Extended Stormwater Detention Basin Design for Pollutant Removal

by

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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.
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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);
\( C' \) = influent pollutant concentration (SWMM);
\( C_{ \text{eff}} \) = downstream weighted pollutant concentration;
\( C_{\text{BMP}} \) = pollutant concentration leaving the pond;
\( D \) = detention time;
\( E(\cdot) \) = expected value of random variable;
\( I \) = inflow rate (SWMM);
\( k \) = \( \beta \gamma/[(\alpha \alpha + \beta)(\alpha \alpha + \gamma)] \);
\( m \) = \( \alpha \gamma/(\alpha \alpha + \beta)(\gamma - \beta) \);
\( n \) = index for current event;
\( O \) = outflow rate (SWMM);
\( R \) = removal fraction (SWMM);
\( R_{\text{max}} \) = maximum removal fraction (SWMM);
\( S \) = empty space in detention pond;
\( T \) = \( \min [c + aX_n, b] \);
\( t \) = 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.);
\( \alpha \) = \( 1/E(X_1) \);
\( \beta \) = \( 1/E(X_2) \);
\( \gamma \) = \( 1/E(X_3) \);
\( \eta \) = overall efficiency;
\( \eta_{\text{BMP}} \) = settling efficiency (efficiency in the pond);
\( \eta_{\text{FL}} \) = capture efficiency;
\( \theta \) = first order decay coefficient (SWMM);
\( \Theta \) = \( R/\Delta t \) (SWMM);
\( \lambda \) = 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

Withdrawal Rate
"a" in/hr

Storage "b" in.

By-pass "y" in.
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 detainted 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; $X_4(n)$ = 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

$$T(n) = \min \left\{ S(n-1) + aX_3(n-1), b \right\}$$  \hspace{1cm} (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:

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

(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:

\[
T(n) < X_1(n) - aX_2(n)
\]  

(2-3)

and the by-pass volume is:

\[
Y(n) = X_1(n) - aX_2(n) - T(n) \quad \text{for} \quad Y(n) > 0.
\]  

(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 \( t_1, t_2, \ldots t_n \) 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

\[
dV = [adt][1 - F_R(t)]
\]  
(3-1)

in which: \( F_R(t) = P(R \leq t) = \) probability that the residence time is less than 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

\[
dV = V[F_R(t + dt) - F_R(t)]
\]  
(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

\[
adt[1 - F_R(t)] = V f_R(t) dt
\]  
(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 \( n \)th 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 \( n \)th 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 \( n \)th event will be:
\[ D(n) = \frac{V(n)}{a} \quad \text{for} \quad 0 \leq V(n) \leq b \tag{3-7} \]

where: \( D(n) \) = the detention time for the \( n \)th 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 \( D(n) > X_s(n) \). 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 \( V(n)/a > X_s(n) \). 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 \( X_s(n) \) and the detention time can be defined as:

\[ D(n) = \min \left( \frac{V(n)}{a}, X_s^{(a)} \right) \quad \text{for} \quad 0 \leq V(n) \leq b. \tag{3-8} \]

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 \( n \)th runoff event is given as:

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

\( (3.9) \)

\[
P[S(n)\leq s \mid S(n-1)=c] = k \left( \exp\left[-\alpha (c-s)\right] + \frac{\alpha a}{\gamma} \exp\left[-\alpha(b-s)-\frac{\gamma a}{c}(b-c)\right]\right)
\]  

\( (3.10) \)  

For \( 0 < s \leq c \)

\[
P[S(n)\leq s \mid S(n-1)=c] = 1 - m \left( \exp\left[-\frac{\beta a}{b-c}(s-c)\right] - \exp\left[-\frac{\gamma a}{c}(s-c)\right]\right)
\]  

\( (3.11) \)

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

\[
+ \frac{k\alpha a}{\gamma} \exp\left[-\alpha(b-s)-\frac{\gamma a}{c}(b-c)\right]\quad \text{for } c\leq s < b
\]

and

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

\( (3.12) \)
where $k$ and $m$ are defined as:

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

and

$$m = \frac{\alpha \gamma a}{(\alpha a + \beta)(\gamma - \beta)} \quad (3-14)$$

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 $S(n)$:

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

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, $X_3(n)$, 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)
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 \( n \)th 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 \( S(n) = 0 \).

\[
P(Y>0) = P[S(n) = 0]
\]

(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:

\[
D(n) = \min \left( \frac{b}{a} , X_3(n) \right) \quad \text{for } S(n) = 0.
\]

(3-17)

Similar to Eq.(3-15), the detention time for event \( n \) will be defined as \( \frac{b}{a} \) 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 \( \frac{b}{a} \) because \( X_3(n) > \frac{b}{a} \). Figure 3-5 illustrates the case when \( X_3(n)<\frac{b}{a} \). The pond is filled past capacity and the next event
Figura 3-5. Detención Tiempo igual a Tiempo Entre Eventos
(By-pass Situation)
arrives before the pond is emptied. The detention time is defined as $X_s(n)$.

### 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 $n$th event, is not dependent on the interevent time for the $n$th event, $X_s(n)$ [the time between the $n$th and the $n+1$ event], $S(n)$ and $X_s(n)$ are physically and statistically independent random variables. Therefore, the probability that $D(n)$ is greater than some value $d$ can be expressed as:

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

$$= P(S(n) \leq b - ad) P(X_s \geq d) \quad \text{for} \quad 0 < d < \frac{b}{a}.$$  

(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 $c \leq s < b$.

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

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

Substituting equation (3-11) into equation (3-18) the resulting expression for the
probability that D is greater than some threshold value is:

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

for \(0 < d \leq \frac{b-c}{a}\)  

(3-19)

and

\[
P(D(n) \leq d) = 1 - P(D(n) \geq d) .
\]

(3-20)
Therefore, the probability \( D(n) \) is less than some threshold \( d \) is expressed as:

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

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

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

\[
\text{for } 0 < d \leq \frac{b - c}{a}.
\]

(3-21)

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 \( s \leq c < b \). If \( s \) is set equal to \( b - ad \) the resulting expression is:

\[
\text{Case 2: } \frac{b - c}{a} < d < \frac{b}{a}
\]

Substituting Eq.(3-10) into Eq.(3-18) the resulting expression for the probability \( d \) is greater than some threshold value is:
\[
P[D(n) \geq d] = k \left( \exp\left[ -\alpha(c - b + ad) \right] + \frac{\alpha a}{\gamma} \exp\left[ -\alpha ad - \frac{\gamma}{a}(b - c) \right] \right) \exp[-\gamma d]
\]
\[
\text{for } \frac{b - c}{a} < d < \frac{b}{a}.
\]

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

\[
P[D(n) \leq d] = 1 - k \left( \exp\left[ -d(\alpha a + \gamma) - \alpha(c - b) \right] + \frac{\alpha a}{\gamma} \exp\left[ -d(\alpha a + \gamma) - \frac{\gamma}{a}(b - c) \right] \right)
\]
\[
\text{for } \frac{b - c}{a} < d < \frac{b}{a}.
\]

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:

\[
P(D(n) = 0) = P(S(n) = b) \ P(X_{\gamma} \geq 0) \quad \text{for } d = 0.
\]

---

CH. 3 ESTIMATING DETENTION TIME 27
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 $X_a(n) \geq 0$ is unity, Eq.(3-24) becomes:

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

for $d = 0$ .

The expression for the probability that $D(n) = \frac{b}{a}$ is:

$$P\left(D(n) = \frac{b}{a}\right) = P(S(n) = 0) \cdot P\left(X_a \geq \frac{b}{a}\right) \quad \text{for } d = \frac{b}{a} .$$

(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 ≥ b/a). The probability S(n)=0 is given by Eq.(3-9) and the probability X_3 ≤ 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

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

(3-28)

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 \( d = 0 \)

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

\[ - \frac{k\alpha a}{\gamma} \exp \left[ -d(\alpha a + \gamma) - \frac{\gamma}{a}(b - c) \right] \] (3-21)

for \( 0 < d \leq \frac{b-c}{a} \)

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

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

for \( \frac{b-c}{a} < d < \frac{b}{a} \)

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

\[
f'_n(d) = \frac{d}{dd} P[D(n) \leq d].
\]

Therefore, the probability density function can be expressed as:

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

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

for \( 0 < d < \frac{b-c}{a} \) (3-30)

and

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

for \( \frac{b-c}{a} < d < \frac{b}{a} \) (3-31)

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:

\[
E(D) = \int_{b-c/a}^{b-c} d \left\{ \gamma \exp(-\gamma d) - m(\gamma - \beta) \exp\left[ -\frac{b}{a}(b-c) - d(\gamma - \beta) \right] + \frac{k\alpha \gamma}{a} \left( \alpha a + \gamma \right) \exp\left[ -d(\alpha a + \gamma) - \frac{\gamma}{a}(b-c) \right] \right\} dd
\]

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

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

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

(3-34)

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 $n$th 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 $n$th 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

$$E[D|S(n-1) = b] = \frac{\beta}{(\alpha a + \beta)(\alpha a + \gamma)} \left[ 1 - \exp\left( -\frac{b}{a}(\alpha a + \gamma) \right) \right].$$  (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 $\beta$ 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 $\alpha^{-1}$ [$\alpha$ is the reciprocal of the average runoff volume, $E(X_i)$] at the rate $a$. That is, the expected detention time must equal $(\alpha a)^{-1}$. For large interevent times, $\gamma$ goes to zero and for short durations $\beta$ 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 (Schuler, 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
4.3 Application of SWMM

The SWMM S/T Block is used here to develop a set of standardized curves relating settling efficiency ($\eta_{BMP}$) 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 $\eta_{BMP}$ 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
TABLE 4-1. Summary of Rainfall Zone Characteristics (USEPA, 1986)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Period</th>
<th>Volume (in.)</th>
<th>Duration (hr)</th>
<th>Interval (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>c.v</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>Annual</td>
<td>0.26</td>
<td>1.46</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.32</td>
<td>1.38</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>Annual</td>
<td>0.36</td>
<td>1.45</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.40</td>
<td>1.57</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>Annual</td>
<td>0.49</td>
<td>1.47</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.48</td>
<td>1.52</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>Annual</td>
<td>0.58</td>
<td>1.46</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.52</td>
<td>1.54</td>
<td>5.2</td>
</tr>
<tr>
<td>5</td>
<td>Annual</td>
<td>0.33</td>
<td>1.74</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.38</td>
<td>1.71</td>
<td>3.2</td>
</tr>
<tr>
<td>6</td>
<td>Annual</td>
<td>0.17</td>
<td>1.51</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.17</td>
<td>1.61</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>Annual</td>
<td>0.48</td>
<td>1.61</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.26</td>
<td>1.35</td>
<td>11.4</td>
</tr>
<tr>
<td>8</td>
<td>Annual</td>
<td>0.14</td>
<td>1.42</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.14</td>
<td>1.51</td>
<td>2.8</td>
</tr>
<tr>
<td>9</td>
<td>Annual</td>
<td>0.15</td>
<td>1.77</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.18</td>
<td>1.74</td>
<td>3.1</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Region</th>
<th>$X_1$</th>
<th>$X_2$</th>
<th>$X_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E(X_1)$ (in)</td>
<td>$cv$</td>
<td>$E(X_2)$ (hr)</td>
</tr>
<tr>
<td>00</td>
<td>0.1584</td>
<td>1.10</td>
<td>12.58</td>
</tr>
<tr>
<td>100</td>
<td>0.2917</td>
<td>1.00</td>
<td>6.57</td>
</tr>
<tr>
<td>200</td>
<td>0.4052</td>
<td>1.07</td>
<td>6.88</td>
</tr>
<tr>
<td>400</td>
<td>0.6581</td>
<td>0.99</td>
<td>8.19</td>
</tr>
<tr>
<td>600</td>
<td>0.2063</td>
<td>1.33</td>
<td>4.81</td>
</tr>
<tr>
<td>700</td>
<td>0.5457</td>
<td>1.03</td>
<td>21.02</td>
</tr>
<tr>
<td>T100</td>
<td>0.2655</td>
<td>1.01</td>
<td>6.59</td>
</tr>
<tr>
<td>A100</td>
<td>0.2917</td>
<td>1.00</td>
<td>6.57</td>
</tr>
</tbody>
</table>
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]:

\[
R = \left( a_{12} e^{a_{12} x_2^a} + a_{13} e^{a_{13} x_3^a} + a_{14} e^{a_{14} x_4^a} + a_{15} e^{a_{15} (x_5^a, x_6^a)} x_7^a x_8^a x_9^a x_{10}^a x_{11}^a \right)^a
\] (4-1)

By setting all of the variables in Eq.(4-1) to zero except: \(x_5 = 1.0; a_2 = 0 \text{ (sec}^{-1})\);
<table>
<thead>
<tr>
<th>b/a=40</th>
<th>b/a=20</th>
<th>b/a=10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>b (in)</strong></td>
<td><strong>a (in/hr)</strong></td>
<td><strong>b (in)</strong></td>
</tr>
<tr>
<td>2.0</td>
<td>.05</td>
<td>2.0</td>
</tr>
<tr>
<td>0.8</td>
<td>.02</td>
<td>0.8</td>
</tr>
<tr>
<td>0.4</td>
<td>.01</td>
<td>0.4</td>
</tr>
<tr>
<td>0.3</td>
<td>.0075</td>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
<td>.005</td>
<td>0.2</td>
</tr>
<tr>
<td>0.1</td>
<td>.0025</td>
<td>0.1</td>
</tr>
<tr>
<td>0.05</td>
<td>.00125</td>
<td>0.05</td>
</tr>
<tr>
<td>0.02</td>
<td>.0005</td>
<td>0.02</td>
</tr>
<tr>
<td>0.005</td>
<td>.000125</td>
<td>0.005</td>
</tr>
</tbody>
</table>
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:

\[ R = R_{max} (1 - e^{-\theta \Delta t}) \]  \hspace{1cm} (4-2)

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

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

\[
C_2 = \frac{C_1 V_1 + \frac{(C_1^1 I_1 + C_2^1 I_2)}{2} \Delta t - \frac{C_1 O_1}{2} \Delta t - \frac{\Theta C_1 V_1}{2} \Delta t}{V_2 \left( 1 + \frac{\Theta \Delta t}{2} \right) + \frac{O_2}{2} \Delta t} \]  \hspace{1cm} (4-3)

in which: \( V \) = reservoir volume, \( \text{ft}^3 \); \( C_i \) = influent pollutant concentration, \( \text{mg/l} \); \( C \) = effluent and reservoir pollutant concentration, \( \text{mg/l} \); \( I \) = Inflow rate, \( \text{ft}^3/\text{sec} \); \( O \) = outflow rate, \( \text{ft}^3/\text{sec} \); \( t \) = time, \( \text{sec} \); \( \Theta \) = decay coefficient, \( \text{sec}^{-1} \); 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 \( \text{(i.e. detention time)} \). Thus, the total pollutant removal efficiency during the entire simulation period is a function of the average detention time for the simulation.

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**CH.4 SETTLING EFFICIENCY**

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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 $C_i^1 = C$ for all $i$. Let this concentration be changed to $C' = \sigma C$. Also, we assume the initial reservoir concentration $C_i$ changes to $C_i' = \sigma C_i$. By substituting $C'$ and $C_i'$, 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 $\sigma$'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 $C'$ 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 ($\eta_{bmp}$). 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:
\[ \eta_{BMP} \text{ (settling efficiency)} = \frac{\text{TSS POUNDS (REMOVED BY DECAY)}}{\text{TSS POUNDS (INFLOW, NET)}} \] (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 \( R_{\text{max}} \) in Eq.(4-2) is kept constant at 0.9. Three different values of \( \theta \) 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. $\eta_{BMP}$ vs. $E(D)$ For Different Drawdown Times ($b/a$) For $\theta = 0.1$
FIGURE 4-5. $\eta_{BMP}$ vs. $E(D)$ For Different Drawdown Times $(b/a)$ For $\theta = 0.2$
FIGURE 4-6. $\eta_{BMP}$ 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 $\eta_{\text{BMP}}$ 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 $\eta_{\text{BMP}}$ 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 $R_{\text{max}}$ and $\theta$ in Eq. (4-3).
FIGURE 4-7. $\eta_{\text{BMP}}$ vs. $E(D)$ For Different Runoff Statistics (Table 4-2) For $\theta = 0.1$
FIGURE 4-8. $\eta_{BMP}$ vs. $E(D)$ For Different Runoff Statistics (Table 4-2) For $\theta = 0.2$
**FIGURE 4-9.** $\eta_{\text{BMP}}$ vs. $E(D)$ For Different Runoff Statistics (Table 4-2) For $\theta = 0.5$
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:

\[
C_{\text{EFF}} = \frac{E(X_1 - Y) C_{\text{BMP}} + E(Y) C_1}{E(X_1)}
\]  

(5-1)

where:  

\( C_{\text{EFF}} \) = 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.

\( C_{\text{BMP}} \) = The concentration of the pollutant leaving the BMP pool after settling takes place.
\[ E(Y) = \text{The expected value of the by-pass volume.} \]

\[ C_i = \text{The initial concentration of pollutant or the concentration of pollutant entering the pond.} \]

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

\[
\frac{E(X_i - Y)}{E(X_i)} = \Pr(Y=0). \tag{5-2}
\]

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, \( \Pr(Y=0) \). Consequently,

\[
\frac{E(Y)}{E(X_i)} = 1 - \Pr(Y=0). \tag{5-3}
\]

The expression for \( \Pr(Y=0) \) is given as:

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

Notice that for a given set of runoff statistics, \( \alpha, \beta, \) and \( \gamma \), and for a given volume, \( b \), \( \Pr(Y=0) \) will decrease as \( a \) decreases. In other words, the volume of water captured within the extended detention pond 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. \( \Pr(Y=0) \) can be viewed
as the capture efficiency, $\eta_{fl}$, 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

$$C_{\text{EFF}} = \left\{ P(Y=0) \right\} C_{\text{BMP}} + \left\{ 1 - P(Y=0) \right\} C_1$$

(5-5)

Eq. (5-5) is an expression for the volumetrically weighted concentration entering the receiving stream. $C_{\text{EFF}}$ 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, $P(Y=0)$. $C_1$ is the concentration of the pollutant arriving at the pond and will remain unchanged for the fraction of water equal to $1-P(Y=0)$. $C_{\text{BMP}}$ can be defined as a fraction of $C_1$ such that

$$C_{\text{BMP}} = C_1 (1 - \eta_{\text{BMP}})$$

(5-6)

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

$$C_{\text{EFF}} = \left\{ P(Y=0) \right\} C_1 \left\{ 1 - \eta_{\text{BMP}} \right\} + \left\{ 1 - P(Y=0) \right\} C_1.$$ 

(5-7)

If the weighted concentration is divided by the initial concentration and the equation is rearranged, the resulting expression is:
1 - \frac{C_{\text{EFF}}}{C_1} = 1 - \{P(Y=0)\} \left\{1 - \eta_{\text{BMP}}\right\} + \left\{1 - P(Y=0)\right\}.
(5-8)

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

\[ \eta = \left\{P(Y=0)\right\} \eta_{\text{BMP}} \]
(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 \( \eta_{FL} \) is a suitable expression representing the fraction of pollutant load that enters 
the BMP pool and \( \eta_{BMP} \) 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 \( \eta_{BMP} \) and \( E(D) \) can be varied based on the pollutant
of interest. The form of $\eta_{FL}$ 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 $\eta_{FL}$ 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 $\eta_{BMP}$ 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 $\eta_{BMP}$ vs. $E(D)$ curve and determine $\eta_{BMP}$.

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

4) Use Eq. (5-10) to determine $\eta$. 

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CH.5 ESTIMATING POLLUTANT REMOVAL EFFICIENCY 64
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, $\eta_{FL}$, are compared to results from the S/T Block. Second, further simulations are made to test the relationships between $\eta_{BMP}$ 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 $\eta$.

6.2 Verification of E(D) and $\eta_{FL}$

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>
<thead>
<tr>
<th>Statistics Block Results: Case 1 Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall Volume = 81.2 in</td>
</tr>
<tr>
<td>Runoff Volume = 21.7 in</td>
</tr>
<tr>
<td>Mean Runoff Volume* = 0.1349 in</td>
</tr>
<tr>
<td>Mean Runoff Duration* = 11.68 hrs</td>
</tr>
<tr>
<td>Mean Interevent Time* = 102.8 hrs</td>
</tr>
<tr>
<td># Runoff Events* = 134</td>
</tr>
<tr>
<td>cv = 2.04</td>
</tr>
<tr>
<td>cv = 0.90</td>
</tr>
<tr>
<td>cv = 1.0</td>
</tr>
</tbody>
</table>

* 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:

---

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

<table>
<thead>
<tr>
<th>Elevation (ft)</th>
<th>Storage (ft³)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>263</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>265</td>
<td>14</td>
<td>0.55</td>
</tr>
<tr>
<td>266</td>
<td>352</td>
<td>0.69</td>
</tr>
<tr>
<td>267</td>
<td>3394</td>
<td>0.81</td>
</tr>
<tr>
<td>268</td>
<td>11032</td>
<td>0.91</td>
</tr>
<tr>
<td>269</td>
<td>23899</td>
<td>1.00</td>
</tr>
<tr>
<td>270</td>
<td>45636</td>
<td>1.09</td>
</tr>
<tr>
<td>271</td>
<td>86656</td>
<td>1.16</td>
</tr>
<tr>
<td>272</td>
<td>228485</td>
<td>49.73</td>
</tr>
<tr>
<td>275</td>
<td>735615</td>
<td>664.77</td>
</tr>
<tr>
<td>278</td>
<td>1515888</td>
<td>1124.12</td>
</tr>
</tbody>
</table>
\[ a = \frac{\sum_{i=0}^{n} V_i}{\sum_{i=0}^{n} \frac{V_i}{Q_i}} \]  

(6-1)

where: \( a \) = (average) withdrawal rate; \( n \) = number of intervals in the rating curve; \( V_i \) = volume corresponding to the \( i \)-th interval; and \( Q_i \) = the discharge for the \( i \)-th 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 \( 1-\eta_{RL} \), where \( \eta_{RL} \) is determined from Eq. (5-4). All these results are compared with those of the SWMM simulation in Table 6-4.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>SWMM Simulation</th>
<th>Stochastic Model*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detention Time</td>
<td>13.37</td>
<td>14.51-14.97</td>
</tr>
<tr>
<td>By-Pass Fraction (Probability)</td>
<td>0.628</td>
<td>0.609-0.632</td>
</tr>
<tr>
<td>Fraction D=b/a or P(D=b/a)</td>
<td>0.413</td>
<td>0.491-0.509</td>
</tr>
<tr>
<td>Fraction D=0 or P(D=0)</td>
<td>0.160</td>
<td>0.133-0.149</td>
</tr>
</tbody>
</table>

* 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
<table>
<thead>
<tr>
<th>Elevation (ft)</th>
<th>Storage (ft$^3$)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>263</td>
<td>0</td>
<td>2.406</td>
</tr>
<tr>
<td>264</td>
<td>38238.4</td>
<td>2.456</td>
</tr>
<tr>
<td>265</td>
<td>76476.8</td>
<td>2.506</td>
</tr>
<tr>
<td>266</td>
<td>114715.2</td>
<td>2.556</td>
</tr>
<tr>
<td>267</td>
<td>152953.6</td>
<td>2.606</td>
</tr>
<tr>
<td>268</td>
<td>192292.0</td>
<td>2.656</td>
</tr>
<tr>
<td>269</td>
<td>229430.4</td>
<td>2.706</td>
</tr>
<tr>
<td>270</td>
<td>267668.8</td>
<td>2.756</td>
</tr>
<tr>
<td>271</td>
<td>305907.2</td>
<td>2.806</td>
</tr>
<tr>
<td>272</td>
<td>344145.6</td>
<td>2.856</td>
</tr>
<tr>
<td>273</td>
<td>382384.0</td>
<td>2.906</td>
</tr>
</tbody>
</table>
determined as 1 - $\eta_{FL}$, where $\eta_{FL}$ is determined from SWMM output by the equation

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

(6-2)

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>
<thead>
<tr>
<th>Parameter</th>
<th>SWMM Simulation</th>
<th>Stochastic Model*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detention Time</td>
<td>15.40</td>
<td>14.02-17.14</td>
</tr>
<tr>
<td>By-Pass Fraction (Probability)</td>
<td>0.253</td>
<td>0.202-0.273</td>
</tr>
<tr>
<td>Fraction D=b/a or P(D=b/a)</td>
<td>0.186</td>
<td>0.137-0.185</td>
</tr>
<tr>
<td>Fraction D=0 or P(0)</td>
<td>0.270</td>
<td>0.217-0.284</td>
</tr>
</tbody>
</table>

* 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 \[ R_{\text{max}} = 0.9 \text{ and } \theta = 0.1, 0.2 \text{ and } 0.5 \] 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{1cm} (6-3)

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, \( \alpha \), is determined according to Eq.(6-1). These results \([R_{\text{max}} = 0.9 \text{ and } \theta = 0.1, 0.2 \text{ and } 0.5]\) 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 $\eta_{BMP}$ vs. $E(D)$ Curve from Chapter 4 for $\theta=0.1$
Figure 6.3: Results for Triangular Hydrographs (T100) Plotted with the Best Fit \( \eta_{39k} \) vs. \( E(D) \) Curve from Chapter 4 for \( \theta = 0.2 \)
Figure 6-4. Results for Triangular Hydrographs (T100) Plotted with the Best Fit $\eta_{BMP}$ 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 $\eta_{BMP}$ 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 $\eta_{BMP}$ vs. E(D) Curve from Chapter 4 for $\theta=0.2$
FIGURE 6-7. Results for Varying Withdrawal Rate (A100) Plotted with the Best Fit $\eta_{BMP}$ 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 \( R_{\text{max}} \) and a value of 0.6 for \( \theta \). 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 \( \eta_{\text{BMP}} \) vs. \( E(D) \) curve corresponding to \( \theta=0.6 \) and \( R_{\text{max}}=1 \) 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 \( \eta_{\text{BMP}} \) are shown in Table 6-7. The resulting \( \eta_{\text{BMP}} \) 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 \([b/E(X_o)]\) and a normalized discharge \([aE(X_o)/E(X_o)]\). 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 \( E(S_o) \) [Appendix B] as the value of \( c \). These results are shown in Table 6-11. By noting the closeeness 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 $\eta_{BMP}$

$[R_{max} = 1$ and $\theta = 0.6].$

<table>
<thead>
<tr>
<th>a(in./hr.)</th>
<th>b(in.)</th>
<th>Avg. E(D)</th>
<th>$\eta_{BMP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1</td>
<td>.2</td>
<td>0.44</td>
<td>.165</td>
</tr>
<tr>
<td>.05</td>
<td>.2</td>
<td>1.34</td>
<td>.325</td>
</tr>
<tr>
<td>.025</td>
<td>.2</td>
<td>3.59</td>
<td>.544</td>
</tr>
<tr>
<td>.02</td>
<td>.2</td>
<td>4.80</td>
<td>.613</td>
</tr>
<tr>
<td>.005</td>
<td>.05</td>
<td>7.76</td>
<td>.750</td>
</tr>
<tr>
<td>.005</td>
<td>.1</td>
<td>13.60</td>
<td>.834</td>
</tr>
<tr>
<td>.005</td>
<td>.2</td>
<td>21.83</td>
<td>.895</td>
</tr>
<tr>
<td>.0025</td>
<td>.1</td>
<td>25.6</td>
<td>.923</td>
</tr>
<tr>
<td>.00125</td>
<td>.05</td>
<td>27.87</td>
<td>.936</td>
</tr>
<tr>
<td>.0005</td>
<td>.02</td>
<td>29.38</td>
<td>.946</td>
</tr>
<tr>
<td>.000125</td>
<td>.005</td>
<td>30.18</td>
<td>.953</td>
</tr>
<tr>
<td>.001</td>
<td>2</td>
<td>62.5</td>
<td>.999</td>
</tr>
</tbody>
</table>
FIGURE 6-8. $\eta_{\text{BMP}}$ vs. $E(D)$ [$R_{\text{max}}=1.0$ and $\theta=0.6$]
**TABLE 6-8.** Runoff parameters for 1953 and the 24.6 yr. Record (MIT=8 hrs.) [Goforth et al., 1983]

<table>
<thead>
<tr>
<th>Rainfall Data Set</th>
<th>Number of events per year</th>
<th>Runoff Volume, $X_1$</th>
<th>Runoff Duration, $X_2$</th>
<th>Interevent Time, $X_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (in)</td>
<td>Coefficient of Variation</td>
<td>Mean (in)</td>
</tr>
<tr>
<td>24.6-year record</td>
<td>72</td>
<td>0.217</td>
<td>1.194</td>
<td>6.438</td>
</tr>
<tr>
<td>1953</td>
<td>71</td>
<td>0.223</td>
<td>1.102</td>
<td>6.887</td>
</tr>
</tbody>
</table>
**Table 6-9.** Comparison of Flow Capture Efficiency ($\eta_{FL}$) and Pollutant Removal Efficiency ($\eta$) as a Function of Basin Volume and Constant Discharge Rate: Simulation Results 1953 Data (Goforth et al., 1983).

<table>
<thead>
<tr>
<th>Normalized discharge ratio, $aE(X_0)/E(X_1)$</th>
<th>Normalized Volume Ratio $b/E(X_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>1 $\eta_{FL}$</td>
<td>0.344</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.343</td>
</tr>
<tr>
<td>2 $\eta_{FL}$</td>
<td>0.398</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.373</td>
</tr>
<tr>
<td>4 $\eta_{FL}$</td>
<td>0.468</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.373</td>
</tr>
<tr>
<td>7 $\eta_{FL}$</td>
<td>0.542</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.365</td>
</tr>
<tr>
<td>10 $\eta_{FL}$</td>
<td>0.611</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.342</td>
</tr>
</tbody>
</table>

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| Normalized discharge ratio, \( aE(X_0)/E(X_1) \) | Normalized Volume Ratio \( b/E(X_1) \) |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                                 | 0.40  | 0.77  | 1.49  | 3.82  | 8.61  |
| \( c=0 \)                       | \( c=b \) | \( c=0 \) | \( c=b \) | \( c=0 \) | \( c=b \) | \( c=0 \) | \( c=b \) |
| E(D)                            | 34.2  | 32.4  | 54.0  | 46.3  | 80.5  | 55.9  | 117  | 58.9  | 124  | 58.9  |
| \( \eta_{FL} \)                 | .313  | .365  | .425  | .561  | .502  | .786  | .526  | .979  | .526  | 1.00  |
| \( \eta_{IBMP} \)               | .96   | .96   | .99   | .98   | 1.00  | .99   | 1.00  | 1.00  | 1.00  | 1.00  |
| \( \eta \)                      | .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  |
| \( \eta_{FL} \)                 | .370  | .397  | .511  | .583  | .636  | .797  | .698  | .980  | 1.00  | .700  |
| \( \eta_{IBMP} \)               | .87   | .86   | .94   | .92   | .98   | .96   | 1.0   | .97   | .97   | 1.0   |
| \( \eta \)                      | .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  |
| \( \eta_{FL} \)                 | .439  | .451  | .586  | .621  | .735  | .816  | .831  | .982  | .836  | 1.00  |
| \( \eta_{IBMP} \)               | .75   | .75   | .83   | .82   | .90   | .87   | .97   | .88   | 1.00  | .88   |
| \( \eta \)                      | .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  |
| \( \eta_{FL} \)                 | .511  | .517  | .648  | .660  | .795  | .838  | .902  | .984  | .910  | 1.00  |
| \( \eta_{IBMP} \)               | .60   | .60   | .70   | .70   | .79   | .77   | .90   | .80   | .98   | .80   |
| \( \eta \)                      | .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   |
| \( \eta_{FL} \)                 | .565  | .569  | .691  | .702  | .828  | .855  | .933  | .986  | .941  | 1.00  |
| \( \eta_{IBMP} \)               | .44   | .44   | .60   | .60   | .70   | .66   | .82   | .72   | .96   | .73   |
| \( \eta \)                      | .249  | .250  | .415  | .421  | .580  | .564  | .765  | .710  | .903  | .730  |
### TABLE 6-11. Stochastic Methodology Results c=E(S_a) for Table 6-9.

<table>
<thead>
<tr>
<th>Normalized discharge ratio, (aE(X_0)/E(X_1))</th>
<th>Normalized Volume Ratio (b/E(X_1))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>1 (E(D))</td>
<td></td>
</tr>
<tr>
<td>(\eta_{FL})</td>
<td>33.7</td>
</tr>
<tr>
<td>(\eta_{BMP})</td>
<td>0.332</td>
</tr>
<tr>
<td>(\eta)</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>0.319</td>
</tr>
<tr>
<td>2 (E(D))</td>
<td></td>
</tr>
<tr>
<td>(\eta_{FL})</td>
<td>17.2</td>
</tr>
<tr>
<td>(\eta_{BMP})</td>
<td>0.382</td>
</tr>
<tr>
<td>(\eta)</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>0.328</td>
</tr>
<tr>
<td>4 (E(D))</td>
<td></td>
</tr>
<tr>
<td>(\eta_{FL})</td>
<td>8.1</td>
</tr>
<tr>
<td>(\eta_{BMP})</td>
<td>0.446</td>
</tr>
<tr>
<td>(\eta)</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>0.339</td>
</tr>
<tr>
<td>7 (E(D))</td>
<td></td>
</tr>
<tr>
<td>(\eta_{FL})</td>
<td>4.1</td>
</tr>
<tr>
<td>(\eta_{BMP})</td>
<td>0.515</td>
</tr>
<tr>
<td>(\eta)</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>0.298</td>
</tr>
<tr>
<td>10 (E(D))</td>
<td></td>
</tr>
<tr>
<td>(\eta_{FL})</td>
<td>2.6</td>
</tr>
<tr>
<td>(\eta_{BMP})</td>
<td>0.568</td>
</tr>
<tr>
<td>(\eta)</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>0.249</td>
</tr>
</tbody>
</table>

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. \( E(S_\alpha) \) [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

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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 straightforward 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, $\eta_{FL}$, the settling efficiency, $\eta_{BMP}$, and the overall removal efficiency, $\eta$, 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 $\theta = 0.1 \text{ hr}^{-1}$ and $R_{\text{exc}} = 0.9$ 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):

\[
\begin{align*}
\text{INFLOW, TOTAL (TSS, POUNDS)} & \quad = 1.5985 \times 10^6 \\
\text{INFLOW, NET (TSS, POUNDS)} & \quad = 4.4842 \times 10^5 \\
\text{REMOVED BY DECAY (TSS, POUNDS)} & \quad = 3.1503 \times 10^5
\end{align*}
\]

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:

\[
\eta_{FL} = 0.281.
\]

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

\[
\eta_{BMP} = 0.702.
\]
Calculating the overall efficiency:

\[ \eta = \eta_{FL} \eta_{BMP} \]

\[ = 0.197 \]

**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 \( \eta_{BMP} \) for each E(D):

\( \eta_{BMP} = 0.68 \)  for c=0
\( \eta_{BMP} = 0.66 \)  for c=b

*Step 3:* Use Eq. (5-4) to calculate the capture efficiency (\( \eta_{FL} \)) for \( b=0.1 \) in. and \( a=0.0025 \) in/hr:

\( \eta_{FL} = 0.266 \)  for c=0
\( \eta_{FL} = 0.328 \)  for c=b

*Step 4:* Use Eq. (29) to calculate the overall efficiency, \( \eta \):

\( \eta = 0.181 \)  for c=0
\( \eta = 0.216 \)  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: \( \theta = 0.6 \text{ hr}^{-1} \) and \( R_{\text{max}} = 1.0 \). Also assume \( c = E(S_a) \). Note: Theoretically, there are an infinite number of a and b combinations that will produce a single overall efficiency. In general, the overall efficiency (\( \eta \)) 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 (\( \lambda \)) 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 (\( \lambda \)) [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 ($\lambda$) for 25% impervious area. The rainfall volume-runoff volume conversion factor ($\lambda$) is 0.2. Therefore, the runoff statistics for the watershed are:

\[
\begin{align*}
X_1 &= 0.20 \times 0.49 = 0.098 \text{ in.} \\
X_2 &= 6.2 \text{ hrs.} \\
X_3 &= 89 \text{ hrs.}
\end{align*}
\]

**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 ($\Delta a, \Delta b$) for iteration, and a maximum value for each design variable ($a_{\text{max}}, b_{\text{max}}$). For simplicity, let $a_o = \Delta a$ and $b_o = \Delta b$.

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

**Step 2c:** Follow steps 1-4 from problem 1 to calculate $E(D)$, $\eta_{\text{BMP}}$, $\eta_{\text{FL}}$, and $\eta$.

**Step 2d:** If $\eta$ 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:

\[
a = 0.00187 \text{ in./hr.}; \ b = 0.137 \text{ in.}; \ c = [E(S_a)] = 0.061 \text{ in.}; \ E(D) = 30.066 \text{ hrs.;}
\]

$\eta_{\text{BMP}} = 0.735$; $\eta_{\text{FL}} = 0.952$; and $\eta = 0.699$.  

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FIGURE 6-10. Runoff Coefficient 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.
Table 6-12. Projected Average Pollutant Removal Rates For Online Detention Control BMP's (NVPDC, 1979).

<table>
<thead>
<tr>
<th>Land Use/Impervious %</th>
<th>NPS Mgt. Storage (in.)</th>
<th>NPS Release Rates (in./day)</th>
<th>Annual Sediment Removal (%)</th>
<th>Annual Total Phosphorous Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-Lot Single Family (12% Impervious)</td>
<td>0.10</td>
<td>0.10</td>
<td>88</td>
<td>33</td>
</tr>
<tr>
<td>Medium-Density Single Family (25% Impervious)</td>
<td>0.21</td>
<td>0.21</td>
<td>89</td>
<td>40</td>
</tr>
<tr>
<td>Townhouse/Garden Apartment (40% Impervious)</td>
<td>0.33</td>
<td>0.33</td>
<td>88</td>
<td>48</td>
</tr>
<tr>
<td>High Rise Residential (70% Impervious)</td>
<td>0.54</td>
<td>0.54</td>
<td>93</td>
<td>43</td>
</tr>
<tr>
<td>Industrial (70% Impervious)</td>
<td>0.54</td>
<td>0.54</td>
<td>93</td>
<td>43</td>
</tr>
<tr>
<td>Shopping Center (90% Impervious)</td>
<td>0.78</td>
<td>0.78</td>
<td>94</td>
<td>47</td>
</tr>
</tbody>
</table>
From Chart A the required storage for 526.7 acres and 18% imperviousness is:

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

and for a 48 hr drawdown time:

\(a (\text{in/hr}) = 0.155 \text{ in./hr.} = 0.00323 \text{ in./hr.} = 1.714 \text{ cfs}\)

**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 \((\lambda)\) for 18% impervious area. The rainfall volume-runoff volume conversion factor \((\lambda)\) is 0.15. Therefore, the runoff statistics for the watershed are:

\[
X_1 = 0.15 \times 0.36 = 0.054 \text{ in.} \\
X_2 = 5.9 \text{ hrs.} \\
X_3 = 77 \text{ hrs.}
\]

To determine the settling efficiency for phosphorous, the \(\eta_{\text{BMP}}\) 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:

\[
a = 0.00119 \text{ in./hr.} = 0.632 \text{ cfs.} \\
b = 0.119 \text{ in.} = 227,519 \text{ ft.}^3 = 5.22 \text{ ac.-ft.}
\]

where: \(c = 0.061 \text{ in.; } E(D) = 30.829 \text{ hrs.; } \eta_{\text{BMP}} = 0.464; \eta_{\text{PL}} = 0.86; \text{ and } \eta = 0.400\).
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-$\eta_{BMP}$ 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)-$\eta_{BMP}$ pairs to find the appropriate $\eta_{BMP}$ 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.
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 characteristics 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


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 \( F(x) \).

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

(A-1)

obtained by interchanging the order of integration as follows:

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

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

(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

\[
1(z < x) = \begin{cases} 
1 & \text{if } 0 \leq z < x, \\
0 & \text{otherwise},
\end{cases}
\]  

(A-3)
and then

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

\[= \int_0^\infty \left[ \int_0^\infty 1(z < x) f(x) \, dx \right] \, dz = \int_0^\infty \left[ \int_z^\infty f(x) \, dx \right] \, dz.\]
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 given in Eqs. (3-9), (3-10), (3-11), and (3-12) we can evaluate the conditional expected value for S for a given S as

\[
E[S | S = c] = \int_c^b s f_s ds + \int_0^c s f_s ds + b P(S = b)
\]

which yields

\[
E[S | S = c] = c - \frac{k}{\alpha} + \frac{a}{\gamma} - \frac{ka}{\gamma} + \frac{ma}{\beta} + \frac{k}{\alpha} \exp(-\alpha c)
\]

\[-\frac{ma}{\beta} \exp\left(-\frac{b \beta}{a} + \frac{b c}{a}\right) + \frac{ka}{\gamma} \exp\left(-\alpha b - \frac{\gamma b}{a} + \frac{\gamma c}{a}\right)
\]

\[-\left(b - kb - mb + a - \frac{ma}{\gamma} - \frac{kab}{\gamma} + \frac{mbb}{\gamma}\right) \exp\left(-\frac{\gamma b}{a} + \frac{\gamma c}{a}\right).
\]

In Eq (B-2) to remove the effect of \(\gamma\), 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 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 \(E[S | b] = b\).

In addition, if a=0 the role of interevent time is removed. Because a=0, the empty space

APPENDIX B. EXPECTED END OF THE EVENT STORAGE
c at the end of the previous event remains unchanged until the next event arrives. Because of the nonnegativity of \( S_a \), 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 \( [1-\exp(-\alpha c)] \) multiplied by the average event volume, \( 1/\alpha \). Therefore, at the end of the event, the leftover empty space will be \( c - 1/\alpha [1-\exp(-\alpha c)] \). For \( a=0 \) we have \( k \) approaches 1 and \( m \) approaches zero and therefore from Eq.(B-2):

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

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

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

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,

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

(B-5)

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

To obtain an expected value for \( S_n \) we set \( c = \delta b \) for \( 0 \leq \delta \leq 1 \) and for uniformly distributed \( \delta \), we obtain

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

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

(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 : Two lines with heading to be printed on output. *
*==========================================================================* A1 'Example Storage/Treatment Model'
A: 'Arbitrary storm event'
* The 'Bl' 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 JL,
    = 2, Input is from an external input file
    and Group JL.
  * 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.

* B1 Line:
  * NOTAPE JNS NDT DS NU NP ICOST METRIC SAREA
  * 1 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.

* 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.

* ISTA\(T(1)\) 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.

**PNAMEI(IN,1)** : Pollutant 1 name. Required only if NOTAPE = 1 (Group B1).
**PUNITI(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 and NOTAPE = 1. (Group B1)

**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).

* 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.

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].

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 a_j.

EQUATION 7-1
G3  0  0  -0.003028  0  0  0  0  0  0  0  0.45  -0.45  0.0  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) : Residual 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
* 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 coefficient 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 0 5.
H3 8.0 1000. 0 0 0 5.
H3 8.5 1000. 0 0 0 5.
H3 9.0 1000. 0 0 0 5.
H3 9.5 1000. 0 0 0 5.
H3 10.0 1000. 0 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.

* 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).

* 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.

* 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 B1).
  * 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 B1).

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.

Use line H8 to define the initial conditions in detention unit I.

Note: The following concentrations must be given with dimensions consistent with those entered in Group B1 (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.

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.

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 = INSTITANTOUS FLOW IN CFS AT TCAR
* PCAR1 = INSTANTANEOUS SUSPENDED SOLIDS CONCENTRATION AT TCAR
* TCAR  QCAR  PCAR1
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
SW 1 0 20
MM 7 1 2 3 4 12 13 14
$STORAGE
*
A1 'NEABSCO CREEK TRIBUTARY'
A1 '1 pond'
*****
* # 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
***
E1 0 0 0 'TSS' 'mg/l'
*****
F1 '1 pond'
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 *******$1 pond******
** 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

APPENDIX C. SWMM FILES
133
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<th>TSS(mg/l)</th>
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<td>351.6667</td>
<td>0</td>
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</table>

******

$ENDPROGRAM
Exhibit C.3 Typical S/T Block Output File

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 occurred 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

APPENDIX C. SWMM FILES 135
# 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 (NPC)............. 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

__________________________

APPENDIX C. SWMM FILES
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

<table>
<thead>
<tr>
<th>SEPT</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 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 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 :

<table>
<thead>
<tr>
<th>DEPTH, FT</th>
<th>SURFACE AREA, SQ FT</th>
<th>STORAGE, CU FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREATED OUTFLOW, CFS</td>
<td>RESIDUAL FLOW, CFS</td>
<td></td>
</tr>
<tr>
<td>0.000E-01</td>
<td>0.000E-01</td>
<td>0.000E-01</td>
</tr>
<tr>
<td>1.3280E+00</td>
<td>0.000E-01</td>
<td>0.000E-01</td>
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<td>1.3280E+00</td>
<td>1.000E+00</td>
<td>1.9119E+04</td>
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<td>1.9119E+04</td>
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</tr>
<tr>
<td>1.3280E+00</td>
<td>0.000E-01</td>
<td>1.9119E+05</td>
</tr>
</tbody>
</table>

INITIAL CONDITIONS:

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

APPENDIX C. SWMM FILES

138
****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 10:00
The excess has been bypassed. Further messages will be suppressed.

1

********* ENTIRE SIMULATION UNIT SUMMARIES *********

JAN 1, 1990, 0 00 TO JAN 1, 1994, 0 00 00.

<table>
<thead>
<tr>
<th>UNIT</th>
<th>PARAMETER</th>
<th>VOLUME</th>
<th>TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CU FT</td>
<td>POUNDS</td>
</tr>
<tr>
<td>1</td>
<td>INFLOW,TOTAL</td>
<td>2.5604E+08</td>
<td>1.5985E+06</td>
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<tr>
<td></td>
<td>INFLOW,NET</td>
<td>7.1825E+07</td>
<td>4.4842E+05</td>
</tr>
<tr>
<td></td>
<td>BYPASS</td>
<td>1.8420E+08</td>
<td>1.1500E+06</td>
</tr>
<tr>
<td></td>
<td>TREATED OUTFLOW</td>
<td>7.1800E+07</td>
<td>1.3342E+05</td>
</tr>
<tr>
<td></td>
<td>RESIDUAL FLOW</td>
<td>0.0000E-01</td>
<td>0.0000E-01</td>
</tr>
<tr>
<td></td>
<td>REMOVED BY DECAY</td>
<td>-</td>
<td>3.1503E+05</td>
</tr>
<tr>
<td></td>
<td>REMAINING</td>
<td>0.0000E-01</td>
<td>0.0000E-01</td>
</tr>
<tr>
<td></td>
<td>EVAPORATION</td>
<td>0.0000E-01</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>INITIAL COND.</td>
<td>0.0000E-01</td>
<td>0.0000E-01</td>
</tr>
<tr>
<td></td>
<td>PERCENT ERROR</td>
<td>0.0134</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

===> 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. ***********
* """""""" 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 i Unit number of the interface
* or utilized
* Interface file saved file (any valid DOS filename)
* $ 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:
* Al Line :
* ISTART : Starting date, yr/mo/day
* TSTART : Starting time, decimal hours

APPENDIX C. SWMM FILES
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 [m^3/s].
EBASE : Cutoff storm event volume, inches [millimeters].
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 LOCQ 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

* 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

* End your input data set with a $ENDPROGRAM.

$ENDPROGRAM
SW 1 20 50
MM 7 1 2 3 4 12 13 14
@ 20 'g9094$q0s.f1'
$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 0.0
** Print controls
B2 1 1 0
** Output Controls
C1 1001 0000 0000 1001 1001
***
$ENDPROGRAM
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

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This is an implementation of EPA SWMM 4.05 "Nature is full of infinite causes which have never occurred 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
******************************************************************************

APPENDIX C. SWMM FILES
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. Transferred input locations........... 1
No. Transferred 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" #

<table>
<thead>
<tr>
<th>Peak Flow</th>
<th>Event Duration</th>
<th>Interevent Duration</th>
<th>Total Flow</th>
<th>Average Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table of return period and frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Graph of return period</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Graph of frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moments</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

==> 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.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Event</th>
<th>Standard</th>
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</table>

<table>
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<tr>
<th>Constituent</th>
<th>Event</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef. of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analyzed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>Event Duration</td>
<td>6.572</td>
</tr>
<tr>
<td>0.8957</td>
<td>2.026</td>
<td>34.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.887</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Event</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef. of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analyzed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>Inter-event Duration</td>
<td>69.90</td>
</tr>
<tr>
<td>0.9805</td>
<td>2.011</td>
<td>4698.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68.54</td>
</tr>
</tbody>
</table>

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
parameter(nevent=325, nnum=3*nevent)
DIMENSION EP(nnum), R(97), epl(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.GT.nevent) EP(J)=ep1(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)=ep2(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)=ep3(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)
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(IA1-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
  END
  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

APPENDIX D. COMPUTER PROGRAMS 153
Exhibit D.2 Output from "Expr.for"

<table>
<thead>
<tr>
<th>RUNOFF</th>
<th>DURATION</th>
<th>INTER EVENT TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0766</td>
<td>1.3748</td>
<td>104.1431</td>
</tr>
<tr>
<td>0.2982</td>
<td>0.9750</td>
<td>20.9267</td>
</tr>
<tr>
<td>0.2061</td>
<td>9.6837</td>
<td>156.7158</td>
</tr>
<tr>
<td>0.0616</td>
<td>6.7491</td>
<td>47.9104</td>
</tr>
<tr>
<td>0.0793</td>
<td>3.0352</td>
<td>253.4969</td>
</tr>
<tr>
<td>0.6846</td>
<td>19.5897</td>
<td>91.4636</td>
</tr>
<tr>
<td>0.1688</td>
<td>4.8001</td>
<td>21.1831</td>
</tr>
<tr>
<td>0.0660</td>
<td>5.7865</td>
<td>9.6594</td>
</tr>
<tr>
<td>0.0517</td>
<td>1.8762</td>
<td>117.0718</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RUNOFF</th>
<th>DURATION</th>
<th>INTER EVENT TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2806</td>
<td>2.6156</td>
<td>5.7725</td>
</tr>
<tr>
<td>0.0317</td>
<td>22.2545</td>
<td>134.5855</td>
</tr>
<tr>
<td>0.9529</td>
<td>9.6284</td>
<td>7.6376</td>
</tr>
<tr>
<td>0.4425</td>
<td>2.9626</td>
<td>102.5345</td>
</tr>
<tr>
<td>0.1833</td>
<td>12.2679</td>
<td>15.2015</td>
</tr>
<tr>
<td>0.1151</td>
<td>0.4857</td>
<td>139.4742</td>
</tr>
<tr>
<td>0.3543</td>
<td>0.0703</td>
<td>30.0535</td>
</tr>
<tr>
<td>0.2548</td>
<td>16.4519</td>
<td>93.0996</td>
</tr>
<tr>
<td>0.2676</td>
<td>14.4263</td>
<td>12.3943</td>
</tr>
<tr>
<td>0.2396</td>
<td>16.5178</td>
<td>6.5335</td>
</tr>
<tr>
<td>0.0197</td>
<td>2.2734</td>
<td>1.8782</td>
</tr>
</tbody>
</table>

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

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

ZE:  ZES$ = INPUT$(2, #1)
     IF LEFT$(ZES$, 1) = "*" THEN
     LINE INPUT #1, CMMT5$
     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
ZS$ = "== #.##### #.### #.### #.### #.### #.### #.###
#### =="  
'======================================================================
'==Echo input======================================================================

OPEN OUTFLS$ 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

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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;
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, "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%

C1$ = COMMAND$
1 = LEN(C1$)

FOR I = 1 TO 1
C$ = MID$(C1$, I, 1)

' Test for character being a blank or a tab.
IN (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
This subroutine echos the input to the output file.

Methodology for Extended Detention basin Design

Developed and Written by

Edwin W. Watkins

Echo Input

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

ETAFL1 = K * EXP(-ALPH * C)
ETAFL2 = K * (ALPH * A / GAM) * EXP(-B * (ALPH + GAM / A) + (GAM / A) * C)

ETAFL = 1 - (ETAFL1 + ETAFL2)

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 maintains 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
                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;
                        END SELECT
                        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 SELECT
END ELOOP

APPENDIX D. COMPUTER PROGRAMS
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 description 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 procedure 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 "R1R6.ETA" *
* Line A3 contains the values for runoff volume, X1 (in), runoff *
* duration, X2 (hrs.), interevent time, X3 (hrs.), and watershed area, *
* WA (acres). *
* *
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
*******************************************************************************

APPENDIX D. COMPUTER PROGRAMS 168
## 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

<table>
<thead>
<tr>
<th>E(D)</th>
<th>etaBMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.44</td>
<td>0.165</td>
</tr>
<tr>
<td>1.34</td>
<td>0.325</td>
</tr>
<tr>
<td>3.59</td>
<td>0.544</td>
</tr>
<tr>
<td>4.7</td>
<td>0.613</td>
</tr>
<tr>
<td>7.76</td>
<td>0.75</td>
</tr>
<tr>
<td>13.6</td>
<td>0.834</td>
</tr>
<tr>
<td>21.83</td>
<td>0.895</td>
</tr>
<tr>
<td>25.6</td>
<td>0.923</td>
</tr>
<tr>
<td>27.87</td>
<td>0.936</td>
</tr>
<tr>
<td>29.38</td>
<td>0.946</td>
</tr>
<tr>
<td>30.18</td>
<td>0.953</td>
</tr>
<tr>
<td>62.5</td>
<td>0.999</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>a(in/hr)</th>
<th>b(in)</th>
<th>c(in)</th>
<th>E(D)[hrs.]</th>
<th>etaf</th>
<th>etab</th>
<th>eta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00011</td>
<td>0.343</td>
<td>0.108</td>
<td>89.000</td>
<td>0.701</td>
<td>0.999</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00132</td>
<td>0.147</td>
<td>0.061</td>
<td>42.504</td>
<td>0.721</td>
<td>0.971</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00187</td>
<td>0.137</td>
<td>0.061</td>
<td>30.066</td>
<td>0.735</td>
<td>0.952</td>
<td>0.699</td>
</tr>
<tr>
<td>0.00264</td>
<td>0.147</td>
<td>0.073</td>
<td>21.883</td>
<td>0.782</td>
<td>0.895</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00352</td>
<td>0.157</td>
<td>0.085</td>
<td>16.455</td>
<td>0.818</td>
<td>0.855</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00484</td>
<td>0.176</td>
<td>0.106</td>
<td>11.912</td>
<td>0.864</td>
<td>0.810</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00529</td>
<td>0.186</td>
<td>0.116</td>
<td>10.929</td>
<td>0.880</td>
<td>0.796</td>
<td>0.701</td>
</tr>
<tr>
<td>0.00573</td>
<td>0.196</td>
<td>0.126</td>
<td>10.075</td>
<td>0.895</td>
<td>0.783</td>
<td>0.701</td>
</tr>
<tr>
<td>0.00617</td>
<td>0.206</td>
<td>0.135</td>
<td>9.327</td>
<td>0.907</td>
<td>0.773</td>
<td>0.701</td>
</tr>
<tr>
<td>0.00661</td>
<td>0.216</td>
<td>0.145</td>
<td>8.665</td>
<td>0.918</td>
<td>0.763</td>
<td>0.700</td>
</tr>
<tr>
<td>0.00705</td>
<td>0.225</td>
<td>0.155</td>
<td>8.077</td>
<td>0.927</td>
<td>0.755</td>
<td>0.700</td>
</tr>
</tbody>
</table>

APPENDIX D. COMPUTER PROGRAMS 170
| 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

Appendix D. Computer Programs
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