DISCUSSION DOCUMENT

FUNDAMENTAL CONCEPTS FOR POND SYSTEMS

INTRODUCTION

The purpose of this document is to explain the basic principles of stormwater storage pond systems. Material balance principles will be used to derive important relationships and to explain relevant definitions.

SYSTEM DEFINITION

Figure 1 illustrates the basic system diagram for a stormwater pond. A fundamental feature of this system is that its operation is not steady-state. The hydraulic and pollutant loadings vary appeciably with time. Storage within the vessel makes the effluent hydrograph differ from that of the influent. Separation of the pollutants, in both suspended and dissolved forms, within the pond can result in both positive and negative removal efficiencies as a function of time and the many mechanisms that control the process. If there is a continuous dry-weather flow through the pond, the effect of storm events is modified by that flow, and vice-versa. In cases without a continuous dry-weather flow (baseflow), operation of the system is completely intermittent and both the storm event and the inter-event quiescent period must be considered.

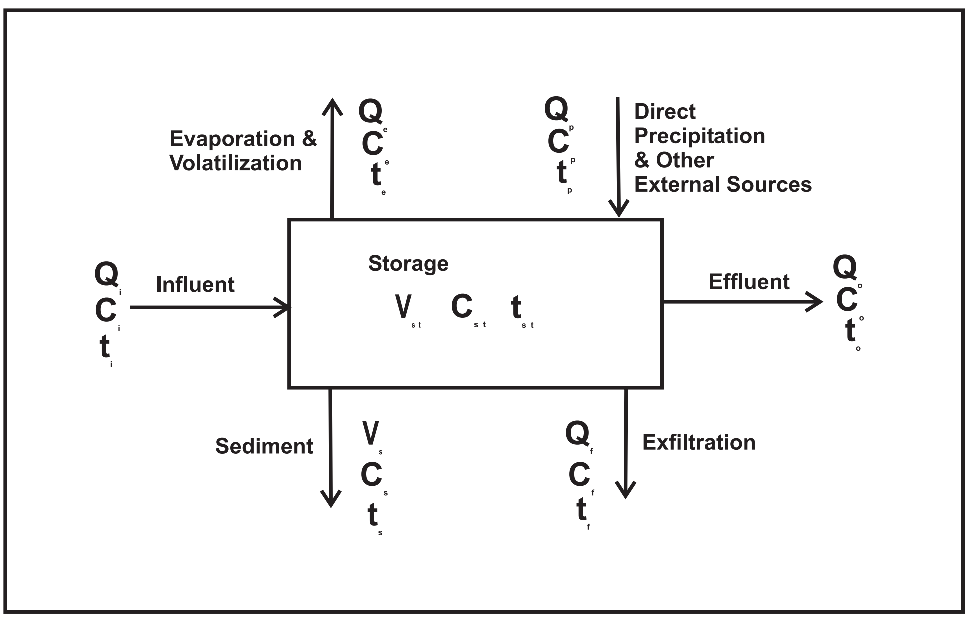


Figure 1: Stormwater Pond Material Balance Diagram

In Figure 1, “Q” represents a flow rate, “C” represents a pollutant concentration and “V” represents a volume. The symbol “t” represents a time period over which the respective flows, concentrations or volumes are being considered, or are of significance. As will be discussed, this time frame is of particular importance in the determination of system performance, particularly in situations that include long inter-event periods (quiescent or low-flow conditions) or emptying of the vessel between events.

Inlet flow (Q_i) and outlet flow (Q_o) are typically represented by time-series graphs called *hydrographs*. Monitoring of the inlet and outlet concentrations may not always continue for the full duration of the respective flows, or for sufficient time to establish complete mass balances. Methods of sampling also vary and can affect the reliability of the resulting performance data.

The volume of water in the pond is typically variable, resulting from the flow-throttling effect of the effluent structure. Concentrations in the pond may be measured only in the more intensive studies. Storage time in the pond has various meanings, as discussed in the next section of this document.

Exfiltration, through the pond sides or a semi-pervious dam, may be a significant factor in some installations. Conversely, a high water table in the vicinity of the pond may result in infiltration of groundwater into the treatment facility. The quality of infiltration/exfiltration is generally estimated by summing the other flows.

In most stormwater pond studies, losses and gains to and from the atmosphere are seldom considered. These factors are more relevant to lake studies and lake modeling. However, other non-point contributions to the pond can result from waterfowl and other wildlife, including overland drainage from the surrounding area.

The volume and quality of the sediment are important considerations in stormwater ponds. The residence time is governed by decomposition rates and clean-out frequency.

The material balance diagram provides the basis for computing material (mass and volume) balances for the system. An understanding of the dynamics of the system is also necessary to design monitoring programs, and to define parameters representing system performance.

QUANTITY CONSIDERATIONS

Stormwater ponds are often designed in accordance with runoff quantity, quality and erosion control objectives. The characteristics relevant to runoff quantity and erosion control will be discussed with reference to actual data from a stormwater storage pond (Figure 2). This example will help to illustrate not only the basic principles but also some of the constraints associated with the analysis of real-world data.

Figure 2a contains the rainfall *hyetograph* and the runoff *hydrograph*. The hyetograph is a plot of rainfall depth versus time; unlike the example in Figure 2a, this data set is often plotted as a bar graph using an inverted y-scale. The hydrograph is a plot of runoff flow rate versus time; in this case, the hydrograph contains the inflow to the stormwater pond. Given the surface area of the catchment, both data sets can be converted to volumes of water, or to a uniform depth of water over the catchment area. The runoff coefficient for the catchment is the ratio of the runoff volume (or depth) to the rainfall volume (or depth); in this case, the value of the runoff coefficient was 0.28. The runoff coefficient is a measure of the ability of the catchment to retain rainfall, such that it percolates into the ground or returns to the atmosphere through evaporation and transpiration, rather than generating runoff. A high value of the runoff coefficient is indicative of a large percentage of impervious surfaces in the catchment. In this example, a little more than one-quarter of the rainfall was measured as runoff.

Various event characteristics related to time and intensity can be extracted from Figure 2a:

- The lag time of the catchment may be expressed as the time delay between the start of the rainfall and the start of runoff at the point of measurement. This quantity may be influenced by the frequency of observation; in the example data set, the rainfall was reported hourly and the runoff was reported every 5 minutes. Lag times also reflect the intensity of the storm, since a light rainfall may be largely contained in depression storage.
- The centroids of the hyetograph and hydrograph may be computed (from the first moment) and used to represent the variables as existing in points of time. This approach is useful in computing inter-event times. The time difference between the centroids also provides an alternative means of characterizing the catchment lag time, one that takes the total volume into consideration and is not biased by the initial rainfall intensity. Baseflow is not included in the calculation of the runoff hydrograph centroid, such that the centroid represents the average runoff conditions independent of the dry-weather flow.
- The durations of both the rainfall event and the runoff are also of interest. Because of the distance over which the runoff must flow, and the resistance to flow created by different surfaces and different paths of flow, the duration of runoff must exceed the duration of rainfall. The duration of the runoff event is measured from the appearance of a flow greater than the baseflow (or dry-weather flow) and ending with the return to baseflow. However, the end of the runoff event may be defined somewhat subjectively because surface and subsurface storage can cause the tails of the runoff curves to persist for long time periods.
- Each curve may be represented by its peak factor: the ratio of the maximum value to the mean. Because of flow attenuation in the catchment, the peak factor for the runoff is expected to be less than that of the rainfall. In some cases, the temporal relationships of the rainfall and runoff peaks may be documented (e.g., a peak-to-peak lag time); however, in events with multiple peaks, the significance of such relationships is not clear. In this case, the peak rainfall and the peak runoff flow were essentially simultaneous, a situation which would not be expected under most (simpler) conditions.
- The base flow, or dry-weather flow, may be different before and after the event. A prolonged dry period before the event would cause a small base flow. The rainfall event would be expected to increase the elevation of the groundwater table, promoting infiltration into the sewer system, and residual surface and subsurface water would enter subgrade drains and other parts of the system slowly. Consequently, the baseflow after the event would be elevated for a considerable time, making estimation of the duration of runoff difficult. The base flow may not return to the initial conditions before the next rainfall event. In the example, the initial and final base flows were

smoothed and extended for illustrative purposes; the initial value was 0.025 m^3/s and the final value was 0.050 m^3/s.

Figure 2b contains the runoff hydrograph and the pond effluent hydrograph. Several system characteristics can be determined.

- The lag time of the pond may be expressed as the time delay between the start of the runoff flow (pond influent) and the start of the pond effluent flow. Several factors can influence this variable. In the example, the base effluent flow was often too small to be measured with the installed equipment and some manual extrapolation was employed to adjust the curve[1]. In some cases, a combination of evaporation and exfiltration from the pond can lower the surface of the water below the effluent control structure, producing a storage volume that would otherwise be unavailable and delaying the start of the effluent flow.
- The centroids of the hydrographs may be computed (from the first moment) and used to represent the variables as existing in points of time. The time difference between the centroids is defined as the *hydraulic detention time*, or the average time by which the bulk of fluid is held back or detained by the pond. The hydraulic detention time is determined primarily by the throttling effect of the effluent control structure. It is a measure of the ability of the facility to smooth and extend the runoff hydrograph to reduce its impact on the receiving stream.
- Differences in the durations of the influent and effluent hydrographs are another measure of the flow throttling effect of the facility. Normally, the effluent duration would be expected to exceed the influent duration. However, in this case, the effluent duration was less than that of the influent because of the shapes of the curves and the possible (extra) storage volume. In addition, the effluent was seen to exceed the influent at times, as a result of the irregularity of the rainfall and runoff curves; hence, the pond provided a flow smoothing function as well as attenuation. Also in this case, the average effluent flow was observed to be greater than the average influent flow, as a consequence of uncertainty in the initial conditions.
- Because of flow attenuation in the pond, the peak factor for the effluent is expected to be less than that of the runoff (influent). In some cases, the temporal relationships of the influent and effluent peaks may be documented (e.g., a peak-to-peak lag time); however, in events with multiple peaks, the significance of such relationships is not clear.
- The effluent base flow may be less than the influent base flow because of evaporation and exfiltration losses from the pond. At other sites, groundwater may flow into the pond causing the effluent base flow to exceed that of the influent. Also, the initial and final effluent base flows may be different because of changes in these gain or loss rates and in the influent base flow. In this example, the initial effluent base flow was 0.019 m^3/s and the final value was 0.022 m^3/s. The initial and final evaporation/exfiltration losses were therefore approximately 0.006 m^3/s and 0.028 m^3/s respectively. These estimates were affected by the poor quality of the initial data; if the initial effluent base flow had actually been closer to zero, the losses would have been similar.

Figure 2c contains the active (or dynamic) storage volume of the pond together with the influent and effluent hydrographs. The storage volume is calculated from the two sets of flow data. This graph is particularly useful as a means of testing the volumetric balance of the data set. Any deviation from zero storage at the end of the event indicates inaccuracy in the flow measurements and/or the estimation of other gains or losses. In this case, the evaporation/exfiltration losses were estimated from the initial data alone. Failure to include the final baseflow conditions in the calculation procedure is evident in the upward slope of the storage curve after the event. The overall volumetric error was 9%; if measurement of the small initial outflow had been feasible, the computed error may have been smaller.

The water level in the pond is another variable of interest. Water level measurements provide an independent check on volumetric data, providing that a reasonable stage-storage relationship can be derived for the pond based on its geometry. In the example, the pond level was not measured but survey data resulted in a linear stage-storage relationship over the range of active storage volumes. Hence, the pond level is proportional to the stored volume. Knowledge of the water level also permits the computation of another typical pond parameter:

- The *drawdown time* is defined as the period between the maximum water level and the minimum level (dry-weather or antecedent level) in the pond. A theoretical drawdown curve for a pond may be taken as the stage-discharge relationship of a specific effluent control structure. The theoretical value would be approached in practice only if there was no influent flow at the time that the pond was draining. Because there is typically some inflow during this time, the value of the actual drawdown time is expected to exceed that of the theoretical curve.

Summary – Stormwater Quantity

Table 1 summarizes the hydraulic characteristics of the pond stormwater event used as an example in Figure 2. The underlying principle for runoff quantity analysis is that the displacement of water is acknowledged. In other words, the emphasis is on bulk water quantities. The actual molecules of water entering the system are not necessarily those exiting the system within the timeframe considered. Hence, these quantity relationships should not be confused with the water quality relationships discussed in the next section.

[1] Further examination of the effluent level and flow signals may lead to re-interpretation of the initial flow data. Instrument data will be the subject of a future discussion of data analysis procedures.

Table 1: Hydraulic Characteristics – Example Pond Event

Parameter	Rainfall	Runoff - Influent	Pond Effluent
Volume (cubic metres)	32,380	8,950	8,130
Duration (minutes)	1,200	1,350	1,075[1]
Runoff Coefficient		0.28	
Pond Volumetric Error[2] (%)			9
Peak Factor	7.6	5.2	3.3
Peak Reduction			43%
Lag Time (minutes)			
- start-to-start		70	420[1]
- centroid-to-centroid		238	129
- peak-to-peak[3]		n/a	n/a
Pond Drawdown Time (minutes)			645

Notes: [1] Difficulty measuring initial effluent flow reduced the duration and increased the lag time.
[2] Volumes and volumetric error are determined after accounting for baseflow.
[3] Peak-to-peak time intervals can not be adequately defined in a multi-peak event.

QUALITY CONSIDERATIONS

Stormwater quality refers to the pollutants in the water. Runoff pollutant concentrations typically vary with time as a result of erosive forces (flow rate) and the duration of runoff events. Consequently, water quality data are often represented by *pollutographs*. Pollutographs are measured by collecting discrete samples at uniform time intervals, and are graphed as time-series data sets.

The fate of pollutants in a pond or other treatment system is determined by the physical, chemical and biological forces to which the pollutants are exposed, and the duration of exposure. Each element of fluid that enters the treatment system has a specific residence time (or retention time) within that system. The *hydraulic residence time* is determined by the pond volume, the flow rate and the flow patterns within the pond. The flow rate and the volume of water within the pond vary as described under the heading of “quantity considerations”. The flow patterns are determined by several factors including the geometry of the pond, hydraulic conditions at the inlet and outlet, thermal stratification, density stratification and wind effects.

Because different elements of fluid can take different paths through the pond, a range of residence times exists for each facility. This range is quantified as a residence time distribution, which is measured through the use of an inert tracer material. The tracer is added to the inlet flow at a point in time and concentrations in the outflow are measured as a function of time. The average residence time is measured as the centroid of the residence time distribution curve.

The fate of pollutants in a treatment system may be predicted knowing the hydraulic residence time and a "decay rate" specific to each pollutant. The decay rate is the rate of reaction for substances that are destroyed or transformed within the treatment system, or the settling rate for suspended material that is retained within the system. Reaction rates for specific pollutants depend on many physical, chemical and biological factors. Some pollutants may be both settled and reacted. Some substances may be produced within the pond, for example by photosynthesis. Hence, the residence time of a pollutant is specific to each situation. For inert suspended materials, residence time is determined in part by the frequency of clean-out operations. Inert soluble materials such as chloride may follow the flow paths and leave the ponds in the effluent or the exfiltration flow, but may also be stored for extended periods of time in density layers within the ponds.

No tracer tests were undertaken for the pond used as an example above. Hence, the hydraulic residence times were not determined. A general impression of the hydraulic residence time may be obtained by assuming steady-state flow, an average pond volume and plug-flow conditions (no mixing of influent and pond contents and no short-circuiting of flow). If the average flow were 0.1 m^3/s and the average volume were 7000 m^3 (both consistent with the above example), the hydraulic residence time would be 1,170 minutes (19.4 hr.) under plug-flow conditions. Short-circuiting of flow, internal mixing and other factors would tend to reduce that value, on average. However, since many rainfall/runoff events are shorter than 19 hours, some of the runoff may be expected to reside in the pond for several days (inter-event periods). Also, eddy currents and dead spaces within the ponds can hold elements of water and associated pollutants for extended periods of time and produce long tails on the residence time distribution curves.

DISCUSSION

Hydraulic detention time and hydraulic residence time (a.k.a. hydraulic retention time) are two distinctly different concepts and are used for different purposes. Detaining, delaying or holding back runoff is an important aspect of hydraulic control – the flattening of runoff hydrographs. Retaining, storing or holding volumes of stormwater is an important aspect of pollution control – the destruction or separation of pollutants. Detention times and residence times can be vastly different within any given system. Figure 3 illustrates extreme conditions that emphasize the choice of appropriate system characteristics.

A long, narrow pond with inlet and outlet structures at either end (Figure 3a) forces the flow to proceed under essentially "plug-flow" conditions, such that each element of flow entering the pond has essentially the same residence time as well as the maximum time permitted by the pond volume and flow rate. The average residence time under such conditions could be measured in days. The water level in the pond, however, responds quickly to inflow. If there is minimal effluent flow throttling, the effluent hydrograph could follow very quickly after the influent hydrograph, resulting in a hydraulic detention time of minutes.

The other extreme case is a long, thin pond with the inlet and outlet structures located very close together (Figure 3b). The pond may be large with good effluent flow throttling, resulting in a long hydraulic detention time. However, elements of the influent flow can proceed quickly from the inlet structure to the outlet structure or, if stored for longer periods of time, would not migrate far from the two structures such that they are discharged before significant treatment can occur. The hydraulic residence time in this case is very short, and much of the volume of the pond is essentially inactive from the perspective of quality control.

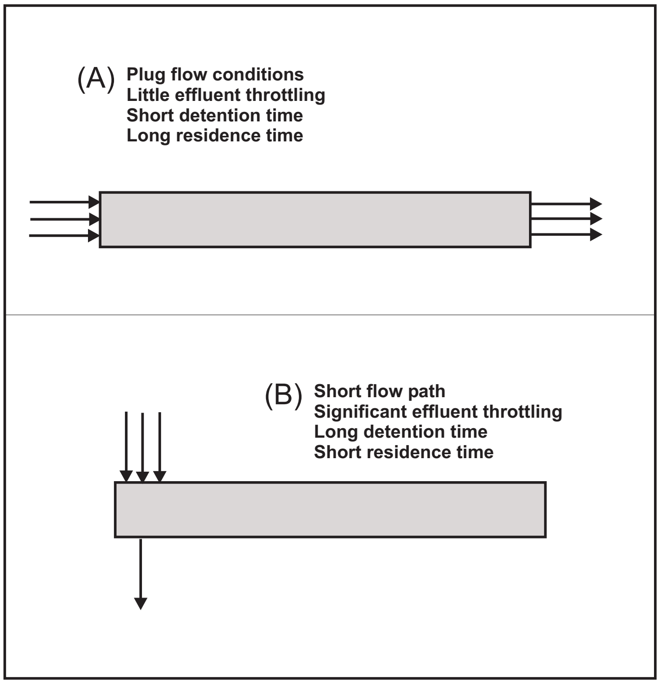


Figure 3: Detention and Residence Time Scenarios

There is a tendency in the stormwater literature to interchange – or at least confuse - hydraulic detention time and hydraulic residence time. Hydraulic detention time may be discussed (incorrectly) in the context of settling rates or treatment efficiency. Assuming that pond geometry guidelines are followed, a reasonable correlation between detention and retention times would likely exist and, by extension, a correlation between detention time and treatment efficiency. However, such correlations do not imply a cause-and-effect relationship, nor can they be used to examine removal mechanisms. Only an extensive review of performance data would indicate whether any such correlations may be reliable, and within what range of system geometry.

PERFORMANCE

Volume, Mass and Concentration

The total volume and total pollutant mass found in any water or wastewater stream may be determined by summation over the appropriate time intervals. For example, with reference to Figures 1 and 2, the influent volume (V_i) and influent pollutant mass (M_i) are calculated as:

$$V_i = \sum_{k=T1}^{T3} Q_{i_k} \Delta t_k \qquad (1)$$

$$M_i = \sum_{k=T1}^{T3} C_{i_k} Q_{i_k} \Delta t_k \qquad (2)$$

where: Q = flow measured over finite time interval, Δt
C = concentration of a specified pollutant measured over finite time interval, Δt
T1 represents the start of the runoff (influent) flow
T3 represents the end of the runoff (influent) flow

The flow-weighted average influent pollutant concentration ($\overline{C}_i$) may be determined from the total influent mass and the total influent volume:

$$\overline{C}_i = \frac{M_i}{V_i} \qquad (3)$$

Similarly, the volume, mass and a flow-proportioned mean concentration may be calculated for the effluent or any other significant flow.

Ideally, the average pollutant concentration measured at a specific location for one event is determined by integration of continuous data or the summation of multiple flow-weighted discrete observations. However, sampling programs seldom generate sufficient data for a rigorous analysis. The average concentration is often determined from composite samples. Important considerations include whether or not the composite sample was flow-proportioned (flow-weighted) and whether the sampling period included all of the runoff event[2].

[2] The selection and programming of sampling equipment, as well as other sampling logistics considerations will be the subject of a subsequent report.

Given appreciable temporal variation in most storm events (i.e., in hydrograph and pollutograph shapes), the lack of flow-proportioned samples can result in appreciable error. The worst case scenario consists of simultaneous peaking of the hydrograph and pollutograph, such that high concentrations occur at high flow and a large mass of pollutant is transported during that part of the event. Hence, the type of sampling should be indicated when an average concentration is reported.

Figure 4 contains a hypothetical example of the effect of using simple average concentrations, or non-flow-proportioned composite samples to determine pollutant loads. In this example, the pollutographs for two events are identical. The hydrographs have different shapes but represent the same total runoff volume. In the first scenario, with similar hydrograph and pollutograph shapes, the mass loading error resulting from the use of a simple average concentration is 30%. As the curve shapes become dissimilar, the error is reduced (9% in the second scenario). Much larger errors can be caused by simultaneous peaking of the hydrograph and pollutograph.

An average concentration, measured at a specified location over the duration of one event, is typically called the *event mean concentration* (EMC). Ideally, the type of sampling used to determine the EMC should be indicated:

EMC^{p} = flow-proportioned event mean concentration

EMC^{t} = time-averaged or non-flow-proportioned event mean concentration

Event Efficiency -- Load-Based

Load-based efficiency (LE) is defined as the ratio of the mass of a specific pollutant removed to the corresponding influent concentration[3]. This parameter may also be referred to as *mass efficiency*. The *LE* is determined by considering the entire event cycle: the time from the start of the stormwater flow to the end of the effluent drawdown curve. Equation 4 is written using the summation of incremental mass quantities (the product of flow and pollutant concentration over finite observation intervals). Ideally, all sources and destinations of flow and pollutants would be considered; practically, only the influent and effluent are included in the definition of efficiency.

$$LE = \frac{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k - \sum_{k=T2}^{T4} Q_{o_k} C_{o_k} \Delta t_k}{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k} \tag{4}$$

[3] In this document, removal efficiency is expressed as a fraction rather than a percentage, primarily to simplify the equations.

Equation 5 is an alternative way of expressing the sums of all mass loads entering *(SOL_{in})* and leaving *(SOL_{out})* the facility.

$$LE = \frac{SOL_{in} - SOL_{out}}{SOL_{in}} \tag{5}$$

In Equation 5, the summations are assumed to be over the time periods relevant to the influent and effluent.

Event Efficiency - Concentration-Based

Considering the system diagram (Fig. 1), if one can assume that there is no significant difference in the influent and effluent flow rates and times ($Q_i = Q_o$, and $t_i = t_o$) the result is the *concentration-based efficiency* (*CE*).

$$CE = \frac{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k - \sum_{k=T1}^{T3} Q_{i_k} C_{o_k} \Delta t_k}{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k} \tag{6}$$

Equation 6 may be simplified to the familiar form of the efficiency equation, using the flow-weighted average concentrations:

$$CE = \frac{\overline{C}_i - \overline{C}_o}{\overline{C}_i} \tag{7}$$

Equation 7 is commonly used for continuous-flow clarifiers with negligible underflow. In stormwater ponds, this simple expression of efficiency is used when flow data are not available. The intent of Equation 7 is that efficiency may be calculated based on assumptions of simplified time and flow rate, but that the concentrations remain flow-proportioned.

In stormwater studies, the Event Mean Concentration (EMC) is an average concentration that may or may not have been flow-proportioned. Using the EMC values, Equation 7 may be re-defined as a concentration-based pollutant removal efficiency for a single event as follows[4]:

[4] Equations 8 and 9 are written as concentration-based efficiencies *(CE)*, assuming that the *EMC* values are not flow-proportioned. If the *EMC* values were derived from flow-proportioned sampling and there was no volumetric loss across the system, the efficiency calculated would be the equivalent of a load-based efficiency *(LE)*.

$$CE = \frac{EMC_i - EMC_o}{EMC_i} \quad (8)$$

$$CE = 1 - \frac{EMC_o}{EMC_i} \quad (9)$$

Residence Time and Intermittent Operation

There are further complications to be considered when examining effluent samples and calculating removal efficiencies. These considerations are consequences of the long residence times and intermittent operation common to stormwater treatment systems.

Ideally, removal efficiency should be associated with each element (or incremental volume) of suspension that enters the treatment system. Each element of fluid entering the system contains a specific matrix of pollutants that will be removed in accordance with their characteristics, the hydraulic and other conditions in the system, and the time during which the element of fluid resides in the system. Comparison of the characteristics of that element of fluid, as it leaves the system, with its initial characteristics would provide a true measure of treatment efficiency.

Consider a large wet pond treatment system:

- Effluent flow at the start of an event consists primarily of displaced fluid that had been in the pond since the previous event or had accumulated during the intervening dry-weather period. The long residence times for these elements of fluid would probably result in pollutant concentrations equivalent to the non-settleable (non-treatable) residual concentrations.
- As the event progresses, the component of the effluent flow generated by the current event begins to increase. Some influent flow will mix with the pond contents and some elements of the influent may short-circuit to reach the effluent structure before the majority of the flow. The result is measurement in the effluent stream of partly diluted and partly settled current-event influent.
- In moderate-size events, the remainder of the influent fluid elements would reside in the pond until the next event or until they are gradually displaced by dry-weather flow. These elements would be expected to receive the maximum treatment efficiency possible for the specific installation.
- In large events, the total contents of the pond may eventually be exchanged. The effluent would then reflect only the current influent conditions and the treatment efficiency of the pond in continuous (flow-through) operation mode.

Effluent samples are typically collected during each runoff event and only for the duration of the event hydrographs. Effluent quality from that sampling period may be compared directly to the influent quality from the same event to estimate treatment efficiency. The result is a measure of the change in water quality across the pond, and the reduction in pollutant loading during that specific event. However, that procedure ignores the residence time in the system and may introduce significant errors in examining the removal mechanisms and determining the overall environmental loadings from the facility.

Ideally, the least error would result from continuous measurement of influent and effluent during both wet-weather and dry-weather. Short-term efficiency would be best represented by comparison of influent samples to effluent samples with the latter offset by the residence time in the system. However, the residence time could not be measured on a continuous basis because it is a distribution that is influenced by many physical factors, and it is measured by a pulse addition of a tracer. The concept of following elements of fluid through the treatment system may be appropriate to numerical simulation techniques[5].

Inter-event (or dry-weather) flow and pollutant loading are often not considered. Low flows and small concentrations may be difficult to measure, and differential concentrations (removals) may not be significant numbers. However, the long dry-weather time periods can conceptually result in large volumes and pollutant masses.

Practically, composite samples are collected for each event and few - if any - samples are collected between events. Hence, the data analysis options are: (1) compare the effluent data to the influent data of the same event, (2) compare the effluent data to the influent data of the previous event, or (3) calculate efficiency based only on long time periods considering the total influent and effluent masses (long-term mass efficiency). The latter option will provide the best estimate of system efficiency.

Long-Term Efficiency - Load-Based

Load-based efficiency calculations provide the most accurate method of determining long-term efficiency. In this procedure, the summations are made over the full time frame of interest (several events, a season, a year or several years).

[5] Numerical simulation of stormwater ponds will be the subject of a subsequent report.

The sum-of-loads concept described in Equation 5 may be expressed in terms of EMC values and event volumes *(V)*. Hence, the efficiency ratio based on mass load for a single event is:

$$LE_{emc} = 1 - \frac{EMC_o \times V_o}{EMC_i \times V_i} \tag{10}$$

An average efficiency ratio could be calculated for several events:

$$ALE_{emc} = \frac{\sum_{j=1}^{m} LE_j}{m} \tag{11}$$

where: m represents the number of events.

However, a simple average of efficiencies gives equal importance (weight) to each event, regardless of event size. A better estimate of long-term efficiency is obtained by totaling the mass quantities over the time period of interest:

$$SLE_{emc} = 1 - \frac{\sum_{j=1}^{m} EMC_{o_j} \times V_{o_j}}{\sum_{j=1}^{m} EMC_{i_j} \times V_{i_j}} \tag{12}$$

Table 2 contains an example of the extent to which averaging of event performance can distort the estimate of long-term efficiency. In this hypothetical example, one large event, one small event and two moderate-sized events each have reasonable TSS removal efficiencies. A simple average of the four efficiencies, however, does not adequately represent actual system performance.

These definitions of efficiency are not as rigorous as those derived from material balance principles. The difference is that the composite samples that are used to determine the *EMC* values were not necessarily flow-proportioned. However, from a practical perspective (given current sampling practice), mass loading based on *EMC* values and averaged over as large a variety of events as possible is the best feasible method of representing stormwater pond performance.

Table 2: Hypothetical Data Set - Effect of Averaging Performance Data

Event No.	Volume	*EMC* in	*EMC* out	% Rem.	Mass in	Mass out
1	2,000	125	50	60	250,000	100,000
2	500	110	15	86	55,000	7,500
3	10,000	165	120	27	1,650,000	1,200,000
4	1,500	115	30	74	172,500	45,000
ALE				62		
Total					2,127,500	1,352,500
SLE				36		

Long-Term Efficiency – Concentration-Based

Flow and volume data are not always available; consequently, pollutant mass can not be determined. In such cases, an average event mean concentration *(AEMC)* may be calculated for several events, for example over one year or a runoff season.

$$AEMC = \frac{\sum_{j=1}^{m} EMC_j}{m} \qquad (13)$$

where: m represents the number of events.

Similarly, long-term *average efficiency (ACE)* can be calculated from *AEMC* values[6]:

$$ACE^* = \frac{AEMC_i - AEMC_o}{AEMC_i} \qquad (14)$$

$$ACE^* = 1 - \frac{AEMC_o}{AEMC_i} \qquad (15)$$

[6] As in equations 8 and 9, the average efficiencies in equations 14 to 16 are written as concentration-based values *(ACE)* assuming that the *EMC* values were not flow-proportioned and that influent volume does not necessarily equal effluent volume.

Alternatively, individual efficiencies can be averaged. Numerically, averaging the concentrations over a season and calculating a seasonal efficiency based on averages is not the same as calculating individual *EMC*-based efficiencies and averaging them *($ACE^{*} \neq ACE^{\#}$)*.

$$ACE^{\#} = \frac{\sum_{j=1}^{m} CE_j}{m} \tag{16}$$

Correlating Efficiency to Hydraulic Load and System Parameters

For design purposes, anticipated pollutant removal efficiency must be correlated to the hydraulic load and to parameters that describe the treatment facility. As previously introduced in the Discussion section, such correlations are not easily determined and may not be reliable predictors of performance.

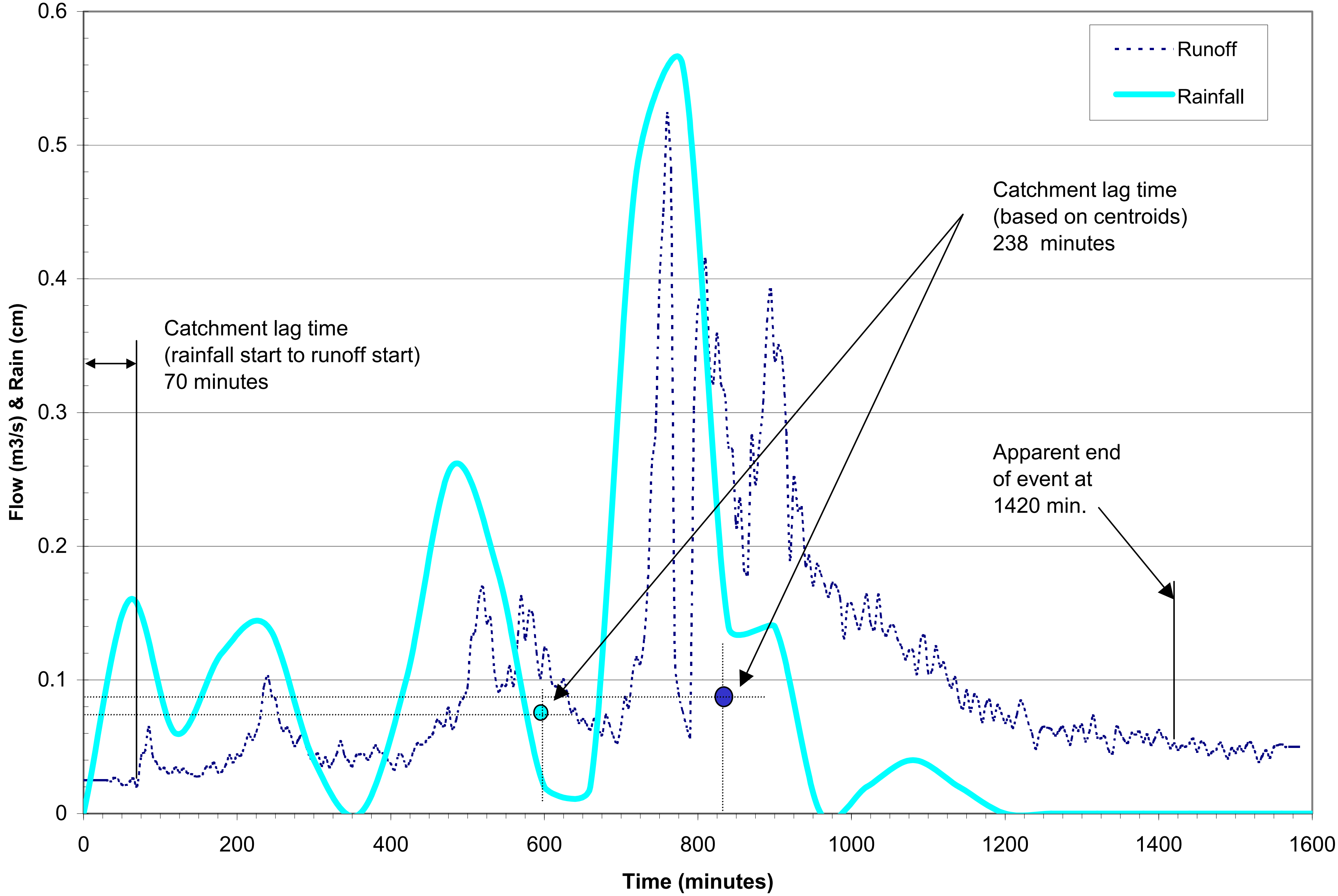
The traditional method of reporting clarifier performance is to correlate removal efficiency to the surface loading rate, or surface overflow rate (SOR). The SOR is the hydraulic load per unit surface area of the separation vessel, generally in units of metres per hour ($m^3/hr \div m^2$). The SOR may be shown to be the numerical equivalent of the critical settling rate, or the settling rate of a particle that travels the full depth of the vessel in the hydraulic residence time[7]. However, the correlation applies to vessels with vertical sides and fixed surface areas, as well as to cases in which the hydraulic load is constant or varies little in the time frame relevant to the hydraulic residence time. These conditions do not apply to stormwater ponds.

From a mechanistic perspective, performance could be related to the settling rate of the suspended particles, the depth of the pond and the hydraulic residence time. Or, more simply, the performance data could be correlated with the hydraulic residence time. Unfortunately, the hydraulic residence time is a generally unknown quantity, and it is influenced by both flow-through conditions and inter-event times.

From a practical perspective, there may be two reasonable approaches to the problem. A set of simplifying assumptions may lead to a suitable correlation. For example, given conformity to geometric guidelines, the volume of the pond – perhaps as a function of the surface area and other properties of the catchment – may be an adequate parameter for correlation to performance. A more complex, but potentially more reliable method, would be to develop a generic simulator that could take both pond geometry and seasonal loading dynamics into consideration in predicting pond performance[8].

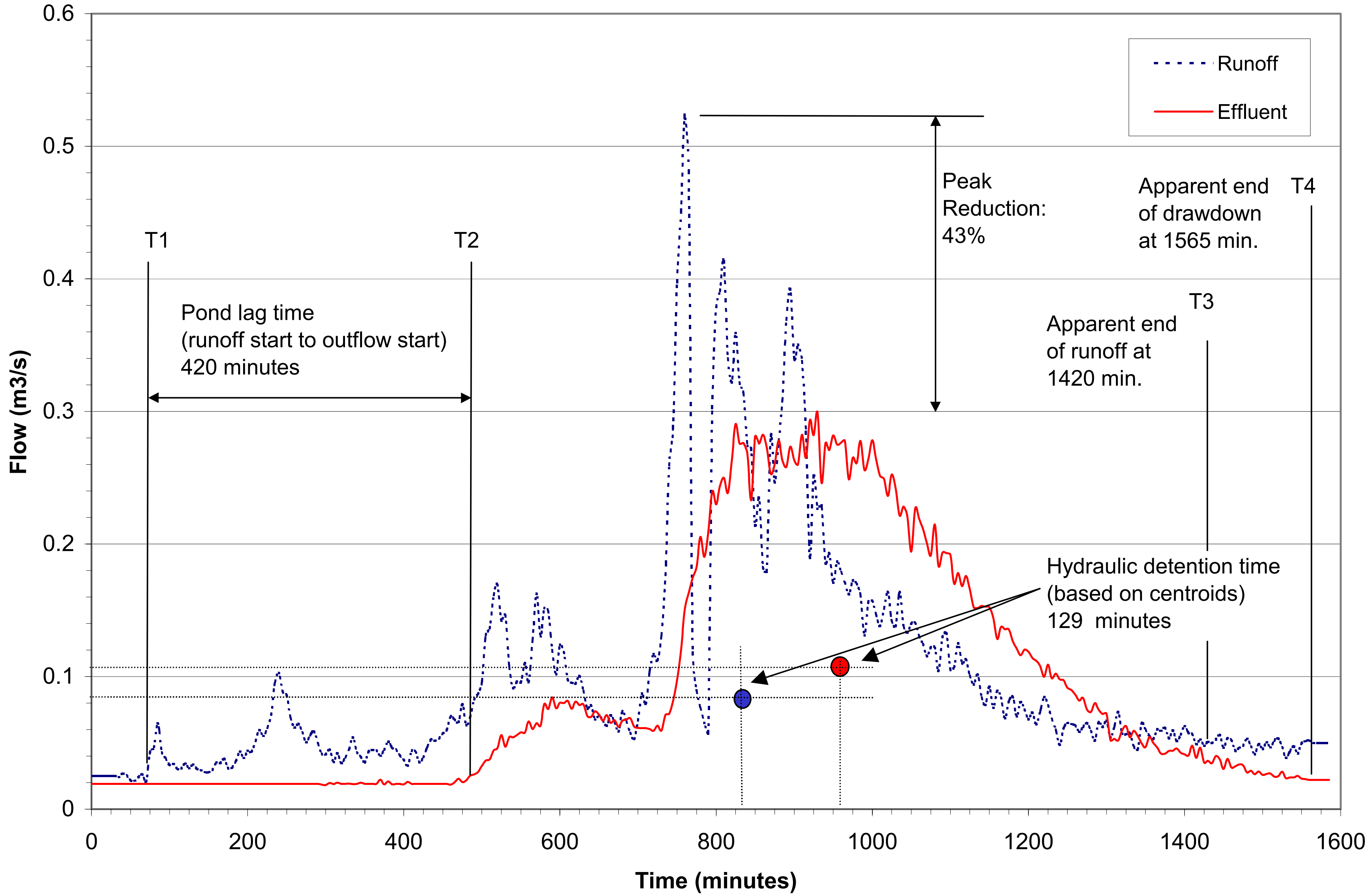
[7] The derivation may be found in most sanitary engineering text books.
[8] These concepts will be pursued in a subsequent report.

Figure 2a



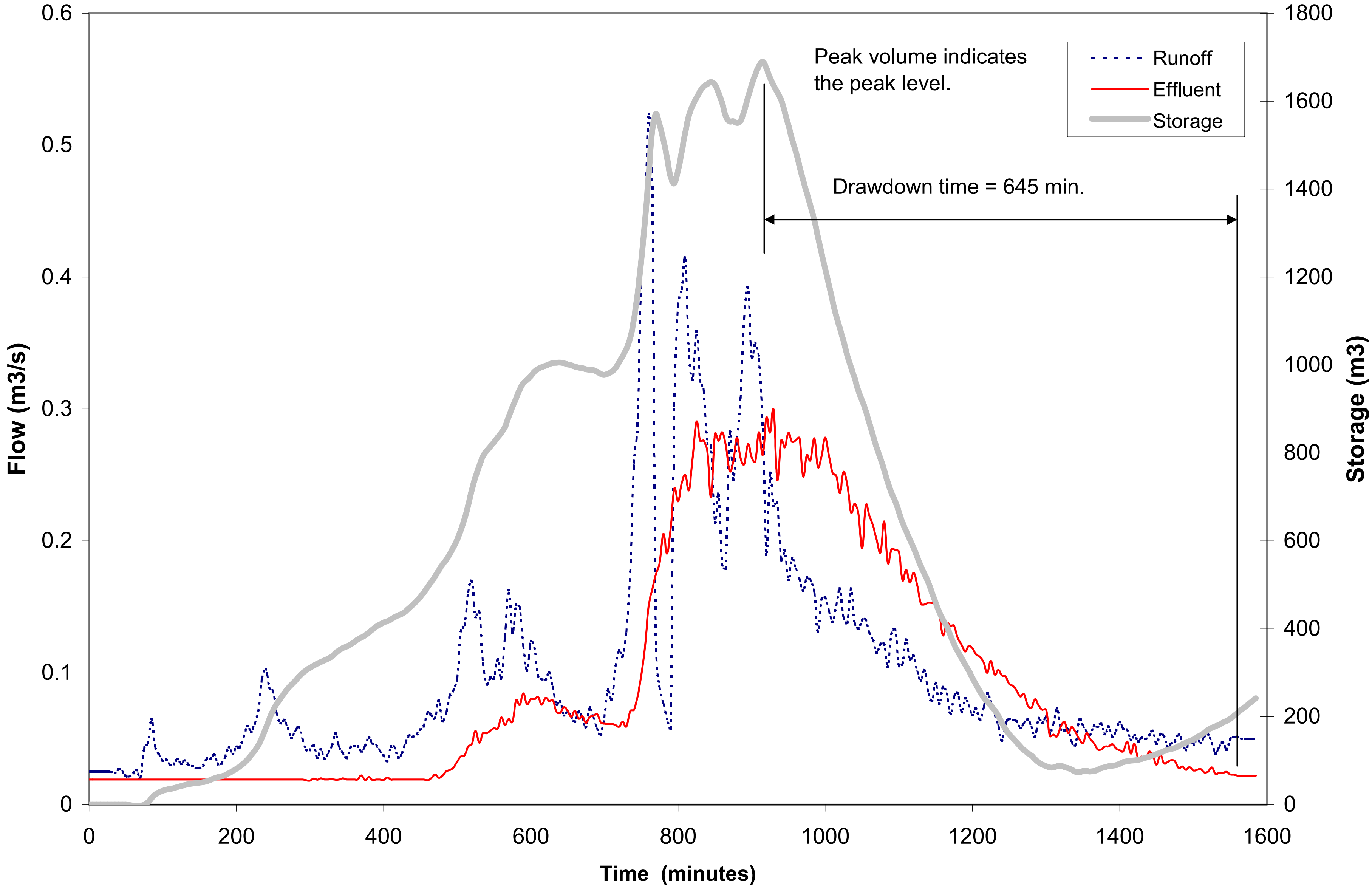
Flow (m3/s) & Rain (cm)
0.6
0.5
0.4
0.3
0.2
0.1
0
Runoff
Rainfall
Catchment lag time
(based on centroids)
238 minutes
Catchment lag time
(rainfall start to runoff start)
70 minutes
Apparent end
of event at
1420 min.
0
200
400
600
800
1000
1200
1400
1600
Time (minutes)

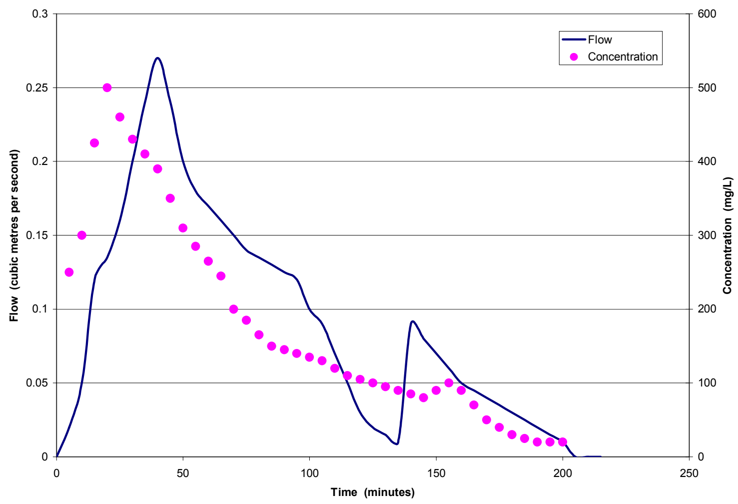
Figure 2b

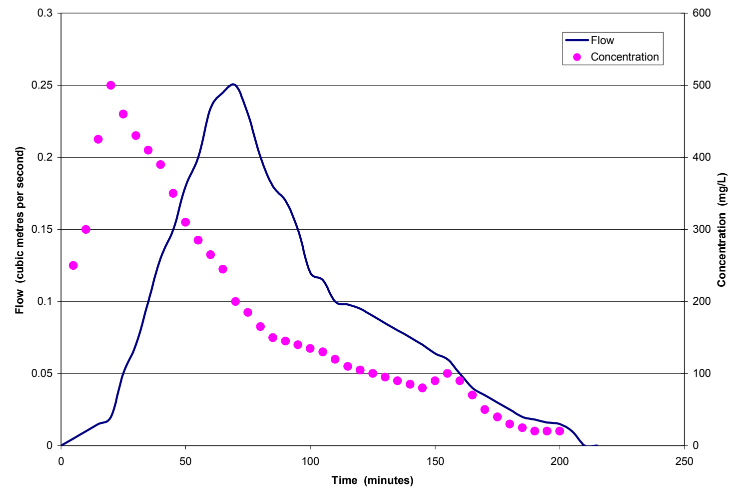


Runoff
Effluent
Peak Reduction: 43%
Apparent end of drawdown at 1565 min.
T4
T3
Apparent end of runoff at 1420 min.
T1
T2
Pond lag time (runoff start to outflow start) 420 minutes
Hydraulic detention time (based on centroids) 129 minutes
Flow (m3/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
200
400
600
800
1000
1200
1400
1600
Time (minutes)

Figure 2c


Peak volume indicates
the peak level.
Drawdown time = 645 min.
Runoff
Effluent
Storage
Flow (m3/s)
Storage (m3)
Time (minutes)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
200
400
600
800
1000
1200
1400
1600
1800
0
200
400
600
800
1000
1200
1400
1600





Scenario 1: Similar Hydrograph & Pollutograph Shapes

Total runoff volume =	1,170 m^3
Total pollutant mass =	301 kg
Average pollutant concentration =	180 mg/L
Pollutant mass estimated from avg. concentration =	211 kg
Mass loading estimate error =	30 %

Scenario 2: Hydrograph & Pollutograph Displaced in Time

Total runoff volume =	1,170 m^3
Total pollutant mass =	233 kg
Average pollutant concentration =	180 mg/L
Pollutant mass estimated from avg. concentration =	211 kg
Mass loading estimate error =	9 %

Figure 4: Hypothetical Data Set - Effect of Using Average Concentration Data