Chapter I

Models for Water Quality Control by Stormwater Ponds

Fabian Papa, Barry J. Adams and Graham J. Bryant

The design of stormwater management quality control ponds is largely based on empirical practices which have been developed over time by water resources engineers. Of much more value to practitioners, and more importantly the environment they protect, is sound engineering design founded on a scientific basis. At present, the modeling of stormwater management facilities for both quantity as well as quality control is often accomplished using event and/or continuous simulation analysis methods. Analytical probabilistic models, based on long-term rainfall statistics, have been developed as an alternative approach and have proven to be reliable when compared to continuous simulation models for the estimation of stormwater quantity control performance. As more emphasis has been placed on environmental impacts, and how non-point source pollution, namely urban runoff, can be mitigated, these analytical models have been extended for the prediction of water quality control performance of urban drainage systems as well.

In this chapter, these analytical model results are compared to those of continuous simulation models for the quality control performance of stormwater management ponds, namely extended detention dry and wet ponds. The estimates of pollution control performance of these facilities are compared with respect to storage volume for various detention times, catchment areas and pond depths. The objective of this exercise is to illustrate the applicability of the analytical models for use in lieu of, or in conjunction with, continuous simulation

models. The results of the analytical models compare favourably with those of continuous simulation models for planning level analyses. For extended detention dry ponds servicing catchment areas of 10 to 100 ha with depths of 1.0 to 1.5 m and detention times of 24 to 48 hr, the difference in predicted suspended solids removal is generally less than 5 to 10% for all practical storage volumes. For wet ponds servicing catchment areas of 10 to 100 ha, with permanent pool depths of 1.0 m and active storage depths of 0.5 m, and active storage detention times of 6 to 48 hr, the difference in predicted suspended solids removal is between 10 and 30% for all practical storage volumes.

The pollution control performance of extended detention wet ponds is estimated using a constant ratio of active storage volume to permanent pool volume. This ratio is demonstrated to substantially impact the long term pollution control performance of the facility since the different storage zones are subjected to different pollutant removal mechanisms. An investigation is undertaken to determine the optimal combination of active storage volume and permanent pool storage volume for a given set of conditions. These results are generated using the analytical models and can be a valuable guide to the engineer in the preliminary design of urban runoff quality control ponds.

1.1 Introduction

Stormwater management ponds can be one of the few practical and effective means of controlling both the quantity and quality of stormwater runoff from urban catchments. The quantity control aspects of analysis and design are hydraulically based and have been well established over time. Of more recent concern, however, is the non-point source pollution of receiving waters due to runoff from urban catchments. As a result, stormwater ponds have also been used to enhance the quality of runoff entering receiving waters.

The principal mechanism for pollution control from quality control ponds is the sedimentation of suspended solids in the water column. In general, the pollution control provided by such a pond increases as the detention time of the runoff increases according to traditionally used settling equations. Therefore, it is typical to design quality control ponds to detain water in storage for longer periods of time when compared to stormwater quantity control ponds, which are primarily used as a means of attenuating peak flows from the drainage system.

The primary objective of this work is to model the performance of stormwater quality control ponds, including both extended detention dry and wet ponds, with varying detention times using continuous simulation models as well as analytical probabilistic models. Furthermore, the comparison of results between the two modeling approaches (i.e. simulation vs. analytical) is undertaken to evaluate the use of analytical models as an alternative to continuous

simulation models for planning level analyses. In addition, analytical models can be effectively used in studies to determine trends that may be anticipated prior to performing full scale simulations. An illustration of this application is also given herein where the analytical models are used to estimate the performance of extended detention wet ponds for varying ratios of active storage volume to permanent pool storage volume.

1.2 Continuous Simulation Model

Results from continuous simulation modeling experiments (Adams, 1996) were obtained in order to allow the comparison of analytical probabilistic models with continuous simulation models for stormwater quality control ponds. The data used was generated using a series of models; that is, the EPA Stormwater Management Model (SWMM) version 4.30 was employed to generate runoff from various catchments and MTOPOND used the output from the SWMM model to predict total suspended solids (TSS) removal efficiencies for various pond configurations.

The RAIN block of SWMM was used to read hourly rainfall data for the period of 1960 to 1992 (Toronto Pearson International Airport Meteorological Data, Station 6158733). This data represented the rainfall period (March 1 to November 30) of each year and was subsequently used in the RUNOFF block to estimate hourly runoff flow values.

Table 1.1 gives the catchment characteristics which were modeled in the simulations. Values of infiltration rates relate to Horton's equation for infiltration. In addition, SWMM requires a value for the width of the catchment in order to compute time of concentration. A catchment width of 400 m was used for the 10 ha catchment while a catchment width of 2000 m was used for the 100 ha catchment. Input to the SWMM model also included evaporation data from the Canadian Climate Normals (Hamilton, Ontario).

Table 1.1 Catchment characteristics for SWMM simulations.

Area (ha)	10 - 100
Imperviousness (%)	50
Slope (%)	1
Impervious Manning's n	0.013
Pervious Manning's n	0.25
Impervious Depression Storage (mm)	1.5
Pervious Depression Storage (mm)	4.5
Minimum Infiltration Rate (mm/hr)	7.5
Maximum Infiltration Rate (mm/hr)	50
Infiltration Decay Rate (s ⁻¹)	0.00055

The runoff series generated by the RUNOFF block of SWMM was then used as input to the MTOPOND model. The MTOPOND model was based on the POND model (MOEE, 1994). This model calculates particle removal from the quiescent and dynamic settling of suspended solids and tracks spills and the TSS discharge from both the controlled outflow from the pond and the spills. This model was run in the first flush mode whereby flow bypasses the pond when the pond is full or the inflow rate is higher than an input threshold value. All flow which bypasses the pond is considered a spill. For further details of the implementation of the MTOPOND model, see Adams (1996).

The time series of runoff from the 10 ha and 100 ha drainage areas were simulated through both extended detention dry and wet ponds. Extended detention dry ponds contain only an active storage zone in which detained water is treated. Extended detention wet ponds contain both a permanent pool and an active storage zone. For purposes of the present work, a constant ratio of active storage volume to permanent pool volume of 1:2 was used. For each pond configuration, simulations were run for ten different active storage volumes and four detention times (6, 12, 24 and 48 hr). In addition, for extended detention dry ponds, two active storage depths (1 m and 1.5 m) were simulated. For extended detention wet ponds, one permanent pool depth (1 m) was simulated.

1.3 Analytical Modeling of Stormwater Management Ponds

The SUDS (Statistical Urban Drainage Simulator) models are a family of analytical probabilistic models developed at the University of Toronto and follow from the original probabilistic models developed by Howard (1976), Smith (1980) and Adams and co-workers (e.g. 1984). These models are closed-form mathematical expressions requiring relatively few input parameters and, as a result, performance characteristics can be computed very efficiently.

The SUDS models are developed analytically using derived probability distribution theory assuming exponential probability density functions for various rainfall characteristics, namely the rainfall duration, rainfall volume and interevent time. The exponential distribution requires a single parameter which is equivalent to the inverse of the mean characteristic value observed as follows:

$$f_x(x) = \begin{cases} \alpha e^{-\alpha x} & x > 0 \\ 0 & \text{otherwise} \end{cases} \quad (1.1)$$

Long term meteorological records have been analyzed for various locations across Canada for varying interevent time definitions (IETDs). The IETD is the minimum temporal spacing required between rainfall events to consider the events as being separate. From the analyses of these meteorological records, parameters for the exponential distributions discussed above have been estimated. Furthermore, studies conducted at the University of Toronto (e.g. Kauffman, 1987) have shown that results from the SUDS models for Toronto meteorological statistics most closely agree with those from the STORM continuous simulation model for quantity control when an IETD of 2 hours is used. Therefore, for Lester B. Pearson (Toronto) International Airport Data, an IETD of 2 hours is used in this study. Table 1.2 gives the resulting parameter values.

Table 1.2 Parameter values for exponential probability distributions.

Interevent Time Definition, IETD	2 hr
Parameter for Exponential PDF of Rainfall Duration, λ	0.282/hr
Parameter for Exponential PDF of Rainfall Interevent Time, ψ	0.0230/hr
Parameter for Exponential PDF of Rainfall Volume, ζ	0.200/mm
Average Annual Number of Rainfall Events, Ω	104.0

1.3.1 Extended Detention Dry Ponds

The extended detention dry pond has an active storage zone only and exhibits continuous flow-through conditions during the periods in which it has contents and/or receives runoff. Therefore, it is assumed that dynamic settling is the principal mechanism of TSS removal. The long term pollution control performance of extended detention dry ponds using the SUDS extension models is characterized by the following expression (Adams, 1996; derived from Adams and Bontje, 1984):

$$C_p = E_d \left\{ 1 - \left[\frac{\frac{\lambda}{\Omega}}{\frac{\lambda}{\Omega} + \frac{\zeta}{\phi}} \right] \left[\frac{\frac{\psi}{\Omega} + \frac{\zeta}{\phi} \exp \left[- \left(\frac{\psi}{\Omega} + \frac{\zeta}{\phi} \right) S_A \right]}{\frac{\psi}{\Omega} + \frac{\zeta}{\phi}} \right] \right\} \quad (1.2)$$

where:

- C_p = the long-term TSS removal expressed as a fraction,
- E_d = the overall TSS removal efficiency
- S_A = the active storage volume (mm),
- h_A = the depth of the pond (m),
- Ω = the controlled constant release rate from the pond (mm/hr),
- t_d = the detention (drawdown) time of a full pond (hr).
- λ, ψ and ζ = meteorological parameters describing rainfall statistics (Table 1.2), and
- ϕ = the runoff coefficient.

The volume measures expressed as depth (mm) are implied as depth of water across the total catchment area. The term E_d is derived using the Camp-Dobbins model for dynamic settling, viz. (Fair and Geyer, 1954):

$$\eta_d = 1 - \left[1 + \frac{1}{n} \cdot \frac{V_s}{Q/A} \right]^{-n} \quad (1.3)$$

where:

- η_d = the dynamic settling removal efficiency,
- n = the pond settling performance factor (or turbulence factor),
- V_s = the settling velocity of the particle size of concern (m/hr), and
- Q/A = the surface loading rate (m/hr) where Q is the steady-state flow through rate of the pond (m^3/hr) and A is the average surface area of the pond (m^2).

This model for TSS removal (i.e. dynamic settling) is used since, during the period of particle settling, there is flow into and/or out of the pond and, hence, there is fluid turbulence. Equation 1.2 is essentially the long-term fraction of runoff processed through the pond multiplied by the overall removal efficiency of the pond thus yielding the long-term fraction of pollution, measured as TSS, removed.

The surface loading rate can also be expressed as follows:

$$\frac{Q}{A} = \frac{h_A}{t_s} \quad (1.4)$$

where:

- t_s = the average steady-state detention time of the active storage zone (hr).

This quantity (t_s) is taken to be one-half the detention, or drawdown, time of the active storage zone as follows:

$$t_s = \frac{1}{2} \cdot t_d = \frac{1}{2} \cdot \frac{S_A}{\Omega} \quad (1.5)$$

where:

t_d = the drawdown time (time required to drain a full pond with no further inflow) and is defined as S_A/Ω (h).

Thus, Equation 1.4 can be rewritten as:

$$\frac{Q}{A} = \frac{2h_A \Omega}{S_A} \quad (1.6)$$

Substituting Equation 1.6 into Equation 1.3 yields:

$$\eta_d = 1 - \left[1 + \frac{V_s}{n \cdot h_A} \cdot \frac{S_A}{2 \cdot \Omega} \right]^{-n} \quad (1.7)$$

Equation 1.7 applies only to a single particle size with a known settling velocity. A more representative measure of pollutant removal efficiency would consider the range of particle sizes found in stormwater. Using a settling velocity distribution, the overall fractional TSS removal efficiency is given by (Adams, 1996):

$$E_d = \sum_{i=1}^n F_i \left\{ 1 - \left[1 + \frac{V_{si}}{n \cdot h_A} \cdot \frac{S_A}{2 \cdot \Omega} \right]^{-n} \right\} \quad (1.8)$$

where:

V_{si} = the average settling velocity (m/hr), and
 F_i = the fraction of the total mass, contained in the i^{th} size fraction.

The turbulence or short-circuiting factor used herein is $n=3$ representing *good performance* (Fair and Geyer, 1954). The settling velocity distribution used herein was developed from results of the Nationwide Urban Runoff Program conducted by the U.S. EPA as well as some Canadian research efforts and is provided in Table 1.3.

Table 1.3 Settling velocity distribution of particles in stormwater (MOEE, 1994).

Size Fraction i	% of Particle Mass F _i	Avg. Settling Velocity V _{si} (m/hr)
1	20	0.00914
2	10	0.0468
3	10	0.0914
4	20	0.457
5	20	2.13
6	20	19.8

1.3.2 Extended Detention Wet Ponds

For the case of the extended detention wet pond, incoming runoff is assumed to first displace the contents of the permanent pool until such a time when the water level exceeds the permanent pool level, at which point water begins filling the active storage zone and is discharged from the active storage zone of the pond at a controlled release rate. For events where both the permanent pool and active storage volumes are exceeded, runoff is bypassed upstream of the pond thus constituting a spill. This provision results in no treatment of a spill. Treatment of stormwater in the permanent pool is assumed to occur via quiescent settling between runoff events whereas, similar to the dry pond, dynamic settling is assumed to occur for runoff passing through the active storage zone. The long term pollution control performance of extended detention wet ponds is characterized by the following expression whose derivation is described in detail by Adams (1996):

$$\begin{aligned}
 C_p = E_q & \left[1 - \exp\left(-\zeta \frac{S_p}{\phi}\right) \right] \\
 + E_d & \left\{ 1 - \left[\frac{\frac{\lambda}{\Omega}}{\frac{\lambda}{\Omega} + \frac{\zeta}{\phi}} \right] \left[\frac{\frac{\psi}{\Omega} + \frac{\zeta}{\phi} \exp\left[-\left(\frac{\psi}{\Omega} + \frac{\zeta}{\phi}\right) S_A\right]}{\frac{\psi}{\Omega} + \frac{\zeta}{\phi}} \right] \right\} \exp\left(-\zeta \frac{S_p}{\phi}\right) \quad (1.9)
 \end{aligned}$$

where:

- S_p = the volume of the permanent pool (mm),
- h_p = the depth of the permanent pool (m), and
- S_d = the depression storage (mm).
- E_d = the TSS removal efficiency of the active storage zone (equivalent to Equation 1.8) and
- E_q = the overall TSS removal efficiency of the permanent pool and is derived below.

The removal of TSS within the permanent pool of an extended detention wet pond is assumed to occur via the mechanism of quiescent settling between runoff events; that is, during periods of zero inflow. The analytical probabilistic models used herein approximate this period of zero runoff as the interevent period (i.e. period between two successive rainfalls), denoted as b . The quiescent settling model is:

$$\eta_q = \frac{V_s}{v_o} \quad (1.10)$$

where:

- η_q = the quiescent settling removal efficiency for a single particle with a settling velocity V_s (m/hr) and
- v_o = the overflow rate (m/hr) defined as

$$v_o = \frac{Q}{A} = \frac{h_p}{b} \quad (1.11)$$

From sedimentation theory, the removal efficiency of a single particle size by quiescent settling can be expressed:

$$\eta_q = \begin{cases} V_s \frac{b}{h_p} & b < \frac{h_p}{V_s} \\ 1 & b \geq \frac{h_p}{V_s} \end{cases} \quad (1.12)$$

In order to estimate the long-term pollution control performance afforded by the permanent pool zone of an extended detention wet pond, the mean, or expected value, of the removal efficiency is required. From Equation 1.12, it is evident that removal efficiency (η_q) is a function of the interevent time (b) which is a random variable that can be described probabilistically using an exponentially distributed probability density function (PDF) as follows (Eagleson, 1972; Howard, 1976; Adams and Bontje, 1984; Adams et al., 1986):

$$f_B(b) = \psi e^{-\psi b} \quad (1.13)$$

Using derived probability distribution theory (Benjamin and Cornell, 1970), the PDF of removal efficiency, η_q , can be derived from the PDF of interevent time, b (Equation 1.13), through the functional relationship described by Equation 1.12. This derivation is done in two parts (Adams, 1996):

$$\text{Part 1: } b \geq \frac{h_p}{V_s}$$

$$\text{Prob}[\eta_q = 1] = \text{Prob}\left[b \geq \frac{h_p}{V_s}\right] = \int_{b=\frac{h_p}{V_s}}^{\infty} \psi e^{-\psi b} db = e^{-\psi \frac{h_p}{V_s}} \quad (1.14)$$

$$\text{Part 2: } b < \frac{h_p}{V_s}$$

$$\begin{aligned} F_{\eta_q}(\eta_o) &= \text{Prob}[\eta_q \leq \eta_o] \\ &= \text{Prob}\left[b < \eta_o \frac{h_p}{V_s}\right] = \int_{b=0}^{\eta_o \frac{h_p}{V_s}} \psi e^{-\psi b} db = 1 - e^{-\psi \left(\eta_o \frac{h_p}{V_s}\right)} \end{aligned} \quad (1.15)$$

which is the cumulative distribution function (CDF) of η_q over the range where the settling period (interevent time) is less than the time required to remove all the particles with the settling velocity V_s (i.e. $b < h_p/V_s$). The PDF is the derivative of Equation 1.15 as follows:

$$f_{\eta_q}(\eta_o) = \frac{d F_{\eta_q}(\eta_o)}{d \eta_o} = \psi \frac{h_p}{V_s} \exp\left(-\eta_o \psi \frac{h_p}{V_s}\right) \quad (1.16)$$

The expected value of η_q is then

$$\begin{aligned} \bar{\eta}_q &= \int_0^1 \eta_o \cdot \left[\psi \frac{h_p}{V_s} \exp\left(-\eta_o \psi \frac{h_p}{V_s}\right) \right] d\eta_o + 1 \cdot \exp\left(-\psi \frac{h_p}{V_s}\right) \\ &= \frac{V_s}{\psi h_p} \left[1 - \exp\left(-\psi \frac{h_p}{V_s}\right) \right] \end{aligned} \quad (1.17)$$

Equation 1.16 can be further generalized into an expression for the overall fractional TSS removal efficiency employing a settling velocity distribution; viz:

$$E_q = \sum_{i=1}^n F_i \left\{ \frac{V_{Si}}{\psi \cdot h_p} \left[1 - \exp\left(\frac{-\psi \cdot h_p}{V_{Si}} \right) \right] \right\} \quad (1.18)$$

1.3.3 Experiments

The above analytical models were used to estimate pollutant removal efficiencies for comparison with the continuous simulation model estimates. The input parameters used in the SUDS models included the runoff coefficient, ϕ , which is taken to be 0.5. This value is based upon results generated using the RAIN and RUNOFF modules of SWMM.

Total suspended solids removal efficiencies are calculated for both the extended detention dry and wet ponds for varying detention times (i.e. 6, 12, 24 and 48 hr) as well as for varying storage volumes. In addition, two pond depths (1 m and 1.5 m) are analyzed for the dry pond case and only one configuration is modeled for the wet pond case (1 m permanent pool depth and 0.5 m active storage depth). The analytical models for pollution control are based on unit catchment area calculations and are thus insensitive to the catchment area used. As with the continuous simulation modeling runs, a constant ratio of active storage volume to permanent pool volume of 1:2 is assumed. The results from the analytical models are compared to the results obtained from the continuous simulation models discussed above.

As it is inappropriate to base the design of a wet pond on an arbitrary ratio of active storage volume to permanent pool volume, the effect of this ratio on pollution control performance is also analyzed. It is anticipated that these results will contribute to the scientifically-based design of wet ponds with respect to how much storage should be allocated to both the permanent pool and active storage zones.

1.4 Discussion of Results

1.4.1 Extended Detention Dry Ponds

Figures 1.1 to 1.6 plot the percent total suspended solids (TSS) removal against active storage volume in the range of 0 to 20 mm normalized over the catchment areas. The quality control performance results were generated for dry

ponds with detention times of 6, 12, 24 and 48 hours. Of these detention times, the 24 and 48 hour detentions are probably the more realistic detention times for most applications.

Figure 1.1 shows the pollution control performance of an extended detention dry pond, servicing a 10 ha catchment with a pond depth of 1 m for detention times of 6 to 12 hours, with respect to storage volume. In general, the analytical models over-estimate the TSS removal, when compared to the simulation results, by less than about 10%. The departure between the results decreases for the longer detention times. These detention times (i.e. 6 and 12 hours) are typically shorter than what would be expected in practice. Nonetheless, the model results tend to agree favourably with each other. Figure 1.2 presents the results for the 24 and 48 hour detention times for the same catchment size and pond depth. The correlation between the models for these longer detention times is quite remarkable, exhibiting a maximum departure of approximately 5%. For the 24 hour detention time, the analytical models consistently over-estimate the TSS removal when compared to the continuous simulation model results. For the 48 hour detention times, the analytical model results are virtually coincident with the continuous simulation model results for storage volumes up to 500 m³ (or 5 mm normalized over the catchment area). Thereafter, the analytical models marginally under-estimate the pollution control performance when compared to the simulation results. For the sake of brevity, not all

Figure 1.1 TSS removals of extended detention dry ponds, 10ha catchment, 1m pond depth, 6 & 12 hr cases.

Figure 1.2 TSS removals of extended detention dry ponds, 10ha catchment, 1m pond depth, 24 & 48 hr cases.

Figure 1.3 TSS removals of extended detention dry ponds, 1 m pond depth, 24 hr case.

Figure 1.4 TSS removals of extended detention dry ponds, 1 m pond depth, 48 hr case.

Figure 1.5 TSS removals of extended detention dry ponds, 10 ha catchment, 24 hr case.

the comparisons are shown for the 100 ha catchment areas nor for the 1.5 m ponding depth. Figure 1.3 shows the comparison of model results for a detention time of 24 hours and for different catchment areas (i.e. 10 and 100 ha). It is important to note that the analytical models are derived using unit catchment areas and are thus insensitive to variations in catchment area. Figure 1.4 presents this comparison for a detention time of 48 hours. In general, the analytical model results are effectively the same results as the continuous simulation models. Figures 1.5 and 1.6 show the model comparisons for ponding depths of 1 m and 1.5 m where the catchment area is 10 ha.

The results shown in Figure 1.5 are those for a 24 hour detention time. For a pond depth of 1 m, the departure between modeling results is typically less than 5% whereas for a pond depth of 1.5 m, this figure is consistently less than about 3%. Figure 1.6 gives the comparison for a detention time of 48 hours. In general, the analytical model results compare quite favourably to the continuous simulation results within the practical range of pond depths.

Figure 1.6 TSS removals of extended detention dry ponds, 10 ha catchment, 48 hr case.

1.4.2 Extended Detention Wet Ponds

The comparison of the analytical modeling results with the continuous simulation modeling results for extended detention wet ponds is given in Figure 1.7. The analytical models exhibit a sharp rise in the level of pollution control performance as storage volumes increase whereas the curves for the continuous

Figure 1.7 TSS removals of extended detention wet ponds, 10 ha catchment, 1 m permanent pool, 0.5 m active storage depth.

simulation model are more gradual. Both sets of curves reveal that the pollution control performance of wet ponds is relatively insensitive to the active storage detention time used. The quality control performance results from the analytical models show negligible sensitivity to the detention times analyzed and in fact the curves representing different active storage detention times converge onto a single curve as storage volumes increase. This is a result of the active storage zone not contributing significantly to the overall pollution control performance. This, in turn, is directly related to the arbitrarily-set ratio of active storage volume to permanent pool volume, in this case 1:2. Therefore, as the storage volume increases, the permanent pool storage increases by twice the amount that the active storage volume increases and, thus, fewer rainfall events will utilize the active storage zone, thereby reducing its importance in long-term pollution control. Therefore, it is considered useful to investigate the quality control performance of extended detention wet ponds for varying ratios of active storage volume to permanent pool volume, which is the topic of the subsequent section.

In general, the analytical models do not seem to estimate the relative quality control performance of extended detention wet ponds when compared to the continuous simulation model. Therefore, further development of these models is warranted to improve their reliability such that they may be used with reasonable confidence by researchers and practitioners alike.

1.5 Investigation of Active Storage Volume to Permanent Pool Volume Ratio

This section investigates the effect of changing the ratio of the active storage volume to the permanent pool volume (hereafter referred to as the ratio) of extended detention wet ponds in order to illustrate its effect on the pollution control performance of such ponds. The analyses presented in Figures 1.8 and 1.9 are performed using a constant pond depth for consistency, whereas Figure 1.10 illustrates the effect of varying pond depths on the performance characteristics. In each of Figures 1.8 to 1.10, the thickest curve with the square markers represents the same set of conditions and is, hence, the same curve. This is done in an attempt to aid readers visualize the results.

Figure 1.8 indicates that, depending on the detention time of the active storage zone, there exists an optimal ratio at which TSS removal is maximized. The figure also indicates that there is a *starting level* of pollution control at a ratio

Figure 1.8 Extended detention wet pond analysis using analytical models, 10 ha catchment, 1.5 m total pond depth, 6 mm total storage.

approaching zero which is due solely to the permanent pool. By increasing the proportion of active storage there is an improvement, albeit marginal, in TSS removal to a point and then a decrease in performance thereafter. This effect is especially serious for longer detention times (i.e. 48 hours) where the quality

Figure 1.9 Extended detention wet pond analysis using analytical models, 10 ha catchment, 1.5 m total pond depth, 24 hr detention time.

Figure 1.10 Extended detention wet pond analysis using analytical models, 10 ha catchment, 24 hr detention time, 6 mm total storage.

control provided by the permanent pool alone is greater than any combination of active storage and permanent pool storage for the set of conditions analyzed herein.

Figure 1.9 illustrates the impact of the ratio on TSS removal for various total storage volumes (active and permanent pool combined). The results indicate that there is a ratio, depending on the total storage volume, which optimizes pollution control. In general, as the storage volume increases, the value of the optimal ratio increases or, simply put, the active storage zone can contribute relatively more to long term TSS removal as the storage volumes increase. However, the increased benefit attainable by including an active storage zone is slight at best, and is not considered of great significance.

Figure 1.10 shows the general impact of total pond depth (active and permanent pool combined). The results are quite similar and encourage the use of shallow ponds for stormwater quality control. There exist practical limits, however, to the extent to which shallow pond depths can be constructed. All three curves show essentially the same trend and optimal combination of storage zones with the exception that the levels of control are shifted vertically.

1.6 Summary and Conclusions

The comparison of the analytical model results for long term pollution control with those from continuous simulation model for extended detention dry ponds is very favourable, especially considering the level of effort required to produce each set of results. A practical implication of this finding is that, at the planning stage of urban drainage systems, the analytical models can be employed with confidence to estimate system performance for pollution control for significantly less cost than their more comprehensive counterparts. This is especially useful where the time and funding required to perform full scale simulations may not be available. It is important to note that the employment of such models does not preclude the subsequent use of more comprehensive continuous simulation models for more detailed analysis and design.

For the extended detention wet pond, the agreement between the analytical models with the continuous simulation models is much less favourable. Further investigation of these models is therefore recommended, namely the investigation of the underlying causes of high-early TSS removals.

The ratio of active storage volume to permanent pool volume is assumed to be constant for all analyses conducted earlier in this work, in order to allow comparison of continuous simulation model results with analytical model results. This ratio, however, can affect the quality control performance of the stormwater management facility differently for different design characteristics. Although the agreement between modeling results for the wet pond is not good, it is useful to

illustrate the application of the analytical models in performing less than routine investigations. The analytical models are easily used to investigate various ratios of active storage volume to permanent pool volume in terms of quality control performance. Furthermore, these results are anticipated to be similar to those that would be obtained using a continuous simulation, since both the analytical models and the continuous simulation models exhibited similar characteristics with respect to the lack of importance of the active storage zone, especially for large storage volumes. These analyses yield an optimal combination of storage components which maximizes the level of pollution control attainable by the facility. In general, wet ponds favour no active storage zone for improving the long term pollution control performance.

The results presented herein indicate that the active storage zone contributes relatively little to the quality-control performance of extended detention wet ponds particularly as detention times increase. This would encourage the use of wet ponds of this sort with an active storage zone to be used primarily for runoff quantity control purposes. This will eliminate the need for dual-cell stormwater management facilities which, in most cases are eyesores in an urban landscape. It will also provide perhaps a recreational facility with social benefits. The net result, in terms of stormwater management, will be peak flow attenuation by the active storage zone and quality control by the permanent pool.

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Notation

A	Average Surface Area of the Pond (m^2)
b	Rainfall Interevent Time (hr)
C_p	Long Term Pollution Control Performance
E_d	Overall Removal Efficiency of Suspended Solids by Dynamic Settling
E_q	Overall Removal Efficiency of Suspended Solids by Quiescent Settling
F_i	Fraction of Total Mass Contained in i^{th} Size Fraction
h_A	Depth of Active Storage Zone (m)
h_p	Depth of Permanent Pool (m)
IETD	Interevent Time Definition
n	Turbulence or Short-Circuiting Constant in Camp- Dobbins Equation

PDF	Probability Density Function
Q	Steady-State Flow Through Rate of the Pond (m^3/hr)
S_A	Active Storage Volume (mm)
S_d	Depression Storage (mm)
S_p	Permanent Pool Storage Volume (mm)
t_d	Average Detention Time of Active Storage Zone (hr)
t_s	Average Steady-State Detention Time of Pond (hr)
TSS	Total Suspended Solids
V_{Si}	Average Settling Velocity of i^{th} Size Fraction (m/hr)
ϕ	Runoff Coefficient
η_d	TSS Removal Efficiency for a Single Particle Size by Dynamic Settling
η_q	TSS Removal Efficiency for a Single Particle Size by Quiescent Settling
λ	Parameter for Exponential PDF of Rainfall Duration (hr^{-1})
Ω	Controlled Release Rate from Pond (mm/hr)
ψ	Parameter for Exponential PDF of Rainfall Intervent Time (hr^{-1})
ζ	Parameter for Exponential PDF of Rainfall Volume (mm^{-1})

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