Chapter 8

Performance Analysis of Urban Runoff Quality Control Ponds by Continuous Simulation.

Alexandre Gordine

HBT AGRA Ltd

2233 Argentia Road, Mississauga, Ontario, L5N 2X7

Barry J. Adams

Department of Civil Engineering

University of Toronto, Toronto, Ontario, M5S 1A4

Continuous simulation models are developed to characterize the performance of four types of stormwater quality control ponds: retention basins (infiltration facilities), extended detention ponds, sedimentation ponds with displacement, and wet settling ponds/tanks. The performances of these stormwater quality control facilities are modelled under different design and operating conditions. The long term pollutant removal and average annual pollutant loading from the pond systems are used as the performance criteria. Effects of design storm volume and duration, catchment location, land use, configuration of the basin, operation policy, outflow rate, detention time, and type of pollutant on the performance of these facilities are examined. It is demonstrated that the design storm volume and duration requirements, as specified in the MOE/MNR Interim Stormwater Quality Control Guidelines, are not sufficient to properly design the stormwater quality control facilities. According to the Guidelines, the same facility may be either over designed or provide insufficient stormwater

Gordine, A. and B.J. Adams. 1994. "Performance Analysis of Urban Runoff Quality Control Ponds By Continuous Simulation." *Journal of Water Management Modeling* R176-08. doi: 10.14796/JWMM.R176-08.

© CHI 1994 www.chijournal.org ISSN: 2292-6062 (Formerly in Current Practices in Modelling the Management of Stormwater Impacts. ISBN: 1-56670-052-3)

quality control depending on local climatic and catchment conditions. Recommendations for the design of urban runoff quality control ponds are made on the basis of the simulation analyses.

8.1 Introduction

It is widely recognized that stormwater can be a significant source of water pollution. Water quality degradation resulting from urban stormwater runoff necessitates a thorough analysis of the problem and the development of appropriate codes to protect the receiving waters. Such a code is given by the Interim Stormwater Quality Control Guidelines for New Development, which was developed for the Province of Ontario jointly by the Ministries of the Environment and Natural Resources (1991). These Guidelines are based on suspended solids removal and bacteria die off and provide for protection of coldwater and warmwater fisheries and selective water uses (e.g., recreation and aesthetics). The required treatment of stormwater is regulated using a sizing rule approach based on design storm volume and duration as follows:

Volume control guidelines are to be applied as runoff control limits for 13 or 25 mm daily precipitation totals. By ensuring that the runoff generated by daily precipitation events of either 13 or 25 mm is infiltrated or free of pollutants, acceptable water quality conditions will exist for significant periods of the year.

It may be argued that the specification of a design storm volume and duration is not sufficient to properly design stormwater quality control facilities. Performance of the facilities, expressed in terms of the long term pollutant removal and average annual pollutant loading from the pond systems, depends on many other factors, such as catchment location, land use, configuration of the basin, operation policy, outflow rate, detention time, and type of pollutant to be removed. The effects of all these factors on the performance of different types of stormwater quality control facilities are examined using continuous simulation models (Gordine, 1993).

8.2 Continuous Simulation Models

A number of simplifying assumptions about runoff generation, pollutant transport and removal processes are made in the models. Runoff quantities are computed by the coefficient method. A runoff coefficient of 0.65 is used to model the rainfall-runoff process on industrialized watersheds and a value of 0.25 is used for residential developments.

The pollutant generation process is simulated on the basis of a unit event mean concentration. Pollutant transport is not explicitly addressed in the

program. Stormwater with a constant unit concentration goes directly into the control facility. No deposition, reaction, or scour of additional pollutant is assumed to take place in the transport system.

In accordance with the US EPA recommendations, pollutants are characterized by the number of size fractions, settling velocity distribution, and settleable fraction of the pollutant. Five settling fractions are assigned for total suspended solids (TSS). For metals (Cu, Zn), total kjeldahl nitrogen (TKN), biological oxygen demand (BOD), and chemical oxygen demand (COD), it is assumed that there would be no significant association with the largest size fraction, and computations were performed using the next four smaller size fractions. Suspended solids are 100% settleable by definition (settleable fraction equals one). For Cu, Zn, TKN, BOD, and COD, the estimated settleable fraction is 0.5.

Pollutant removal in sedimentation facilities is simulated with standard methodology used by the US EPA (1986). Sedimentation is the major mechanism of pollutant removal in detention basins. Settling under dynamic and quiescent conditions is distinguished. Dynamic conditions are defined in this work as periods of time with positive inflow into the basin. Initially, the settleable concentration of each fraction is computed. The removal equation (dynamic or quiescent as appropriate) is applied every time step to each fraction. After settling, fraction concentrations are summed yielding the overall concentrations of particular pollutants. Dissolved pollutants go through the ponds unchanged. It is noted that equations for dynamic and quiescent settling used in this work are the best available to date. Keeping in mind the complexity of the phenomena being studied, it is clear that these approximations and underlying assumptions may be quite far from the reality under certain specific conditions and should be treated with caution.

Pollutant removal in retention (sedimentation) devices is easier to handle. Stormwater that enters the facility is "lost" from the system. Accordingly, pollutants (dissolved and particulate) present in the water are also removed from the system. Therefore, no special simulation of pollutant behaviour is required. The percentage pollutant removal merely equals the percentage of stormwater volume controlled by the device. Resuspension of pollutants and clogging of infiltration facilities are not addressed in this work.

Hourly precipitation data from the AES are used as input to the model. The quality of the input data should be known and understood in order to judge the true value of the results of simulation. Missing hourly data and missing daily records are identified as possible problems with precipitation data. A model to screen AES precipitation records is used in order to assess the amount of missing information. Based on the result of screening, precipitation data are read selectively to skip defective records (Gordine, 1993).

8.3 Facilities Analyzed by Simulation

Four types of stormwater quality control facilities, also referred to as Best Management Practices (BMPs), are analyzed in this work: retention basins (infiltration facilities); extended detention ponds; sedimentation ponds with displacement; and wet settling ponds/tanks.

Retention basins capture stormwater “permanently”. Once the runoff enters the basin, it is never directly discharged into the receiving water body. Infiltration facilities are typical examples of such retention basins.

The extended detention pond is defined as a settling pond with a constant outflow rate regardless of the inflow conditions. Water is discharged from the ponds during and between runoff events at a constant rate until the pond is empty.

The sedimentation pond with displacement is defined as a settling pond which does not provide volume control. Water is not discharged from the facility between runoff events, and a permanent pool of water is maintained.

Wet settling ponds are defined as sedimentation devices consisting of two parts: i) a permanent pool and ii) a working volume which is used to receive stormwater runoff, detain it for a certain period of time (quiescent detention time) and release it into the receiver at a certain rate. Tanks are operated in the same manner but do not have a permanent pool.

The design storm volume and duration, required by the MOE/MNR Guidelines, should be translated into the actual dimensions of the stormwater quality control facility. Obviously, it is the runoff volume produced by the storm rather than the storm volume itself which is important. The initial rule would be to derive the volume of the BMP as a product of the design storm volume, watershed area, and runoff coefficient. The storm duration is not employed in this case, and it is not always clear how to apply storm duration to the sizing of different BMPs. Operating rules of a particular facility dictate whether the design storm duration is applicable to its sizing. The effect of the design storm duration on the performance of stormwater quality control ponds is studied under the following assumptions:

- 1) If a specified quiescent detention time is provided by the device, i.e. there is no outflow from the basin during the storm event unless it is an overflow, the storm duration is not applicable for the sizing of the BMP. The BMP volume is determined as a product of the design storm volume, the runoff coefficient, and the watershed area. Wet settling ponds (tanks) and sedimentation ponds with displacement fall into this category.
- 2) If no quiescent detention time is provided by the facility (i.e. outflow from the basin takes place simultaneously with the runoff event), the volume of the basin is reduced by the amount of water which

can leave the pond during the specified storm duration. For example, if the initial sizing rule yields a basin volume of 5000 m³, the outflow rate from the basin (e.g. infiltration through the bottom or pumping rate) is given as 100 m³/h, and the design storm duration is set at 12 hours, then the ultimate basin volume is computed as 5000 m³ - 12 h * 100 m³/h = 3800 m³. Thus, the BMP volume is reduced by the amount of water which leaves the basin during the design storm duration. Retention basins (infiltration facilities) and extended detention ponds fall into this category.

Prior to interpreting results, drawing conclusions, and making recommendations, it should be noted that this is but one possible way to interpret and apply the design storm duration as given in the MOE/MNR Guidelines; however, it is an interpretation which has met with some general favour.

8.4 Retention Basin (Infiltration Facility)

The major design parameters for infiltration facilities are the volume of the basin, the area of the bottom subject to infiltration, and the hydraulic conductivity of the underlying soil. The effects of the design storm volume and duration, the soil type, the climatic conditions (catchment location), and the catchment land use on the performance of infiltration facilities are examined. The following conclusions are drawn from the simulation results (Gordine, 1993):

- 1) As can be seen from Figure 8.1, identical facilities located in different parts of the province of Ontario result in different long term pollutant removals and mass loadings. The difference in long term removals is pronounced for small to moderately sized basins (7 to 20 mm design storm volumes) and may be as high as 15%-20%.
- 2) Simulated relationships between infiltration facility configuration (depth and surface area) and performance show that a shallow basin with a larger surface area provides better removal than a deeper one. The advantage of a shallow basin is more pronounced for smaller facilities (10 -15 mm design storm volume) and is smaller for design storm volumes larger than 20 mm. Figure 8.2 illustrates this point.
- 3) As can be seen from Figures 3a and 3b, infiltration facilities servicing less pervious industrialized catchments and more pervious residential developments provide the same long term percentage pollutant removal, but average annual pollutant mass loadings from

the industrial sites are substantially higher compared to residential developments due to the higher runoff volumes.

- 4) The effects of the design storm duration on performance of retention basins (infiltration facilities) are modelled for different soil types, basin configurations (depth and surface area), and land uses. Figure 8.4 illustrates that longer design storm durations result in lower pollutant removals and that the design storm duration has a stronger impact on the performance of facilities with higher infiltration rates. The usage of the 24 hour storm duration in the design of infiltration facilities results in substantial decreases in long term removals (15% to 30%) compared to conservative design schemes which do not account for the storm duration.
- 5) Generally, retention basins (infiltration facilities) are effective in removing pollutants from surface water discharges. On average, about 80% long term pollutant removal may be expected for a 13 mm design rainfall volume and over 90% long term pollutant removal for a 25 mm design rainfall volume. The increase in the volume of the facility results in higher pollutant removals and lower pollutant mass loadings to surface waters.

8.5 Extended Detention Pond

The effects of the design storm volume and duration on extended detention pond performance under different climatic conditions, for different land use patterns on the watershed, different types of pollutants, and different operation modes and drainage times (outflow rates) are examined. The following results are obtained from the simulation results (Gordine, 1993):

- 1) The performance of the extended detention pond depends on the operation mode, i.e., whether the runoff in excess of the pond capacity is routed through the facility and overflowed via an emergency spillway, thereby receiving partial treatment (flow-through mode), or diverted from the pond and discharged into the receiving water body without any treatment (by-pass mode). As can be seen from Figure 8.5, the advantage of the flow-through mode is more pronounced for smaller facilities and may be as high as 8-10% greater long term suspended solids removal for design storm volumes of 10-13 mm. The advantage of one operation mode over another diminishes as the facility becomes bigger.

- 2) Similar to that observed for infiltration facilities, identical extended detention ponds located in different parts of Ontario have different performances. Extended detention ponds servicing highly impervious industrialized catchments and more pervious residential developments provide the same long term percentage pollutant removal, but the average annual pollutant mass loadings from the industrial sites are substantially higher compared to residential developments due to their higher runoff volumes.
- 3) Removals of different types of pollutants by extended detention ponds are demonstrated in Figure 8.6. It can be seen that about 65% of the suspended solids can be removed by the extended detention pond. Removal of metals and nutrients by sedimentation is less than 30%. This result is directly attributable to the assumptions regarding pollutant types analyzed in the model.
- 4) The outflow rate from the pond is represented in terms of the time required to drain the pond at a constant rate. It is shown that longer times to drain the pond (smaller outflow rates) result in better pollutant removals. Approximately 50-55% removal of suspended solids is expected from the extended detention pond with a 24 hour drainage time. The pond with a 72 hour drainage time removes 60-65% of the suspended solids. Figure 8.7 illustrates the point.
- 5) It is demonstrated that extended detention ponds designed for rainfall volumes greater than about 13 mm and 20 mm for the flow-through and by-pass operation modes, respectively, are over-designed in the sense that the marginal improvements in pollutant removal over 13 mm (20 mm) designs are negligible. This holds true for different types of pollutants, times to drain (outflow rates), and types of land use (See Figures 5, 6, and 7).

8.6 Sedimentation Pond with Displacement

Effects of catchment location, type of pollutants, basin configuration, and type of land use on the relationships between the performance of the sedimentation pond with displacement and its volume were studied with the simulation model. The following conclusions are drawn from the simulation results (Gordine, 1993):

- 1) Catchment location is a less important factor affecting the performance of the sedimentation pond with displacement compared to other stormwater quality control facilities (i.e., infiltration

facilities or extended detention ponds). As can be seen from Figure 8.8, removals curves, derived for different locations in Ontario, are clustered very closely together.

- 2) Pond depth is not a significant factor to be considered in designing a sedimentation pond with displacement. Shallower ponds with larger surface areas remove pollutants marginally better than deeper ponds, but the advantage is small, which is demonstrated in Figure 8.9. Practical considerations, such as safety, land cost, aesthetics, etc., would govern the final selection of the pond configuration.
- 3) Percentage long term pollutant removal is not sensitive to the land use pattern on the watershed because the runoff coefficient is accounted for in the design. Pollutant mass loadings are higher from the more impervious industrial sites due to higher runoff volumes and potential pollutant loads.
- 4) The performance of sedimentation ponds with displacement strongly depends on the type of pollutant to be removed. The long term removal of suspended solids is approximately two times higher than the removal of metals and nutrients. This result is again a consequence of the assumptions regarding pollutant type involved in the model (Gordine, 1993).
- 5) The principal characteristic of the sedimentation pond with displacement is its volume. Removals increase smoothly as the volume of the pond increases. Sedimentation ponds with displacement are effective in the long term removal of suspended solids. Removals by the pond designed for a 13 mm storm range from 60% to 70%, while the 25 mm pond design is expected to remove 75-80% of the suspended solids.

8.7 Wet Settling Pond/Tank

It is assumed here that the 13(25) mm design storm volume required by the MOE/MNR Guidelines applies to the working volume. The design storm duration is not applicable to the sizing of wet settling ponds/tanks because of the nature of their operation.

The performance of wet settling ponds of various designs (depth and area of the facility, various combinations of working and permanent volumes) operated in different modes (flow-through vs by-passed overflow mode, different quiescent detention times and outflow rates) and under different conditions

(catchment location, land use pattern on the watershed, types of pollutants) is simulated. The following conclusions are drawn from the simulation results (Gordine, 1993):

- 1) It is demonstrated that identical wet settling ponds located in different parts of Ontario may have different performances. The maximum difference in performance is approximately 10%.
- 2) Pond configuration (depth and surface area) does not have strong influence on the performance. A twofold increase in the pond area due to a smaller depth results in only moderate (5-8%) performance improvements.
- 3) Land use patterns on the watershed affect both the long term pollutant removals and the average annual mass loadings. The presence of a permanent pool results in slightly (3-5%) higher removals when residential areas are served.
- 4) The effect of the operation mode on the performance of wet settling ponds is more pronounced for facilities with smaller working volumes. Figure 8.10 illustrates that the pond with a working volume designed on the basis of a 13 mm rainfall operated in the flow-through mode removes 10-17% more (depending on the permanent volume) suspended solids compared to the identical pond operated in by-passed overflow mode. For the pond with a 25 mm design storm working volume, the advantage of the flow-through operation mode over the by-passed overflows mode is only 5-7%, which can be seen from Figure 8.11.
- 5) The effects of quiescent detention time and time required to drain the working volume (outflow rate) on the performance of wet settling ponds (tanks) are interdependent. The best choice of quiescent detention time and drainage time also strongly depends on the working and permanent volumes of the facility. Quiescent detention times less than 24 hours with a low rate of release result in the highest removals by the wet settling ponds when designed on the basis of a 25 mm rainfall and a permanent volume of 12 mm. Figure 8.12 illustrates this fact. Wet settling ponds with a working volume designed on the basis of a 13 mm rainfall exhibit an abrupt decrease in performance with increased quiescent detention time, which is clearly shown in Figure 8.13. Instant discharge (as in the extended detention pond) would be preferable in this case. As can be seen from Figure 8.14, the settling tank sized on the basis of a

Figure 8.1
Effect of catchment location and design storm volume on long term pollutant removal by infiltration facilities.

Figure 8.2
Effect of basin depth and design storm volume on long term pollutant removal by infiltration facilities.

Figure 8.3a
Effect of land use and design storm volume on long term pollutant removal by infiltration facilities.

Figure 8.3b
Effect of land use and design storm volume on average annual pollutant loading from the infiltration facilities

Figure 8.4
Effect of soil type and design storm duration on long term pollutant removal by infiltration facilities.

Figure 8.5
Effect of operation mode and design storm volume on long term pollutant removal by extended detention ponds.

Figure 8.6
Effect of type of pollutant and design storm volume on long term pollutant removal by extended detention ponds.

Figure 8.7
Effect of time to drain (outflow rate) and design storm volume on long term pollutant removal by extended detention ponds.

Figure 8.8
Effect of catchment location and design storm volume on long term pollutant removal by sedimentation ponds with displacement.

Figure 8.9
Effect of pond depth and design storm volume on long term pollutant removal by sedimentation ponds with displacement.

Figure 8.10
Effect of operation mode and permanent pool volume on long term pollutant removal by wet settling ponds designed on a 13 mm storm.

Figure 8.11
Effect of operation mode and permanent pool volume on long term pollutant removal by wet settling ponds designed on a 25 mm storm

Figure 8.12
Effect of time to drain and quiescent detention time on long term pollutant removal by wet settling ponds designed on a 25 mm storm.

Figure 8.13
Effect of time to drain and quiescent detention time on long term pollutant removal by wet settling ponds designed on a 13 mm storm.

Toronto, 1941-1990; Industrial Land Use
No Permanent Volume; Tank Depth: 2 m
Design Storm Volume: 25 mm

Figure 8.14
Effect of time to drain and quiescent detention time on long term pollutant removal by settling tanks.

Toronto, 1941-1990; Industrial Land Use
Detention Time: 24 h; Time to Drain: 24 h
Pond Depth: 4 m

Figure 8.15
Effect of design storm and permanent pool volumes on long term pollutant removal by wet settling ponds.

25 mm design storm volume not only requires a low release rate but also a longer quiescent detention times (24 to 36 hours). A short period of quiescent detention (not more than 24 hours) is needed for the settling tank designed on the basis of a 13 mm rainfall (Gordine, 1993).

The sensitivity of the wet settling pond performance to the permanent and working volumes is analyzed. It is shown that the working volume is more effective in pollutant removal than the permanent volume. As can be seen in Figure 8.15, the same long term pollutant removal, say 60%, may be achieved either by a settling tank designed for a 22 mm rainfall (the actual volume of the tank is $22 \text{ mm} * 0.65 = 14.3 \text{ mm}$ runoff from catchment), or by a wet settling pond with a 6 mm permanent volume and working volume designed on the basis of a 16 mm storm (the total volume is $6 \text{ mm} + 16 \text{ mm} * 0.65 = 16.4 \text{ mm}$). This example illustrates that a certain objective (a required percentage removal) may be achieved by a smaller and cheaper facility if the stormwater is released after some detention rather than kept permanently. Aesthetic, recreational, and other intangible values are not addressed here.

8.8 Conclusions

The general conclusion of this study is that the design storm volume and duration are not sufficient to specify sizing rules for stormwater quality control facilities. Other factors, such as catchment location, land use, configuration of the basin, operation policy, outflow rate, detention time, and type of pollutant, should also be considered. It is demonstrated that identical facilities located in different parts of Ontario may have different performances. The difference in long term pollutant removals may be as high as 15-20%.

In terms of pollutant removal, BMP configuration (surface area and depth) is not a significant factor to be considered in designing a stormwater quality control facility. Shallower ponds with larger surface areas remove pollutants marginally better than deeper ponds, but the advantage is small. Practical considerations, such as safety, land cost, aesthetics, etc., would govern the final selection of the pond configuration.

Performance of detention (settling) ponds strongly depends on the type of pollutant to be removed. On average, percentage long term suspended solids removal ranges from 60% to 70%, while removal of heavy metals (Cu, Zn), TKN, BOD, and COD is about 30%.

Performance of the extended detention and wet settling ponds depends on the operation mode, i.e., whether the runoff in excess of pond capacity is routed through the facility and overflowed via an emergency spillway, thereby receiving partial treatment (flow-through mode), or diverted from the pond and discharged into the receiving water body without any treatment (by-pass mode).

The advantage of the flow-through mode may be as high as 8-10%.

Percentage long term pollutant removal is not sensitive to the land use pattern on the watershed, but pollutant mass loadings are higher from the less pervious industrial sites than from residential sites due to higher runoff volumes and potential pollutant loads.

The effects of quiescent detention time, time required to drain the basin (outflow rate), and size of the facility on its performance are interdependent. In most cases, 24 hours of is an optimal quiescent detention period for the larger basins, designed on the basis of a 25 mm rainfall, while smaller facilities, sized on the basis of a 13 mm storm, exhibit an abrupt decrease in performance with increased quiescent detention time. Instant discharge would be preferable in this case.

A design storm volume of 25 mm may be redundant as is the case of the extended detention pond. The maximal pollutant removal is achieved by a smaller basin. The permanent pool is much less efficient in pollutant removal than the working volume of the pond which is drained after a certain period of settling. Infiltration basins are the most efficient means of stormwater quality control; removals up to 98% of pollutants are expected. However, this is the most unreliable type of BMP; it is subject to clogging, may cause groundwater contamination, and does not perform well in winter. These limitations are noted, but they are not addressed in this work.

References

Gordine, A. 1993. Performance Analysis of Stormwater Quality Control Facilities by Continuous Simulation. M.A.Sc. Thesis, Department of Civil Engineering, University of Toronto, Toronto, Canada.

MOE. 1991. Stormwater Quality Best Management Practices. Ontario Ministry of the Environment. June 1991.

MOE and MNR. 1991. Interim Stormwater Quality Control Guidelines for New Development. Ontario Ministry of the Environment, Ontario Ministry of Natural Resources. May 1991.

US EPA, 1983. Final Report of the Nationwide Urban Runoff Program. Water Planning Division. Washington, District of Columbia.

US EPA, 1986. Methodology For Analysis of Detention Basins for Control of Urban Runoff Quality -US EPA. 440/5-87-001. September 1986.

US EPA, 1990. Urban Targeting and BMP Selection. An Information and Guidance Manual for State NPS Program Staff Engineers and Managers. Final Report. EPA Contract No. 68-C8-0034.