $D(n)$ given in Eq.(3-7) is not appropriate if $V(n)/a > X_3(n)$. The volume of water in the pond at the end of event n, $V(n)$, is considered to receive "treatment" for the time it takes to empty that volume or the interevent time period, whichever is smaller. Within the concept of the cyclic runoff process, the detention time for event n is confined to the time within cycle n. Therefore, $D(n)$ can not exceed $X_3(n)$ and the detention time can be defined as:

$$D(n) = \min\left(\frac{V(n)}{a}, X_3^{(n)}\right) \qquad \text{for} \quad 0 \le V(n) \le b. \qquad (3\text{-}8)$$

From the problem description in Chapter 2, by assuming exponential probability distributions for runoff volumes, durations, and interevent time the probability distribution

for the amount of empty space available at the end of runoff event n, S(n) can be derived [Loganathan et al. (1985)]. The derived probability distribution of the available storage at the end of the nth runoff event is given as:

$$P[S(n) = 0 \mid S(n-1) = c] = k \left(\exp[-\alpha c] + \frac{\alpha a}{\gamma} \exp\left[-b\left(\alpha + \frac{\gamma}{a}\right) + \frac{\gamma}{a}c\right] \right) \qquad (3\text{-}9)$$

$$P[S(n) \le s \mid S(n-1) = c] = k \left(\exp\left[-\alpha(c-s)\right] + \frac{\alpha a}{\gamma} \exp\left[-\alpha(b-s) - \frac{\gamma}{a}(b-c)\right] \right) \qquad (3\text{-}10)$$

$$\text{for } 0 < s \le c$$

$$
\begin{aligned}
P[S(n) \le s \mid S(n-1) = c] = {}& 1 - m \left(\exp\left[-\frac{\beta}{a}(s-c)\right] - \exp\left[-\frac{\gamma}{a}(s-c)\right] \right) \\
& - (1-k) \exp\left[-\frac{\gamma}{a}(s-c)\right] \\
& + \frac{k\alpha a}{\gamma} \exp\left[-\alpha(b-s) - \frac{\gamma}{a}(b-c)\right] \qquad \text{for } c \le s < b
\end{aligned}
\qquad (3\text{-}11)
$$

and

$$P[S(n) = b \mid S(n-1) = c] = m \left(\exp\left[-\frac{\beta}{a}(b-c)\right] - \frac{\beta}{\gamma} \exp\left[-\frac{\gamma}{a}(b-c)\right] \right) \qquad (3\text{-}12)$$

where k and m are defined as:

$$k = \frac{\beta \gamma}{(\alpha a + \beta)(\alpha a + \gamma)} \qquad\qquad (3\text{-}13)$$

and

$$m = \frac{\alpha \gamma a}{(\alpha a + \beta)(\gamma - \beta)} \; . \qquad\qquad (3\text{-}14)$$

The parameter c is defined as the value of the available storage at the end of the previous runoff event, S(n-1). V(n) can be defined as the difference between the maximum storage available and the empty space at the end of event n. As a result, Eq.(3-8) can be rewritten in terms of S(n):

$$D(n) = \min \left(\frac{b - S(n)}{a} \; , \; X_3(n) \right) \qquad \text{for} \quad 0 \le S(n) \le b \; . \qquad (3\text{-}15)$$

It should be noted that the only period of time during the runoff cycle available for detention is the time between runoff events or interevent time. The duration of runoff, $X_2(n)$, is not considered part of D(n). Eq.(3-15) is graphically represented by Figures 3-2 and 3-3. The detention time in Figure 3-2 is defined by the volume of water in the pond. Event n fills the pond to a certain volume, b-S(n), at the end of the event the volume of water in the pond begins to decrease at a constant rate, a. Event n+1 does not arrive at the pond until after the pond is empty. Because (b-S(n))/a is less than $X_3(n)$, the detention time for cycle n is defined as (b-S(n))/a. The detention time in Figure 3-3 is
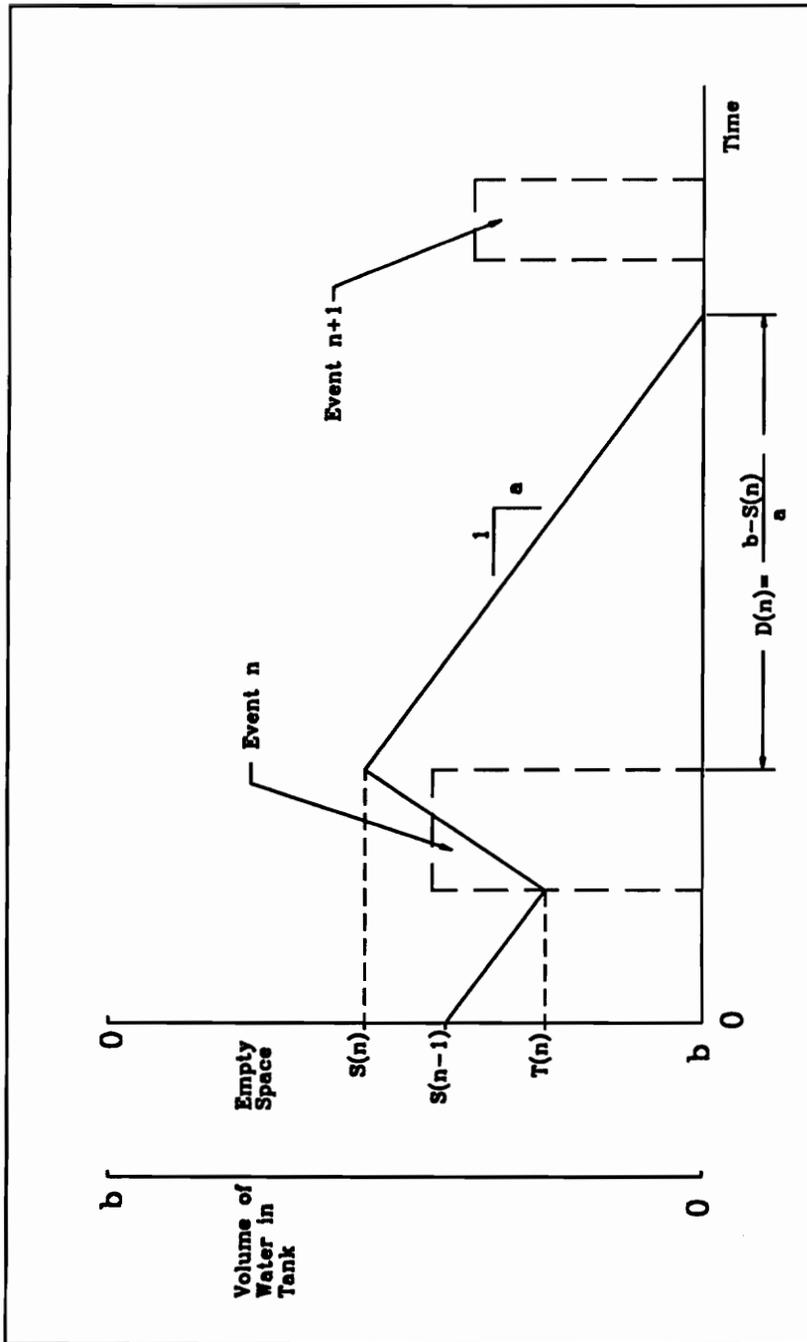
FIGURE 3-2. Detention Time Less Than Interevent Time
(Nonoverflow Condition)
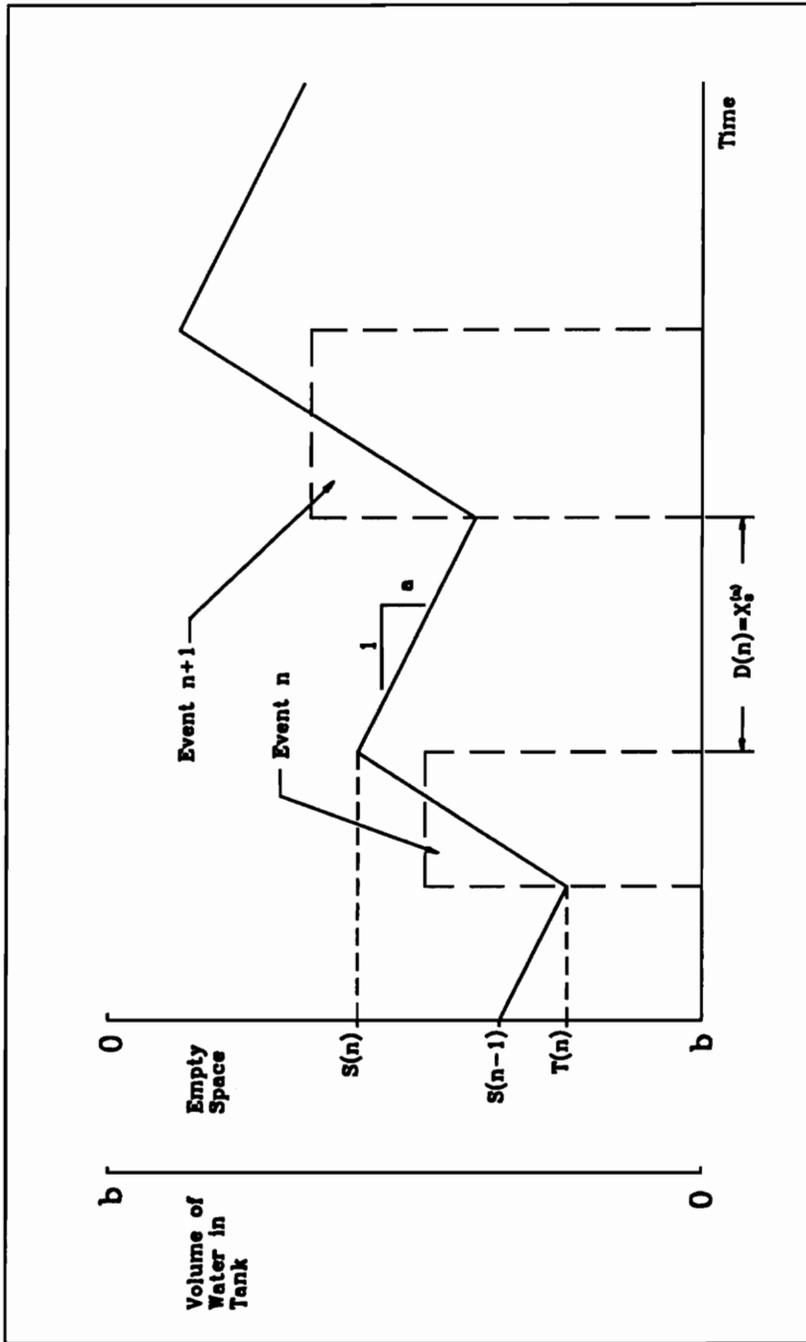
FIGURE 3-3. Detention Time equal to Interevent Time
(No By-pass)

defined by the interevent duration or $X_3(n)$. Event n again fills the pond to a certain volume b-S(n), but event n+1 arrives before the total volume is released from the pond. Therefore, the detention time for the nth runoff cycle is defined as the interevent time $X_3(n)$.

If a by-pass situation occurs, the available storage at the end of event n will be forced to zero. Because of the limited storage volume there is a finite probability a by-pass will occur, S(n) = 0 [see Eq.(3-9)]. The probability that a by-pass will occur is equal to the probability S(n) = 0.

$$P(Y>0) = P[S(n) = 0] \qquad\qquad (3-16)$$

where Y is by-pass.

The detention time for events that have by-pass are defined in the same manner as normal events. By forcing S(n)= 0, Eq.(3-15) will take the form:

$$D(n) = \min\left(\frac{b}{a}, X_3(n)\right) \qquad \text{for } S(n) = 0 \ . \qquad (3-17)$$

Similar to Eq.(3-15), the detention time for event n will be defined as b/a if event n+1 arrives after the pond has been emptied. This scenario is depicted in Figure 3-4. Event n fills the pond past capacity and causes a by-pass. The empty space at the end of event n is defined as zero. The detention time is simply b/a because $X_3(n) > b/a$. Figure 3-5 illustrates the case when $X_3(n)<b/a$. The pond is filled past capacity and the next event
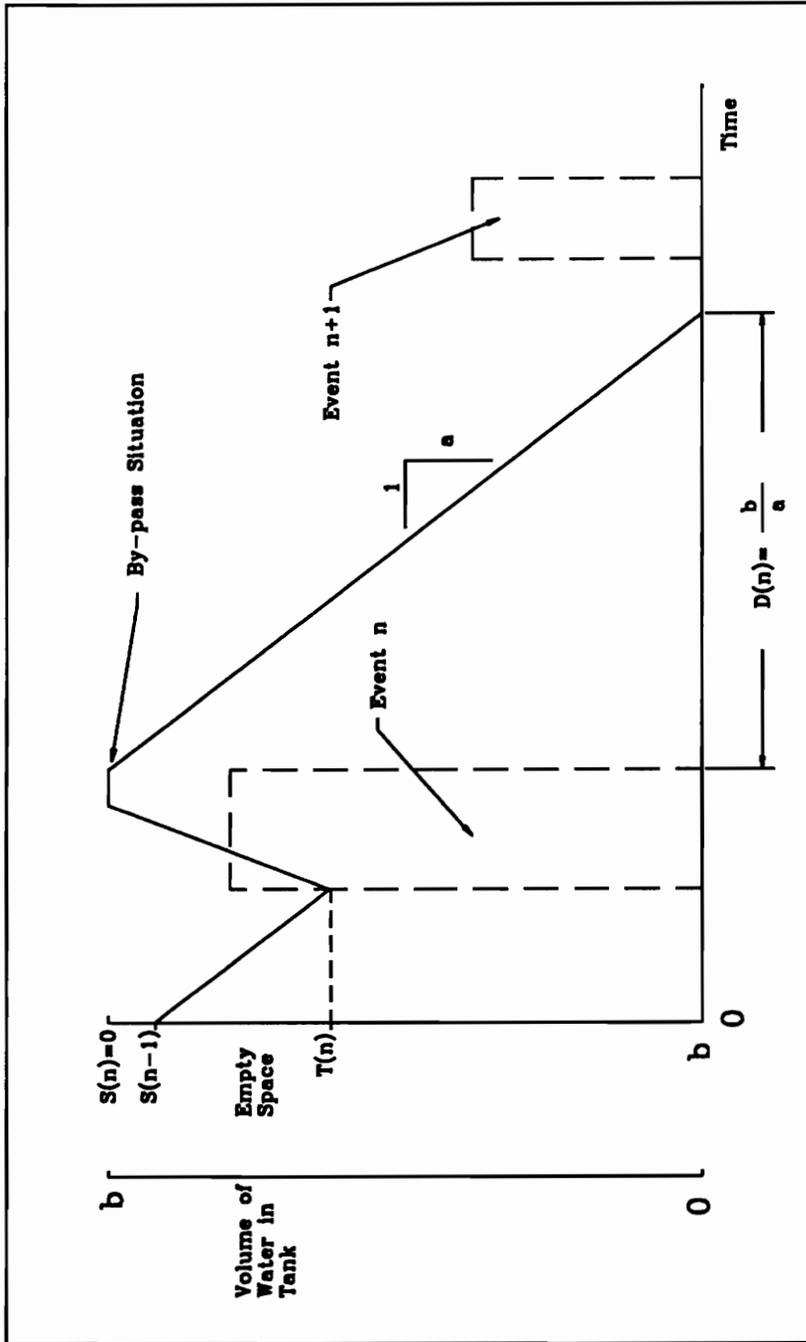
FIGURE 3-4. Detention Time less than Interevent Time
(By-pass Situation)
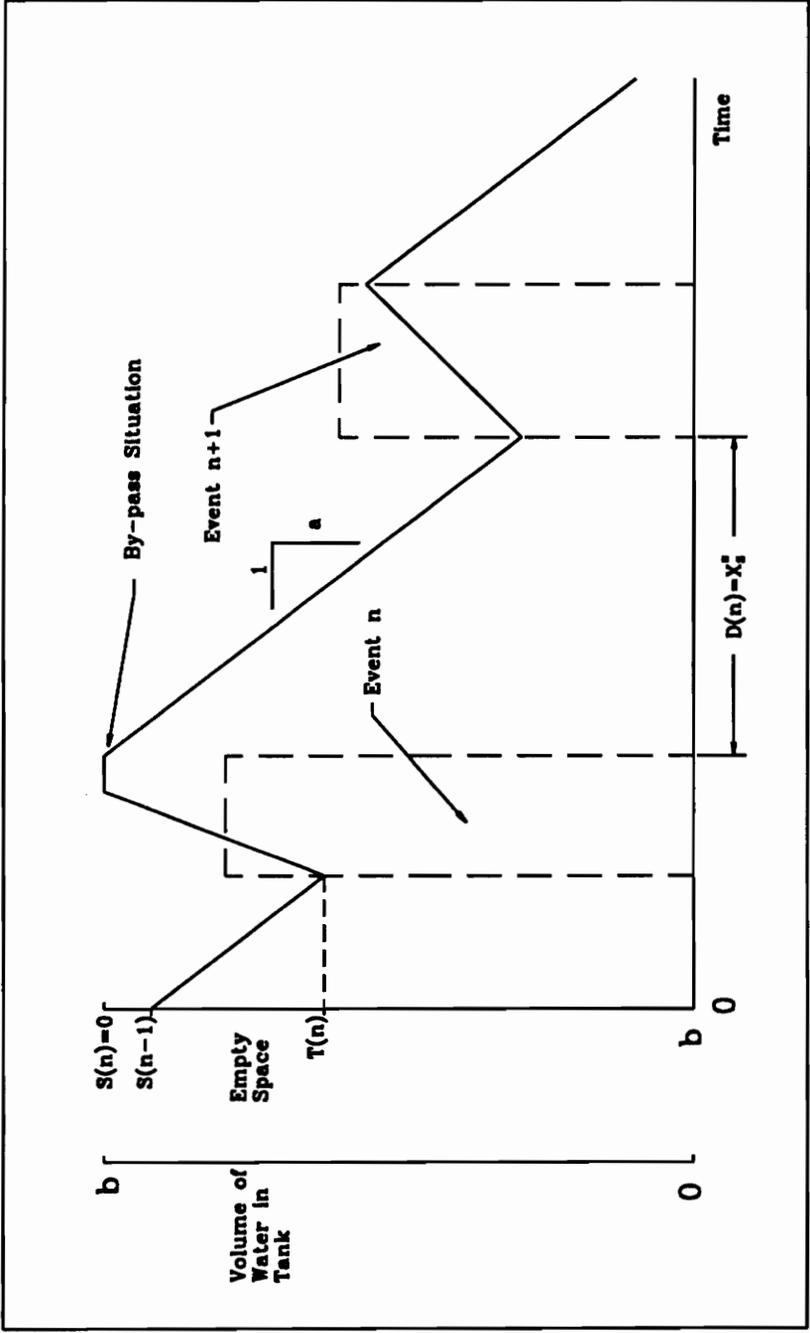
FIGURE 3-5. Detention Time equal to Interevent Time (By-pass Situation)

arrives before the pond is emptied. The detention time is defined as $X_3(n)$.

3.3 Derivation of the Distribution For Detention Time

The distribution of D(n) can be derived based on Eqs. (3-9), (3-10), (3-11), (3-12), and (3-15). Because S(n), the empty storage at the end of the nth event, is not dependent on the interevent time for the nth event, $X_3(n)$ [the time between the nth and the n+1 event], S(n) and $X_3(n)$ are physically and statistically independent random variables. Therefore, the probability that D(n) is greater than some value d can be expressed as:

$$P[D(n) \geq d] = P\left(\frac{b - S(n)}{a} \geq d\right) P(X_3 \geq d)$$

$$= P(S(n) \leq b - ad) \, P(X_3 \geq d) \qquad \text{for } 0 < d < \frac{b}{a} \, . \tag{3-18}$$

This general expression can be used to define the probability for a specified range. Also note that because D(n) can neither exceed b/a nor be below zero, there will be two probability point masses at these extremes. The distribution of detention time between zero and b/a can be derived by considering Eqs. (3-10) and (3-11) defining the distributions of S(n). For Case 1, the distribution of S(n) is defined for the range c≤s<b.

If s is set equal to (b-ad) the resulting expression is:

Case 1: $0 < d \leq \dfrac{b-c}{a}$.

Substituting equation (3-11) into equation (3-18) the resulting expression for the

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probability that D is greater than some threshold value is:

$$P[D(n) \geq d] = \left(1 - m\left(\exp\left[-\frac{\beta}{a}(b - ad - c)\right] - \left[\exp\frac{\gamma}{a}(b - adc)\right]\right)\right.$$

$$-(1 - k)\exp\left[-\frac{\gamma}{a}(b - ad - c)\right]$$

$$\left. + \frac{k\alpha a}{\gamma}\exp\left[-\alpha ad - \frac{\gamma}{a}(b - c)\right]\right)\exp[-\gamma d] \qquad (3\text{-}19)$$

$$\text{for } 0 < d \leq \frac{b - c}{a}$$

and

$$P(D(n) \leq d) = 1 - P(D(n) \geq d) . \qquad (3\text{-}20)$$

Therefore, the probability D(n) is less than some threshold d is expressed as:

$$P[D(n) \leq d] = \left(1 - \exp[-\gamma d]\right) + m\left(\exp\left[-\frac{\beta}{a}(b-c) - d(\gamma - \beta)\right]\right)$$

$$-\exp\left[-\frac{\gamma}{a}(b-c)\right]\right) + (1-k)\exp\left[-\frac{\gamma}{a}(b-c)\right] \qquad (3\text{-}21)$$

$$-\frac{k\alpha a}{\gamma}\exp\left[-d(\alpha a + \gamma) - \frac{\gamma}{a}(b-c)\right]$$

$$\text{for } 0 < d \leq \frac{b-c}{a} \, .$$

Note that if c=0, Eq. (3-21) will define the distribution of d between 0 and b/a.

For Case 2, S(n) is defined in the range s≤c<b. If s is set equal to b-ad the resulting expression is :

Case 2: $\dfrac{b-c}{a} < d < \dfrac{b}{a} \, .$

Substituting Eq.(3-10) into Eq.(3-18) the resulting expression for the probability d is greater than some threshold value is:

$$P[D(n) \geq d] = k \left(\exp\left[-\alpha(c - b + ad) \right] \right.$$

$$\left. + \frac{\alpha a}{\gamma} \exp\left[-\alpha a d - \frac{\gamma}{a}(b - c) \right] \right) \exp[-\gamma d] \qquad (3\text{-}22)$$

$$\text{for } \frac{b-c}{a} < d < \frac{b}{a} \; .$$

Rearranging according to Eq.(3-20), Eq. (3-22) becomes:

$$P[D(n) \leq d] = 1 - k \left(\exp\left[-d(\alpha a + \gamma) - \alpha(c - b) \right] \right.$$

$$\left. + \frac{\alpha a}{\gamma} \exp\left[-d(\alpha a + \gamma) - \frac{\gamma}{a}(b - c) \right] \right) \qquad (3\text{-}23)$$

$$\text{for } \frac{b-c}{a} < d < \frac{b}{a} \; .$$

Note that if c=b, Eq.(3-23) will define the distribution of d between 0 and b/a.

Eqs.(3-21) and (3-23) define the distribution of d between 0 and b/a, but the distribution also consists of point probability masses for d = 0 and d = b/a. The probability that D(n) is equal to zero is obtained as follows:

$$P(D(n) = 0) = P(S(n) = b) \; P(X_3 \geq 0) \qquad \text{for } d = 0 \; . \qquad (3\text{-}24)$$

The physical interpretation for the point mass at zero is that the event was not detained in the pond. The available storage at the end of the nth event was equal to the total volume of storage available, b. In other words, no water is residing in the pond at the end the event. For example, if the pond is empty upon the arrival of the nth event, the detention time would be zero if the runoff rate was less than the withdrawal rate, a. The smaller the withdrawal rate, a, the smaller $P(D(n)=0)$ will be. The probability $S(n)=b$ is given by Eq. (3-12). Substituting Eq.(3-12) into (3-24) and noting that the probability $X_3(n) \geq 0$ is unity, Eq.(3-24) becomes:

$$P[D(n)=0] = m \left(\exp\left[-\frac{\beta}{a}(b-c)\right] - \frac{\beta}{\gamma} \exp\left[-\frac{\gamma}{a}(b-c)\right] \right)$$

(3-25)

for $d = 0$.

The expression for the probability that $D(n) = b/a$ is:

$$P\left(D(n) = \frac{b}{a}\right) = P(S(n)=0) \; P\left(X_3 \geq \frac{b}{a}\right) \qquad \text{for } d = \frac{b}{a} \; .$$

(3-26)

The point mass at $d=b/a$ can be interpreted as the probability the pond is completely filled (by-pass occurs) and the interevent time is greater than b/a. The volume of water that passes through the BMP control device (from full storage) is considered to experience detention time equal to b/a. It must be noted that positive detention time is applicable only for the portion of runoff captured. The by-pass portion does not experience any

detention and must be considered separately. Physically, if the pond is full and the next event does not arrive before the pond is completely emptied, the detention time is equal to b/a. The size of the point mass depends on the relative sizes of b and a. If b is held constant, the point mass at b/a will increase as the withdrawal rate decreases. If a is held constant, the point mass at b/a will increase as b decreases. The detention time will be equal to the drawdown time if the runoff volume is sufficient to fill the pond to the full pool condition at the end of the runoff event [S(n)=0] and the interevent time is large enough to accommodate the complete draining of the pond, i.e. ($X_3 \geq b/a$). The probability S(n)=0 is given by Eq.(3-9) and the probability $X_3 \leq b/a$ is given by the equation:

$$P\left(X_3 \geq \frac{b}{a}\right) = \exp\left(-\frac{\gamma b}{a}\right).$$ (3-27)

Substituting Eq. (3-26) becomes

$$P\left(D(n) = \frac{b}{a}\right) = k\left(\exp\left[-\alpha c - \frac{\gamma b}{a}\right] + \frac{\alpha a}{\gamma} \exp\left[-b\left(\alpha + \frac{\gamma}{a}\right) - \frac{\gamma}{a}(b-c)\right]\right)$$ (3-28)

$$\text{for } d = \frac{b}{a}.$$

The probability distribution for the detention time has been derived as:

$$P[D(n)=0] = m\left(\exp\left[-\frac{\beta}{a}(b-c)\right] - \frac{\beta}{\gamma}\exp\left[-\frac{\gamma}{a}(b-c)\right]\right)$$

(3-25)

for d=0

$$P[D(n)\leq d] = \left(1-\exp[-\gamma d]\right) + m\left(\exp\left[-\frac{\beta}{a}(b-c) - d(\gamma-\beta)\right]\right.$$

$$\left.-\exp\left[-\frac{\gamma}{a}(b-c)\right]\right) + (1-k)\exp\left[-\frac{\gamma}{a}(b-c)\right]$$

(3-21)

$$-\frac{k\alpha a}{\gamma}\exp\left[-d(\alpha a+\gamma) - \frac{\gamma}{a}(b-c)\right]$$

for $0 < d \leq \dfrac{b-c}{a}$

$$P[D(n)\leq d] = 1 - k\left(\exp\left[-d(\alpha a+\gamma) - \alpha(c-b)\right]\right.$$

$$\left.+\frac{\alpha a}{\gamma}\exp\left[-d(\alpha a+\gamma) - \frac{\gamma}{a}(b-c)\right]\right)$$

(3-23)

for $\dfrac{b-c}{a} < d < \dfrac{b}{a}$

and

$$P\left(D(n) = \frac{b}{a}\right) = k\left(\exp\left[-\alpha c - \frac{\gamma b}{a}\right] + \frac{\alpha a}{\gamma}\exp\left[-b\left(\alpha + \frac{\gamma}{a}\right) - \frac{\gamma}{a}(b-c)\right]\right)$$

(3-28)

$$\text{for } d = \frac{b}{a} \ .$$

The probability density function of detention time is equal to the derivative of the probability distribution function with respect to d:

$$f_D(d) = \frac{d}{dd} P[D(n) \leq d] \ .$$

(3-29)

Therefore, the probability density function can be expressed as:

$$f_D(d) = \gamma \exp(-\gamma d) - m(\gamma - \beta)\exp\left[-\frac{\beta}{a}(b-c) - d(\gamma - \beta)\right]$$

$$+ \frac{k\alpha a}{\gamma}\left(\alpha a + \gamma\right)\exp\left[-d(\alpha a + \gamma) - \frac{\gamma}{a}(b-c)\right]$$

(3-30)

$$\text{for } 0 < d < \frac{b-c}{a}$$

and

$$f_D(d) = k(\alpha a + \gamma)\exp\left[-d(\alpha a + \gamma)\right]\left(\exp\left[-\alpha(c-b)\right] + \frac{\alpha a}{\gamma}\exp\left[-\frac{\gamma}{a}(b-c)\right]\right)$$

(3-31)

$$\text{for } \frac{b-c}{a} < d < \frac{b}{a}$$

with point masses at d=0 and d=b/a given by equations (3-28) and (3-31) respectively.

Note that f(d) is continuous at (b-c)/a. The expected value for detention time is obtained as:

$$E(D) = \int d \; dF_D(d) \; . \tag{3-32}$$

This Stieltjes integral is evaluated as:

$$E(D) = \int_{0^+}^{\frac{b-c}{a}} d \left\{ \gamma \exp(-\gamma d) - m(\gamma - \beta) \exp\left[-\frac{\beta}{a}(b-c) - d(\gamma - \beta)\right] \right.$$

$$\left. + \frac{k\alpha a}{\gamma}\left(\alpha a + \gamma\right) \exp\left[-d(\alpha a + \gamma) - \frac{\gamma}{a}(b-c)\right] \right\} \; dd$$

$$+ \int_{\frac{b-c}{a}}^{\frac{b^-}{a}} d \left\{ k(\alpha a + \gamma) \exp\left[-d(\alpha a + \gamma)\right] \left(\exp\left[-\alpha(c-b)\right] \right. \right. \tag{3-33}$$

$$\left. \left. + \frac{\alpha a}{\gamma} \exp\left[-\frac{\gamma}{a}(b-c)\right] \right) \right\} \; dd$$

$$+ \frac{b}{a} k \left(\exp\left[\alpha c - \frac{\gamma b}{a}\right] + \frac{\alpha a}{\gamma} \exp\left[-b\left(\alpha + \frac{\gamma}{a}\right) - \frac{\gamma}{a}(b-c)\right] \right) \; .$$

Simplifying

$$
E(D) = \exp\left[-\frac{\gamma}{a}(b-c)\right] \left\{ \frac{c-b}{a} - \frac{1}{\gamma} + \left(\frac{m}{a} + \frac{k}{a}\right)(b-c) + \frac{m}{(\gamma-\beta)} \right.
$$

$$
+ \frac{k}{(\alpha a + \gamma)}\left(1 + \frac{\alpha a}{\gamma}\left(1 - \exp\left[-\frac{b}{a}(\alpha a + \gamma)\right]\right)\right)\right\} \qquad (3\text{-}34)
$$

$$
- \frac{m}{(\gamma-\beta)}\exp\left[-\frac{\beta}{a}(b-c)\right] - \frac{k}{(\alpha a + \gamma)}\exp\left[-\alpha c - \frac{b}{a}\gamma\right] + \frac{1}{\gamma} \; .
$$

3.4 Choosing c

To evaluate Eq.(3-34), the storage at the end of the (n-1)th event [S(n-1)] must be assumed [c=S(n-1)]. The obvious choice is to evaluate E(D) at c=b and c=0 which will give the lower and upper bounds for E(D), respectively. These two values may simply be averaged to obtain a single E(D). As an alternative, one may consider using the expected value of S(n) given by Eq. (B-6) and derived in Appendix B as the value of c in Eq. (3-34). The resulting value for E(D) will fall between the lowerbound E(D) [c=b] and the upperbound E(D) [c=0].

When S(n-1)=b, there is no carryover storage from the previous event and the pond contains only that amount of water which is left over by the current, namely the nth event. Therefore, over the possible range of values for c, the minimum amount of water

in the tank at the end of the nth event, V(n), is obtained when c=b. For a given interevent time and withdrawal rate, the minimum E(D) will be obtained when V(n) is the smallest [note Eq. (3-8)]. As a result, the lowerbound E(D) is obtained when c=b. In contrast, when c=0 (a full pond at the end of the previous event) the maximum amount of water in the tank at the end of the nth event, V(n), is obtained. Therefore, the upperbound detention time is obtained when c = 0.

For the lowerbound (the basin is empty at the end of the (n-1)th event with S(n-1) = b), from Eq. (3-34) by putting c=b, the expectation of the detention time is obtained as

$$E[D|S(n-1) = b] = \frac{\beta}{(\alpha a + \beta)(\alpha a + \gamma)} \left[1 - \exp\left(-\frac{b}{a}(\alpha a + \gamma) \right) \right]. \tag{3-35}$$

To obtain a conservative estimate of E(D), we assume that the event duration is not included in the detention time. Let us assume that the event durations are very small, so that β is large. If the interevent time is large with a sufficiently large pond capacity, then one would expect the detention time to be equal to the drainage time of the volume α^{-1} [α is the reciprocal of the average runoff volume, $E(X_1)$] at the rate a. That is, the expected detention time must equal $(\alpha a)^{-1}$. For large interevent times, γ goes to zero and for short durations β is large. For a large value of b the entire runoff will be captured and Eq. (3-35) precisely yields $(\alpha a)^{-1}$ as the expected detention time.

3.5 Verification of E(D)

Eq. (3-34) is verified through simulation using the EPA Stormwater Management Model [SWMM, Huber and Dickinson, 1988] in Chapter 6. Eq.(3-34) will prove to be an accurate estimator for the actual detention in an extended detention stormwater facility. E(D) will prove to be a much superior design tool than the drawdown time which is commonly used in design today.

CHAPTER 4

SETTLING EFFICIENCY

4.1 Role of Detention Time

The removal of pollutants in a detention basin is primarily dependent on the amount of time made available for pollutants to settle [Grizzard et al., 1986; Martin, 1988; Nix, 1985; Randall et al., 1982; and Schueler, 1987]. As a result, pollutant removal can be plotted as a function of settling time. Schueler (1987) reports pollutant removal as a function of settling time. His results were compiled from column study tests conducted at the Occoquan Watershed Monitoring Lab (OWML) and are presented in Figure 4-1. In this research, the expected detention time is a measure of settling time. To estimate the settling efficiency as a function of detention time a suitable relationship between settling efficiency and expected detention time should be established. In the absence of actual pond data, one can use the curves reported by Schueler (1987). Another option is to develop a set of standard curves for specified pollutants by simulation using a theoretical removal algorithm, such as complete mixing. The latter method is employed in this study. The SWMM Storage/Treatment (S/T) Block is used in conjunction with Eq.(3-34) to compute the settling efficiency as a function of detention time.
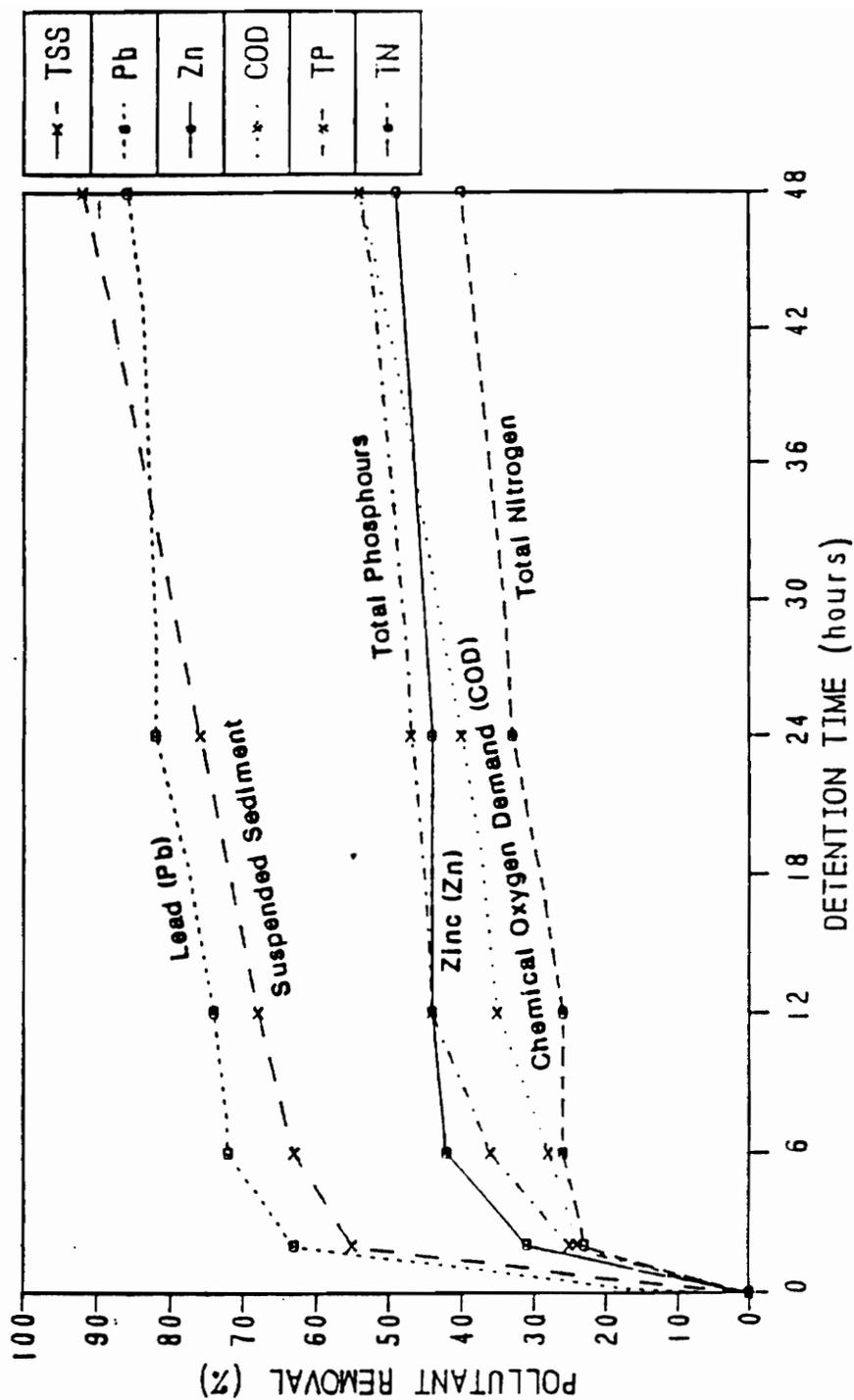
FIGURE 4-1. Removal Rate vs. Detention Time For Selected Pollutants. Note: Based on OWML (1983) settling column data. Average values for seven tests. Removal equivalent to 4 feet of settling (Schueler, 1987).

4.2 Capabilities of EPA SWMM S/T Block

The EPA SWMM Storage/Treatment Block has approximately eight subroutines and is approximately 2000 FORTRAN lines long [Huber and Dickinson, 1988]. The capabilities of the S/T block include [Nix et al., 1988]:

1. The ability to model a wide variety of storage basin geometries and outlet structures.

2. The capability to perform continuous simulations and evaluate the long term pollutant removal efficiency.

3. A provision for modeling detention basins as plug-flow or completely mixed reactors.

4. The modeling of pollutants as first order reactants in the completely mixed mode.

The S/T Block simulates the behavior of storage-treatment facilities over a specified number of time steps. The input setup for the S/T block is given in Appendix C as Exhibit C.1. The Puls method for reservoir routing [Viessman, 1977] is used to route the flow through the system. Inflow hydrographs can be passed from other SWMM blocks or other models via interface files or directly input by the user. A set of elevation-storage-discharge relationships is used to determine the volume of water in the facility and the discharge rate. Pollutants are routed through the system using one of two methods: plug-flow or completely mixed. Removal is modeled by a user supplied removal equation [see Eq. (4-1)] or discrete particle [Type I] settling. For a detailed description of the capabilities of the SWMM S/T Block the reader is referred to the user's

manual [Huber and Dickinson, 1988; also see Appendix C, Exhibit C.1].

4.3 Application of SWMM

The SWMM S/T Block is used here to develop a set of standardized curves relating settling efficiency (η_{BMP}) and the expected detention time. A series of simulations were run to determine the relationship between the analytical detention time and the removal efficiency from the SWMM simulations. This relationship is shown to be independent of runoff statistics and pond configuration. Therefore, the family of curves produced here can be considered a standard design aid to determine a η_{BMP} for designing extended detention basins..

4.3.1 Hydrograph Generation

A sequence of hydrographs are synthetically generated from exponentially distributed runoff volumes, durations and interevent times. USEPA (1986) has divided the nation into nine rainfall zones and has provided rainfall statistics in terms of mean depth, duration, and interevent time for each zone (Figure 4-2 and Table 4-1). The annual statistics were used in the generation of the sequence of hydrographs. For simplicity, a runoff coefficient of 100% was chosen. Therefore, the mean runoff depths were equal to the mean annual rainfall depths from Table 4-1. Further, it was assumed that the mean durations and interevent times for runoff were equal to the mean annual durations and
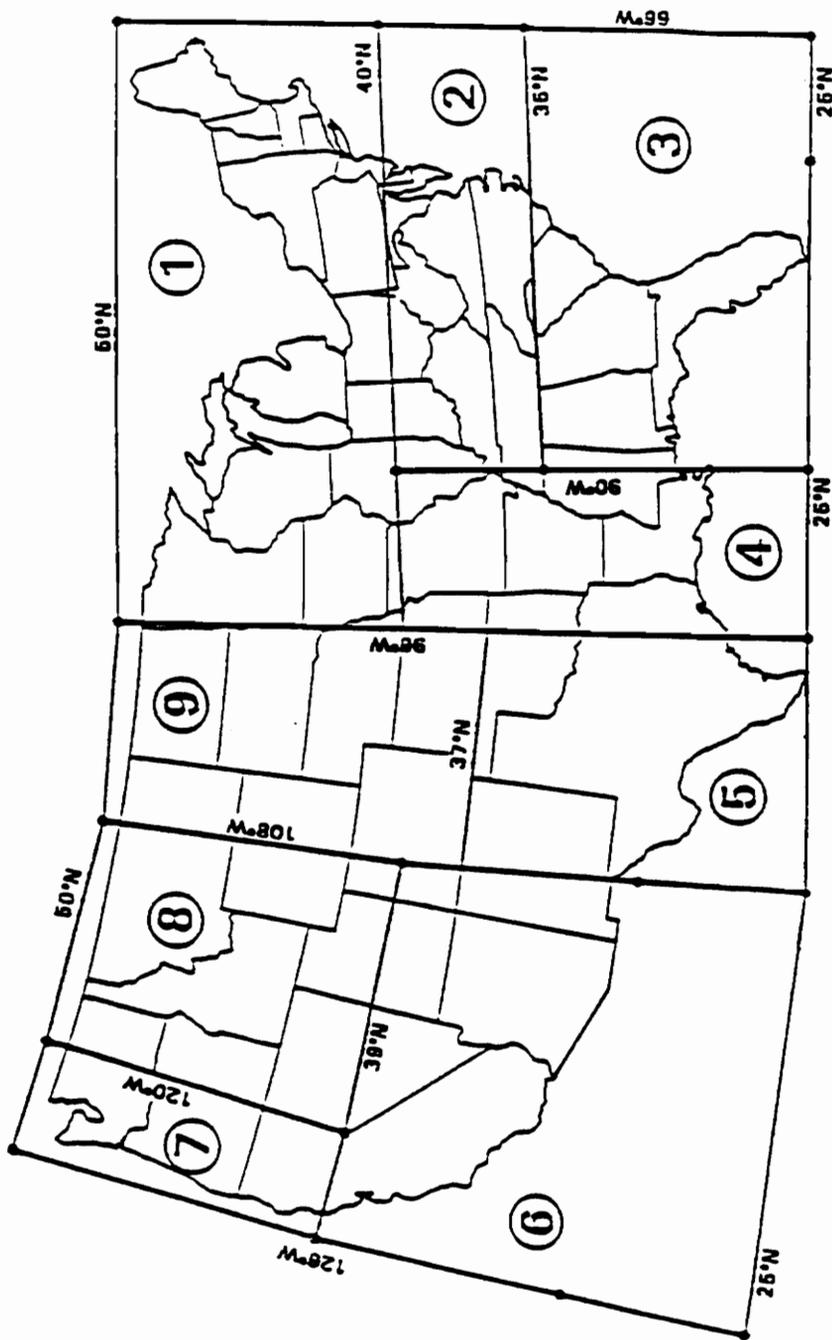
FIGURE 4-2. Rainfall Zones (USEPA, 1985)

TABLE 4-1. Summary of Rainfall Zone Characteristics (USEPA, 1986)

Zone	Period	Volume (in.)		Duration (hr)		Interval (hr)	
		Mean	c.v	Mean	c.v	Mean	c.v
1	Annual	0.26	1.46	5.8	1.05	73	1.07
	Summer	0.32	1.38	4.4	1.14	76	1.06
2	Annual	0.36	1.45	5.9	1.05	77	1.05
	Summer	0.40	1.57	4.2	1.09	77	1.08
3	Annual	0.49	1.47	6.2	1.22	89	1.05
	Summer	0.48	1.52	4.9	1.33	68	1.01
4	Annual	0.58	1.46	7.3	1.17	99	1.00
	Summer	0.52	1.54	5.2	1.29	87	1.06
5	Annual	0.33	1.74	4.0	1.07	108	1.41
	Summer	0.38	1.71	3.2	1.08	112	1.49
6	Annual	0.17	1.51	3.6	1.02	277	1.48
	Summer	0.17	1.61	2.6	1.01	425	1.26
7	Annual	0.48	1.61	20.0	1.23	101	1.21
	Summer	0.26	1.35	11.4	1.20	188	1.15
8	Annual	0.14	1.42	4.5	0.92	94	1.39
	Summer	0.14	1.51	2.8	0.80	125	1.41
9	Annual	0.15	1.77	4.4	1.20	94	1.24
	Summer	0.18	1.74	3.1	1.14	78	1.31

interevent times for rainfall. The statistics for regions 1, 2, 4, 6, and 7 were input into "expr.for" (FORTRAN program given in Appendix D as Exhibit D.1) to generate the exponential random variates. These regions were chosen because they represent a wide variety of statistics for depth, duration, and interevent time. The runoff statistics for the test watershed (see Chapter 6 for watershed description) were also used as input. These statistics are given as region 00 in Table 4-2.

"Expr.for" generates exponentially distributed random numbers for runoff depth, duration and interevent time for a specified set of statistics (typical input and output files are given in Appendix D). The original input statistics are slightly modified by this procedure due to the limited sample size. The runoff depths were converted to flow rates by dividing the runoff depth by the runoff duration. The values for runoff duration and interevent times were rounded to even ten minute intervals for the continuous simulation. This list of events is converted to a four year continuous hydrograph by "jprep.bas" (BASIC program given in Appendix D as Exhibit D.3). This hydrograph is used as input into SWMM S/T Block as J1 cards (see Appendix C, Exhibits C.2). A typical section of a continuous hydrograph is shown in Figure 4-3. This modification of the generated events to a sequence of hydrographs further changes the original runoff statistics [$E(X_1)$, $E(X_2)$, $E(X_3)$] found in Table 4-1. To determine the existing statistics for the runoff data the Statistics Block in SWMM is used.
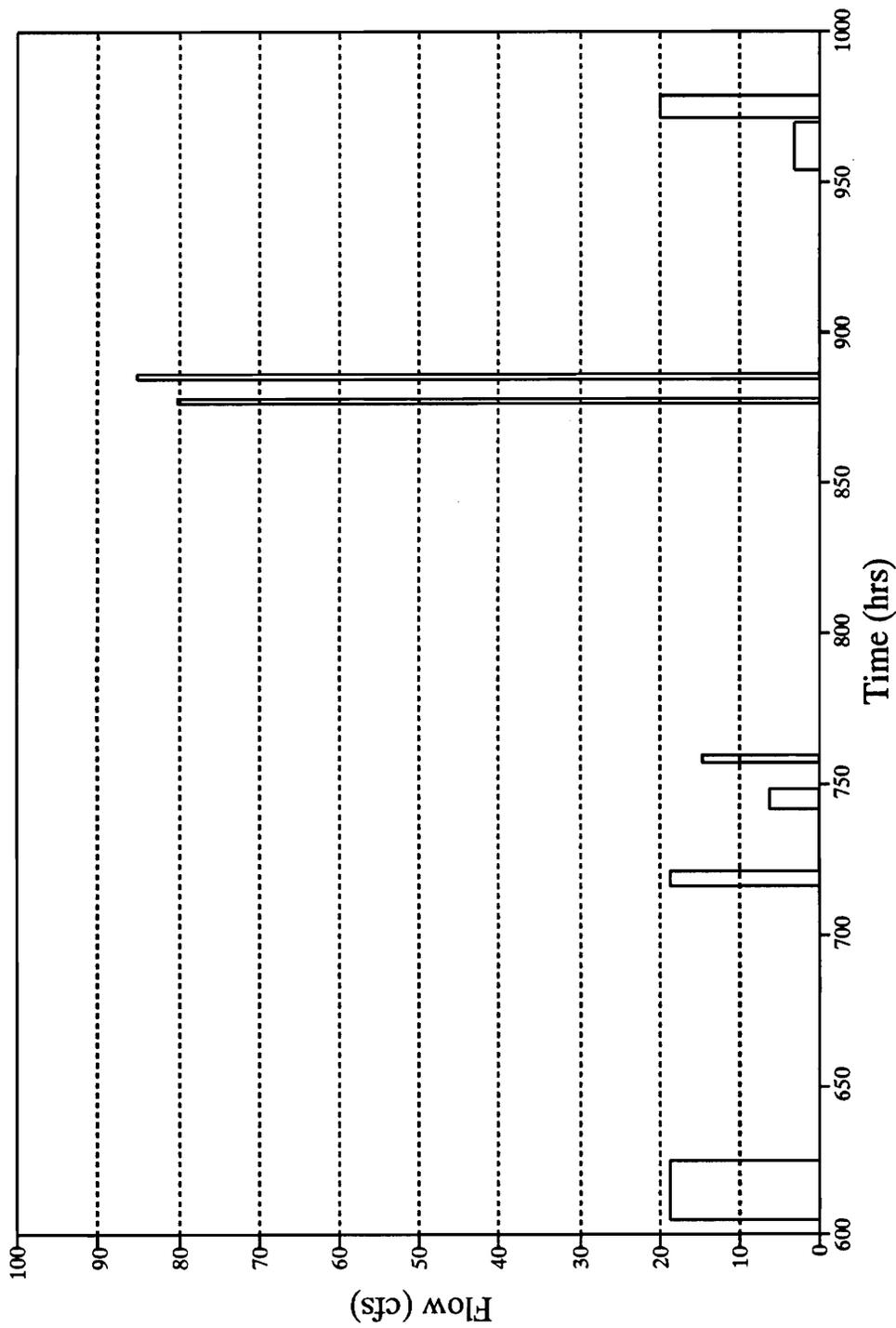
FIGURE 4-3. Typical Section of a Generated Rectangular Hydrograph

The Statistics Block in SWMM is used to analyze the generated sequence of hydrographs. A description of the input requirements for the Statistics Block is given in Appendix C, Exhibit C.4. The user inputs required for the Statistics Block are a base flow (BASE) and a minimum interevent time (MIT) [See Appendix C, Exhibit C.4 and C.5, Card B1]. A typical Statistic Block input file is given in Appendix C as Exhibit C.5. Because of the shape of the hydrographs [note Figure 4-3], the minimum interevent time and baseflow parameters were set very close to zero. The output from the Statistics Block can be extensive [Huber and Dickinson, 1988] but for this exercise only the first two moments for the runoff volume, duration, and interevent time were required. A typical output from the Statistics Block is given in Appendix C, Exhibit C.6. The statistics for the hydrographs used in this exercise are given in Table 4-2. The regions are now denoted as 100, 200, 400, 600, and 700 because of the aforementioned change in statistics from those found in Table 4-1. The statistics for the test watershed are given as region 00. Note that the statistics are closely exponential (coefficients of variation [c.v.] close to unity).

4.3.2 Pond Configuration

The generated hydrographs were routed through different detention pond configurations. The ponds used are characterized by a volume, b, and a withdrawal rate, a, given in Table 4-3. The pond configurations in the SWMM input file are given by the

---

TABLE 4-2. Regional Runoff Statistics

Region	X_1		X_2		X_3	
	$E(X_1)$ (in)	cv	$E(X_2)$ (hr)	cv	$E(X_3)$ (hr)	cv
00	0.1584	1.10	12.58	1.00	103.1	0.96
100	0.2917	1.00	6.57	0.90	69.88	0.98
200	0.4052	1.07	6.88	0.88	73.77	0.96
400	0.6581	0.99	8.19	0.93	103.3	0.99
600	0.2063	1.33	4.81	0.77	241.1	0.97
700	0.5457	1.03	21.02	1.01	99.72	0.97
T100	0.2655	1.01	6.59	0.89	69.55	0.96
A100	0.2917	1.00	6.57	0.90	69.88	0.98

H3 cards (see Appendix C, Exhibits C.1 and C.2). The values for storage volume are given in cubic feet and the constant discharge is given in cubic feet per second (cfs). These values can be converted to the appropriate units (basin inches and basin inches per hour) given a simple unit conversion using the total basin area which is 526.7 acres. The drainage basin area is not used other than for unit conversion. The pond is given as 10 feet deep but this is not a factor since the withdrawal rate is constant.

4.3.3 Pollutant Removal

As was noted in a previous section, the S/T Block has two methods for pollutant routing: plug flow and completely mixed. The completely mixed option was used in this study. Following the Goforth et al (1983) study a constant inflow concentration of 100 mg/l of pollutant was used. The pollutant concentration is input for nonzero flows in the J1 cards of the SWMM input file (see Appendix C, Exhibits C.2 and C.3).

Pollutant removal is accounted for by using the removal equation from SWMM S/T Block. This equation is given as [Huber and Dickinson, 1988]:

$$R = \left(a_{12} e^{a_1 x_1} x_2^{a_2} + a_{13} e^{a_3 x_3} x_4^{a_4} + a_{14} e^{a_5 x_5} x_6^{a_6} \right.$$
$$\left. + a_{15} e^{(a_7 x_7 + a_8 x_8)} x_9^{a_9} x_{10}^{a_{10}} x_{11}^{a_{11}} \right)^{a_{16}} . \qquad (4\text{-}1)$$

By setting all of the variables in Eq.(4-1) to zero except: $x_3 = 1.0$; $a_3 = -\theta$ (sec $^{-1}$);

TABLE 4-3. Pond Configurations Used for Simulations

b/a=40		b/a=20		b/a=10	
b (in)	a (in/hr)	b (in)	a (in/hr)	b (in)	a (in/hr)
2.0	.05	2.0	.1	2.0	.2
0.8	.02	0.8	.04	0.8	.08
0.4	.01	0.4	.02	0.4	.04
0.3	.0075	0.3	.015	0.3	.03
0.2	.005	0.2	.01	0.2	.02
0.1	.0025	0.1	.005	0.1	.01
0.05	.00125	0.05	.0025	0.05	.005
0.02	.0005	0.02	.001	0.02	.002
0.005	.000125	0.005	.00025	0.005	.0005

$a_{12} = R_{max}$; $a_{13} = -R_{max}$; and $a_{16} = 1.0$; a simple first order decay equation is obtained. The first order equation is given as:

$$R = R_{max}(1 - e^{-\theta \Delta t})$$ (4-2)

where: R= fraction of pollutant mass removed (or decayed) from the pond at every time step; R_{max} = maximum removal fraction ; θ= decay rate (time^{-1}); and Δt= simulation time step (time). Note that for a constant time step and specified values of R_{max} and θ, the fraction of pollutant mass removed, R, becomes a constant.

Pollutant routing is accounted for by the following equation (Huber and Dickinson, 1988):

$$C_2 = \frac{C_1 V_1 + \dfrac{(C_1^I I_1 + C_2^I I_2)}{2} \Delta t - \dfrac{C_1 O_1}{2} \Delta t - \dfrac{\Theta C_1 V_1}{2} \Delta t}{V_2\left(1 + \dfrac{\Theta \Delta t}{2}\right) + \dfrac{O_2}{2} \Delta t}$$ (4-3)

in which: V = reservoir volume, ft^3; C^I =influent pollutant concentration, mg/l; C = effluent and reservoir pollutant concentration, mg/l; I = Inflow rate, ft^3/sec; O = outflow rate, ft^3/sec; t = time, sec; Θ = decay coefficient, sec^{-1}; subscripts 1, 2 = beginning and end of the time step; $\Theta\Delta t$= R [from Eq. (4-2)]. It can be seen from Eq.(4-3) that the total removal for any runoff event is dependent on the number of time steps the volume is held in the pond (i.e. detention time). Thus, the total pollutant removal efficiency during the entire simulation period is a function of the average detention time for the simulation.

It can be proven from Eq. (4-3) that for different but constant influent concentration the percentage of pollutant mass removed is constant. First, note that the I, O, V values are unaffected by the pollutant concentrations. They are completely determined by the flow routing computation. For the case of constant influent concentration we have $C_i^I = C$ for all i. Let this concentration be changed to $C' = \sigma C$. Also, we assume the initial reservoir concentration C_1 changes to $C_1' = \sigma C_1$. By substituting C' and C_1', in Eq. (4-3) we obtain $C_2' = \sigma C_2$. Successive substitutions of updated reservoir concentrations yield $C_3' = \sigma C_3$ etc. When outgoing and incoming mass ratios are considered the σ's cancel which proves that within the framework of Eq. (4-3) a change in the constant initial concentration does not affect the removal efficiency. Therefore, the value chosen for C^I is insignificant.

4.3.4 Settling Efficiency Curves

A series of SWMM simulations were made using the generated hydrographs, pond configurations, and pollutant removal equations outlined above. These simulations provide bench-marks for the settling efficiency vs. E(D) relation. Each simulation produced a single settling efficiency (η_{BMP}). The settling efficiency is determined as the ratio of the load removed (or decayed) to the net (load not carried by the by-pass) load entering the detention basin according to the SWMM output as shown in Appendix C (Exhibit C.1 and C.2). In mathematical terms using the notation in Exhibit C.4:

$$\eta_{BMP} \text{ (settling efficiency)} = \frac{TSS \ POUNDS \ (REMOVED \ BY \ DECAY)}{TSS \ POUNDS \ (INFLOW, NET)} \qquad (4-4)$$

Each combination of pond configuration and hydrograph sequence has a mean hydraulic detention time that is obtained from Eq.(3-34) by averaging the bounding expected detention times corresponding to c=0 and c=b. The average is plotted against the corresponding settling efficiency obtained from the SWMM simulations.

The first set of simulations is carried out to show the independence of drawdown time in determining the settling efficiency. The four year hydrograph sequence with statistics corresponding to region 00 are used. Three different drawdown times (b/a ratios) are selected: 10, 20, and 40 hrs. For each ratio different values of b and a are employed in the S/T block, as given in Table 4-3. The value of R_{max} in Eq.(4-2) is kept constant at 0.9. Three different values of θ are used: 0.1 hr.$^{-1}$, 0.2 hr.$^{-1}$, and 0.5 hr.$^{-1}$ The results are illustrated in Figures 4-4, 4-5, and 4-6. It is obvious that no matter what the drawdown time is, as long as the same detention time is obtained for certain b and a combinations, the same settling efficiency is obtained. In this regard it is noted that each b/a combination in Table 4-3 yields a single expected detention time, as evidenced by Eq. (3-34). It should also be noted that the drawdown time (b/a) is often used as a design criterion for detention ponds. Figures 4-4, 4-5, and 4-6 indicate that the drawdown time is not an accurate representation of the hydraulic detention time.

The second set of simulations is designed to show that the results obtained for
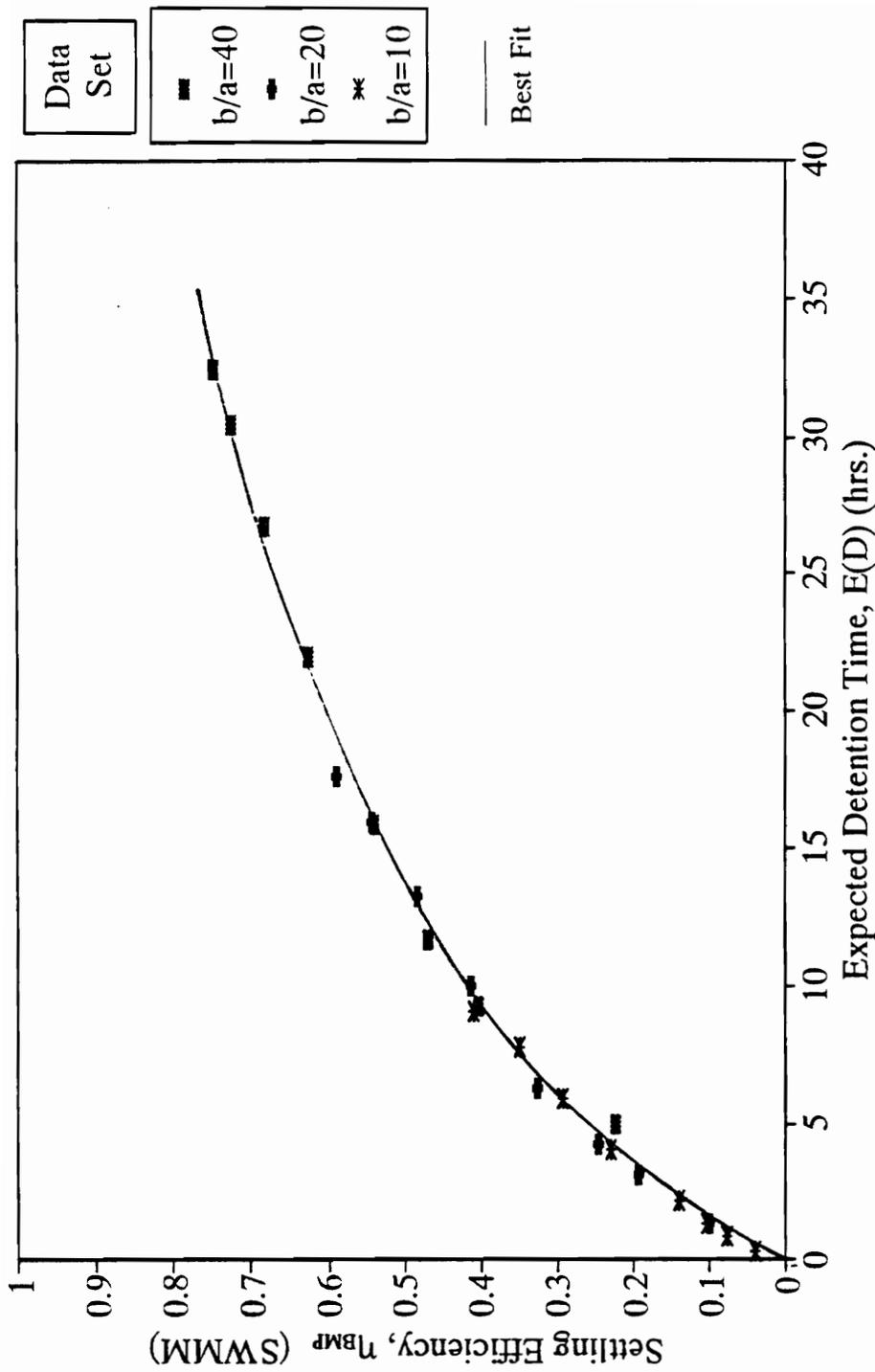
FIGURE 4-4. η_{BMP} vs. E(D) For Different Drawdown Times (b/a) For $\theta = 0.1$
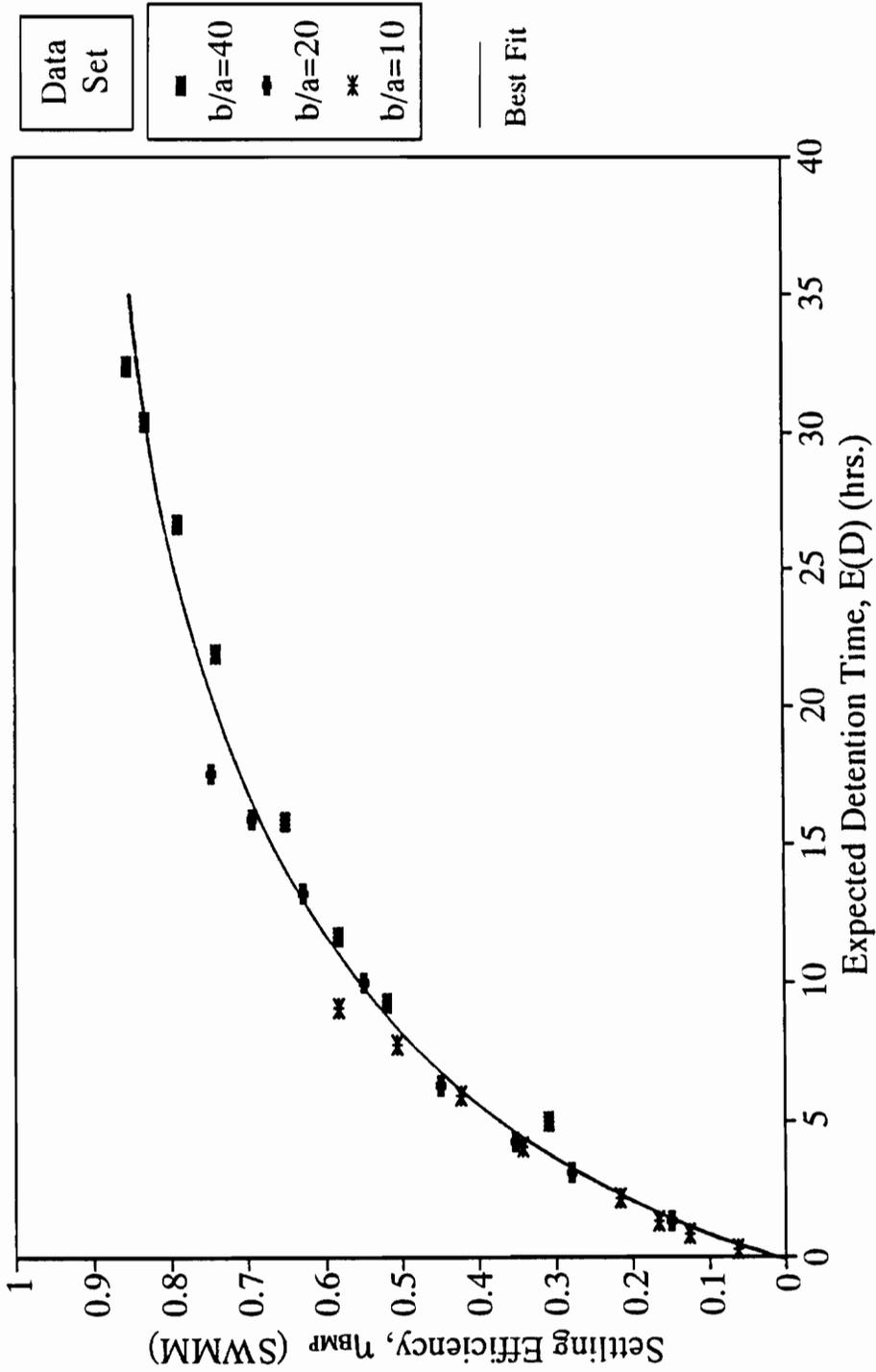
FIGURE 4-5. η_{BMP} vs. E(D) For Different Drawdown Times (b/a) For $\theta = 0.2$
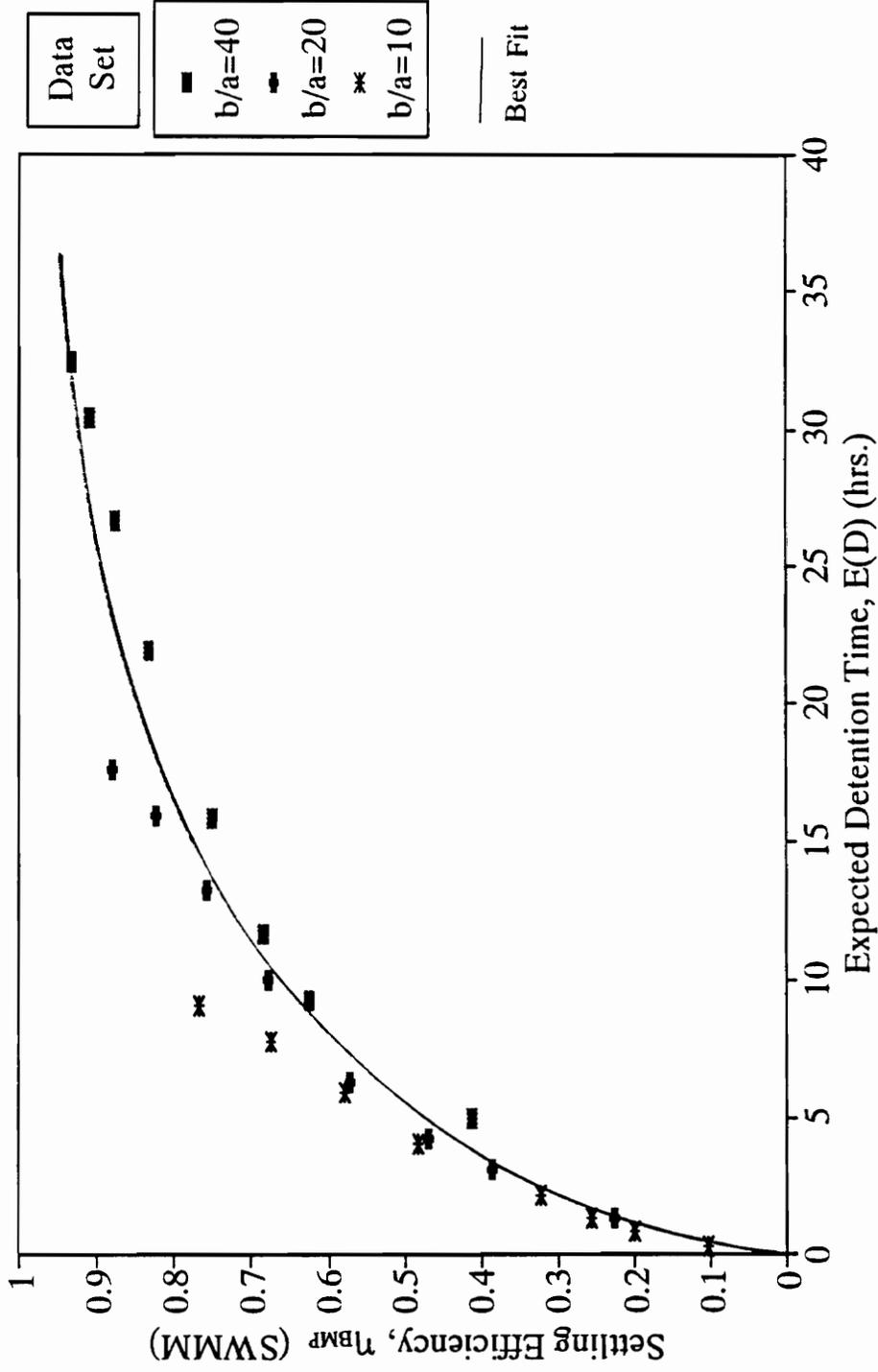
FIGURE 4-6. η_{BMP} vs. E(D) For Different Drawdown Times (b/a) For $\theta = 0.5$

settling efficiency are independent of the runoff statistics and again dependent only on the expected detention time. The different sequences of hydrographs generated according to section 4.3.1 are routed through the S/T block for a fixed b/a ratio. The pond configurations used for this set of simulations correspond to the values given for b and a in Table 4-3 under b/a=40. The results are illustrated in Figures 4-7, 4-8, and 4-9. The efficiency does not vary for different runoff statistics, only for different values of E(D).

The computer experiments performed in this section substantiate the use of the detention time E(D) as an effective parameter to describe the BMP (settling) efficiency. Intuitively, one might think that the high variability in runoff statistics and different pond sizes would obviate a standardized curve of η_{BMP} versus E(D) and that generation of a large set of curves parameterized on these variables may be needed. Fortunately, it is found here that the η_{BMP} versus E(D) curve exhibits an invariant shape that is independent of the aforementioned factors. Notice that the best fit curve for Figure 4-4 is the same as for Figure 4-7, the best fit curve for Figure 4-5 is the same as for Figure 4-8, and etc. The pollutant removal (settling) efficiency is strictly a function of the hydraulic mean residence time, E(D), and the pollutant settling characteristics given as R_{max} and θ in Eq. (4-3).
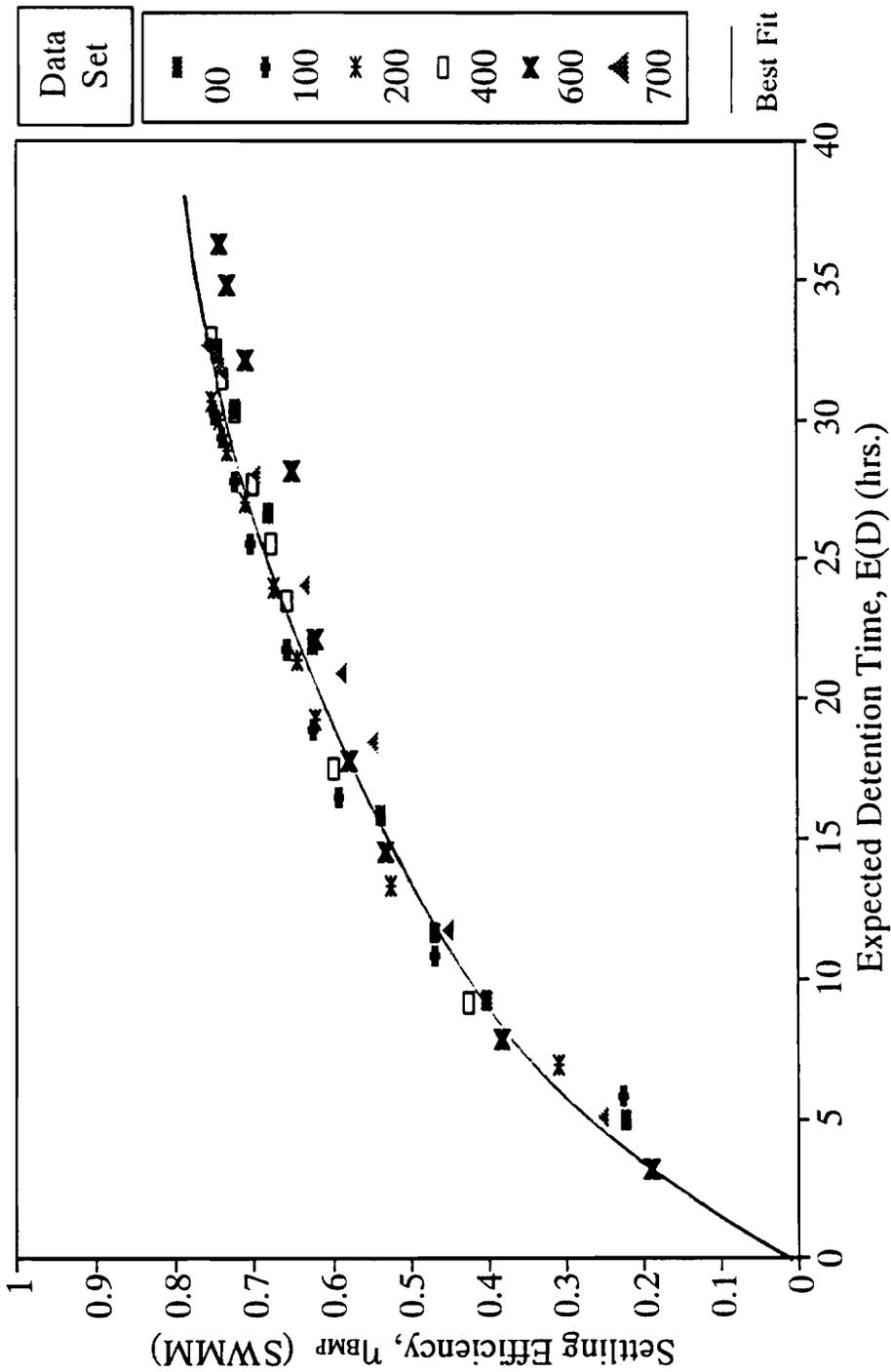
FIGURE 4-7. η_{BMP} vs. E(D) For Different Runoff Statistics (Table 4-2) For $\theta = 0.1$
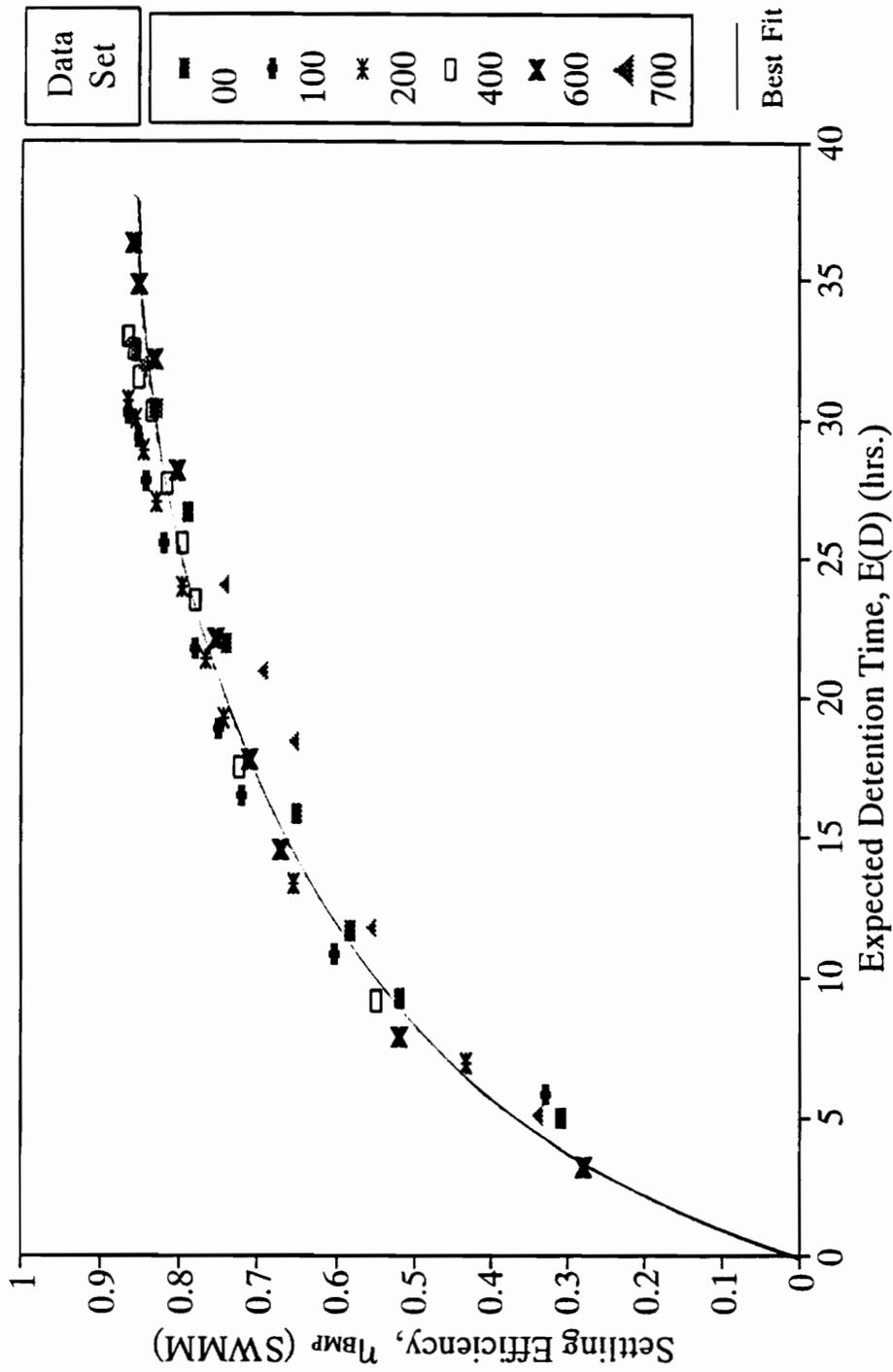
FIGURE 4-8. η_{BMP} vs. E(D) For Different Runoff Statistics (Table 4-2) For $\theta = 0.2$
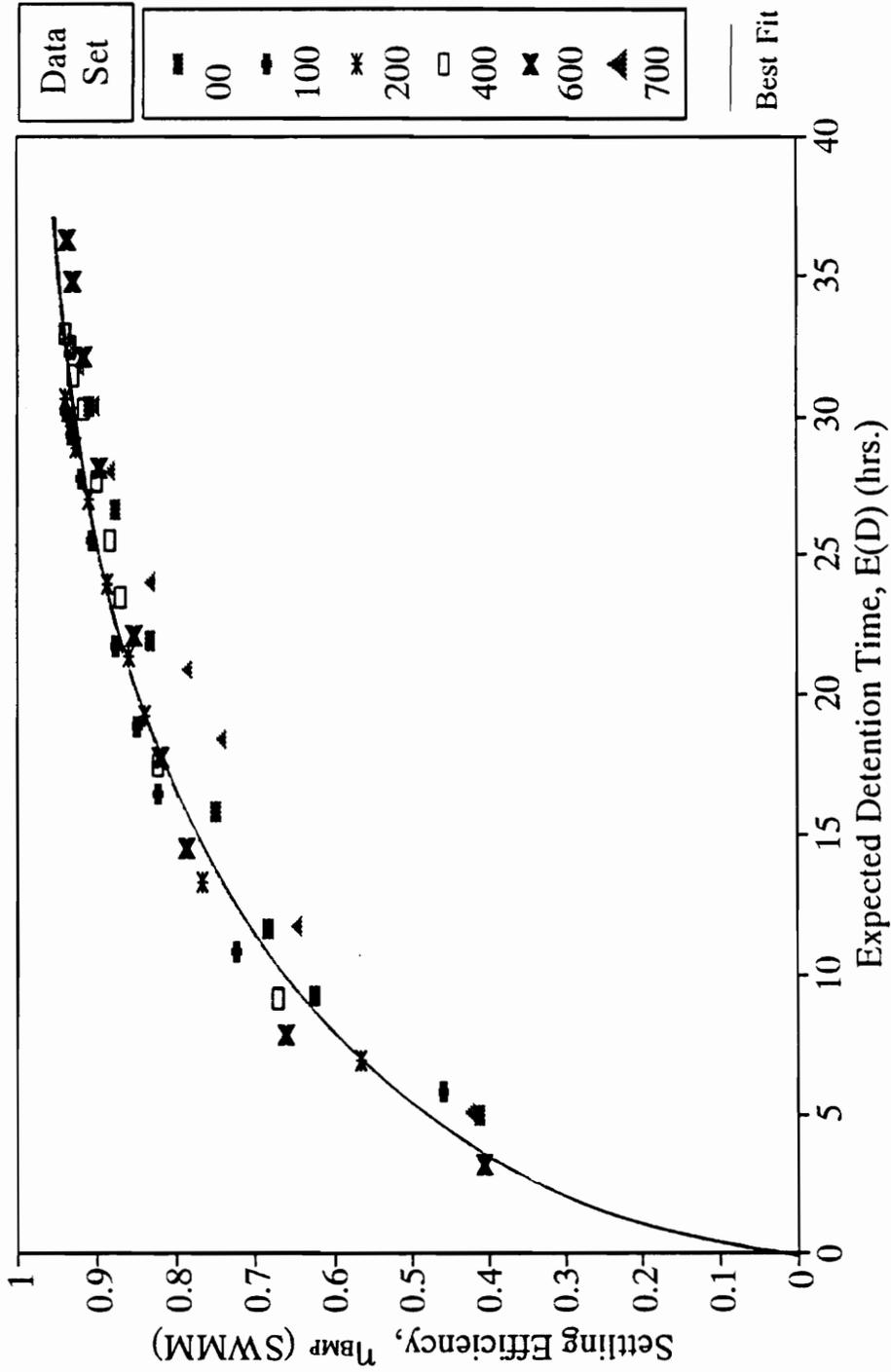
FIGURE 4-9. η_{BMP} vs. E(D) For Different Runoff Statistics (Table 4-2) For $\theta = 0.5$

CHAPTER 5

ESTIMATING POLLUTANT REMOVAL EFFICIENCY

5.1 Introduction

The expected detention time provides a means of estimating the removal process within the pond. As detention time increases, the amount of settling that takes place will increase. This removal pertains only to the amount of runoff captured. The amount not captured becomes by-pass which should be accounted for in the overall efficiency of the pond. The capture efficiency is defined as the fraction of runoff that is contained in the extended detention pool and passes through the extended detention orifice. The BMP efficiency is defined as the fraction of the captured amount that settles to the bottom of the pond and is a function of the detention time. The overall efficiency of a detention pond will depend on the capture efficiency and the BMP efficiency. The detention time does not account for capture efficiency. In fact, the capture efficiency of a pond will go down as the expected detention time rises. The increase in detention time will reduce the effective volume available to capture the runoff volume containing the pollutant load. This decrease in effective volume will increase the probability a by-pass will take place.

In turn, the volume that by-passes the pond will increase.

This chapter introduces a planning methodology for sizing stormwater detention basins for pollutant removal. This methodology will estimate the overall performance of a detention facility for pollutant removal. For a given set of runoff statistics, the overall performance will be dependent on the design parameters, namely the basin volume, b, and the withdrawal rate, a. The expected detention time will be used to estimate the settling efficiency within the pond. The expression for the overall performance will be a combination of settling efficiency and capture efficiency.

5.2 Formulation

If the concentration of the pollutant entering the pond is considered to be constant, the weighted concentration of the pollutant leaving the pond can be expressed as follows:

$$C_{EFF} = \frac{E(X_1 - Y)C_{BMP} + E(Y)C_I}{E(X_1)} \tag{5-1}$$

where: C_{EFF} = The weighted concentration of pollutant entering the receiving stream.

$E(X_1-Y)$ = The expected value of the volume of water passing through the extended detention orifice.

C_{BMP} = The concentration of the pollutant leaving the BMP pool after settling takes place.

$$E(Y) \quad = \quad \text{The expected value of the by-pass volume.}$$

$C_1 \quad = \quad$ The initial concentration of pollutant or the concentration of pollutant entering the pond.

It is assumed that by-pass is the water that does not go through the extended detention device and does not receive treatment. Loganathan et al. (1985) proved that

$$\frac{E(X_1 - Y)}{E(X_1)} = P(Y=0) \ . \tag{5-2}$$

Simply, the fraction of water passing through the extended detention orifice and receiving "treatment" is equal to the probability there is zero by-pass or the fraction of events with by-pass equal to zero, $P(Y=0)$. Consequently,

$$\frac{E(Y)}{E(X_1)} = 1 - P(Y=0) \ . \tag{5-3}$$

The expression for $P(Y=0)$ is given as:

$$P(Y=0) = k \left\{ \exp(-\alpha c) + \frac{\alpha a}{\gamma} \exp\left(-\alpha c - \gamma \frac{(b-c)}{a}\right) \right\} \ . \tag{5-4}$$

Notice that for a given set of runoff statistics, α, β, and γ, and for a given volume, b., $P(Y=0)$ will decrease as a decreases. In other words, the volume of water captured within the extended detention pool will decrease. For the same scenario the expected detention time will increase [note Eq.(3-34)]. This further illustrates that the two stated goals for successful detention pond design: (1) capturing sufficient volume of water; and (2) detaining that volume for a sufficient time, are in direct conflict. $P(Y=0)$ can be viewed

as the capture efficiency, η_{FL}, of a given pond. Equation (5-4) will give the fraction of water that is captured in the pond and subject to extended detention.

Using Eqs.(5-2) and (5-3), Eq.(5-1) can be rewritten as

$$C_{EFF} = \left\{ P(Y=0) \right\} C_{BMP} + \left\{ 1 - P(Y=0) \right\} C_I \qquad (5\text{-}5)$$

Eq. (5-5) is an expression for the volumetrically weighted concentration entering the receiving stream. C_{EFF} is the concentration leaving the detention pond after settling has occurred and is associated with the fraction of water that will travel through the extended detention orifice, $P(Y=0)$. C_I is the concentration of the pollutant arriving at the pond and will remain unchanged for the fraction of water equal to $1\text{-}P(Y=0)$. C_{BMP} can be defined as a fraction of C_I such that

$$C_{BMP} = C_I(1 - \eta_{BMP}) \qquad (5\text{-}6)$$

where η_{BMP} is the pollutant removal efficiency in the BMP pool defined in Chapter 4. Substituting, equation (5-5) becomes

$$C_{EFF} = \left\{ P(Y=0) \right\} C_I \left\{ 1 - \eta_{BMP} \right\} + \left\{ 1 - P(Y=0) \right\} C_I. \qquad (5\text{-}7)$$

If the weighted concentration is divided by the initial concentration and the equation is rearranged , the resulting expression is:

$$1 - \frac{C_{EFF}}{C_I} = 1 - \left\{P(Y=0)\right\} \left\{1 - \eta_{BMP}\right\} + \left\{1 - P(Y=0)\right\}. \tag{5-8}$$

The overall removal efficiency of the extended detention pond , η is equivalent to the left hand side of equation (5-8). Substituting and rearranging, equation (5-8) can be written in the form

$$\eta = \left\{P(Y=0)\right\} \eta_{BMP} \tag{5-9}$$

The first term in the right hand side of Eq. (5-9) is equivalent to the flow capture efficiency of the extended detention pond. $P(Y=0)$ is the percentage of flow that passes through the BMP orifice and experiences "treatment" due to the extended detention. Since the concentration of the pollutant is assumed to be constant, $P(Y=0)$ is also equivalent to the pollutant load that is subject to treatment. The second term in Eq. (5-9) represents the fraction of the pollutant load entering the BMP pool that is removed. The overall efficiency is the product of the capture efficiency and the settling efficiency.

Eq. (5-9) does not consider the effects of the first flush phenomenon. Adjustments to the capture efficiency should be made if first flush effects are observed. The first flush is the condition in which a disproportionate percentage of pollutant load is carried by the early portion of the runoff volume. The pollutant concentration is very high at the beginning of a runoff event and as the pollutant load is removed from the surface, the pollutant load and consequently the pollutant concentration will decrease. The volume

of water that contains the majority load of pollutant is termed the first flush. Equation

(5-9) assumes that the concentration of pollutant is constant for the entire runoff event.

If first flush effects are present, considerations can be made if the term P(Y=0) is

replaced by an expression for pollutant capture efficiency.

Segarra and Loganathan (1992) presented a pollutant capture efficiency term based

on a first order pollutant wash off model. The definitions and assumptions outlined in

Chapter 2 were used as a basis for the derivation of equations. The pollutant capture

efficiency was defined as the ratio of the expected value of the pollutant load captured

by the BMP pool divided by the expected value of the washoff load in the runoff. Di

Toro and Small (1979) outlined a procedure to account for capture efficiency when first

flush effects were taken into account. However, first flush effects are not always present

and local data is needed to justify the assumption that first flush should be considered.

For design purposes it is usually appropriate to proceed assuming first flush does not exist

[Stahre and Urbanos, 1990].

Generically, equation (5-9) can be presented as

$$\eta = \eta_{FL} \eta_{BMP} \tag{5-10}$$

where η_{FL} is a suitable expression representing the fraction of pollutant load that enters

the BMP pool and η_{BMP} is the removal efficiency of the BMP pool based on the expected

detention time. Equation (5-10) provides the advantage of a flexible efficiency equation.

The functional relationship between η_{BMP} and E(D) can be varied based on the pollutant

of interest. The form of η_{FL} can be chosen to consider first flush effects (if enough information is known about the pollutant) or a situation where the first flush effects are not present. If first flush is not present η_{FL} is equal to $P(Y=0)$ given in Eq.(5-4).

5.3 Procedure

The following procedure is used to determine the overall efficiency of an extended detention pond given the watershed runoff statistics [$E(X_1)$, $E(X_2)$, and $E(X_3)$], the pond storage (b), the withdrawal rate (a), and the appropriate η_{BMP} vs. $E(D)$ curve:

1) Use Eq.(3-34) to determine $E(D)$. A value of c must be specified. The bounding expected detention times can be solved for (c=b and c=0) or $E(S_a)$ [See Appendix B] can be used.

2) Enter the appropriate η_{BMP} vs. $E(D)$ curve and determine η_{BMP}.

3) Use Eq.(5-4) to determine η_{FL}. Again, a c must be specified.

4) Use Eq. (5-10) to determine η.

CHAPTER 6

APPLICATIONS

6.1 Introduction

The stochastic equations derived in Chapter 3 and the methodology presented in Chapters 4 and 5 are tested against results obtained from SWMM. First, the expected value of detention time, $E(D)$, and the capture efficiency, η_{FL}, are compared to results from the S/T Block. Second, further simulations are made to test the relationships between η_{BMP} and $E(D)$ obtained in Chapter 4. Third, results from the methodology are compared to simulation results obtained by Goforth et al. (1983). Finally, numerical examples are presented that apply the stochastic equations and design methodology to design problems. A computer program written in BASIC is presented that performs all methodology calculations and also includes a search technique to find solution sets of a and b for a certain η.

6.2 Verification of $E(D)$ and η_{FL}

The verification of the theoretical equation for the expected value of detention time was accomplished by comparing continuous simulation results from SWMM to

results obtained from the stochastic equations in Chapter 3. Two different systems, a natural system (Case 1) and a hypothetical system (Case 2) are modeled. SWMM does not explicitly define detention time. Therefore, it was necessary to manually determine the detention time for each event in the simulations. The average detention time for each the simulation was determined and compared to the results obtained from equation (3-29). In addition, the capture efficiency equation presented in Chapter 5 is compared to results obtained from SWMM.

6.2.1 Site Description

The site used for the modeling procedure is a pilot site chosen by Prince William County, Virginia for their retrofit program. It is located in Dale City, Prince William County, Virginia at the intersection of Dale Boulevard and a tributary of the Neabsco Creek. Watershed characteristics are given in Table 6-1. The watershed drains into a 10 ft. culvert that passes under Dale Boulevard. The outlet structure had previously been retrofitted for flood control purposes. Prince William County has proposed to do an additional retrofit to provide extended detention. A working model of the watershed using the Runoff and Transport Blocks in SWMM is utilized in Case 1. Further simulations simply use the watershed area for unit conversion.

TABLE 6-1. Site Watershed Characteristics

Total area = 526.7 acres

Impervious area = 18%

Depression storage (pervious area) = 0.25 in.

Depression storage (impervious area) = 0.016 in.

Average catchment slope = 0.0278 ft./ft.

Maximum infiltration = 0.277 in./hr.

Minimum infiltration = 0.055 in./hr.

Total Number of Subareas = 14

Total Number of Channels = 24

6.2.2 Case 1

The Runoff and Transport Blocks were used to convert rainfall data into a continuous hydrograph for input to the S/T Block. The rainfall data was obtained from the Occoquan Watershed Monitoring Laboratory (OWML) in Manasas, Virginia. The data was taken from a rain gage located at the lab. OWML is located approximately 15 miles from the watershed site. The data consisted of a continuous record of rainfall volume in 30 minute intervals for the years 1988 through 1991. The years 1990 and 1991 were chosen for input because they were the most complete years in the data set. The data was adapted to a form that was consistent with SWMM input. The simulation was performed and a two year continuous hydrograph at the entrance of the facility was obtained.

The runoff statistics were determined by the Statistics Block in SWMM. As described in Chapter 4, the Statistics Block requires the user to input a minimum interevent time (MIT) and a base flow (BASE). Following Goforth et al.(1983), MIT and BASE values were chosen to obtain a coefficient of variation (c.v.) close to unity for the interevent time. This was accomplished with MIT= 6 hrs. and BASE= 0.5 cfs. The statistics are given in Table 6-2. It should be noted that while the runoff duration and interevent time follow an exponential distribution with coefficients of variation (c.v.) equal to 0.9 and 1.0, respectively, the runoff volume distribution deviates from it, having a c.v. of 2.0.

TABLE **6-2.** Statistics Block Results: Case 1 Simulation

Rainfall Volume = 81.2 in
Runoff Volume = 21.7 in

Mean Runoff Volume[*] = 0.1349 in   cv = 2.04
Mean Runoff Duration[*] = 11.68 hrs   cv = 0.90
Mean Interevent Time[*] = 102.8 hrs   cv = 1.0
Runoff Events[*] = 134

[*]Determined by specifying:
Minimum Interevent Time = 6 hrs.,
Base Flow = 0.5 cfs

Elevation-storage information for the pond was obtained from a topographic survey of the pond site. Elevation-discharge information was obtained from outlet design calculations for a four-inch orifice. The outlet structure design is depicted in Figure 6-1. The Multiple Stage Routing Model [MSRM] contained within the Penn State Urban Hydrology Model [Kibler et al., 1991] was used to develop the Elevation-discharge curve used in the SWMM simulations. Elevation-storage-discharge information is given in Table 6-3. The two year continuous hydrograph was routed through the detention facility using the S/T Block.

The outflow hydrograph from the detention facility was analyzed using the Statistics Block. The output from the Statistics Block includes a listing of each event by peak flow. This list was used to determine the detention time for each event. The volume of water in the pond at the time of the peak flow can be determined by matching the peak flow with a corresponding elevation and consequently, a storage volume. The average withdrawal rate is used in determining the detention time for each event in the simulation. The average withdrawal rate, a, for the BMP pool was determined by calculating the drawdown time weighted average for the rating curve [elevations 263-271] by the equation
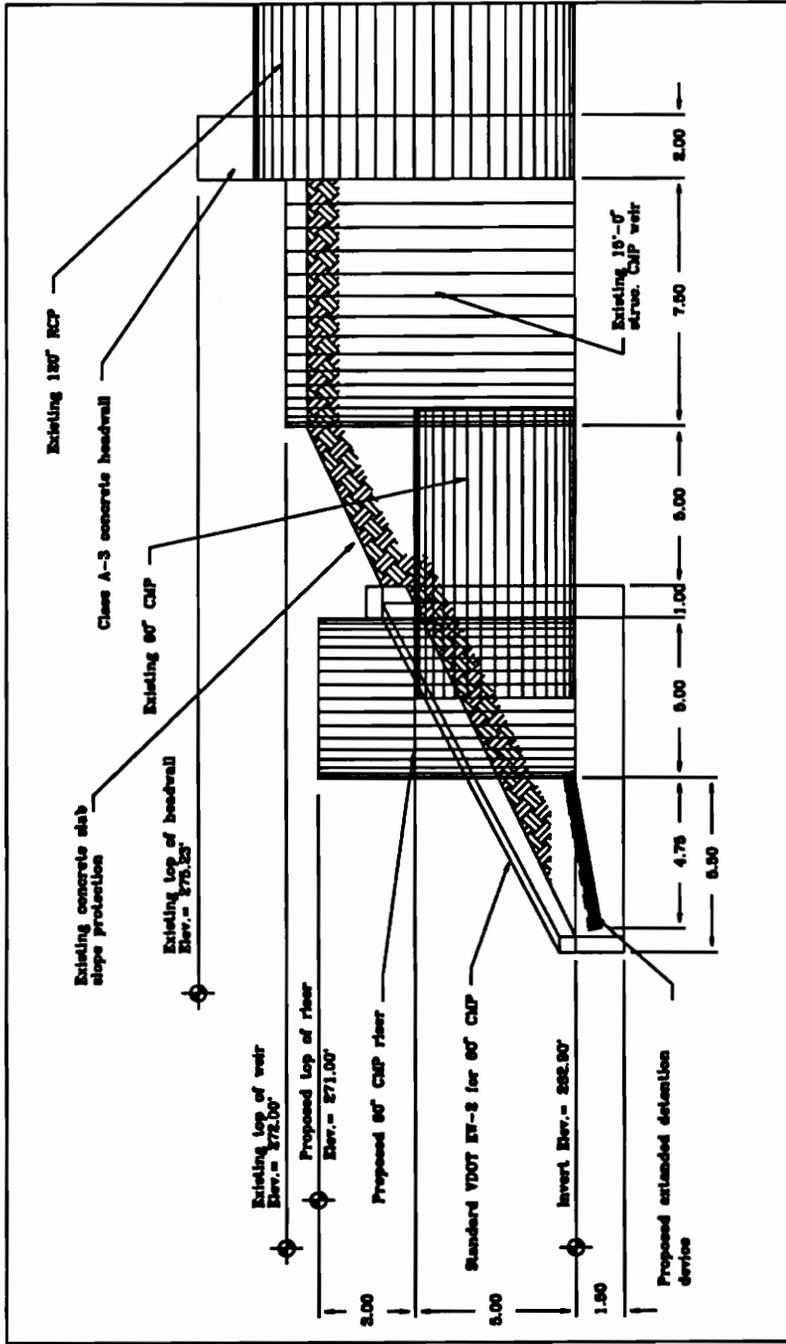
FIGURE 6-1. Outlet Design for Case 1

TABLE 6-3. Elevation-Storage-Discharge Information for Case 1.

Elevation (ft)	Storage (ft³)	Discharge (cfs)
263	0	0
265	14	0.55
266	352	0.69
267	3394	0.81
268	11032	0.91
269	23899	1.00
270	45636	1.09
271	86656	1.16
272	228485	49.73
275	735615	664.77
278	1515888	1124.12

$$a = \frac{\sum\limits_{i=0}^{n} V_i}{\sum\limits_{i=0}^{n} \dfrac{V_i}{Q_i}} \qquad (6\text{-}1)$$

where: a = (average) withdrawal rate; n = number of intervals in the rating curve; V_i = volume corresponding to the ith interval; and Q_i = the discharge for the ith interval. From Eq.(6-1), a was determined to be 1.06 cfs or 0.002 in/hr. The BMP pool [where the water experiences extended detention] is defined by elevation 271. Therefore, b is defined as 86,656 ft^3 or 0.045 basin inches. The detention time for each event was determined according to Eq.(3-8). The average detention time for the 134 events was determined to be 13.37 hrs. The by-pass fraction, the fraction of events with D=b/a, and the fraction of events with D=0 were determined by examining the peak flows and computed detention times for each event.

The runoff statistics [from Table 6-2] along with the pond capacity-withdrawal rate are used in Eq. (3-34) to obtain lower [c=b] and upper [c=0] bound estimates of the expected detention time E(D). Also, from Eqs. (3-25) and (3-28) the point mass probabilities are computed. The by-pass probability is computed as $1\text{-}\eta_{FL}$, where η_{FL} is determined from Eq. (5-4). All these results are compared with those of the SWMM simulation in Table 6-4.

TABLE 6-4. Stochastic Model vs. SWMM Simulation Results for Case 1

Parameter	SWMM Simulation	Stochastic Model[*]
Detention Time	13.37	14.51-14.97
By-Pass Fraction (Probability)	0.628	0.609-0.632
Fraction D=b/a or P(D=b/a)	0.413	0.491-0.509
Fraction D=0 or P(D=0)	0.160	0.133-0.149

[*] A range is given to accommodate values obtained for c=0 and c=b in Eq. (3-34).

6.2.3 Case 2

The second SWMM simulation is for a hypothetical system which fits the assumptions made in the derivation of E(D). The input is a four year series of hydrographs with exponentially distributed runoff volumes, event durations, and interevent times. This continuous hydrograph was created using the same procedure outlined in Chapter 4. The statistics from the continuous hydrograph are given in Table 4-2 as region 00. As in Chapter 4, MIT and BASE were chosen very close to zero because of the nature of the hydrograph shape [note Figure 4-3].

The synthetic pond has a volume, b of 0.2 in. [382384.0 ft.^{3}] and the withdrawal rate, a is 0.005 in/hr [2.656 cfs]. The constant withdrawal rate is modified to accommodate the procedure for finding the peak flow volume. The discharge varies a small amount for each elevation. The elevation-storage-discharge relationship for the synthetic system is given in Table 6-5. The detention time for each event and the average detention time for the simulation is determined using the procedure outlined in section 6.2.2. The average detention time from SWMM is 15.40 hrs. for the 307 events occurring during the four year period.

For Case 2 the by-pass fraction can be determined directly from the SWMM output. Unlike Case 1, only modeled the BMP pool is modeled in Case 2. In SWMM, the incoming flows are by-passed once the pond is full and the by-pass volume is accounted for and given in the output. Therefore, for case 2 the by-pass fraction can be

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TABLE 6-5. Elevation-Storage-Discharge Information for Case 2

Elevation (ft)	Storage (ft^3)	Discharge (cfs)
263	0	2.406
264	38238.4	2.456
265	76476.8	2.506
266	114715.2	2.556
267	152953.6	2.606
268	192292.0	2.656
269	229430.4	2.706
270	267668.8	2.756
271	305907.2	2.806
272	344145.6	2.856
273	382384.0	2.906

determined as 1- η_{FL}, where η_{FL} is determined from SWMM output by the equation

$$\eta_{FL}(\text{Capture efficiency}) = \frac{\text{INFLOW, NET (VOLUME)}}{\text{INFLOW, TOTAL (VOLUME)}} \qquad (6\text{-}2)$$

The values for inflow, net (volume) and inflow, total (volume) are given in the SWMM output file [See Appendix C, Exhibit C.3]. The results for Case 2 are quite close to the results from the stochastic equations. The complete results are shown in Table 6-6.

6.2.4 Observations

The results for Case 1 and Case 2 shown in Tables 6-4 and 6-6 support the validity of Eq.(3-34). In addition, Eq. (5-4) also provides a clear estimate of the fraction of runoff that will by-pass the detention facility and not be subject to any detention. The average detention time for Case 1 fell just outside the range defined by Eq.(3-34). The average detention time for Case 2 for exponentially distributed flows and constant withdrawal rate falls within the range defined by Eq.(3-34).

From Tables 6-4 and 6-6 it is observed that, while the two ponds have very different drawdown times [given by b/a] of 22.5 and 40 hours, the detention times are very close. This clearly illustrates that the actual detention time is not well represented by the drawdown time. The expected detention time considers the random nature of the runoff process to assess the actual detention time in a detention facility. The drawdown time does not consider these factors and will always overestimate the actual detention

TABLE 6-6. Stochastic Model vs. SWMM Simulation Results for Case 2

Parameter	SWMM Simulation	Stochastic Model[*]
Detention Time	15.40	14.02-17.14
By-Pass Fraction (Probability)	0.253	0.202-0.273
Fraction D=b/a or P(D=b/a)	0.186	0.137-0.185
Fraction D=0 or P(0)	0.270	0.217-0.284

[*] A range is given to accommodate values obtained for c=0 and c=b in Eq. (3-34).

time. In these experiments a simple average of the upper and lower limits on the detention time yield detention time values close to that of SWMM. One may consider using Eq. (II.6) given in appendix II for selecting c values to be used in Eqs. (3-34) and (5-4) to obtain an average detention time and capture efficiency, respectively.

6.3 Further Testing of the Settling Efficiency Curves

Additional simulations were performed to further test the relationship between $E(D)$ and settling efficiency. The initial simulations consist of rectangular hydrographs routed through detention structures that have constant withdrawal rates. These simulations adhere to the assumptions made in the theoretical development of $E(D)$. Additional simulations relax these assumptions to test the sensitivity of the relationship between $E(D)$ and settling efficiency.

First, a four year sequence of triangular hydrographs is routed through the pond configurations corresponding to the ratio b/a of 40 hrs [Table 4-3]. The runoff statistics for region 100 [Table 4-2] were used for hydrograph generation. The procedure outlined in Chapter 4 was followed. The results for the triangular hydrographs [R_{max}= 0.9 and θ = 0.1, 0.2 and 0.5] are plotted with the best fit results from Chapter 4 in Figures 6-1, 6-2, and 6-3. These results are important, because they indicate that the settling efficiency versus detention time may not depend on the shape of the incoming hydrographs.

The assumption of constant withdrawal is also relaxed for the final set of

simulations. The triangular hydrographs are routed through detention structures similar to those used in previous simulations, with the exception that the constant withdrawal rates were replaced with rating curves obtained from the standard orifice equation

$$Q = cA\sqrt{2gh} \hspace{4cm} (6\text{-}3)$$

where: c=orifice coefficient equal to 0.6; A= orifice area, which is varied for each pond configuration; g=gravitational constant; and h=height of water over the orifice. The average withdrawal rate, a, is determined according to Eq.(6-1). These results [R_{max}= 0.9 and θ = 0.1, 0.2 and 0.5] are shown in Figures 6-4, 6-5, and 6-6.

It can be observed from Figures 6-4, 6-5, and 6-6 that for small expected detention times the BMP efficiencies for the varying withdrawal rate cases fall above the best fit curves from Chapter 4. This phenomenon can be explained by noting the nature of the rating curve used and the formulations to obtain the results for E(D). For smaller expected detention times, the elevation of water in the pond is lower and the withdrawal rates will be less than the average obtained from Eq.(6-1). Therefore, the actual detention time will be greater than the expected detention time.
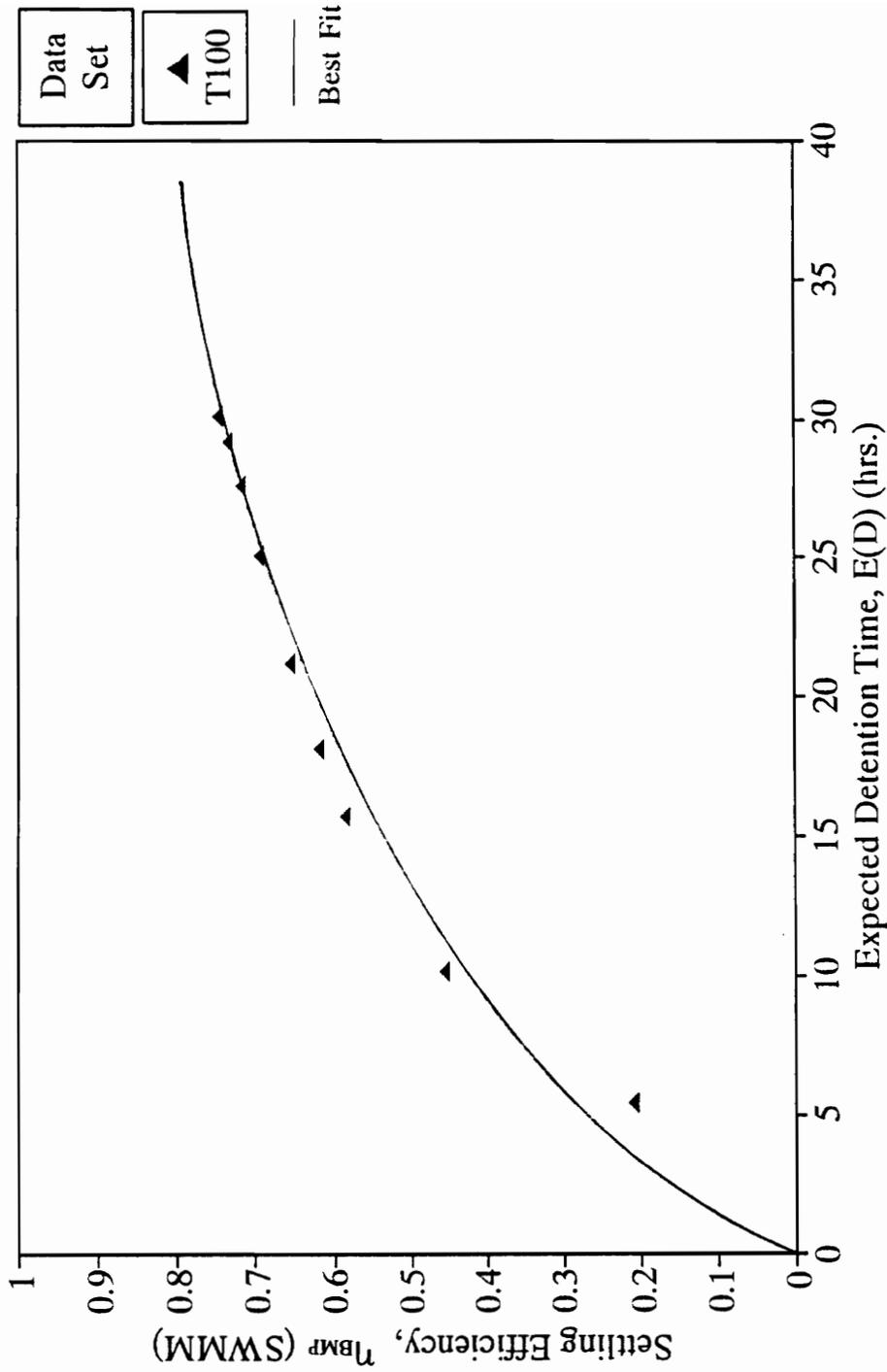
FIGURE 6-2. Results for Triangular Hydrographs (T100) Plotted with the Best Fit η_{BMP} vs. E(D) Curve from Chapter 4 for $\theta=0.1$
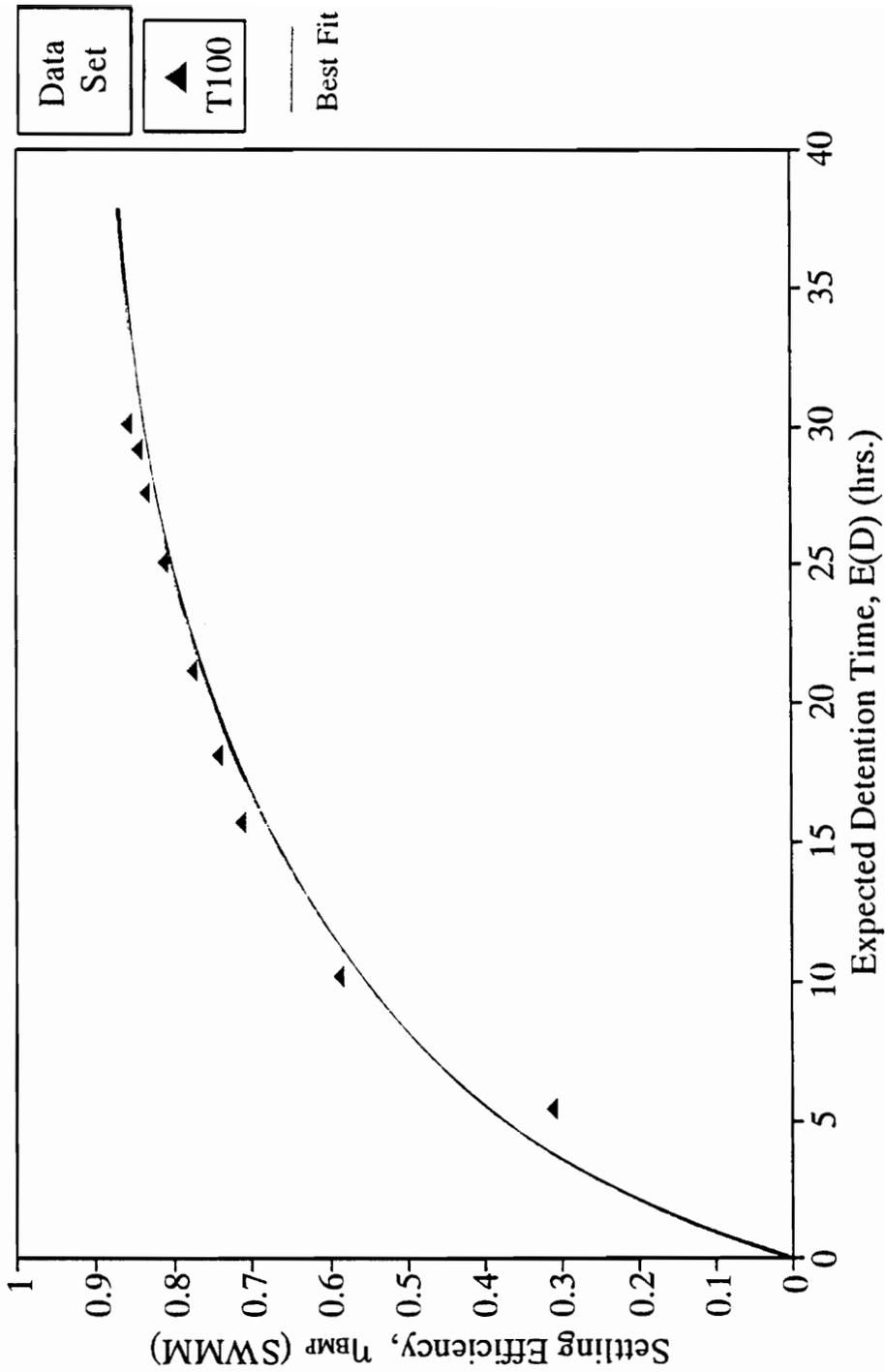
FIGURE 6-3. Results for Triangular Hydrographs (T100) Plotted with the Best Fit η_{BMP} vs. E(D) Curve from Chapter 4 for θ=0.2
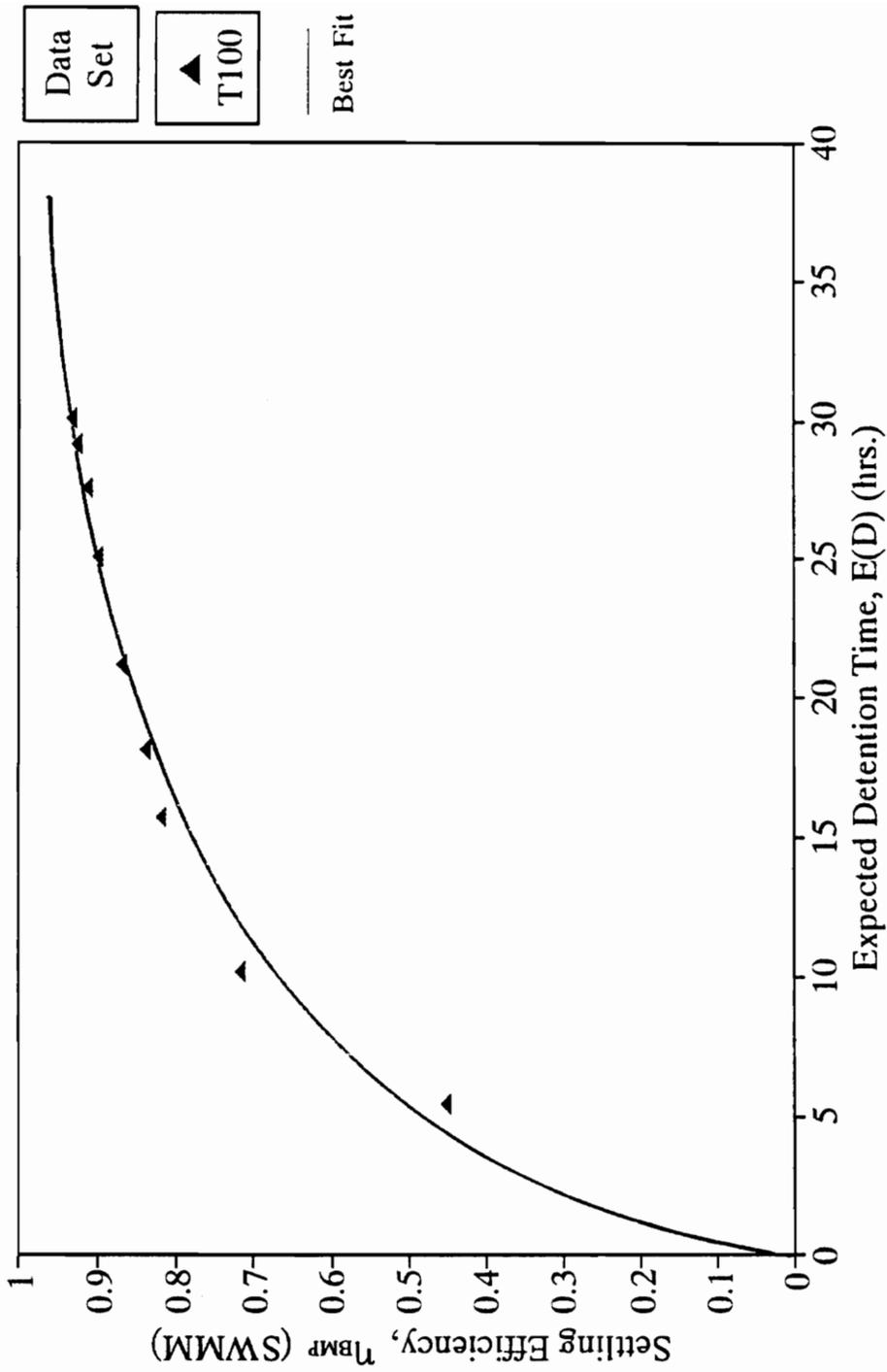
FIGURE 6-4. Results for Triangular Hydrographs (T100) Plotted with the Best Fit η_{BMP} vs. E(D) Curve from Chapter 4 for $\theta=0.5$
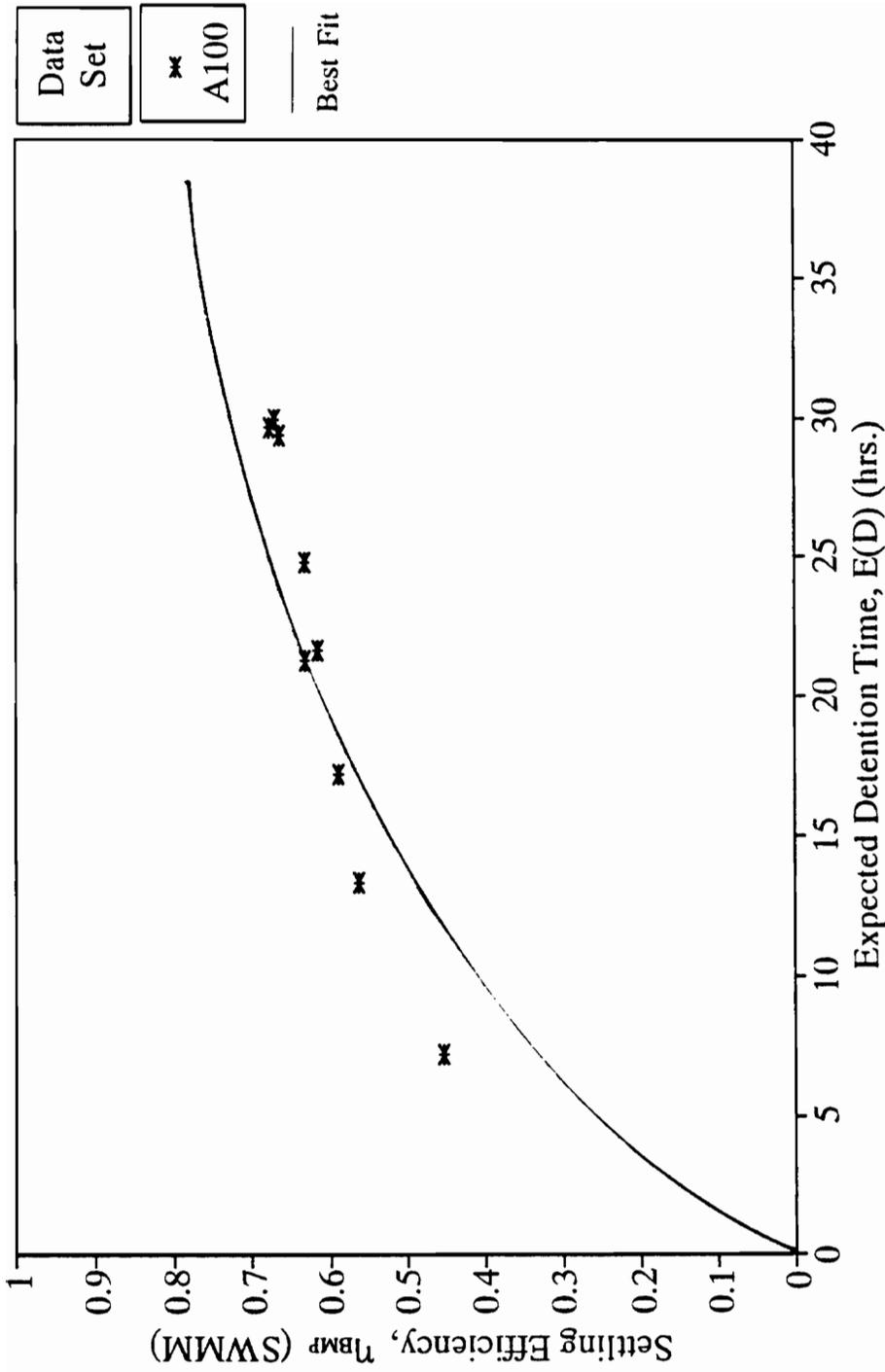
FIGURE 6-5. Results for Varying Withdrawal Rate (A100) Plotted with the Best Fit η_{IBMP} vs. E(D) Curve from Chapter 4 for $\theta=0.1$
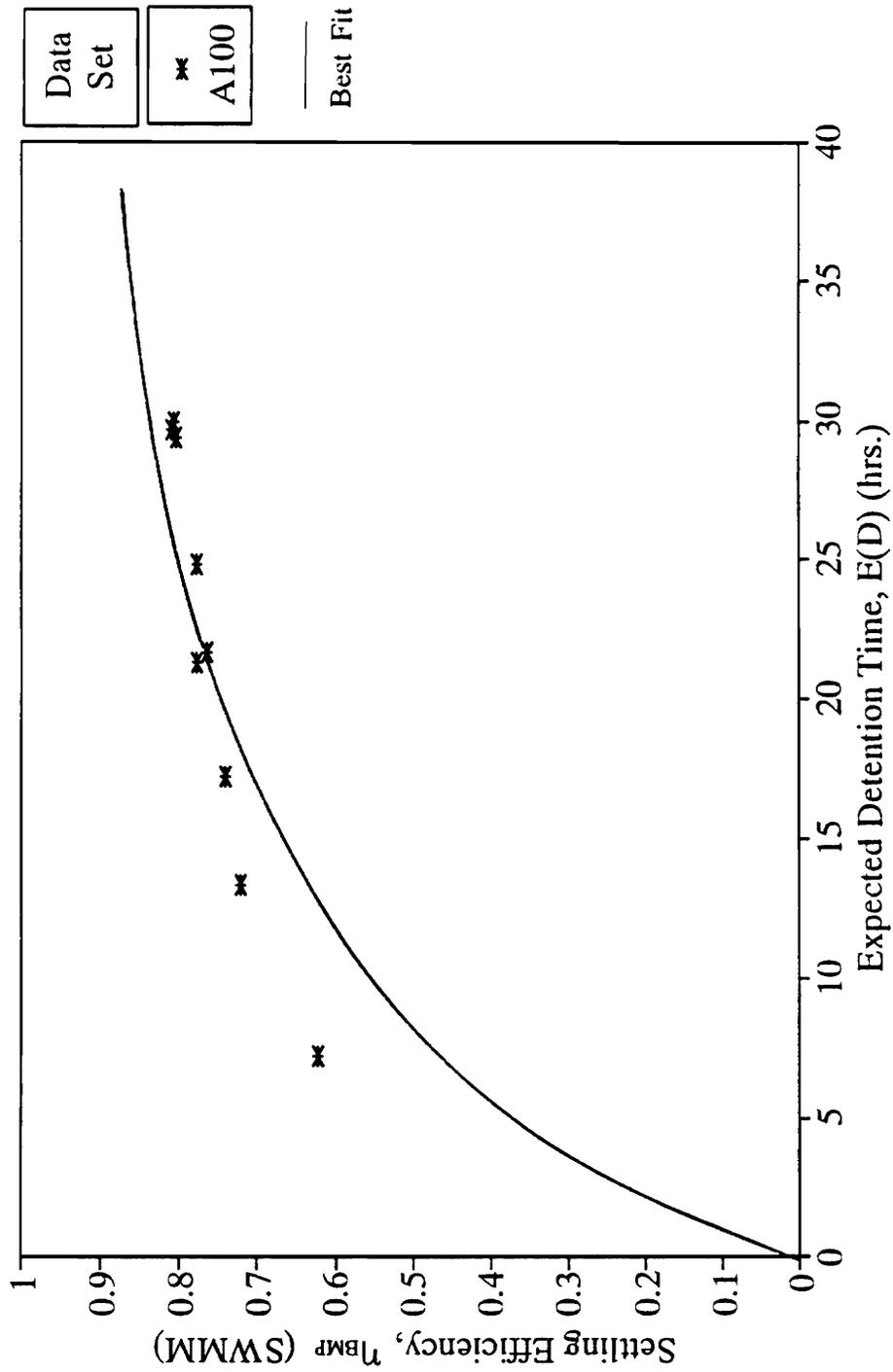
FIGURE 6-6. Results for Varying Withdrawal Rate (A100) Plotted with the Best Fit η_{BMP} vs. E(D) Curve from Chapter 4 for θ=0.2
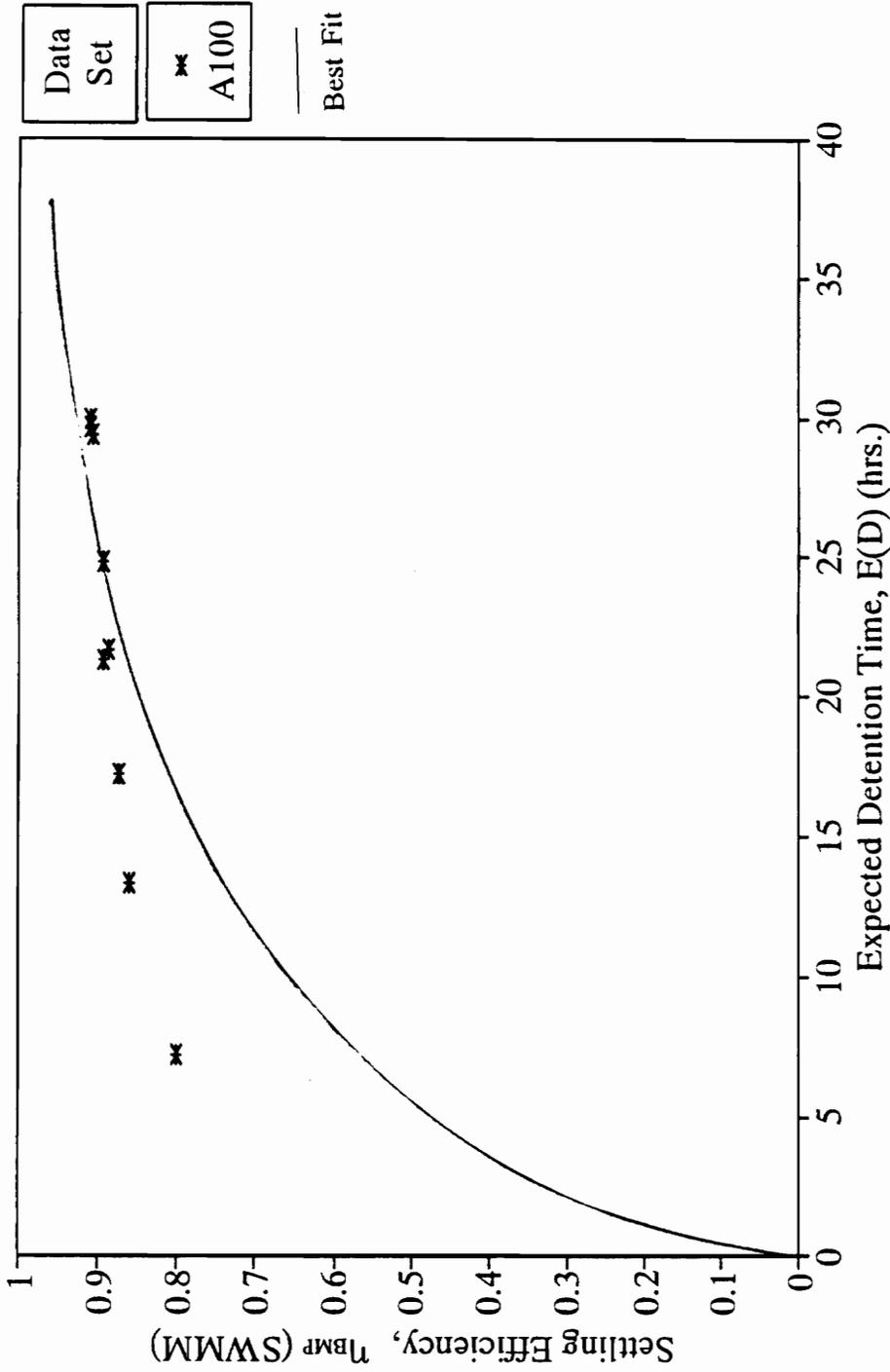
FIGURE 6-7. Results for Varying Withdrawal Rate (A100) Plotted with the Best Fit η_{BMP} vs. E(D) Curve from Chapter 4 for $\theta=0.5$

6.4 A Comparative Application

Goforth et al. (1983) made judicious SWMM simulations to determine the relationship between pond size -withdrawal rate and pollutant removal efficiency. A constant withdrawal rate was utilized as well as the completely mixed-removal equation pollutant routing scheme. Also, a value of 1 was used for R_{max} and a value of 0.6 for θ. A comparison between the present methodology and the results of the Goforth et al. (1983) study is made. For this purpose it was necessary to construct an η_{BMP} vs. E(D) curve corresponding to $\theta=0.6$ and $R_{max}=1$ to duplicate the Goforth et al. setup. This curve was developed from simulation runs using runoff statistics for region 100 (Table 4-2) following the procedure outlined in Chapter 4. The pond configurations used and the corresponding values for E(D) and η_{BMP} are shown in Table 6-7. The resulting η_{BMP} vs. E(D) curve is shown in Figure 6-7. The runoff statistics from the Goforth et al. study are given in Table 6-8. The 1953 data is used for comparison here. The results are given in terms of a normalized volume $[b/E(X_1)]$ and a normalized discharge $[aE(X_3)/E(X_1)]$. The results of the Goforth et al. study are given in Table 6-9.

The results of the present methodology are given in Tables 6-10 and 6-11. Table 6-10 gives the results for the present methodology for c=0 and c=b. A single set of results can be obtained by using $E(S_n)$ [Appendix B] as the value of c. These results are shown in Table 6-11. By noting the closeness of the values from Goforth et al. study [Table 6-9] with the values obtained here [Tables 6-10 and 6-11], it is obvious that the

TABLE 6-7. a and b values used and the resulting values for E(D) and η_{BMP} [$R_{max} = 1$ and $\theta = 0.6$].

a(in./hr.)	b(in.)	Avg. E(D)	η_{BMP}
.1	.2	0.44	.165
.05	.2	1.34	.325
.025	.2	3.59	.544
.02	.2	4.80	.613
.005	.05	7.76	.750
.005	.1	13.60	.834
.005	.2	21.83	.895
.0025	.1	25.6	.923
.00125	.05	27.87	.936
.0005	.02	29.38	.946
.000125	.005	30.18	.953
.001	2	62.5	.999
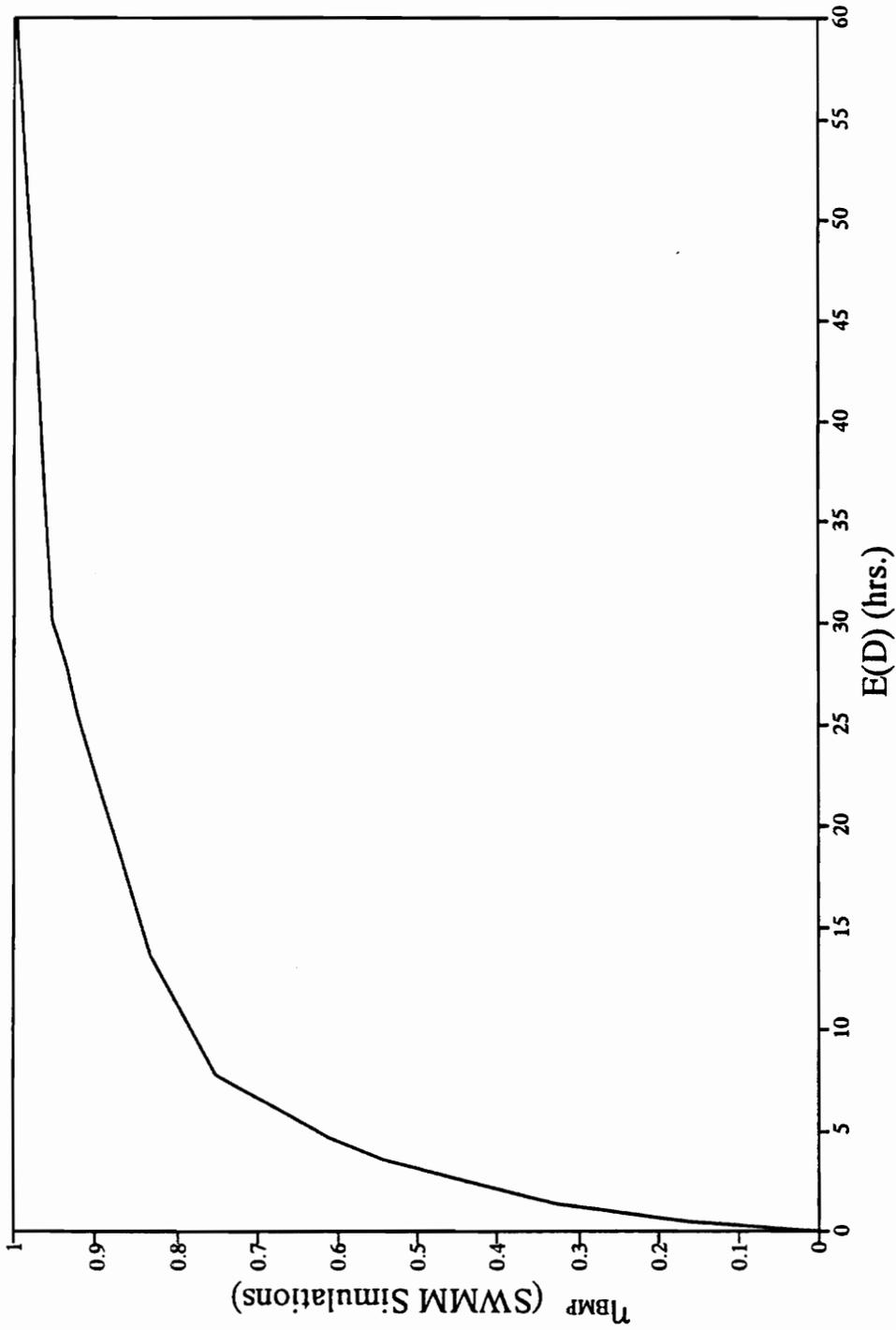
FIGURE 6-8. η_{BMP} vs. E(D) [R_{max}=1.0 and θ=0.6]

TABLE 6-8. Runoff parameters for 1953 and the 24.6 yr. Record (MIT=8 hrs.) [Goforth et al., 1983]

Rainfall Data Set	Number of events per year	Runoff Volume, X_1		Runoff Duration, X_2		Interevent Time, X_1	
		Mean (in)	Coefficient of Variation	Mean (in)	Coefficient of Variation	Mean (in)	Coefficient of Variation
24.6-year record	72	0.217	1.194	6.438	1.030	122.3	0.999
1953	71	0.223	1.102	6.887	1.121	124.3	0.937

TABLE 6-9. Comparison of Flow Capture Efficiency (η_{FL}) and Pollutant Removal Efficiency (η) as a Function of Basin Volume and Constant Discharge Rate: Simulation Results 1953 Data (Goforth et al., 1983).

Normalized discharge ratio, $aE(X_3)/E(X_1)$		Normalized Volume Ratio $b/E(X_1)$				
		0.40	0.77	1.49	3.82	8.61
1	η_{FL}	0.344	0.476	0.613	0.852	1.000
	η	0.343	0.476	0.598	0.847	0.989
2	η_{FL}	0.398	0.552	0.721	0.945	1.000
	η	0.373	0.527	0.690	0.906	0.961
4	η_{FL}	0.468	0.621	0.804	0.962	1.000
	η	0.373	0.532	0.712	0.864	0.905
7	η_{FL}	0.542	0.699	0.839	0.971	1.000
	η	0.365	0.524	0.661	0.792	0.817
10	η_{FL}	0.611	0.744	0.868	0.982	1.000
	η	0.342	0.483	0.603	0.713	0.728

TABLE **6-10.** Stochastic Methodology Results for Table 6-9.

Normalized discharge ratio, $aE(X_3)/E(X_1)$		Normalized Volume Ratio $b/E(X_1)$									
		0.40		0.77		1.49		3.82		8.61	
		c=0	c=b	c=0	c=b	c=0	c=b	c=0	c=b	c=0	c=b
1	E(D)	34.2	32.4	54.0	46.3	80.5	55.9	117	58.9	124	58.9
	η_{FL}	.313	.365	.425	.561	.502	.786	.526	.979	.526	1.00
	η_{BMP}	.96	.96	.99	.98	1.00	.99	1.00	1.00	1.00	1.00
	η	.300	.350	.421	.550	.502	.778	.526	.979	.526	1.00
2	E(D)	17.4	16.8	28.4	25.6	44.8	33.3	84.8	37.2	118	37.3
	η_{FL}	.370	.397	.511	.583	.636	.797	.698	.980	1.00	.700
	η_{BMP}	.87	.86	.94	.92	.98	.96	1.0	.97	.97	1.0
	η	.322	.341	.480	.536	.623	.765	.698	.951	.970	.700
4	E(D)	8.2	8.0	13.4	12.6	21.2	17.2	44.0	20.2	85.4	20.4
	η_{FL}	.439	.451	.586	.621	.735	.816	.831	.982	.836	1.00
	η_{BMP}	.75	.75	.83	.82	.90	.87	.97	.88	1.00	.88
	η	.329	.338	.486	.509	.662	.710	.806	.864	.836	.880
7	E(D)	4.2	4.1	6.8	6.6	10.6	9.2	21.5	11.0	49.5	11.2
	η_{FL}	.511	.517	.648	.660	.795	.838	.902	.984	.910	1.00
	η_{BMP}	.60	.60	.70	.70	.79	.77	.90	.80	.98	.80
	η	.307	.310	.454	.462	.628	.645	.812	.787	.892	.800
10	E(D)	2.6	2.6	4.3	4.2	6.6	5.9	12.8	7.2	31.1	7.3
	η_{FL}	.565	.569	.691	.702	.828	.855	.933	.986	.941	1.00
	η_{BMP}	.44	.44	.60	.60	.70	.66	.82	.72	.96	.73
	η	.249	.250	.415	.421	.580	.564	.765	.710	.903	.730

TABLE 6-11. Stochastic Methodology Results $c=E(S_a)^*$ for Table 6-9.

Normalized discharge ratio, $aE(X_3)/E(X_1)$		Normalized Volume Ratio $b/E(X_1)$				
		0.40	0.77	1.49	3.82	8.61
1	E(D)	33.7	51.1	66.5	97.3	119.6
	η_{FL}	0.332	0.494	0.692	0.923	0.994
	η_{BMP}	0.96	0.98	1.00	1.00	1.00
	η	0.319	0.484	0.692	0.923	0.994
2	E(D)	17.2	27.0	37.8	53.7	84.1
	η_{FL}	0.382	0.554	0.759	0.961	0.998
	η_{BMP}	0.86	0.93	0.97	0.98	1.00
	η	0.328	0.515	0.736	0.942	0.998
4	E(D)	8.1	12.9	18.2	24.0	35.4
	η_{FL}	0.446	0.610	0.802	0.977	1.00
	η_{BMP}	0.76	0.82	0.87	0.91	0.96
	η	0.339	0.500	0.698	0.889	0.96
7	E(D)	4.1	6.6	9.4	11.9	14.7
	η_{FL}	0.515	0.662	0.833	0.983	1.00
	η_{BMP}	0.58	0.69	0.77	0.81	0.84
	η	0.298	0.455	0.641	0.796	0.84
10	E(D)	2.6	4.2	6.0	7.4	8.4
	η_{FL}	0.568	0.700	0.853	0.985	1.00
	η_{BMP}	0.44	0.60	0.68	0.74	0.76
	η	0.249	0.420	0.580	0.729	0.760

Use Eq.(II.6) for c.

methodology presented here is very formidable. Estimates for BMP efficiency and overall efficiency can be made very quickly. These estimates prove to be very close to the long term SWMM simulations performed in the Goforth et. al. study.

Goforth et al. also plotted the solution surface for overall efficiency as a function of the normalized volume and normalized withdrawal rate. A similar plot can be made from the results from the statistical methodology. $E(S_n)$ [Appendix B] is chosen as the value of c in Eqs.(3-34) and (5-4). The two sets of curves are given in Figure 6-8. Some key observations can be made from the plot. It should be noted that for a given normalized volume there are two values of normalized withdrawal rate that produce the same overall efficiency. This demonstrates the performance tradeoff between capture efficiency and BMP efficiency. For a certain b and high values of a, the capture efficiency will be high and the BMP efficiency will be low. Conversely, for that same b and low values of a, the capture efficiency will be low and the BMP efficiency will be high. Since the overall efficiency is the product of the BMP efficiency, there are two withdrawal rates that give the same overall efficiency.

The isoquants generated from the statistical approach duplicate the shape of the simulation plots. This duplication of shape is further evidence that the stochastic model proposed here accounts for the combined effect of capture efficiency and settling efficiency. However, the statistical isoquants fail to duplicate the positioning of the simulation isoquants on the grid. The statistical solution surfaces can be considered
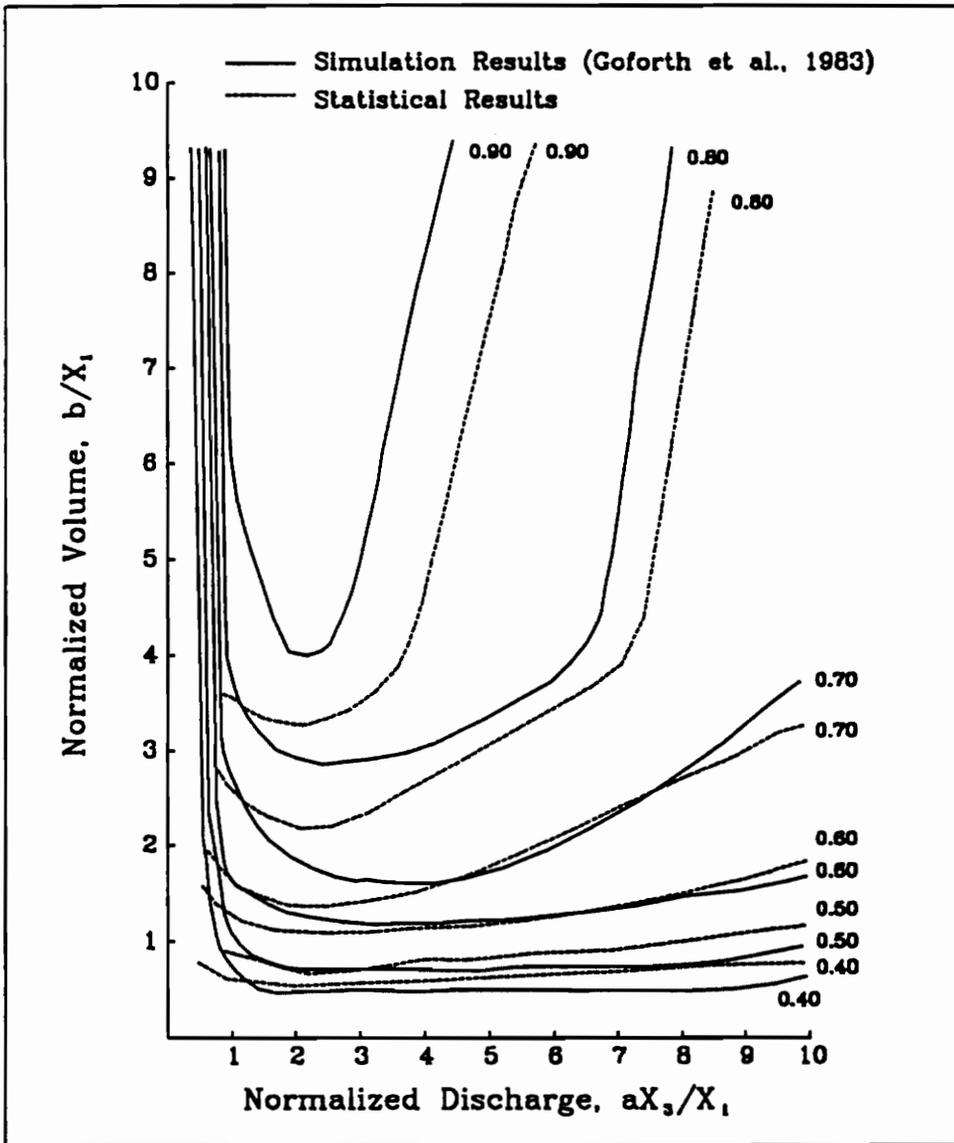
FIGURE 6-9. Solution Surface of Basin Performance: Simulation Results (Goforth et al., 1983) and Stochastic Model Results.

liberal compared to the simulation solutions. For the same efficiency, the statistical method will give smaller basin volume and/or larger discharge rate requirements. This is especially true for the higher efficiencies (80 and 90 per cent). This discrepancy can be accounted for by a failure to pick the appropriate value for c. This is an unavoidable weakness of the statistical method. A value of c must be chosen to proceed with the methodology. However, the discrepancy can be viewed as small when it is noted that the statistical method is presented as a planning stage methodology.

6.5 Numerical Examples

Three numerical examples are given: 1) a straight forward calculation of overall efficiency given a and b; 2) a target overall efficiency is given and the solution set (a, b) that minimizes b is required; and 3) the design methodology presented here is compared to the present methodology used in northern Virginia. In the first problem, the results from a SWMM simulation are used to solve the problem and then the procedure outlined in section 5.3 (Chapter 5) is used to solve the same problem. In the second problem, a computer program is introduced that searches possible solution sets for those that satisfy the target efficiency. In addition, the rainfall statistics from the an EPA region are converted to runoff statistics for use in the model. Finally, results from MEDD are compared to the pond sizing procedure used in northern Virginia.

6.5.1 Problem 1

Determine the capture efficiency, η_{FL}, the settling efficiency, η_{BMP}, and the overall removal efficiency, η, of total suspended solids (TSS) for an extended detention pond with the total storage equal to 0.1 (basin inches) and an average withdrawal rate equal to 0.0025 (basin inches per hour). The runoff statistics for the watershed are given by region 100 in Table 3. Assume the pollutant concentration is constant in the runoff volume and $\theta = 0.1$ hr^{-1} and $R_{max}= 0.9$ for pollutant removal (Same setup as SWMM input file given in Appendix C, Exhibit C.2 and C.3).

Solution (SWMM):

From the SWMM output file (Appendix C):

INFLOW, TOTAL (TSS, POUNDS)   = 1.5985E+06

INFLOW, NET (TSS, POUNDS)   = 4.4842E+05

REMOVED BY DECAY (TSS, POUNDS)   = 3.1503E+05

The capture efficiency is given by Eq.(6-3), since the influent concentration is constant the ratios for volume and TSS will be the same. For this case:

η_{FL} = 0.281.

From Eq.(4-4), the settling efficiency can be calculated as:

η_{BMP} = 0.702.

Calculating the overall efficiency:

$$\eta \quad = \eta_{FL} \, \eta_{BMP}$$

$$= 0.197$$

Solution (Stochastic Model):

Following the steps outlined in section 5.3 for c=0 and c=b:

Step 1: Use Eq. (3-34) to calculate E(D):

E(D)= 26.39 hrs.   for c=0
E(D)= 24.81 hrs.   for c=b

Step 2: Use Figure 4-4 or 4-7 to determine η_{BMP} for each E(D):

η_{BMP}= 0.68   for c=0
η_{BMP}= 0.66   for c=b

Step 3: Use Eq. (5-4) to calculate the capture efficiency (η_{FL}) for b=0.1 in. and

a=0.0025 in/hr:

η_{FL}= 0.266   for c=0
η_{FL}= 0.328   for c=b

Step 4: Use Eq. (29) to calculate the overall efficiency, η:

η= 0.181   for c=0
η= 0.216   for c=b

6.5.2 Problem 2

Determine a and b for a detention basin located in Atlanta, Georgia to achieve an overall removal efficiency of 70% for TSS. The watershed has an impervious area of 25%. Assume the settling parameters for TSS are: $\theta = 0.6$ hr^{-1} and $R_{max} = 1.0$. Also assume $c=E(S_n)$. **Note:** Theoretically, there are an infinite number of a and b combinations that will produce a single overall efficiency. In general, the overall efficiency (η) contour assumes a "U" shape in the space of b versus a, similar to Figure 6-8. To pinpoint a single solution set of b and a we can minimize b. This solution is significant since the minimum required storage is usually sought in design.

Solution:

Step 1: The runoff statistics for the watershed in Atlanta must be determined. We can estimate the runoff statistics from the rainfall statistics for Atlanta and a rainfall volume-runoff volume conversion factor (λ) for the watershed. Atlanta is in EPA rainfall zone 3. From Table 4-1 the mean annual rainfall depth, duration and interevent time for zone 3 are 0.49 in., 6.2 hrs., and 89 hrs. respectively. Assume the runoff duration is equal to the rainfall duration and the interevent time for runoff is equal to the interevent time for rainfall. Figure 6-10 shows a relationship between impervious area and the rainfall volume-runoff volume conversion factor (λ) [Urbonas et al.]. This curve is based on a regression of data taken from the EPA nationwide urban runoff program (NURP)

[USEPA, 1983]. Use Figure 6-10 to determine the runoff coefficient (λ) for 25% impervious area. The rainfall volume-runoff volume conversion factor (λ) is 0.2. Therefore, the runoff statistics for the watershed are:

X_1 = 0.20 x 0.49 = 0.098 in.
X_2 = 6.2 hrs.
X_3 = 89 hrs.

Step 2: Determine the solution set of a and b pairs that satisfy the 70% overall efficiency requirement. This is an iterative process that involves the following steps:

Step 2a: Choose initial estimates for a and b (a_o, b_o), an increments (Δa, Δb) for iteration, and a maximum value for each design variable (a_{max}, b_{max}). For simplicity, let $a_o = \Delta a$ and $b_o = \Delta b$.

Step 2b: Calculate $E(S_n)$ from Eq. (B-6) and let $c = E(S_n)$.

Step 2c: Follow steps 1-4 from problem 1 to calculate E(D), η_{BMP}, η_{FL}, and η.

Step 2d: If η meets the requirement (70%) add the current values of a and b to the solution set.

Step 2e: Repeat steps 2b-2d for each possible combination of a and b.

Step 3: Scan the solution set for the minimum 'b'. The solution is:

a = 0.00187 in./hr.; b = 0.137 in.; c = [$E(S_n)$] = 0.061 in.; E(D) = 30.066 hrs.;

η_{BMP} = 0.735; η_{FL}= 0.952; and η = 0.699.
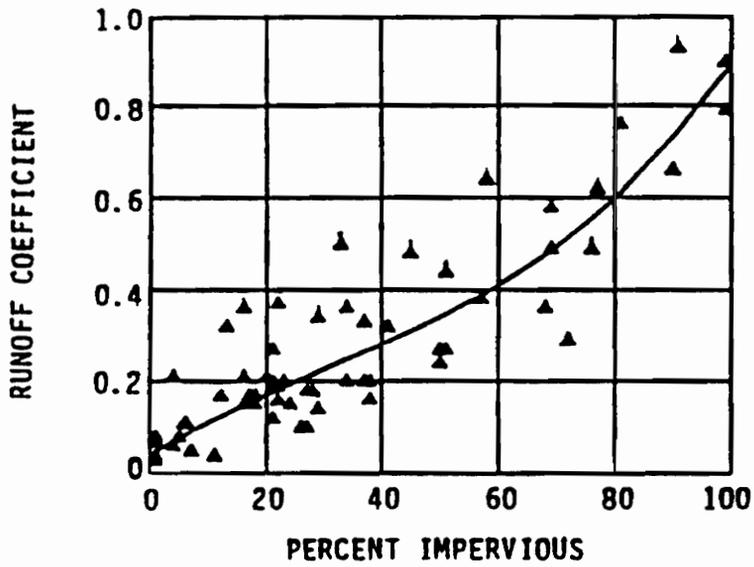
FIGURE 6-10. Runoff Coefficienct Based on NURP Data for 2 year and Smaller Storms [Urbonas et al.,1989].

6.5.3 Problem 3

Determine the storage volume and withdrawal rate required for a detention basin to achieve a 40% reduction in phosphorous load leaving a watershed in northern Virginia that has an area of 526.7 acres [18% impervious]. First, the problem is solved by the method prescribed by the *Northern Virginia BMP Handbook* (Northern Virginia Planning District Commission, NVPDC, 1992) and then by the method proposed here.

Solution (NVPDC):

To achieve a 40% reduction in phosphorous load, NVPDC requires the storage volume be equal to the volume determined by Figure 6-11 (referred to as Chart A) and the brim full drawdown time be 48 hrs. Figure 6-11 was developed from a series of computer experiments performed by NVPDC. The required volume was determined for each specified land use type as the "upper limits for runoff volumes which warranted nonpoint pollution management" (NVPDC, 1979). Long term removal rates for each volume were determined by a series of computer runs using the STORAGE-TREATMENT Model. A constant settling efficiency was used as input for the model based on an assumed detention time of 24 hrs. Further, it was assumed that a drawdown time of 40 hrs. resulted in a detention time of 24 hrs. The results are shown in Table 6-12 (NVPDC, 1979). Figure 6-11 (Chart A) was created by plotting the NPS Storage versus the percentage impervious area for each land use type found in Table 6-12.
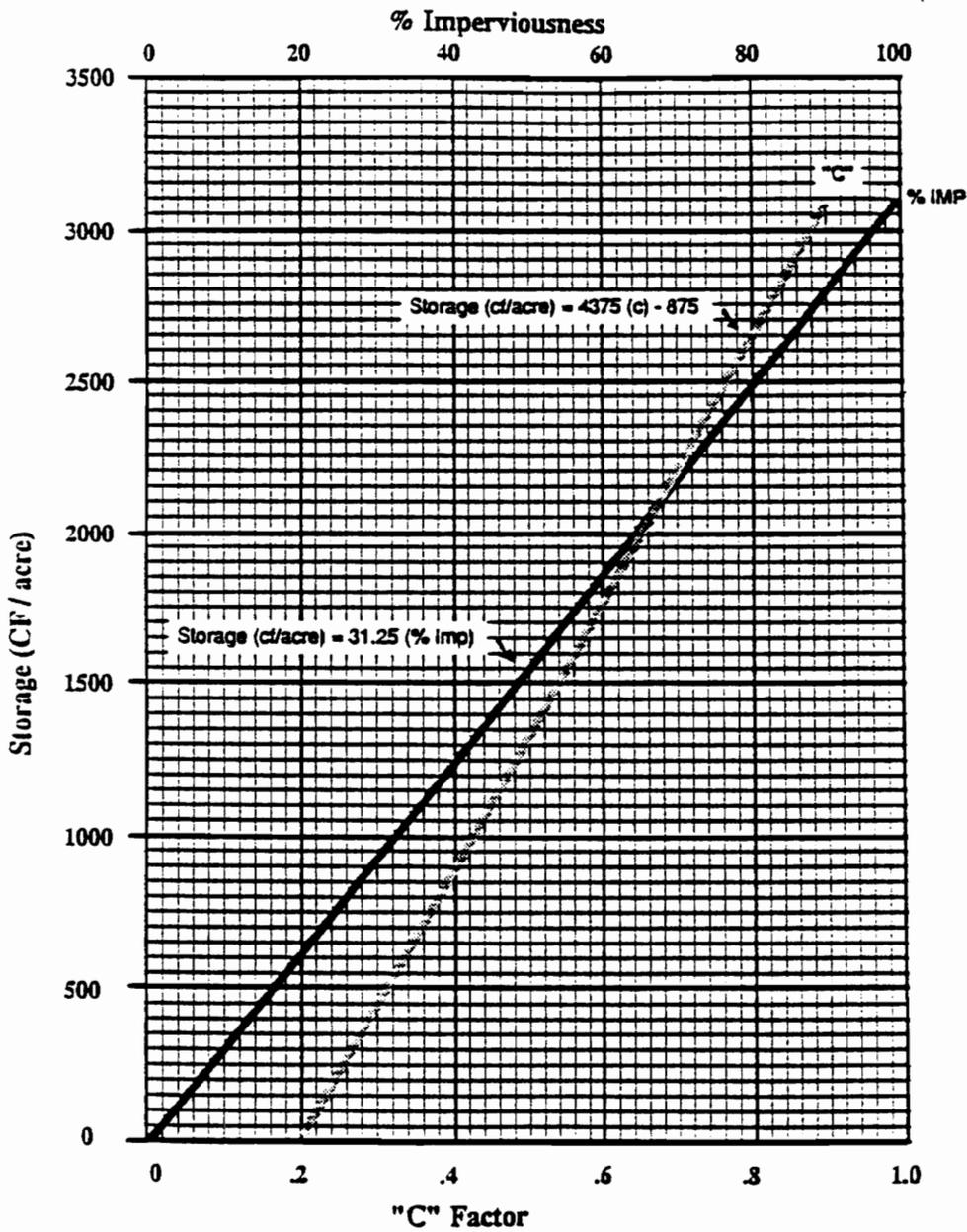
FIGURE 6-11. Chart A, Water Quality Storage Requirements Related to Percent Imperviousness and the Rational Formula "C" Factor [NVPDC, 1992]

TABLE 6-12. Projected Average Pollutant Removal Rates For Online Detention Control BMP's (NVPDC, 1979).

Land Use/ Impervious %	NPS Mgt. Storage (in.)	NPS Release Rates (in./day)	Annual Sediment Removal (%)	Annual Total Phosphorous Removal (%)
Large-Lot Single Family (12% Impervious)	0.10	0.10	88	33
Medium-Density Single Family (25% Impervious)	0.21	0.21	89	40
Townhouse/Garden Apartment (40% Impervious)	0.33	0.33	88	48
High Rise Residential (70% Impervious)	0.54	0.54	93	43
Industrial (70% Impervious)	0.54	0.54	93	43
Shopping Center (90% Impervious)	0.78	0.78	94	47

From Chart A the required storage for 526.7 acres and 18% imperviousness is:

Storage (ft.^{3})   = 31.25 * (18) * 526.7 = 296,268.75 ft.^{3} = 6.80 ac-ft. = 0.155 in.= b

and for a 48 hr drawdown time:

a (in/hr)   = 0.155 in./48 hrs. = 0.00323 in./hr. = 1.714 cfs

Solution (Stochastic Model):

Northern Virginia is in EPA rainfall zone 2. From Table 4-1 the mean annual rainfall

depth, duration and interevent time for zone 2 are 0.36, 5.9, and 77 respectively. Again,

assume the runoff duration is equal to the rainfall duration and the interevent time for

runoff is equal to the interevent time for rainfall. Use Figure 6-10 to determine the runoff

coefficient (λ) for 18% impervious area. The rainfall volume-runoff volume conversion

factor (λ) is 0.15. Therefore, the runoff statistics for the watershed are:

X_1 = 0.15 x 0.36 = 0.054 in.
X_2 = 5.9 hrs.
X_3 = 77 hrs.

To determine the settling efficiency for phosphorous, the η_{BMP} vs. E(D) curve used is the

relationship between pollutant removal percentage and detention time provided in Figure

4-1 for phosphorous. Following the steps outlined in Problem 2, the solution set (a, b)

with the minimum b is:

a   = 0.00119 in./hr.   = 0.632 cfs.

b   = 0.119 in.   = 227,519 ft.^{3} = 5.22 ac.-ft.

where: c = 0.061 in.; E(D) = 30.829 hrs.; η_{BMP} = 0.464; η_{FL}= 0.86; and η = 0.400.

6.5.4 Computer Program "MEDD"

Problems 2 and 3 were solved using the computer program, Methodology for Extended Detention basin Design, MEDD. MEDD is a program written in BASIC that performs the calculations outlined in problems 1 and 2 in the previous sections. The program consists of a main module, MEDD, and seven subroutines. The program code is given in Appendix D as Exhibit D.4. The following is a brief description of each module:

MEDD reads the primary input file and directs the program logic.

Subroutine COMLINE reads the input and output file names if they appear on the command line.

Subroutine ECHOIN echos the input to the output file.

Subroutine RDFL reads the expected detention time-η_{BMP} pairs from the eta input file.

Subroutine SN calculates the expected end of the period storage [Eq.(B-6)].

Subroutine CALC calculates the expected detention time and the capture efficiency [Eqs.(3-34)and (5-4)].

Subroutine INTERP interpolates between the given E(D)-η_{BMP} pairs to find the appropriate η_{BMP} for a calculated E(D).

Subroutine ELOOP performs the loop described by steps 2a-2d in problem 2.

Input for MEDD is provided by an input file. A typical input file is given in Appendix D as Exhibit D.5. Each input requirement is listed and explained. A typical output file is given in Appendix D as Exhibit D.6. The output consists of an echo of the input and a listing of the solution sets of a and b along with corresponding values of c, $E(D)$, η_{BMP}, η_{FL}, and η.

CHAPTER 7

SUMMARY

This research is motivated by the traditional use of drawdown time as a key parameter for the design of extended detention ponds for pollutant removal. Drawdown time overestimates actual detention time. In fact, drawdown time is the upper limit for actual detention time. Presently, drawdown time is used as a surrogate for the actual detention time because of the lack of a methodology to estimate the average detention time. In this paper a closed form, explicit equation for expected detention time is provided. This equation [Eq. (3-34)] incorporates the variable nature of runoff volumes, durations, and interevent times to accurately predict the expected detention time for a given pond configuration.

Furthermore, computer experiments with the EPA SWMM computer program support the use of the expected detention time as an effective parameter in assessing the pollutant settling efficiency within the pond. Detailed simulation tests also reveal an invariant characteristic of the settling efficiency versus expected detention time relationship over a range of runoff statistics. This curve retains its same shape over a range of drawdown times or capacity-withdrawal rate ratios. It is also unaffected by the choice of the constant influent concentration. These charateristics allow a family of

standardized settling-efficiency curves (parameterized only on the settling characteristics of the pollutant in question) to be developed from SWMM simulation runs. The expected detention time is used with these standardized to estimate settling efficiency.

The settling efficiency is combined with an expression for capture efficiency to estimate the overall efficiency of a basin design. From a design point of view, the methodology accounts for the pollutant load captured by the detention pond and the reduction of that load within the pond due to settling. The extended detention design methodology presented here is accurate and easy to use. When tested against results from detailed simulations using SWMM, the methodology performs quite well.

REFERENCES CITED

BMP Handbook for the Occoquan Watershed (1987). Northern Virginia Planning District Commission, NVPDC.

Delleur, J. W. and Padmanabhan, G. (1981). "An Extended Statistical Analysis of Synthetic Nonpoint Urban Quantity and Quality Data." *Proc. Internat. Symp. on Urban Hydrology, Hydraulics, and Sediment Control,* University of Kentucky, Lexington, Ky, 229-238.

Di Toro, D. M. and Small, M. J. (1979). "Stormwater interception and storage," *Journal of Environmental Engineering Division,* ASCE, 105(1), 43-54.

Dorman, M. E. (1991). "A Methodology for the Design of Wet Detention Basins for Treatment of Highway Stormwater Runoff," *M.S. Thesis,* Virginia Tech.

Driscoll, E. D.(1989). "Long Term Performance of Water Quality Ponds," *Design of Urban Runoff Quality Controls,* ASCE, 145-163.

Etoh, T. and Kurita, H. (1992). "A Theory of Efficiency of Storage-Treatment Systems." *Stochastic Hydrology and Hydraulics,* Vol. 6, 89-101.

Fogler, H. S. (1992). *Elements of Chemical Reaction Engineering.* Prentice Hall, Englewood Cliffs, N.J. Chapter 13.

Goforth, G. F., Heaney, J. P. and Huber, W. C. (1983). "Comparison of Basin Performance Modeling Techniques," *Journal of Environmental Engineering Division,* ASCE, 109(5), 1082-1098.

Grizzard, T. J., Randall, C. W., Weand, B. L. and Ellis, K. L. (1986). "Effectiveness of Extended Retention Ponds," *Urban Runoff Quality,* ASCE.

Guidebook for Screening Urban Nonpoint Pollution Management Strategies. (1979). Northern Virginia Planning District Commission, NVPDC.

Howard, C. D. (1976). " Theory of Storage and Treatment-Plant Overflows," *Journal of Environmental Engineering Division,* ASCE, 102(4), 709-722.

Huber, W.C., Heaney, J.P., and Nix, S.J. (1980), "Stormwater Management Model User's Manual-Version III," *EPA Draft Report*, National Environmental Research Center, Cincinnati, Ohio.

Huber, W. C. and Dickinson R. E. (1988). "Storm Water Management Model, Version 4: User's Manual," Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, August 1988.

Levenspiel, O. (1972). *Chemical Reaction Engineering.* Wiley and Sons, New York, N.Y. Chapter 9.

Loganathan, G. V., Delleur, J. W. and Segarra, R. I. (1985). "Planning Detention Storage for Stormwater Management," *Journal of Water Resources Planning and Management Division*, ASCE, 111(4), 382-398.

Martin, E.H. (1989). "Mixing and Residence Times of Stormwater Runoff in a Detention System," *Design of Urban Runoff Quality Controls,* ASCE, 164-179.

Nauman E. B. and Buffham. (1983). *Mixing in Continuous Flow Systems.* Wiley and Sons, New York, N.Y.

Nix, Stephen. J. (1984). "Residence Time in Stormwater Detention Basins" *Journal of Environmental Engineering,* ASCE, 111(1).

Nix, Stephen J., Heaney, J. P., and Huber, Wayne C. (1988). "Suspended Solids Removal in Detention Basins," *Journal of Environmental Engineering*, ASCE, 114 (6).

Northern Virginia BMP Handbook. (1992). Northern Virginia Planning District Commission, NVPDC.

Randall, C. W., Ellis K., Grizzard, T.J., and Knocke W.R. (1982). "Urban Runoff Pollutant Removal by Sedimentation," *Proc. Stormwater Detention Facilities*, New England College, New Hampshire, Aug. 2-6, 205-219.

Schueler, T. B. (1987). *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMP's*, Washington Metropolitan Water Resources Planning Board.

Segarra-Garcia, R., Loganathan, G.V. (1992). "Storm-Water Detention Storage Design under Random Pollutant Lading," *Journal of Water Resources Planning and Management*, ASCE, 111(4).

Stahre, P. and Urbonas, B. (1990). *Stormwater Detention for Drainage, Water Quality and CSO Management*. Prentice Hall, Englewood Cliffs, N.J.

Taylor, H. M. and Karlin S. (1984). *An Introduction to Stochastic Modeling*. Academic Press, Orlando, Florida.

Urbonas, B., Guo, J. C., and Tucker L. S. (1989). "Optimization of Stormwater Quality Capture Volume," *Urban Stormwater Quality Enhancement*, ASCE, 94-110.

U. S. Environmental Protection Agency. (1983). "Results of the Nationwide Urban Runoff Program, Volume I - Final Report," Water Planning Division, NTIS No. PB84-185545, Washington D.C.

U. S. Environmental Protection Agency. (1986). "Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality," *EPA 440/5-87-001*, Office of Water, Nonpoint Source Branch, Washington D.C.

Viessman, J. W. et al. (1977). *Introduction to Hydrology*. 2nd Edition. Harper and Row, Publishers, Inc., New York.

APPENDIX A

EXPECTED VALUE OF A NONNEGATIVE VARIABLE

The following proof is according to Taylor and Karlin (1984). Let X be a nonnegative continuous random variable with density f(x) and distribution function F(x).

$$E[X] = \int_0^\infty [1 - F(z)] \, dz .$$

(A-1)

obtained by interchanging the order of integration as follows:

$$E[X] = \int_0^\infty x \, f(x) \, dx = \int_0^\infty \left(\int_0^x dz \right) f(x) \, dx$$

$$= \int_0^\infty \left[\int_z^\infty f(x) \, dx \right] dz = \int_0^\infty [1 - F(z)] \, dz .$$

(A-2)

Interchanging the order of integration where the limits are variables often proves difficult. The trick of using indicator functions to make the limits of integration constant may simplify matters. In the preceding interchange, let

$$1(z < x) = \begin{cases} 1 & \text{if } 0 \le z < x, \\ 0 & \text{otherwise,} \end{cases}$$

(A-3)

and then

$$\int_0^\infty \left(\int_0^x dz \right) f(x)\,dx = \int_0^\infty \left[\int_0^\infty 1(z < x) f(x)\,dz \right] dx$$

$$= \int_0^\infty \left[\int_0^\infty 1(z < x) f(x)\,dx \right] dz = \int_0^\infty \left[\int_z^\infty f(x)\,dx \right] dz \ .$$

$$(\text{A-4})$$

APPENDIX B

EXPECTED END OF THE EVENT STORAGE

In this appendix an estimator for the end of the period storage is provided which may be used in place of c in Eqs. (3-34) and (5-4) for estimating the expected detention time, $E(D)$ and flow capture efficiency, $P(Y=0)$, respectively. Using the probability distribution of S_n given in Eqs. (3-9), (3-10), (3-11), and (3-12) we can evaluate the conditional expected value for S_n for a given S_{n-1} as

$$E[S_n|S_{n-1}=c] = \int_{0^-}^{c} s\,f_s\,ds + \int_{c}^{b^-} s\,f_s\,ds + b\,P(S_n=b) \qquad \text{(B-1)}$$

which yields

$$E[S_n|S_{n-1}=c] = c - \frac{k}{\alpha} + \frac{a}{\gamma} - \frac{ka}{\gamma} - \frac{ma}{\gamma} + \frac{ma}{\beta} + \frac{k}{\alpha}\exp(-\alpha c)$$

$$- \frac{ma}{\beta}\exp\left(-\frac{\beta b}{a}+\frac{\beta c}{a}\right) + \frac{ka}{\gamma}\exp\left(-\alpha b - \frac{\gamma b}{a}+\frac{\gamma c}{a}\right) \qquad \text{(B-2)}$$

$$- \left(b - kb - mb + \frac{a}{\gamma} - \frac{ma}{\gamma} - \frac{k\alpha ab}{\gamma} + \frac{mb\beta}{\gamma}\right)\exp\left(-\frac{\gamma b}{a}+\frac{\gamma c}{a}\right).$$

In Eq.(B-2) to remove the effect of γ, let us assume c=b (i.e. the tank is empty at the end of the previous event). If a is very large, then we would expect the conditional expected value of S_n to be b. For a tending to a large number, k approaches zero and m goes to $\gamma/(\gamma-\beta)$. When these estimates are used in Eq. (B-2) we obtain $E[S_n \mid b] = b$. In addition, if a=0 the role of interevent time is removed. Because a=0, the empty space

c at the end of the previous event remains unchanged until the next event arrives. Because of the nonnegativity of S_n, and limited empty space c, the pond will be able to capture only those events which have volumes less than c. That is the portion of events which bring volumes less than c is given by [1-exp(-αc)] multiplied by the average event volume, 1/α. Therefore, at the end of the event, the leftover empty space will be c - 1/α [1-exp(-αc)]. For a=0 we have k approaches 1 and m approaches zero and therefore from Eq.(B-2):

$$ E[S_n | c] = c - \frac{1}{\alpha} \left(1 - \exp[-\alpha c] \right) . \tag{B-3} $$

The most important case is when interevent time is taken into consideration and is large. For this case γ tends to zero with k and m also tend to zero; while k/γ and m/γ approach β/[αa(αa + β)] and -αa/[β(αa + β)] respectively. Using the above estimates in Eq.(B-3) we obtain

$$ E[S_n | c] = c + \frac{a}{\gamma} \left(1 - \exp\left[-\frac{\gamma}{a}(b - c) \right] \right) - \frac{1}{\alpha} \left[\frac{\beta}{\alpha a + \beta} \right] \left(1 - \exp(-\alpha b) \right) . \tag{B-4} $$

The second term on the right hand side in Eq.(B-4) is the net empty space added during the interevent time. The last term on the right hand side of Eq.(B-4) is the part of the expected amount that can be accommodated during the an event. An important derivative of Eq.(B-4) is the effective volume, V_E, or the expected amount of empty space available at the onset of an event which should be given by the first two terms of Eq.(B-

---

4). Therefore,

$$V_E = c + \frac{a}{\gamma} \left(1 - \exp\left[-\frac{\gamma}{a}(b - c) \right] \right) . \tag{B-5}$$

This must also equal $E[T_n \mid c]$ which is verified from Eq.(2-1).

To obtain an expected value for S_n we set $c = \delta b$ for $0 \le \delta \le 1$ and for uniformly distributed δ, we obtain

$$E[S_n] = \frac{b}{2} - \frac{k}{\alpha} + \frac{ma}{\beta} + \frac{k}{\alpha^2 b}\left(1 - \exp[-\alpha b] \right) - \frac{ma^2}{\beta^2 b}\left(1 - \exp\left[-\frac{\beta b}{a} \right] \right)$$

$$+ \frac{ka^2}{\gamma^2 b} \exp[-\alpha b]\left(1 - \exp\left[-\frac{\gamma b}{a} \right] \right) + \left(\frac{a}{\gamma} - \frac{ka}{\gamma} - \frac{ma}{\gamma} \right) \exp\left[-\frac{\gamma b}{a} \right] \tag{B-6}$$

$$- \left(\frac{a^2}{\gamma^2 b} - \frac{ma^2}{\gamma^2 b} - \frac{k\alpha a^2}{\gamma^2} + \frac{m\beta a}{\gamma^2} \right)\left(1 - \exp\left[-\frac{\gamma b}{a} \right] \right) .$$

The estimate obtained from Eq.(B-6) is used as the value of c in Eqs. (3-34) and (5-4).

APPENDIX C

STORM WATER MANAGEMENT MODEL (SWMM) FILES

Exhibit C.1 Description of S/T Block Input File Cards (Huber and Dickinson, 1988)

```
*           <<<<<<<<   SWMM 4.05 STORAGE/TREATMENT DATA FILE >>>>>>>>>
*
*           This is an input data file to the SWMM 4.05 STORAGE/TREATMENT
*           Block for modeling water quantity and quality.  All lines with
*           an asterisk in column 1 are comment lines and are ignored
*           by the program.
*
*           Input data is free format and may be up to 230 columns wide.
*           You must have a value for every data column even if the program
*           will not actually use a given value.  There must be at least one
*           space between every input value.  Alphanumeric data should be
*           enclosed in single quotes.
*
*           SWMM uses both American standard units and Metric units.  The
*           examples use feet, cfs, acres, inches and inches/hour.  If
*           Metric is specified substitute meters, cms, hectares,
*           millimeters and millimeters/hour.
*
*===============================================================================
*
*           The SW card sets up the interface files to be used or created.
*           There is one output file (#9) which will contain the hourly
*           flows and pollutant loads for subsequent blocks.
*===============================================================================
*  NBLOCK  JIN(1)  JOUT(1)
SW    1       0       9
*===============================================================================
*           The MM card opens the scratch files to be used by different
*           subroutines.  A certain number (1 for STORAGE/TREATMENT) may be
*           required for each block.
*===============================================================================
*  NITCH  NSCRAT(1) NSCRAT(2) NSCRAT(3) NSCRAT(4) NSCRAT(5) NSCRAT(6)
MM   6        1         2         3         10        11        12
*===============================================================================
*      The @ command is used to permanently save an interface or
*      scratch file.  This line should be placed before the first SWMM
*      block call.  The format of the @ command is as follows:
*===============================================================================
*Column 1    Unit number of the      Name of the interface
*            interface file saved     file (any valid DOS filename)
*            or utilized
*
@                9                     'GRAPH3.INT'
*===============================================================================
$STORAGE     Call the STORAGE/TREATMENT block with a '$' in first column.
*===============================================================================
*      Create title lines for the simulation.  There are two title lines
*         for the STRT Block.  Titles are enclosed in single quotes.
*===============================================================================
*      A1 Line       :
*        Title2      :  Two lines with heading to be printed on output.
*===============================================================================
A1   'Example Storage/Treatment Model'
```

```
A1  'Arbitrary storm event'
*===========================================================================
*      The 'B1' line is for control purposes.
*===========================================================================
*      B1 Line        :
*          NOTAPE     :  Input data source
*                        = 0, Input is from an external input file,
*                        = 1, Input is supplied in Group J1,
*                        = 2, Input is from an external input file
*                             and Group J1.
*          JNS        :  External element number from the external
*                        block (e.g., JN, Group H1, in Transport Block)
*
*                        which routes flow to the S/T Block.  If
*                        NOTAPE = 1, the value of JNS is placed on
*                        the output file.
*          NDT        :  Total number of simulation time steps
*          DS         :  Size of time step, seconds.  Required
*                        only if NOTAPE = 1.
*          NU         :  Number of storage/treatment units (Maximum = 5).
*          NP         :  Number of pollutants routed (Maximum = 3).
*          ICOST      :  Cost calculations performed?
*                        = 0, No
*                        = 1, Yes
*          METRIC     :  Metric input-output.
*                        = 0, Use U.S. customary units
*                        = 1, Use metric units.
*                             Metric input indicated in brackets [].
*          SAREA      : Service area, acres [ha].Required if NOTAPE = 1.
*===========================================================================
*  NOTAPE  JNS  NDT    DS     NU    NP   ICOST  METRIC  SAREA
B1    1    10   50  3600.0    1     1      0      0     165.0
*===========================================================================
*         The C1 line defines the starting and ending date and time.
*===========================================================================
*      C1 Line        :
*          IDATE      :  Date at beginning of simulation
*                        (6 digit number; year, month, day --
*                        e.g. March 10, 1979 = 790310)
*          TIME       :  Time at beginning of simulation
*                        (24 hour clock, e.g., 5:30 p.m. = 17.5
*          ISUM       :  Summary print control parameter
*                        = 0, Print a summary at the end of
*                             the simulation only
*                        = 1, Print an annual summary and a summary
*                             at the end of the simulation
*                        = 2, Print monthly and annual summaries and
*                             a summary at the end of the simulation
*          IDET       :  Detailed print control parameter
*                        = 0, No detailed print of simulation results.
*                        > 0, Detailed print of results is provided
*                        at every time step that is a multiple of
*                        IDET (e.g., IDET = 2, gives a detailed report
*                        at every other time step) during specified
*                        periods (see below and group C2).
*          NPR        :  Number of detailed print periods.  Up to
*                        8 periods may be specified (See Group C2).
```

```
*                        Required only if IDET > 0.
*=================================================================
*    IDATE      TIME        ISUM       IDET       NPR
C1   731128     0.00        0          10         1


*=================================================================
*        The C2 line lists the NPR detailed print periods.
*              NPR (Group C1) periods must be specified.  Only date
*              to date periods may be used (e.g., 790720 to 790806).
*              Required only if IDET > 0 (Group C1).
*=================================================================
*      C2 Line      :
*            ISTART(1)  :  First detailed print period starting
*                          date (e.g., July 20, 1979 = 790720).
*            IEND(1)    :  First detailed print period ending
*                          date (e.g., August 6, 1979 = 790806).
*              .                     .
*                          Repeat for second period, etc. up to
*                          NPR Group C1 periods - place all
*                          ISTART and IEND pairs on a single line.
*              .                     .
*            ISTART(NPR):  Last detailed print period starting date.
*            IEND(NPR)  :  Last detailed print period ending date.
*=================================================================
*    ISTART(1) IEND(1)
C2   731128     731128
*=================================================================
*        Use the D1 line for evaporation data.  Required only if there
*        are detention units.(IDENT(I) = 1 for some units, see Group
*        F2).
*=================================================================
*      D1 Line      :
*            E(1)       :  Evaporation rate, January in./day [mm/day].
*              .                     .
*            E(12)      :  Evaporation rate, December in./day [mm/day]
*=================================================================
*  EVAPORATION DATA
D1  .1    .1   .15  .25    .3   .6   .6   .7   .6    .4    .1   .1


*=================================================================
*        Data groups E1 - E6 define STRT pollutant characterization.
*           Require groups E1 - E6 only if NP > 0 on GROUP B1.
*=================================================================
*      E1 Line      :
*            IPOLL(1)   :  Pollutant 1 selector.  Required only if
*                          NOTAPE = 0 or 2 (Group B1).  The value
*                          selected depends on the order in which the
*                          pollutants were placed on the external input
*                          file.
*                          For example, if suspended solids was the third
*                          pollutant listed on the file and it was desired
*                          for use in the S/T block, then IPOLL(1) = 3.
*            NDIMI(1)   :  Dimensions for pollutant 1.  Required
*                          only if NOTAPE = 1 (Group B1).
*                          = 0, Dimensions are mg/l
*                          = 1, Dimensions are liter (-1)
*                          = 2, Other concentration dimensions are
```

```
*                           used. (e.g., JTU, deg. C. pH)
*          IPART(1)      :  Particle size/specific gravity or
*                           settling velocity distribution parameter
*                           = 0, Distribution not used to
*                               characterize pollutant 1.
*                           = 1, Distribution used to characterize
*                               pollutant 1.
*          PNAME1(IN,1):  Pollutant 1 name.  Required only if
*                          NOTAPE = 1  (Group B1).
*          PUNIT1(IN,1):  Pollutant 1 dimension label.
*                          Required only if NOTAPE = 1 (Group B1).
*          IPOLL(2)      :  Pollutant 2 selector.  Required only if
*                          NP >_ 2 and NOTAPE = 0 or 2 (Group B1).  See
*                          above.
*          NDIMI(2)      :  Dimensions for pollutant 2.  Required only if
*                          NP >_ 2 and NOTAPE = 1 (Group B1).  See above.
*          IPART(2)      :  Particle size/specific gravity or settling
*                          velocity distribution parameter.  Required only
*                          if NP >_ 2 Group B1)  See above.
*          PNAMEI(IN,2):  Pollutant 2 name.  Required only if
*                          NP >_ 2 and NOTAPE = 1.  (Group B1)
*          PUNITI(IN,2):  Pollutant 2 dimension label.  Required only if
*                          NP >_ 2 and NOTAPE = 1. (Group B1)
*          IPOLL(3)      :  Pollutant 3 selector.  Required only if
*                          NP = 3 and NOTAPE = 0 or 2 (Group B1)  See
*                          above.
*          NDIMI(3)      :  Dimensions for pollutant 3.  Required only if
*                          NP = 3 and NOTAPE = 1 (Group B1).  See above.
*          IPART(3)      :  Particle size/specific gravity or settling
*                          velocity distribution parameter.  Required only
*                          if NP = 3. (Group B1).  See above.
*          PNAMEI(IN,3):  Pollutant 3 name.  Required only if NP = 3 and
*                          NOTAPE = 1 (Group B1).
*          PUNITI(IN,3):  Pollutant 3 dimension label.  Required
*                          only if NP = 3 and NOTAPE = 1 (Group B1).
*=================================================================
*    IPOLL NDIM IPART  PNAME    PUNIT IPOLL NDIM IPART PNAME   PUNIT
E1    1    0     0    'TSS '   'mg/l '   2     0    0    ' '    ' '
*=================================================================
*      Note:   GROUPS E2 - E6 are REQUIRED only if IPART (IP) = 1
*                         on group E1 for any pollutants.
*=================================================================
*      E2 Line         :
*          NVS         :  Classification parameter
*                          = 0, Particle size/specific gravity
*                          distribution
*                          is used to classify particles in waste stream.
*                          = 1, Settling velocity distribution is used.
*          NNR         :  Number of particle size ranges or settling
*                          velocities used to classify particles in waste
*                          stream (Max of 10).
*=================================================================
*      Use E3 data group to define particle size (if NVS = 0, group E2 or
*          settling velocity (if NVS = 1, group E2) range data.
*=================================================================
*      E3 Line         :
*          RAN(1,1)    :  Lower bound of size or velocity
```

```
*                       range 1, microns or ft/sec [cm/sec].
*          RAN(1,2)    : Upper bound of size or velocity
*                       range 1, microns or ft/sec [cm/sec].
*                    .                   .
*          RAN(NPR,1) : Lower bound of size or velocity
*                       range NPR, microns or ft/sec [cm/sec].
*          RAN(NPR,2) : Upper bound of size or velocity
*                       range NNR, microns or ft/sec [cm/sec].
*=========================================================================
*          Use E4 data group to specific gravity data.
*                  Required only if NVS = 0 (Group E2).
*=========================================================================
*      E4 Line       :
*          SPG(1)     : Specific gravity for particles in size range 1.
*          SPG(2)     : Specific gravity for particles in size range 2.
*             .                        .
*          SPG(NNR)   : Specific gravity for particles in size range
*                       NNR.
*=========================================================================
*          Use E5 data group waste stream temperature data.
*                  Required only if NVS = 0 (Group E2).
*=========================================================================
*      E5 Line       :
*          TEMP(1)    : Waste stream temperature, January F. [C].
*             .                        .
*          TEMP(12)   : Waste stream temperature, December F. [C].
*=========================================================================
*          Use E6 data group to define the fraction of each pollutant
*          associated with each particle size/specific gravity or
*          settling velocity range (Group E3).  Repeat these lines for
*          each pollutant for which
*
*
*          IPART(IP) = 1 (Group E1).  Required only if NVS = 0 (Group
*          E2).
*=========================================================================
*      E6 Line       :
*          PSD(IP,1)  : Fraction of pollutant IP in range 1.
*          PSD(IP,2)  : Fraction of pollutant IP in range 2.
*             .                        .
*          Repeat for each range up to NNR (Group E2) ranges.
*=========================================================================
*       REPEAT GROUPS F1 - I1 FOR EACH UNIT I.  THERE WILL BE NU (GROUP
*          B1)SETS.  THE UNIT NUMBER IS DICTATED BY THE ORDER IN WHICH
*                  THE SETS OF GROUPS F1 - I1 ARE READ.
*=========================================================================
*      F1 Line       :
*          UNAME(I,ID) : Name of unit.
*=========================================================================
*      UNAME(1,ID)
F1     ' STORAGE'
*=========================================================================
*      Use line F2 to define the general unit parameters and flow
*      directions.
*=========================================================================
*      F2 Line       :
*          IDENT(1)   : Detention modeling parameter
```

```
*                             = 0, Unit is the non-detention type
*                             = 1, Unit is the detention type
*         QMAX(I)    :  Maximum inflow (above which bypass
*                       occurs), cfs [cu.m/sec].
*         QRF(I)     :  Residual flow as a fraction of the inflow.
*                       Required only if IDENT(I) = 0.  Residual flows
*                       for detention units (IDENT(I) = 1) are
*                       determined
*                       in Groups H1, H3, and H6.
*         IDIREC(I,1):  Unit number to which bypass is directed
*                       (must be greater than 1).
*                             = 1 - 5, Downstream S/T unit
*                             = 100, Next block
*                             = 200, Ultimate disposal
*         IDIREC(I,2):  Unit number to which treated outflow is
*                       directed
*                       (must be greater than 1).  See above.
*         IDIREC(I,3):  Unit number to which residuals stream is
*                       directed
*                       (Must be greater than 1).  See above.   If
*                       IDRAW(I) = 0 (Group H1), set equal to any
*                       number > 1.
*========================================================================
*     IDENT   QMAX     RESIDUAL FLOW   IDIREC(1) IDIREC(2) IDIREC(3)
F2      1     125.         0.0            100       100       200
*========================================================================
*     Use data groups G1 - G4 to define Pollutant Removal.
*              Required only if NP > 0 on group B1.
*     REPEAT GROUPS G1 - G3 FOR EACH POLLUTANT FOR WHICH IPART(IP) = 0.
*========================================================================
*     G1 Line      :
*         RMX(I,IP)  :  Maximum removal fraction (<= 1.0).
*========================================================================
*     RMX
G1    1.0
*========================================================================
*     Define the removal equation variable group (Equation 7-1) on line
G2.
*========================================================================
*     G2 Line      :
*         INPUT(I,IP,1):  Program variable for equation variable X1.
*                         = 0, Not used.
*                         For values = 1 - 7, see Table 7-3 in text.
*         INPUT(I,IP,2):  Program variable for equation variable X2.
*                         See above.
*              .                           .
*                         Repeat for each program variable Xi.
*========================================================================
*     REMOVAL EQUATION VARIABLES
G2    0  0  1  0 0 0 0 0 0 0 0
*========================================================================
*     Define Equation 7-1 coefficients on line G3.  The coefficients
*     must be consistent with the units used (see METRIC Group B1).
*========================================================================
*     G3 Line      :
*         A(I,IP,1)  :  Value of coefficient a1.
*         A(I,IP,2)  :  Value of coefficient a2.
```

```
*                .                             .
*            Repeat for each coefficient aj.
*=========================================================================
*     EQUATION 7-1
G3    0 0 -0.003028 0 0 0 0 0 0 0 0.45 -0.45 0.0 0.0 1.0
*=========================================================================
*     Define the Critical Particle Size or Settling Velocity on line G4.
*     Required only if IPART(IP) = 1 (Group E1) for any pollutant and
*          unit I is a non-detention unit, IDENT(I) = 0 (Group F2).
*=========================================================================
*     G4 Line        :
*          PSC(I)      :  Critical particle size, microns, (if NVS = 0,
*                        Group E2) or settling velocity, ft/sec
*                        [cm/sec],
*                        (if NVS = 1, Group E2).
*=========================================================================
*     PSC(I)
G4    10.0
*=========================================================================
*              Data Groups H1 - H8: Detention Unit Data
*              Required only if IDENT(I) = 1 (Group F2)
*=========================================================================
*     Define the general detention unit parameters on line H1.
*=========================================================================
*     H1 Line        :
*          IROUTE(I)   :  Pollutant routing parameter
*                        = 0, Plug flow mode is used.
*                        = 1, Complete mixing mode is used.
*                          (Note:  Particle size or settling velocity
*                          distribution are not routed through
*                          completely-mixed units.)
*          IOUT(I)     :  Treated outflow routing parameter
*                        = 0, The depth-treated outflow relationship is
*                        described by as many as 16 data pairs in Group
*                        H3.
*                        = 1, The depth-treated outflow relationship is
*                        described by a power equation in Group H4.
*                        = 2, The depth-treated outflow relationship is
*                        controlled by the pumps described in Group H5.
*          IDRAW(I)    :  Residuals stream draw-off scheme
*                        <_ -1, A residual stream is drawn off starting
*                        at every -IDRAW(I) time step (if possible).
*                        = 0, Residuals are never drawn off.
*                        >_ 1, A residuals stream (if available) is
*                        drawn off
*                        only after IDRAW(I) time steps of no inflow or
*                        treated outflow.
*          IRES(I)     :  Residual stream routing parameter
*                        Required only if IDRAW(I) not = 0
*                        = 0, The depth-residual flow relationship is
*                        described by as many as 16 data pairs in Group
*                        H3.
*                        = 1, The depth-residual flow relationship is
*                        described by a power equation in Group H6.
*=========================================================================
*     PLUG FLOW ROUTING IS BEING USED
*     IROUTE     IOUT     IDRAW       IRES
```

```
H1       0          1          1          0
*==============================================================================
*      Detention unit (plug flow only) parameters, required when
*      pollutants
*   are characterized by a particle size/specific gravity or settling
*   velocity distribution.  Thus, the H2 line is required only if
*   IPART(IP) = 1, for any pollutant (Group E1) and IROUTE(I) = 0 (Group
*   E2).
*==============================================================================
*      H2 Line      :
*         ALEN(I)   :  Travel length for plug flow, ft [m].
*         AMAN(I)   :  Manning's roughness coefficent for
*                      detention unit surfaces.
*==============================================================================
*    ALEN(I)   AMAN(I)
H2    0.0       0.0
*==============================================================================
*      Data for Sets of Depth, Surface Area, Volume,
*               Treated Outflow and Residual Flow
*
*   Each line contains a column for a unit depth and the corresponding
*   values of area, volume, treated outflow, and residual flow.  The
*   columns for treated outflow and residual flow may be left blank
*   depending
*   on the values of IOUT(I) and IRES(I) in Group H1.  If no values for
*   volume are entered, the program estimates volume from the
*   depth-surface
*   area relationship. Order the data from the bottom of the unit
*   SDEPTH(I,1) = 0.0) to the maximum depth (including freeboard).
*               There may be as many as 16 lines.
*==============================================================================
*      H3 Line      :
*         SDEPTH(I,MM) :  A unit depth, ft [m].
*         SAREA(I,MM)  :  Surface area corresponding to the above
*                         depth, sq. ft [sq. m].
*         SSTORE(I,MM) :  Volume corresponding to the above depth
*                         cu. ft [cu. m].
*         SQQOU(I,MM)  :  Treated outflow at the above depth
*                         cfs [cu.m/sec].
*         SQQRS(I,MM)  :  Residuals stream flow at the above depth
*                         cfs[cu.m/sec].
*                         Occurs only when IDRAW(I) (Group H1) permits.
*==============================================================================
*    DEPTH     AREA    VOLUME   TREATED OUTFLOW RESIDUAL FLOW
H3    0.0     1000.    0              0             5.

H3    8.0     1000.    0              0             5.

H3    8.5     1000.    0              0             5.

H3    9.0     1000.    0              0             5.

H3    9.5     1000.    0              0             5.

H3   10.0     1000.    0              0             5.
*==============================================================================
*   Depth vs. Treated Outflow Power Equation (Equation 7-3) on line H4.
```

```
*    Required only if IOUT(I) = 1 (Group H1).  Coefficients must be
*         consistent with the units used. (See METRIC, Group B1.)
*=================================================================
*     H4 Line       :
*         C1          : Depth-treated outflow equation coefficient, C1.
*         D0          : Depth below which no treated outflow occurs, D0.
*         C2          : Depth-treated outflow equation coefficient, C2.


*=================================================================
*     C1        C2        C3
H4   66.66      8.        1.5
*=================================================================
*    Use the H5 data group to define any treated outflow pumping.
*         Required only if IOUT(I) = 2 (Group H1).
*=================================================================
*     H5 Line       :
*         DSTART(I,1): Depth at which pumping rate QPUMP(I,1)
*                       begins, ft [m].
*         DSTART(I,2): Depth at which pumping rate QPUMP(I,2)
*                       begins, ft [m].  Must be >_ DSTART(I,1).
*         QPUMP(I,1) : Pumping rate when depth >_ DSTART(I,1)
*                       cfs [cu.m/sec].
*         QPUMP(I,2) : Pumping rate when depth >_ DSTART(I,2)
*                       cfs [cu.m/sec].
*         DSTOP(I)   : Depth below which all pumping stops,
*                       ft [m].  Must be <_ DSTART(I,1).
*=================================================================
*   DSTART(I,1) DSTART(I,2) QPUMP(I,1) QPUMP(I,2) DSTOP(I)
H5      0.0         0.0        0.0        0.0        0.0
*=================================================================
*    Define the Depth vs. Residual Flow Power Equation (Equation 7-4)
*    on line H6.  Required only if IRES(I) = 1 (Group H1).
*    Coefficients
*    must be consistent with the units used (see METRIC, Group B1).
*=================================================================
*     H6 Line       :
*         C3          : Depth-residual flow equation coefficient.
*         D1          : Depth below which no residual flow occurs.
*         C4          : Depth-residual flow equation coefficient.
*=================================================================
*   C3   D1   C4
H6 0.0  0.0  0.0
*=================================================================
*   Use data group H7 to define Sludge Generation in Unit I.
*      Required only if I is a plug-flow detention unit (IROUTE(I) = 0,
*             Group H1) and NP > 0 (Group B1).
*=================================================================
*     H7 Line       :
*         NPSL(I)     : Pollutant responsible for sludge generation.
*                       Required
*                       only if a sludge depth warning message is
*                       desired.
*                       = 0, Not used.
*                       = 1, 2, or 3, Pollutant used to generate sludge
*                       volume (must correspond to the position in
*                       Group E1.
*         SLDEN(I)    : Concentration of pollutant NPSL(I) in sludge.
```

```
*                        Required only if NPSL(I) >_ 1.  The dimensions
*                        used must be consistent with those indicated
*                        by NDIM(I) (Group E1).
*            SLDMAX(I)  :  Maximum sludge depth, ft [m].  A warning
*                        message is printed if this depth is exceeded
*                        by the accumulated sludge.  Required only if
*                        NPSL(I) >_ 1.
*=================================================================
*     NPSL   SLDEN  SLDMAX
H7     2     20000.   1.
*=================================================================
*    Use line H8 to define the initial conditions in detention unit I.
*=================================================================
*     H8 Line      :
*            WARN(I)    :  Total volume of water in unit at the
*                        start of the simulation, cu.ft [cu.m]
*
*    Note: The following concentrations must be given with dimensions
*          consistent with those entered in Group E1 (NDIM(IP)) if
*          NOTAPE = 1 (Group B1) or on the external input file if NOTAPE
*          = 2.
*
*            PCO(I,1)   :  Concentration of pollutant 1 in the unit at
*                        the start of the simulation.  Used only if NP
*                        >= 1
*                        (Group B1) and WARN(I) > 0.0.
*            PCO(I,2)   :  Concentration of pollutant 2 in the unit volume
*                        at the start of the start of the simulation.
*                        Used only if NP >= 2 (Group B1) and WARN(I) >
*                        0.0.
*            PCO(I,3)   :  Concentration of pollutant 3 in the unit volume
*                        at the start of the start of the simulation.
*                        Used only if NP = 3 (Group B1) and WARN(I) >
*                        0.0.
*=================================================================
*    WARN      PCO(1)  PCO(2)   PCO(3)
H8   4000.       25.    0.0       0.0
*=================================================================
*    Use line I1 to enter Cost Data for Equations 7-5 to 7-8
*        (Capital Costs) and Equations 7-9 to 7-12 (Operation and
*        Maintenance Costs).  The coefficients must be consistent with
*        the units used (see METRIC, Group B1).  Required only if
*        ICOST = 1 on GROUP B1.
*=================================================================
*     I1 Line      :
*            KPC(I,1)   :  Type of cost variable used in calculating
*                        initial capital cost.
*                        = 0, Not used.
*                        = 1, Maximum allowable inflow, QMAX(I),
*                          cfs [cu.m/sec] is used.
*                        = 2, Maximum inflow observed during simulation,
*                          QMAXS(I), cfs [cu.m/sec], is used.
*                        = 3, Maximum allowable storage, VMAX(I)
*                          cu.ft [cu.m] is used.  (Not applicable
*                          if IDENT(I) = 0, Group F2).
*                        = 4, Maximum storage observed during
*                          simulation,
```

```
*                                    VMAXS(I), cu.ft. [cu.m] is used (Not
*                                    applicable
*                                    if IDENT(I) = 0   (Group F2).
*            CC(I,1)     :  Initial capital cost equation coefficient, a.
*            CC(I,2)     :  Initial capital cost equation coefficient, b.
*            KPC(I,2)    :  Type of cost variable used in calculating
*                           operation and maintenance costs.  See list for
*                           initial capital cost (above).
*            CC(I,3)     :  Operation and maintenance cost equation
*                           coefficient, d.
*            CC(I,4)     :  Operation and maintenance cost equation
*                           coefficient, f.
*            CC(I,5)     :  Operation and maintenance costs equation
*                           coefficient, h.
*===============================================================
*     KPC(I,1) CC(I,1) CC(I,2) KPC(I,2) CC(I,3) CC(I,4) CC(I,5)
I1      0.0      0.0     0.0      0.0     0.0     0.0     0.0
*==================================================================
*                  Input Flow and Pollutant Time Series
*
*               REQUIRED ONLY IF NOTAPE = 1 OR 2 (GROUP B1)
*
*    All flows and concentrations are instantaneous values at the
*       indicated time.  A constant time interval is not required;
*       linear interpolation is used to obtain intermediate values of
*       flow and concentrations.  Hence, the difference between two time
*       entries, TCAR, should not be less than the time step, DS,
*       unless a step function input is desired.
*
*    The concentration units must be identical to those in Group E1
*       (NDIM(IP)) if NOTAPE = 1, Group B1, or on the external input
*       file if NOTAPE = 2.
*==================================================================
*     J1 Line        :
*          TCAR       :  Time of day, decimal hours, e.g., 6:30 p.m. =
*                        18.5.
*                        If the first TCAR value is <= initial time,
*                        the program will read succeeding J1 data groups
*                        until TCAR >= initial time.  If simulation goes
*                        beyond one day, i.e., times > 24.0, then
*                        continue
*                        with times greater than 24.  I.e., TCAR should
*                        not
*                        be reset at beginning of day.
*          QCAR       :  Flow entering S/T plant (at unit 1), cfs
*                        [m3/sec].
*          PCAR(1)    :  Concentration of pollutant 1 entering S/T plant
*                        (at unit 1).  Used only if NP >= 1 (Group B1)
*                        and QCAR > 0.0
*          PCAR(2)    :  Concentration of pollutant 2 entering S/T plant
*                        (at unit 1).  Used only if NP >= 2 (Group B1)
*                        and QCAR > 0.0
*          PCAR(3)    :  Concentration of pollutant 3 entering S/T plant
*                        (at unit 1).  Used only if NP = 3 (Group B1)
*                        and QCAR > 0.0
*==================================================================
*    TCAR  = TIME IN HOURS
```

```
*    QCAR  = INSTANTANEOUS FLOW IN CFS AT TCAR
*    PCAR1 = INSTANTANEOUS SUSPENDED SOLIDS CONCENTRATION AT TCAR
*    TCAR     QCAR     PCAR(1)
J1   0.0      65.8      300.
J1   1.0      65.8      300.
J1   2.0      77.1      220.
J1   3.0       6.6      225.
J1   4.0       0.1        5.
J1   5.0       7.2      110.
J1   6.0       0.8      140.
J1   7.0      15.2      200.
J1   8.0       2.8      300.
J1   9.0       0.2      300.
J1  10.0       1.0      5.0
J1  50.0       1.0      5.0
*=======================================================================
*           End your input data set with a $ENDPROGRAM.
$ENDPROGRAM
```

Exhibit C.2 S/T Block Input File

```
SW  1  0  20
MM  7  1  2  3  4  12  13  14
$STORAGE
*
A1  'NEABSCO CREEK TRIBUTARY'
A1  '$1pond'
******
*             *# time steps*   *time step (sec)*
B1  1  300     210384                  600              1  1  0  0  526.7
*****
*   *starting date*    *starting time*
C1     900101                  0.0              0  0  0  0
*****
***Evaporation by month***
D1 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
***
E1  0  0  0  'TSS'  'mg/l'
******
F1  '$1pond'
F2  1 9999 0 200 100 901
******
*Pollutant Removal Equation
****
*    RMX
G1  0.9
*****************************************************************************
**   X1    X2     X3    X4     X5    X6     X7    X8     X9    X10    X11
G2   0     0     1.0    0      0     0      0     0      0     0      0
*****************************************************************************
** a1  a2   a3     a4  a5   a6   a7   a8   a9   a10  a11  a12   a13   a14  a15  a16
G3 0  0  -.000028  0   0    0    0    0    0    0    0   0.9  -0.9   0    0    1.0
********
********
H1 1   0   0   0
* a=.0025 b=.1 in ********$1pond******
** Depth (ft) ** Srf Area (sq. ft) ** Vol (cu ft) ** Q (cfs) ***
H3     0              0                    0           1.328           0
H3     1           19119.2              19119.2        1.328           0
H3     2           19119.2              38238.4        1.328           0
H3     3           19119.2              57357.6        1.328           0
H3     4           19119.2              76476.8        1.328           0
H3     5           19119.2              95596.0        1.328           0
H3     6           19119.2             114715.2        1.328           0
H3     7           19119.2             133834.4        1.328           0
H3     8           19119.2             152953.6        1.328           0
H3     9           19119.2             172072.8        1.328           0
H3    10           19119.2             191192.0        1.328           0
***
H8 0 0 0 0
```

```
***
*****   Time (hrs)    Q(cfs) TSS(mg/1)
J1           0         0         0
J1       0.166667  29.5914      100
J1           1.5   29.5914      100
J1       1.666666       0         0
J1         105.5         0         0
J1      105.6667 162.4349       100
J1      106.6667 162.4349       100
J1      106.8334       0         0
J1         127.5         0         0
J1      127.6667  11.3035       100
J1      137.3334  11.3035       100
J1         137.5         0         0
J1      293.8334       0         0
J1      294.0001 4.847426       100
J1      300.6667 4.847426       100
J1      300.8334       0         0
J1      348.3334       0         0
J1         348.5 13.87593       100
J1         351.5 13.87593       100
J1      351.6667       0         0
-------------//---------------------
J1      34741.17       0         0
J1      34741.34 5.380225       100
J1      34750.34 5.380225       100
J1       34750.5       0         0
J1      34781.67       0         0
J1      34781.84 125.4136       100
J1      34782.84 125.4136       100
J1      34783.01       0         0
J1      34917.34       0         0
J1      34917.51 106.1398       100
J1      34922.34 106.1398       100
J1      34922.51       0         0
J1      34940.84       0         0
J1      34941.01 3.674106       100
J1      34948.68 3.674106       100
J1      34948.84       0         0
J1         35064       0         0
*****
$ENDPROGRAM
```

Exhibit C.3 Typical S/T Block Output File

```
1         *************************************************
          *        Environmental Protection Agency        *
          *         Storm Water Management Model          *
          *               Version 4.05                    *
          *************************************************

                          Developed by

          *************************************************
          *              Metcalf & Eddy, Inc.             *
          *              University of Florida            *
          *         Water Resources Engineers, Inc.       *
          *                September 1970                 *
          *************************************************

                           Updated by

          *************************************************
          *              University of Florida            *
          *            Camp Dresser & McKee, Inc.         *
          *                                               *
          *    March     1975        November  1977       *
          *    November  1981        December  1990       *
          *************************************************


          *************************************************
          *      This is a new release of SWMM.  If any   *
          *       problems occur in running this model    *
          *       please contact Dr. Wayne Huber at the   *
          *              University of Florida            *
          *               Phone 1-904-392-0846            *
          *************************************************


          *************************************************
          *   This is an implementation of EPA SWMM 4.05  *
          *   "Nature is full of infinite causes which    *
          *    have never occured in experience" da Vinci *
          *************************************************


     ###########################################
     #        File names by SWMM Block         #
     #        JIN  -> Input to a Block         #
     #        JOUT -> Output from a Block       #
     ###########################################

        JIN for Block #     1 File #     0   JIN.UF

        JOUT for Block #    1 File #    20   JOT.UF


     ###########################################
```

```
# Scratch file names for this simulation. #
###########################################

NSCRAT #      1 File #     1  SCRT1.UF

NSCRAT #      2 File #     2  SCRT2.UF

NSCRAT #      3 File #     3  SCRT3.UF

NSCRAT #      4 File #     4  SCRT4.UF

NSCRAT #      5 File #    12  SCRT5.UF

NSCRAT #      6 File #    13  SCRT6.UF

NSCRAT #      7 File #    14  SCRT7.UF


****************************************************
*     Parameter Values on the Tapes Common Block   *
****************************************************

  Number of Subcatchments in the Runoff Block (NW)....  100
  Number of Channel/Pipes in the Runoff Block (NG)....  150
  Runoff Water quality constituents (NRQ).............   10
  Runoff Land Uses per Subcatchment (NLU).............    5
  Number of Elements in the Transport Block (NET).....  150
  Number of Storage Junctions in Transport (NTSE).....   30
  Number of Input Hydrographs in Transport (NTH)......   80
  Number of Elements in the Extran Block (NEE)........  200
  Number of Groundwater Subcatchments in Runoff (NGW).  100
  Number of Interface locations for all Blocks (NIE)..  200
  Number of Pumps in Extran (NEP).....................   20
  Number of Orifices in Extran (NEO)..................   60
  Number of Tide Gates/Free Outfalls in Extran (NTG)..   25
  Number of Extran Weirs (NEW)........................   60
  Number of Extran printout locations (NPO)...........   30
  Number of Tide elements in Extran (NTE).............   20
  Number of Natural channels (NNC)....................   20
  Number of Storage junctions in Extran (NVSE)........   20
  Number of Time history data points in Extran(NTVAL).   50
  Number of Data points for variable storage elements
  in the Extran Block (NVST)..........................   25
  Number of Input Hydrographs in Extran (NEH).........  100


###########################################
# Entry made to Storage/Treatment model. #
# Storage/Treatment model written by the #
# University of Florida,  June 1981.      #
#      Last Updated December, 1990.       #
###########################################


          INPUT DATA SOURCE        :   INPUT ON LINE J1
```

```
          EXTERNAL ELEMENT NUMBER    :       300

          NUMBER OF TIME STEPS       :      210384

          TIME STEP SIZE,SECONDS     :      600.0

          NUMBER OF S/T UNITS        :          1

          COST MODEL USED?           :         NO

          STARTING DATE              :     1/ 1/90

          STARTING TIME              :    0:  0:  0

          INPUT/OUTPUT UNITS         :    U.S. CUSTOMARY

          TRIBUTARY AREA,ACRES       :      526.7

          NUMBER OF POLLUTANTS       :          1

          POLLUTANT 1                :     TSS

              UNITS                  :     mg/l
              PART. SIZE/VEL. USED?:         NO


          MONTHLY EVAPORATION RATES, IN/DAY

              JAN     FEB     MAR     APR     MAY    JUNE    JULY    AUG
      SEPT    OCT     NOV     DEC

              0.000   0.000   0.000   0.000   0.000   0.000   0.000
   0.000   0.000   0.000   0.000   0.000
   1

          UNIT CHARACTERISTICS


          ************************
          UNIT #  1 CHARACTERISTICS
          ************************


          GENERAL UNIT DESCRIPTION:

          NAME                   : $1pond
          TYPE OF UNIT           : DETENTION
          MAX. ALLOWABLE INFLOW,CFS: 9999.


          FLOW DIRECTIONS:
          BYPASS TO UNIT #           200
          TREATED OUTFLOW TO UNIT # 100
          RESIDUALS TO UNIT #        901

          ===> NOTE: UNIT 100 IS THE NEXT BLOCK AND UNIT 200 IS ULTIMATE
```

```
DISPOSAL


          POLLUTANT REMOVAL MECHANISM:

          POLLUTANT           : TSS
          REMOVAL MECHANISM   : REMOVAL EQUATION
          MAX. REMOVAL FRAC.  :     0.9000
          VARIABLE TYPES      :     0    0    1    0    0    0    0    0
  0    0    0
          COEFFICIENT VALUES :    0.000E-01  0.000E-01 -2.800E-05
0.000E-01  0.000E-01  0.000E-01  0.000E-01  0.000E-01
                                   0.000E-01  0.000E-01  0.000E-01
9.000E-01 -9.000E-01  0.000E-01  0.000E-01  1.000E+00



          DETENTION UNIT CHARACTERISTICS:

          POLLUTANT ROUTING METHOD : COMPLETELY MIXED
          RESIDUALS DRAW-OFF SCHEME: NEVER DRAWN OFF

          DEPTH-AREA-STORAGE-FLOW RELATIONSHIPS :

               DEPTH,FT     SURFACE AREA,SQ FT     STORAGE,CU FT
  TREATED OUTFLOW,CFS     RESIDUAL FLOW,CFS

               0.0000E-01          0.0000E-01          0.0000E-01
1.3280E+00            0.0000E-01
               1.0000E+00          1.9119E+04          1.9119E+04
1.3280E+00            0.0000E-01
               2.0000E+00          1.9119E+04          3.8238E+04
1.3280E+00            0.0000E-01
               3.0000E+00          1.9119E+04          5.7358E+04
1.3280E+00            0.0000E-01
               4.0000E+00          1.9119E+04          7.6477E+04
1.3280E+00            0.0000E-01
               5.0000E+00          1.9119E+04          9.5596E+04
1.3280E+00            0.0000E-01
               6.0000E+00          1.9119E+04          1.1472E+05
1.3280E+00            0.0000E-01
               7.0000E+00          1.9119E+04          1.3383E+05
1.3280E+00            0.0000E-01
               8.0000E+00          1.9119E+04          1.5295E+05
1.3280E+00            0.0000E-01
               9.0000E+00          1.9119E+04          1.7207E+05
1.3280E+00            0.0000E-01
               1.0000E+01          1.9119E+04          1.9119E+05
1.3280E+00            0.0000E-01

          INITIAL CONDITIONS:

              VOLUME,CU FT                 : 0.0000E-01
              POLLUTANT CONCENTRATIONS     :
                  TSS       ,mg/l          : 0.0000E-01
              INITIAL POLLUTANT LOAD       :
                  TSS       ,              : 0.0000E-01 POUNDS
```

```
*****************************************************
* NOTE: IF THERE IS ONLY ONE UNIT THE PLANT         *
*          PERFORMANCE SUMMARY WILL NOT BE PRINTED. *
*****************************************************


===>  Note !! UNIT  1 HAS EXCEEDED THE MAXIMUM STORAGE VOLUME ON  1/
5/90 AT 10  0
      The excess has been bypassed.  Further messages will be
suppressed.
1
****************************************
*    ENTIRE SIMULATION UNIT SUMMARIES *
****************************************
  JAN  1, 1990,  0 0: 0 TO  JAN  1, 1994,  0 0: 0.


  UNIT       PARAMETER         VOLUME      TSS
                               CU FT       POUNDS
  ----     ----------------    ----------  ----------

   1     INFLOW,TOTAL        2.5604E+08  1.5985E+06
         INFLOW,NET          7.1825E+07  4.4842E+05
         BYPASS              1.8420E+08  1.1500E+06
         TREATED OUTFLOW     7.1800E+07  1.3342E+05
         RESIDUAL FLOW       0.0000E-01  0.0000E-01
         REMOVED BY DECAY        -       3.1503E+05
         REMAINING           0.0000E-01  0.0000E-01
         EVAPORATION         0.0000E-01      -
         INITIAL COND.       0.0000E-01  0.0000E-01
         PERCENT ERROR           0.0134      0.0010




===> Storage/Treatment simulation ended normally.

===> SWMM 4.05 Simulation ended normally.

********************************************************
*        SWMM 4.05 Simulation Date and Time Summary   *
********************************************************
* Starting Date... January    7, 1993                 *
*           Time...        15:43:46: 4                 *
*   Ending Date... January    7, 1993                 *
*           Time...        15:53:29:51                 *
* Elapsed Time...             9.717 minutes.           *
********************************************************
```

Exhibit C.4 Description of Statistic Block Input File Cards (Huber and Dickinson, 1988)

```
*              <<<<<<<<   SWMM 4.05 STATISTICS BLOCK DATA FILE >>>>>>>>>
*
*          This is an input data file to the SWMM 4.05 STATISTICS
*       Block for analyzing a rainfall, flow or water quality time
*       series.
*       All lines with an asterisk in column 1 are comment lines and are
*       ignored by the program.
*
*       Input data is free format and may be up to 230 columns wide.
*       You must have a value for every data column even if the program
*       will not actually use a given value.  There must be at least one
*       space between every input value.  Alphanumeric data should be
*       enclosed in single quotes.
*
*       SWMM uses both American standard units and Metric units.  The
*       examples use feet, cfs, acres, inches and inches/hour.  If
*       Metric
*       is specified substitute meters, cms, hectares, millimeters and
*       millimeters/hour.
*=================================================================
*       The SW card sets up the interface files to be used or created.
*       There is one output file (#9) which will contain the hourly
*          flows and pollutant loads for subsequent blocks.
*=================================================================
*   NBLOCK   JIN(1)   JOUT(1)
SW     1        8        9
*=================================================================
*   The MM card opens the scratch files to be used by different
*   subroutines.
*   A certain number (0 for STATISTICS) may be required for each block.
*=================================================================
=====
*   NITCH   NSCRAT(1) NSCRAT(2) NSCRAT(3) NSCRAT(4) NSCRAT(5) NSCRAT(6)
MM    6        1         2         3        10        11        12
*=================================================================
*    The @ command is used to permanently save an interface or
*    scratch file.  This line should be placed before the first SWMM
*    block call.  The format of the @ command is as follows:
*=================================================================
*Column 1    Unit number of the        Name of the interface
*            interface file saved      file (any valid DOS filename)
*            or utilized
*
@               8                        'RUNOFF6.INT'
*=================================================================
$STATISTICS        Call the STATISTICS Block with a '$' in first column.
*=================================================================
*    The 'A1' line defines the starting and ending time and date.
*       The meaning of the values listed on each line are as follows:
*=================================================================
*    A1 Line      :
*            ISTART  :  Starting date, yr/mo/day
*            TSTART  :  Starting time, decimal hours
```

```
*                IEND     :  Ending date, yr/mo/day
*                TEND     :  Ending time, decimal hours
*                INLOG    :  Calculate natural log moments of storm event
*                            data as well as arithmetic mean and std. dev.
*                JCUBE    :  Storm events are listed in cubic feet
*                            [cubic meters] instead of inches [mm].
*=====================================================================
*    ISTART  TSTART  IEND    TEND   INLOG   JCUBE
A1   600101   0.0   600801   0.0     0       0
*=====================================================================
*        The 'B1' line defines control information for the Statistics
*        Block.
*=====================================================================
*      B1 Line        :
*                MIT      :  Minimum intervent time, decimal hours.
*                BASE     :  Cutoff flow (baseflow), cfs [m3/s].
*                            Flow used to separate events.
*                EBASE    :  Cutoff storm event volume,inches [millimeters].
*                            Storm events below EBASE are not included in
*                            the statistical analysis.
*                LOCRQ    :  Flow location requested.
*                LOCRN    :  Rainfall gage for analysis.
*                NPR      :  Number of pollutants requested.
*                NPOINT   :  Number of events printed in tables.
*                            Print only the top NPOINT flows, events etc.
*                            IF NPOINT is 0 then all events are printed.
*                METRIC   :  Requests type of units for output
*                            = 0, U.S. customary,
*                            = 1, Metric.
*                LRET     :  Units of return period,
*                            = 0, Return period in years,
*                            = 1, Return period in months.
*                A        :  Plotting postion parameter(see text for
*                            explanation).
*=====================================================================
*  MIT   BASE   EBASE LOCRQ   LOCRN NPR NPOINT METRIC LRET   PLOTTING POS(A)
*=====================================================================
B1  0.1  0.0     0.0     1      0     1    50     0     1          0.4
*=====================================================================
*        The 'B2' line defines print control information.
*=====================================================================
*      B2 Line        :
*                KSEQ     :  Request to print sequential series
*                            of flow events?  No = 0, Yes = 1.
*                KTERM    :  Code for terminating program if number of
*                            events exceeds allowable memory space.
*                            =0, Do not terminate (perform analyses
*                            on those events already identified).
*                            =1, Terminate program (no event analysis
*                            performed).
*                KTSEQS   :  Code for printing sequential series if the
*                            number of events exceed limit and KTERM = 1.
*                            = 0, Do not print sequential series.
*                            = 1, Print sequential series of those
*                                 events already identified.
*=====================================================================
*  KSEQ   KTERM   KTSEQS
```

```
B2   1        0        1
*=============================================================================
*     The 'B3' line defines the interface file location
*                       of water quality information.
*                       Required only if NPR > 0 on Data Group B1.
*                       If NPR = 0 then skip to Data Group C1.
*=============================================================================
*     B3 Line        :
*        IPOLRQ(1)   :  First pollutant requested, identified
*                       by position on interface file.
*                            .                    .
*        IPOLRQ(NPR):   Last pollutant requested, identified by
*
*                       position on interface file.
*=============================================================================
*     IPOLRQ
B3      1
*=============================================================================
*         Enter the C1 line only if LOCRQ on Data Group B1 is > 0.
*=============================================================================
*         The C1 line describes the Statistics Block Options for Flow.
*
*     This data group controls the printing or plotting of information on
* magnitude, return period and frequency for each of the five flow
* parameters.
* In all cases, No = 0, Yes = 1.  The control information is entered as
* a four
* digit integer number with each column controlling a different table or
* graph.
*
*             First column  - table of magnitude, return period
*                             and frequency.
*             Second column - print graph of magnitude versus
*                             return period.
*             Third column  - print graph of magnitude versus
*                             frequency.
*             Fourth column - print moments.
*
*     For example, enter 1111 to print/plot all tables/graphs, 1000 to
*  print the table only, 1100 to print the table and the graph of
*  magnitude versus return period only, and 0000 to bypass
*  printing/plotting
*  of the flow parameter.
*=============================================================================
*     C1 Line        :
*        ISFLOW(1,1) :  Request for total flow?
*        ISFLOW(1,2) :  Request for average flow?
*        ISFLOW(1,3) :  Request for peak flow?
*        ISFLOW(1,4) :  Request for event duration?
*        ISFLOW(1,5) :  Request for interevent duration?
*=============================================================================
*   ISFLOW(1,1) ISFLOW(1,2) ISFLOW(1,3) ISFLOW(1,4) ISFLOW(1,5)
C1       1001        1001        1001        1001        1001
*=============================================================================
*             Data Group D1 is only required if NPR > 0 on Data Group B1.
*=============================================================================
*     The D1 line describes the Statistics Block Options for Water
```

```
*       Quality.
*
* If NPR > 0 use one D1 Data Group for each pollutant requested, up to
*    ten sets of D1 lines, in the order defined by Group B2.  The first
*    index of ISPOLL(K,I,J) identifies the pollutant.  Follow the
*    instructions for Data Group C1 in entering data for Data Group D1.
*=====================================================================
*       D1 Line      :
*       ISPOLL(1,1,1)   :   Request for total load?
*       ISPOLL(1,1,2)   :   Request for average load?
*       ISPOLL(1,1,3)   :   Request for peak load?
*       ISPOLL(1,1,4)   :   Request for flow weighted average
*                           concentration?
*       ISPOLL(1,1,5)   :   Request for peak concentration?
*=====================================================================
* ISPOLL(1,1,1)   ISPOLL(1,1,2) ISPOLL(1,1,3) ISPOLL(1,1,4) ISPOLL(1,1,5)
D1      1001            1001          1001          1001          1001
*=====================================================================
*          Enter the E1 line only if LOCRN on Data Group B1 is > 0.
*=====================================================================
*    The E1 line describes the Statistics Block Options for Rainfall
*    Analysis.
*
*    Follow the instructions for Data Group C1 in entering data
*                            for Data Group E1.
*=====================================================================
*       E1 Line      :
*          ISFLOW(2,1) :  Request for total volume?
*          ISFLOW(2,2) :  Request for average intensity?
*          ISFLOW(2,3) :  Request for peak intensity?
*          ISFLOW(2,4) :  Request for event duration?
*          ISFLOW(2,5) :  Request for interevent duration?
*=====================================================================
*    ISFLOW(2,1) ISFLOW(2,2) ISFLOW(2,3) ISFLOW(2,4) ISFLOW(2,5)
* E1        1001        1001        1001        1001        1001
*=====================================================================
*                End your input data set with a $ENDPROGRAM.
$ENDPROGRAM
```

Exhibit C.5 Statistics Block Input File

```
SW 1 20 50
MM 7 1 2 3 4 12 13 14
@ 20 'g9094$0s.fl'
$STATISTICS
** starting date * starting time * ending date * ending time *
A1    900101              0.0              940101              0.0        0 0
** MIT * BASE *
B1 .01    0.01     0  300 0  0  0  0  0.0
** Print controls
B2 1 1 0
** Output Controls
C1 1001 0000 0000 1001 1001
***
$ENDPROGRAM
```

Exhibit C.6 Statistics Block Output File

```
1              ************************************************
               *       Environmental Protection Agency        *
               *       Storm Water Management Model            *
               *              Version 4.05                     *
               ************************************************

                            Developed by

               ************************************************
               *            Metcalf & Eddy, Inc.              *
               *            University of Florida             *
               *       Water Resources Engineers, Inc.        *
               *              September 1970                  *
               ************************************************

                             Updated by

               ************************************************
               *            University of Florida             *
               *          Camp Dresser & McKee, Inc.          *
               *                                              *
               *   March     1975         November  1977     *
               *   November  1981         December  1990     *
               ************************************************


               ************************************************
               *     This is a new release of SWMM.  If any   *
               *       problems occur in running this model   *
               *       please contact Dr. Wayne Huber at the  *
               *              University of Florida           *
               *              Phone 1-904-392-0846            *
               ************************************************


               ************************************************
               *  This is an implementation of EPA SWMM 4.05  *
               *  "Nature is full of infinite causes which    *
               *   have never occured in experience" da Vinci *
               ************************************************



   ##########################################
   #       File names by SWMM Block          #
   #         JIN  -> Input to a Block         #
   #         JOUT -> Output from a Block      #
   ##########################################

     JIN for Block #    1 File #    0  JIN.UF
    JOUT for Block #    1 File #   20  JOT.UF
     JIN for Block #    2 File #   20  JOT.UF
    JOUT for Block #    2 File #   30  JOT.UF

   ##########################################
```

```
# Scratch file names for this simulation. #
##########################################

NSCRAT #      1 File #      1   SCRT1.UF
NSCRAT #      2 File #      2   SCRT2.UF
NSCRAT #      3 File #      3   SCRT3.UF
NSCRAT #      4 File #      4   SCRT4.UF
NSCRAT #      5 File #     12   SCRT5.UF
NSCRAT #      6 File #     13   SCRT6.UF
NSCRAT #      7 File #     14   SCRT7.UF


*****************************************************
*     Parameter Values on the Tapes Common Block    *
*****************************************************

   Number of Subcatchments in the Runoff Block (NW)....   100
   Number of Channel/Pipes in the Runoff Block (NG)....   150
   Runoff Water quality constituents (NRQ).............    10
   Runoff Land Uses per Subcatchment (NLU).............     5
   Number of Elements in the Transport Block (NET).....   150
   Number of Storage Junctions in Transport (NTSE).....    30
   Number of Input Hydrographs in Transport (NTH)......    80
   Number of Elements in the Extran Block (NEE)........   200
   Number of Groundwater Subcatchments in Runoff (NGW).   100
   Number of Interface locations for all Blocks (NIE)..   200
   Number of Pumps in Extran (NEP).....................    20
   Number of Orifices in Extran (NEO)..................    60
   Number of Tide Gates/Free Outfalls in Extran (NTG)..    25
   Number of Extran Weirs (NEW)........................    60
   Number of Extran printout locations (NPO)...........    30
   Number of Tide elements in Extran (NTE).............    20
   Number of Natural channels (NNC)....................    20
   Number of Storage junctions in Extran (NVSE)........    20
   Number of Time history data points in Extran(NTVAL).    50
   Number of Data points for variable storage elements
   in the Extran Block (NVST)..........................    25
   Number of Input Hydrographs in Extran (NEH)........   100


#####################################
# Statistical Analysis Block written #
#    by the University of Florida.    #
#    Last updated December, 1990.     #
# See data examples or STATS.DOC for #
#information on three new parameters.#
#####################################


       #################################
       #      Stats Block input commands   #
       #################################

Minimum interevent time (hours).......      0.01
NPOINT (number of printed events).....         0

METRIC (0-U.S. standard, 1-Metric)....         0
LRET (return period units)............         0
```

```
A (plotting position parameter)....... 0.000
Calculate logarithmic moments.(INLOG). 0

Use inch or millimeter flow JCUBE = 0,
or cfs or cms flow values   JCUBE = 1.        0

Print sequential series (KSEQ)........       0
Terminate program parameter (KTERM)...       0
KTSEQS................................        0



#########################################
# Header information from interface file: #
#########################################

Title from first computational block:
NEABSCO CREEK TRIBUTARY
$1pond

Title from immediately preceding computational block
NEABSCO CREEK TRIBUTARY
$1pond

Name of preceding block:................S/T BLOCK
Initial Julian date (IDATEZ).....................     0
Initial time of day in seconds (TZERO)...........   0.0
No. Transfered input locations...................     1
No. Transfered pollutants........................     1
Size of total catchment area (acres)............. 526.70
Numbers (JCE=0) or Alphanumeric (JCE=1)..........     0

###############################################
# Element numbers of interface inlet locations: #
###############################################
     300

######################################
# Quality parameters on interface file: #
######################################

No. Name       Units      Type of units
--- ----       -----      -------------
 1  TSS        mg/l           0

Conversion factor to cfs for flow units
on interface file.  Multiply by:     1.00000


###############################################
#  The period of time for which the statistical  #
#           analysis is being performed is:    #
###############################################

  Starting date...............900101  Starting time... 0.00 hours
  Ending date.................940101  Ending time..... 0.00 hours
```

```
###################################################
#  The period of time for which the statistical  #
#            analysis is being performed is:     #
###################################################

  Starting Julian date........ 90001   Starting time... 0.00 seconds
  Ending Julian date.......... 94001   Ending time..... 0.00 seconds

The minimum interevent time has been defined as      0.01 hours.

****************************************************
* The flow location number requested for Statistical *
* Analysis is:        300                          *
****************************************************

****************************************************
* The rain location number requested for Statistical *
* Analysis is:        0                            *
****************************************************

U.S. customary units are used in input/output.

The number of quality parameters
requested for statistical analysis is..         0
The base blow to separate events is....   0.1000 cfs.
Threshold event flow inches (cfs)......   0.0000



###########################################
#  The statistical options requested for  #
#       flow rate are indicated by "1"    #
###########################################

                                          Total Flow   Average Flow
Peak Flow   Event Duratn   Interevent Duratn
                                          ------------ --------------
----------- ------------- ------------------
Table of return period and frequency           0            0
     0             0              0
Graph of return period                         0            0
     0             0              0
Graph of frequency                             0            0
     0             0              0
Moments                                        1            0
     0             1              1


===> Program execution continuing.  Data will be
     read from the interface file and separated into events.

===> The first date and time on the interface file
     are    90001 and     600.00 seconds


===> End of interface file reached.
```

```
   ===> Last Julian date and time read
        are   94001 and        0.00 seconds

   ===> Program continuing with analysis of events.

   ===> The number of years within the period of
        analysis rounded to the nearest year,  is       4.

   ===> The number of events within the period of
        analysis is                             459.

#####################################################################
###############
   Moments
#####################################################################
###############

   Constituent           Event                              Standard
Coef. of    Coef. of
      Analyzed        Parameter      Mean     Variance   Deviation
Variation    Skewness
      ----------    ----------------   --------   --------   ----------
----------   ----------
      Flow          Total Flow  0.2917       8.4768E-02  0.2911
0.9980       1.652

#####################################################################
###############
   Moments
#####################################################################
###############

   Constituent           Event                              Standard
Coef. of    Coef. of
      Analyzed        Parameter      Mean     Variance   Deviation
Variation    Skewness
      ----------    ----------------   --------   --------   ----------
----------   ----------
      Flow          Event Duration  6.572       34.66      5.887
0.8957       2.026

#####################################################################
###############
   Moments
#####################################################################
###############

   Constituent           Event                              Standard
Coef. of    Coef. of
      Analyzed        Parameter      Mean     Variance   Deviation
Variation    Skewness
      ----------    ----------------   --------   --------   ----------
----------   ----------
      Flow Interevent Duration  69.90       4698.      68.54
0.9805       2.011

   ===>  Stats Block terminated normally.
```

```
===> SWMM 4.05 Simulation ended normally.

**********************************************************
*          SWMM 4.05 Simulation Date and Time Summary    *
**********************************************************
* Starting Date... January      7, 1993                  *
*          Time...           12:55:25:84                  *
*   Ending Date... January      7, 1993                  *
*          Time...           13: 5:53:53                  *
*  Elapsed Time...                 10.467 minutes.        *
**********************************************************
```

APPENDIX D

COMPUTER PROGRAMS FOR DATA PREPARATION

Exhibit D.1 "Expr.for" (Press et al., 1986)

```
      parameter(nevent=325,nnum=3*nevent)
       DIMENSION EP(nnum),R(97),ep1(nnum),ep2(nnum),ep3(nnum)
       data alpha,beta,gamma/7.4129,0.0856,0.0097/
       open(6,file='g94c.prn',status='unknown')
       write(6,19) nevent
19     format(2x,'total number of events=',i5)
       WRITE(6,20)
20     FORMAT(//10X,'RUNOFF',6X,'DURATION',8X,'INTER EVENT TIME')
       IDUM=-1234
       sum1=0.0
       sum2=0.0
       sum3=0.0
       do 21 j=1,nnum
       EP(J)=RAN1(IDUM)
       IF(J.LE.nevent)EP(J)=-ALOG(EP(J))/ALPHA
       IF(J.LE.nevent)EP1(J)=ep(j)
       ncut=2*nevent
       IF(J.GT.nevent.AND.J.LE.ncut)EP(J)=-ALOG(EP(J))/BETA
       IF(J.GT.nevent.AND.J.LE.ncut)EP2(J-nevent)=ep(j)
       IF(J.GT.ncut.AND.J.Le.nnum)EP(J)=-ALOG(EP(J))/GAMMA
       IF(J.GT.ncut.AND.J.Le.nnum)EP3(J-ncut)=ep(j)
21     continue
       WRITE(6,22) (EP(J),EP(J+nevent),EP(J+ncut),J=1,nevent)
22     format(2x,f10.4,8x,f10.4,10x,f10.4)
       do 31 j=1,nevent
       sum1=sum1+ep1(j)
       sum2=sum2+ep2(j)
       sum3=sum3+ep3(j)
31     continue
       ave1=sum1/float(nevent)
       ave2=sum2/float(nevent)
       ave3=sum3/float(nevent)
       sum4=0.0
       sum5=0.0
       sum6=0.0
       do 32 j = 1,nevent
       sum4=sum4+(ep1(j)-ave1)*(ep1(j)-ave1)
       sum5=sum5+(ep2(j)-ave2)*(ep2(j)-ave2)
       sum6=sum6+(ep3(j)-ave3)*(ep3(j)-ave3)
32     continue
       std1=sum4/float(nevent-1)
       std2=sum5/float(nevent-1)
       std3=sum6/float(nevent-1)
       std1=sqrt(std1)
       std2=sqrt(std2)
       std3=sqrt(std3)
       write(6,33)ave1,std1
       write(6,34)ave2,std2
       write(6,35)ave3,std3
33     format(//2x,'mean runoff volume=',f10.4,3x,'std.dev=',f10.4)
34     format(/2x,'mean duration=',f10.4,3x,'std.dev=',f10.4)
```

```
35      format(/2x,'mean inter event time=',f10.4,3x,'std.dev=',f13.4)
        STOP
        END
        function ran1(idum)
        DIMENSION R(97)
        PARAMETER (M1=259200,IA1=7141,IC1=54773,RM1=3.8580247E-6)
        PARAMETER (M2=134456,IA2=8121,IC2=28411,RM2=7.4373773E-6)
        PARAMETER (M3=243000,IA3=4561,IC3=51349)
        DATA IFF /0/
        IF (IDUM.LT.0.OR.IFF.EQ.0) THEN
          IFF=1
          IX1=MOD(IC1-IDUM,M1)
          IX1=MOD(IA1*IX1+IC1,M1)
          IX2=MOD(IX1,M2)
          IX1=MOD(IA1*IX1+IC1,M1)
          IX3=MOD(IX1,M3)
          DO 11 J=1,97
            IX1=MOD(IA1*IX1+IC1,M1)
            IX2=MOD(IA2*IX2+IC2,M2)
            R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
11        CONTINUE
          IDUM=1
        ENDIF
        IX1=MOD(IA1*IX1+IC1,M1)
        IX2=MOD(IA2*IX2+IC2,M2)
        IX3=MOD(IA3*IX3+IC3,M3)
        J=1+(97*IX3)/M3
        IF(J.GT.97.OR.J.LT.1)go to 23
        ran1=r(j)
        R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
        GO TO 24
23      WRITE(6,*)'J.GT.97.OR.J.LT.1'
24      RETURN
        END
```

Exhibit D.2 Output from "Expr.for"

```
total number of events=  500


            RUNOFF        DURATION         INTER EVENT TIME
           0.0766          1.3748             104.1431
           0.2982          0.9750              20.9267
           0.2061          9.6837             156.7158
           0.0616          6.7491              47.9104
           0.0793          3.0352             253.4969
           0.6846         19.5897              91.4636
           0.1688          4.8001              21.1831
           0.0660          5.7865               9.6594
           0.0517          1.8762             117.0718
---------------//---------------//--------------------
           0.2806          2.6156               5.7725
           0.0317         22.2545             134.5855
           0.9529          9.6284               7.6376
           0.4425          2.9626             102.5345
           0.1833         12.2679              15.2015
           0.1151          0.4857             139.4742
           0.3543          0.0703              30.0535
           0.2548         16.4519              93.0996
           0.2676         14.4263              12.3943
           0.2396         16.5178               6.5335
           0.0197          2.2734               1.8782


mean runoff volume=     0.2668   std.dev=      0.2695

mean duration=      6.0234   std.dev=      5.9564

mean inter event time=   69.1946   std.dev=         66.4056
```

Exhibit D.3 "Jprep.bas"

```
OPEN "c:\a\gf.prn" FOR INPUT AS #1
OPEN "c:\a\gfj1.swm" FOR OUTPUT AS #2
TM = 0
a$ = "J1    ########.##    ########.##    ####.##"
DT = .166666667#
dum = 0
P0 = 0
P1 = 100
NSTM = 300
FOR I = 1 TO NSTM
INPUT #1, X2, X3, Q
        TM = TM + DT
        PRINT #2, USING a$; TM; Q; P1
        TM = TM + X2
        PRINT #2, USING a$; TM; Q; P1
        TM = TM + DT
        PRINT #2, USING a$; TM; dum; P0
        TM = TM + X3 - 2 * DT
        PRINT #2, USING a$; TM; dum; P0
NEXT I
CLOSE #1
CLOSE #2
END
```

Exhibit D.4 MEDD code

```
'===============================================================================
'=====              Methodology for Extended Detention basin Design        =====
'=====                              MEDD                                    =====
'=====                                                                      =====
'===== A program that performs preliminary sizing calculations for =====
'=====        detention basins designed to perform as BMPs                 =====
'=====                                                                      =====
'=====                     Developed and Written by                        =====
'=====                                                                      =====
'=====                         Edwin W. Watkins                            =====
'=====                                                                      =====
'===============================================================================


'===Declare Statements===================================

DECLARE SUB Comline (NumArgs!, Args$(), MaxArgs!)
DECLARE SUB SN ()
DECLARE SUB CALC ()
DECLARE SUB RDFL ()
DECLARE SUB INTERP ()
DECLARE SUB ELOOP ()
DECLARE SUB ECHOIN ()

COMMON SHARED X1, X2, X3, ALPH, BETA, GAM, A, B, C, D, K#, M#, Z$, CMETH
COMMON SHARED ETAF, ETAT, ETAB, ETAB(), T(), NUMPTS, CSN, METH, FLETA$,
EP
COMMON SHARED DELA, DELB, OUTFL$, INFL$, WSHED$, DC, PMETH, WA
DIM T(NUMPTS), ETAB(NUMPTS)
'=======================================================
ST$ = TIME$
'===Read Input File==========================================

REDIM FL$(1 TO 2)
CALL Comline(N, FL$(), 2)
        INFL$ = UCASE$(FL$(1))
        OUTFL$ = UCASE$(FL$(2))
ERASE FL$

IF N < 1 THEN INPUT "Enter the name of the input file:", INFL$
IF N < 2 THEN INPUT "Enter the name of the output file:", OUTFL$

OPEN INFL$ FOR INPUT AS #1

ZA:    ZA$ = INPUT$(2, #1)
   IF LEFT$(ZA$, 1) = "*" THEN
        LINE INPUT #1, CMMT$
        GOTO ZA
   END IF
INPUT #1, WSHED$

ZB:    ZB$ = INPUT$(2, #1)
   IF LEFT$(ZB$, 1) = "*" THEN
        LINE INPUT #1, CMMT$
```

```
            GOTO ZB
      END IF
INPUT #1, METH, CMETH, PMETH, FLETA$

ZC:    ZC$ = INPUT$(2, #1)
    IF LEFT$(ZC$, 1) = "*" THEN
          LINE INPUT #1, CMMT$
          GOTO ZC
    END IF
INPUT #1, X1, X2, X3, WA

ZD:    ZD$ = INPUT$(2, #1)
    IF LEFT$(ZD$, 1) = "*" THEN
        LINE INPUT #1, CMMT4$
        GOTO ZD
    END IF
INPUT #1, A, B, DC

ZE:    ZE$ = INPUT$(2, #1)
    IF LEFT$(ZE$, 1) = "*" THEN
        LINE INPUT #1, CMMT5$
        GOTO ZE
    END IF
INPUT #1, ETAT, EP, DELA, DELB

CLOSE #1
'==========================================================================
'===Initial calculations===================================================
D = 0
ETAF = 0
ALPH = 1 / X1
BETA = 1 / X2
GAM = 1 / X3

Z$ = "=== ##.#####  ##.###      ##.###     ###.###    ##.###  ##.###
##.### ==="
'==========================================================================
'===Echo input=============================================================

OPEN OUTFL$ FOR OUTPUT AS #2
CALL ECHOIN

'===Read eta file==========================================================
CALL RDFL
'==========================================================================
'===Select method==========================================================

SELECT CASE METH
'==========================================================================
        CASE 1
          SELECT CASE CMETH
            CASE 1
            C = 0
            CASE 2
            C = B
            CASE 3
            C = DC * B
```

```
            CASE 4
            CALL SN
          END SELECT

                CALL CALC
                CALL INTERP

                ETA = ETAF * ETAB
                SELECT CASE PMETH
                CASE 1
                PRINT #2, USING Z$; A; B; C; D; ETAF; ETAB; ETA
                CASE 2
                PRINT #2, USING Z$; A * (X3 / X1); B / X1; C; D; ETAF;
ETAB; ETA

                CASE 3
                PRINT #2, USING Z$; A * 1.008333 * WA; B * WA * 3630; C;
D; ETAF; ETAB; ETA
                END SELECT
'================================================================
        CASE 2
        CLS : LOCATE 12, 27
        PRINT "Be patient, MEDD is thinking!"
        CALL ELOOP
        CLS : LOCATE 12, 30
        PRINT "Thanks for using MEDD"
        LOCATE 13, 33
        PRINT "Have a Nice day"
        DO
                LOCATE 15, 26
                PRINT "Press any key to continue"
        LOOP UNTIL INKEY$ <> ""


END SELECT


ET$ = TIME$

PRINT #2,
PRINT #2, "========================================="
PRINT #2, "====Starting Time="; ST$
PRINT #2, "====Ending Time  ="; ET$
PRINT #2, "========================================="

CLOSE #2
END
```

```
SUB Comline (NumArgs, Args$(), MaxArgs) STATIC

' This subroutine reads the input and output files from the command line
'

FALSE% = 0
TRUE% = NOT FALSE%
NumArgs = 0
In = FALSE%

Cl$ = COMMAND$
l = LEN(Cl$)

FOR i = 1 TO l
C$ = MID$(Cl$, i, 1)

'Test for character being a blank or a tab.
      IF (C$ <> " " AND C$ <> CHR$(9)) THEN

                  ' Test to see if you're already inside an argument.
                  IF NOT In THEN
                          NumArgs = NumArgs + 1
                          In = TRUE%
                  END IF

                  ' Add the character to the current argument.
                  Args$(NumArgs) = Args$(NumArgs) + C$
      ELSE
                  ' Found a blank or a tab.
                  In = FALSE%
      END IF
NEXT i
END SUB
```

```
SUB ECHOIN
'This subroutine echos the input to the output file=============
'
PRINT #2,
"==================================================================
"
PRINT #2, "=====        Methodology for Extended Detention basin Design
   ====="
PRINT #2, "=====                           MEDD
   ====="
PRINT #2, "=====
   ====="
PRINT #2, "===== A program that performs preliminary sizing calculations
for ====="
PRINT #2, "=====       detention basins designed to perform as BMPs
   ====="
PRINT #2, "=====
   ====="
PRINT #2, "=====                   Developed and Written by
   ====="
PRINT #2, "=====
   ====="
PRINT #2, "=====                      Edwin W. Watkins
   ====="
PRINT #2, "=====
   ====="
PRINT #2,
"==================================================================
"
'
PRINT #2,
PRINT #2,
"******************************************************************
"
PRINT #2, "Echo Input"

PRINT #2,
PRINT #2, "===== Watershed/Site description: "; WSHED$
PRINT #2, "===== Watershed Area (Acres.)    : "; WA
PRINT #2,
PRINT #2, "==================Runoff Statistics
Input====================="
PRINT #2, USING "===== Mean Runoff Volume    =   #.### (in.)"; X1
PRINT #2, USING "===== Mean Runoff Duration  = ###.##  (hrs.)"; X2
PRINT #2, USING "===== Mean Interevent Time  =####.##  (hrs.)"; X3
PRINT #2,
"==================================================================
"
PRINT #2,
PRINT #2, USING "===== Design Method      Used  METH = #"; METH
PRINT #2, USING "===== 'c' value used          CMETH = #"; CMETH
PRINT #2, USING "===== Print Method       Used PMETH = #"; PMETH
PRINT #2, "===== Eta BMP file used       FLETA = "; FLETA$
PRINT #2, "===== Output file is          OUTFL = "; OUTFL$
PRINT #2,
"==================================================================
"
```

```
'
PRINT #2,
SELECT CASE METH
CASE 2
PRINT #2, "===== For METH = 2  Control Variables
==================================="
PRINT #2, USING "===== Overall Efficiency Target  ETAT = #.### "; ETAT
PRINT #2, USING "===== Tolerance                     EP = #.####"; EP
PRINT #2, USING "===== Delta 'a' Factor           DELA = #.### "; DELA
PRINT #2, USING "===== Delta 'b' Factor           DELB = #.### "; DELB
PRINT #2,
"===================================================================
"
END SELECT
'output
PRINT #2,
"*******************************************************************
"
PRINT #2, "Output"
PRINT #2,
"===================================================================
"
SELECT CASE PMETH
CASE 1
PRINT #2, "=== a(in/hr) * b(in)   * c(in)   * E(D)[hrs.] * etaf * etab *
eta  ===="
CASE 2
PRINT #2, "=== aX3/X1   * b/X1    * c(in)   * E(D)[hrs.] * etaf * etab *
eta  ===="
CASE 3
PRINT #2, "=== a(cfs)   * b(ac-ft)* c(ac-ft)* E(D)[hrs.] * etaf * etab *
eta  ===="
END SELECT
END SUB
```

```
SUB RDFL
'
'This subroutine reads the etafl file

OPEN FLETA$ FOR INPUT AS #3
INPUT #3, NUMPTS
REDIM T(NUMPTS), ETAB(NUMPTS)
        FOR i = 1 TO NUMPTS
                INPUT #3, T(i), ETAB(i)
        NEXT i
CLOSE #3
'
END SUB
```

```
SUB SN

' This subroutine calculates E(Sn)
'
K = (BETA * GAM) / ((ALPH * A + BETA) * (ALPH * A + GAM))
M = (ALPH * GAM * A) / ((ALPH * A + BETA) * (GAM - BETA))

SNP1 = B / 2 - K / ALPH + (M * A) / BETA
SNP2 = K / (ALPH ^ 2 * B) * (1 - EXP(-ALPH * B))
SNP3 = M * A ^ 2 / (BETA ^ 2 * B) * (1 - EXP(-BETA * B / A))
SNP4 = K * A ^ 2 / (GAM ^ 2 * B) * EXP(-ALPH * B) * (1 - EXP(-(GAM * B)
/ A))
SNP5 = (A / GAM - (K * A) / GAM - (M * A) / GAM) * EXP(-(GAM * B) / A)
SNP6 = -(A ^ 2 / (GAM ^ 2 * B) - M * A ^ 2 / (GAM ^ 2 * B))
SNP7 = -(-(K * ALPH * A ^ 2) / GAM ^ 2 + (M * BETA * A) / GAM ^ 2)
SNP8 = (1 - EXP(-GAM * B / A))

C = SNP1 + SNP2 - SNP3 + SNP4 + SNP5 + (SNP6 + SNP7) * SNP8

END SUB
```

```
SUB CALC
'
' This subroutine calculate E(D) and ETAFL

K = (BETA * GAM) / ((ALPH * A + BETA) * (ALPH * A + GAM))
M = (ALPH * GAM * A) / ((ALPH * A + BETA) * (GAM - BETA))

 DP1 = EXP(-GAM / A * (B - C))
 DP2 = ((C - B) / A - 1 / GAM + (M / A + K / A) * (B - C) + M / (GAM -
BETA))
 DP3 = K / (ALPH * A + GAM)
 DP4 = (1 + (ALPH * A) / GAM * (1 - EXP(-B / A * (ALPH * A + GAM))))
 DP5 = M / (GAM - BETA) * EXP(-(BETA / A) * (B - C))
 DP6 = K / (ALPH * A + GAM) * EXP(-ALPH * C - (B / A) * GAM) - 1 / GAM

D = DP1 * (DP2 + DP3 * DP4) - DP5 - DP6

 ETAFP1 = K * EXP(-ALPH * C)
 ETAFP2 = K * (ALPH * A / GAM) * EXP(-B * (ALPH + GAM / A) + (GAM / A) *
C)

ETAF = 1 - (ETAFP1 + ETAFP2)

END SUB
```

```
SUB INTERP
'
'This subroutine interpolates between the E(D) etaBMP pairs for the
'appropriate etaBMP for a given E(D)

FOR i = 1 TO NUMPTS
  IF T(i) > D AND T(i - 1) < D THEN
     ETAB = ETAB(i - 1) + (D - T(i - 1)) / (T(i) - T(i - 1)) * (ETAB(i) -
ETAB(i - 1))
  END IF
  IF D >= T(NUMPTS) THEN ETAB = ETAB(NUMPTS)
NEXT i
END SUB
```

```
SUB ELOOP
'
'This subroutine maintaine the iterative process for METH=2

DA = DELA * X1 / X3
DB = DELB * X1
ANmax = (10 * (X1 / X3)) / DA
Bnmax = 10 * X1 / DB
DIM A(ANmax)
DIM B(Bnmax)
A = 0
B = 0
FOR AN = 1 TO ANmax
    B = DB
    A = A + DA
    A(AN) = A

        FOR BN = 1 TO Bnmax

            B = B + DB
            B(BN) = B

              SELECT CASE CMETH
               CASE 1
               C = 0
               CASE 2
               C = B
               CASE 3
               C = DC * B
               CASE 4
               CALL SN
              END SELECT

CALL CALC
CALL INTERP
ETA = ETAB * ETAF

IF ABS(ETA - ETAT) < EP THEN
        SELECT CASE PMETH
        CASE 1
        PRINT #2, USING Z$; A(AN); B(BN); C; D; ETAF; ETAB; ETA
        CASE 2
        PRINT #2, USING Z$; A(AN) * X3 / X1; B(BN) / X1; C; D; ETAF;
ETAB; ETA
        CASE 3
        PRINT #2, USING Z$; A(AN) * 1.008333 * WA; B(BN) * WA / 12; C *
WA / 12; D; ETAF; ETAB; ETA
        END SELECT
END IF
  NEXT BN

LOCATE 14, 36
Pd = (AN * BN) / (ANmax * Bnmax) * 100
PRINT USING "###% Done"; Pd

 NEXT AN
END SUB
```

Exhibit D.5 Typical MEDD Input File

```
**********************************************************************
****** This is a typical input file for MEDD. The input is free    ******
****** format and comment lines are denoted by '*' in the first    ******
****** column on the right.  All cards must be included and a       ******
****** value must be entered for all variables.                    ******
**********************************************************************
*
* Card A1 is a desrciption of the watershed/site etc. and is only used
* for identification on the output file. The string must be in double
* quotes ""
* *
A1  "ATLANTA"
*
* Card A2 contains the control variables METH, CMETH, and PMETH.  The
* name of the eta file is also on this line.
*
* METH
*
* What design procedure is required:
* METH =1:Overall efficiency is calculated for given values of a and b.
* METH =2:An iterative proceedure is performed to calculate a and b
*         pairs for a given target efficiency.
*
* CMETH
* What c value should be used:
* CMETH =1: c=0
* CMETH =2: c=b
* CMETH =3: c=dc x b
* CMETH =4: c=E(Sn)
*
* PMETH
* How is the output printed:
* PMETH =1: units used: in. and in/hr.
* PMETH =2: units used: dimensionless
* PMETH =3: units used: ac-ft and cfs.
*
* ETAFL
* The name of the eta file to be used in "".
*
*
*   METH    CMETH  PMETH   ETAFL
A2  2       4      1       "R1K6.ETA"
*
* Line A3 contains the values for runoff volume, X1 (in), runoff
* duration, X2 (hrs.), interevent time, X3 (hrs.), and watershed area,
* WA (acres).
*
*    X1     X2     X3     WA
A3 .098    6.2     89     350
*
```

```
* Line A4 contains values for a (in/hr) and b (in) [METH=1] and dC
* [CMETH=3].
*
*    A    B    dC
A4  .1   .5    .2
*
* Line A5 contains the target efficiency etat, the allowable difference
* between the etat and acceptable values. ep, and the increments for a
* and b, dela and delb.
*
* MEDD performs the search for solutions sets of a and b over a 10 by 10
* dimensionless grid.  Such that [a * X3/X1] and [b/X1] vary between 1
* and 10.  Dela and delb are the fractions of [a * X3/X1] and [b/X1],
* respectively that are used to increment the procedure.
*
*    etat    ep    dela    delb
A5   .7     .001    .1      .1
*******************************************************************************
```

Exhibit D.6 Typical MEDD Input Eta File

Description: The first line is the number of E(D) etaBMP pairs. The
pairs are listed as: E(D),etaBMP

```
13
    0, 0
 0.44, 0.165
 1.34, 0.325
 3.59, 0.544
  4.7, 0.613
 7.76, 0.75
 13.6, 0.834
21.83, 0.895
 25.6, 0.923
27.87, 0.936
29.38, 0.946
30.18, 0.953
 62.5, 0.999
```

Exhibit D.7 Typical MEDD Output File

```
================================================================================
=====            Methodology for Extended Detention basin Design     =====
=====                              MEDD                               =====
=====                                                                 =====
===== A program that performs preliminary sizing calculations for    =====
=====        detention basins designed to perform as BMPs            =====
=====                                                                 =====
=====                    Developed and Written by                    =====
=====                                                                 =====
=====                        Edwin W. Watkins                        =====
=====                                                                 =====
================================================================================


********************************************************************************
Echo Input

===== Watershed/Site description: ATLANTA
===== Watershed Area (Acres.)    :   350

====================Runoff Statistics Input=====================================
===== Mean Runoff Volume    =    0.098 (in.)
===== Mean Runoff Duration  =    6.20  (hrs.)
===== Mean Interevent Time  =   89.00  (hrs.)
================================================================================

===== Design Method      Used  METH = 2
===== 'c' value used           CMETH = 4
===== Print Method       Used PMETH = 1
===== Eta BMP file used        FLETA = R1K6.ETA
===== Output file is           OUTFL = ATL.OUT
================================================================================

===== For METH = 2  Control Variables  =========================================
===== Overall Efficiency Target  ETAT = 0.700
===== Tolerance                    EP = 0.0010
===== Delta 'a' Factor           DELA = 0.100
===== Delta 'b' Factor           DELB = 0.100
================================================================================
********************************************************************************
Output
================================================================================
=== a(in/hr) * b(in)   * c(in)   * E(D)[hrs.] * etaf * etab * eta   ====
===   0.00011    0.343      0.108      89.000       0.701   0.999   0.700 ===
===   0.00132    0.147      0.061      42.504       0.721   0.971   0.700 ===
===   0.00187    0.137      0.061      30.066       0.735   0.952   0.699 ===
===   0.00264    0.147      0.073      21.883       0.782   0.895   0.700 ===
===   0.00352    0.157      0.085      16.455       0.818   0.855   0.700 ===
===   0.00484    0.176      0.106      11.912       0.864   0.810   0.700 ===
===   0.00529    0.186      0.116      10.929       0.880   0.796   0.701 ===
===   0.00573    0.196      0.126      10.075       0.895   0.783   0.701 ===
===   0.00617    0.206      0.135       9.327       0.907   0.773   0.701 ===
===   0.00661    0.216      0.145       8.665       0.918   0.763   0.700 ===
===   0.00705    0.225      0.155       8.077       0.927   0.755   0.700 ===
```

```
=== 0.00749   0.245   0.174   7.619   0.942   0.744   0.700 ===
=== 0.00793   0.284   0.209   7.282   0.961   0.729   0.701 ===
=== 0.00804   0.294   0.218   7.193   0.965   0.725   0.699 ===
=== 0.00826   0.323   0.244   7.045   0.974   0.718   0.700 ===
=== 0.00837   0.343   0.261   6.980   0.979   0.715   0.700 ===
=== 0.00848   0.363   0.279   6.910   0.983   0.712   0.700 ===
=== 0.00859   0.392   0.305   6.859   0.987   0.710   0.701 ===
=== 0.00870   0.421   0.330   6.801   0.991   0.707   0.700 ===
=== 0.00881   0.451   0.356   6.741   0.993   0.704   0.699 ===
=== 0.00881   0.461   0.364   6.759   0.994   0.705   0.701 ===
=== 0.00892   0.490   0.390   6.697   0.995   0.702   0.699 ===
=== 0.00892   0.500   0.398   6.715   0.996   0.703   0.700 ===
=== 0.00903   0.539   0.431   6.672   0.997   0.701   0.699 ===
=== 0.00903   0.549   0.439   6.691   0.997   0.702   0.700 ===
=== 0.00914   0.588   0.472   6.651   0.998   0.700   0.699 ===
=== 0.00914   0.598   0.480   6.671   0.998   0.701   0.700 ===
=== 0.00925   0.647   0.521   6.657   0.999   0.701   0.700 ===
=== 0.00925   0.657   0.529   6.679   0.999   0.702   0.701 ===
=== 0.00936   0.696   0.562   6.651   0.999   0.700   0.700 ===
=== 0.00947   0.735   0.594   6.628   1.000   0.699   0.699 ===
=== 0.00947   0.745   0.602   6.653   1.000   0.700   0.700 ===
=== 0.00958   0.784   0.634   6.636   1.000   0.700   0.699 ===
=== 0.00958   0.794   0.641   6.662   1.000   0.701   0.701 ===
=== 0.00969   0.833   0.673   6.651   1.000   0.700   0.700 ===
=== 0.00980   0.872   0.705   6.645   1.000   0.700   0.700 ===
=== 0.00991   0.911   0.736   6.643   1.000   0.700   0.700 ===
=== 0.01002   0.951   0.768   6.646   1.000   0.700   0.700 ===
=== 0.01013   0.990   0.799   6.653   1.000   0.700   0.700 ===

================================================
====Starting Time=16:44:23
====Ending Time  =16:45:24
================================================
```

VITA

The author was born on July 3, 1969. He was raised in Athens, Tennessee. He graduated from McMinn County High School in the spring of 1987 and entered Auburn University that Fall. He graduated with honors from Auburn University in the spring of 1991. Shortly thereafter, he entered Virginia Tech to pursue his Master's degree.

Edwin W. Watkins