Analysis of Urban Runoff Control with Infiltration Facilities

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ABSTRACT

This paper presents two methodologies for estimating the impact of infiltration facilities on reducing stormwater runoff volumes, and pollutant loads, from urban drainage systems. The methodologies have previously been developed using derived probability distribution theory, often referred to in the literature as analytical probabilistic modelling, and differ in that they employ different hydrologic models for the transformation of rainfall to runoff. Moreover, the original model derivations employed herein were developed for the analysis of stormwater detention facilities (dry ponds), and are adapted for the analysis of infiltration facilities. The summary of model expressions presented in this paper permits the reader to perform the necessary calculations to design and analyze the performance of stormwater infiltration facilities with the use of a calculator or computer-based spreadsheet application. Results are generated using the models, and various sensitivity analyses presented, illustrating the power of the models. The models are then used as a basis for comparison with guidelines on the design of such facilities in the province of Ontario, Canada. The results of this comparison suggest that the current guidelines may yield infiltration facilities insufficient in size to meet the performance levels intended to be satisfied by such facilities.

KEYWORDS

Probabilistic models; infiltration facilities; stormwater quality; urban drainage

INTRODUCTION

The management of urban runoff quantity and quality is a major concern across the globe. Alternatives for urban runoff management are termed Best Management Practices (BMPs) and include various types of sources controls, in-system controls and downstream controls. Of the many types of source controls, the use of infiltration facilities to reduce runoff volumes, flow rates and pollutant loads is gaining in popularity. Such facilities include infiltration trenches and fields, porous drainage conduits, porous pavements, etc.

All infiltration facilities have the goal of increasing the direction of surface runoff to groundwater systems and removing contaminants in runoff through physical (filtration), physical-chemical (sorption, ion exchange, chemical reaction) and sometimes biochemical processes. In the design of infiltration facilities, it is essential to understand the relationship between design parameters and their effect on the groundwater system in terms of infiltrated water quantity and quality on both an event and a long-term basis and on both local and watershed scales.

RUNOFF AND POLLUTION CONTROL MODEL

Analytical Probabilistic Models

The modelling approach presented herein is commonly referred to in the literature as Analytical Probabilistic Modelling (Adams and Papa, 2000; Guo and Adams, 1998a,b), and is intended to provide results on the long-term performance of runoff control facilities without the computational burden of continuous simulation modelling. Rather, it employs statistics derived from long-term rainfall records to probabilistically represent rainfall characteristics in deriving expressions for system performance, using recognized methods for modelling the rainfall-runoff transformation and derived probability distribution theory (Benjamin and Cornell, 1970), in a mathematically elegant manner.

There are two main branches of analytical probabilistic models:

- ASTORM, where “A” represents “analytical” and “STORM” represents the fact that the U.S. Army Corps of Engineers’ STORM model for hydrologic losses is used in its formulation. The hyrdrologic parameters used for this model are the runoff coefficient (ϕ) and depression storage (S_d).
- ASWMM, where “A” represents “analytical” and “SWMM” represents the fact that the U.S. Environmental Protection Agency’s SWMM model, which employs Horton’s infiltration equation, for hydrologic losses is used in its formulation. The hydrologic parameters used for this model are the fraction of imperviousness (h), depression storage on impervious areas (S_{di}) and pervious areas (S_{dp}), initial soil infiltration capacity (f_o), ultimate infiltration capacity (f_c), the infiltration capacity decay coefficient (k), and the infiltration capacity recovery decay coefficient (k_d).

The hydrological parameters used for the ASWMM modelling presented herein are provided in Table 1. These parameters have been taken directly from the Stormwater Management Practices Planning and Design Manual (MOEE, 1994) for purposes of comparing the results from the analytical models with the design recommendations made in this document and its successor (MOE, 2003).

Table 1. Hydrologic modelling parameters used in ASWMM modelling.

Model Parameter	Value
Imperviousness, h	Varies; 55% for Base Case
Impervious Area Depression Storage, S_{di}	0.5 mm
Pervious Area Depression Storage, S_{dp}	4.67 mm
Initial Infiltration Capacity, f_o	63.5 mm/h
Ultimate Infiltration Capacity, f_c	10.5 mm/h
Infiltration Capacity Decay Coefficient, k	4.14/h
Infiltration Capacity Recovery Decay Coefficient, k_d	0.00414/h

The ASTORM model requires estimates of two parameters: the runoff coefficient (ϕ) and depression storage (S_d). For purposes of this work, the runoff coefficient is estimated given the imperviousness level identified in Table 1, using the following expression (Wisner et al., 1989):

$$\phi = 0.2 \cdot (1-h) + 0.9 \cdot h$$

The value for the depression storage used in the ASTORM model is calculated to be the area-weighted average of the impervious and pervious depression storages used in the ASWMM model, as follows:

$$S_d = h \cdot S_{di} + (1-h) \cdot S_{dp}$$

Meteorological Input

Based on the statistical analysis of long-term rainfall records in many locations, it has been shown that the rainfall characteristics of volume, duration and interevent time can be adequately represented by exponential probability density functions (PDFs) of the following form (Eagleson, 1972; Adams et al., 1986; Adams and Papa, 2000):

$$f_X(x) = \gamma\, e^{-\gamma x} \text{ where } x \geq 0 \text{ and } \gamma = \frac{1}{\mu_x} = \frac{1}{\sigma_x}$$

The parameter γ is therefore derived from the mean value of the characteristic (x) being analyzed. Table 2 presents a list of meteorologic parameter values used in this paper, as derived from the statistical analysis of rainfall data.

Table 2. Mean rainfall statistics and resultant meteorologic modelling parameters for the period from 1960 to 1992 from measurements taken at Toronto Lester B. Pearson International Airport (Adams and Papa, 2000).

	Mean Value per Event	Meteorologic Parameter Value
Rainfall Volume	5.00 mm	$\zeta = 0.200$/mm
Rainfall Duration	3.55 h	$\lambda = 0.282$/h
Interevent Time	43.4 h	$\psi = 0.0230$/h

In addition to the above parameters, the average annual number of rainfall events ($\theta = 104$) is also derived from the statistical analysis. It is noted that the statistical analysis of rainfall data requires the definition of a minimum interevent time, that is, the minimum temporal separation between the end of one rainfall and the beginning of another in order to consider the rainfalls as separate "events". This is referred to in the literature as the interevent time definition (IETD); the statistics used herein were derived using an IETD value of 2 h. An extensive list of meteorologic parameters for many locations across Canada is available (Adams and Papa, 2000).

Modelling of Infiltration Facility

Modelling the pollution control performance of an infiltration facility is similar to that of a stormwater detention facility (e.g., dry pond) that is able to drain over time, with the exception that the pollution removal in the detention facility is often represented by turbulent settling of suspended solids in the water column, while an infiltration facility is able to trap all of the pollutants that are processed through it. For purposes of this work, a pollutant removal efficiency of unity is employed, based on the foregoing rationale. Correspondingly, the fraction of pollutant mass control (C_P) provided by the facility is therefore equivalent to the fraction of runoff volume control (C_R).

Figure 1 presents a schematic representation of the system modelled in this work.

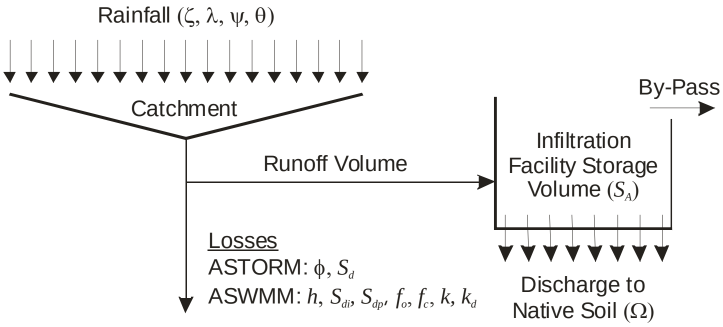


Figure 1. Schematic of urban drainage system illustrating transformation of rainfall to runoff and processing of flows through infiltration facility (adapted from Adams and Papa, 2000).

The design parameters of the infiltration facility include its (active) storage volume (S_A) and the discharge rate to the native soil (Ω). Infiltration facilities are generally located below ground, consisting of clear stone wrapped in a filter fabric along the sides and a sand filter along the bottom to prevent migration of fine particles from the surrounding soils into the void space of the stone, thereby reducing its storage capacity and runoff control effectiveness. The storage capacity is calculated as the product of the facility's volume and the porosity of the clear stone therein. Discharge from the facility is assumed to occur only across its bottom surface, and is calculated as the product of the percolation rate of the soil and the area of the bottom surface (contact area). Similar to Table 1, Table 3 presents the design parameters used herein, similarly taken directly from the Stormwater Management Practices Planning and Design Manual (MOEE, 1994).

Table 3. Infiltration facility design parameters.

Design Parameter	Value
Depth	1.5 m
Porosity	0.4
Percolation Rate of Native Soil	50 mm/h
Contact Area	Varies; 60 m^2 for Base Case
Storage Volume (absolute)	Varies; 36 m^3 for Base Case
Storage Volume, S_A (normalized)	Varies; 3.6 mm for Base Case
Discharge Rate (absolute)	Varies; 3 m^3/h for Base Case
Discharge Rate, Ω (normalized)	Varies; 0.3 mm/h for Base Case

ASTORM Model

The model expressions presented in this section are taken from Adams and Papa (2000); the reader is advised to consult the noted reference for a more thorough treatment of the model development.

The average annual fraction of runoff controlled from an infiltration facility is given by:

$$C_R = 1 - G_P(0)\cdot e^{\zeta\cdot S_d}$$

where $G_P(0)$ is the probability per rainfall event of any spill occurring, and is given by:

$$G_P(0)=\left[\frac{\dfrac{\lambda}{\Omega}}{\dfrac{\lambda}{\Omega}+\dfrac{\zeta}{\phi}}\right]\cdot\left[\frac{\dfrac{\psi}{\Omega}+\dfrac{\zeta}{\phi}e^{-\left(\frac{\psi}{\Omega}+\frac{\zeta}{\phi}\right)\cdot S_A}}{\dfrac{\psi}{\Omega}+\dfrac{\zeta}{\phi}}\right]\cdot e^{-\zeta\cdot S_d}$$

ASWMM Model

The model expressions presented in this section are taken from Chen and Adams (2005), unless otherwise noted; the reader is advised to consult the noted reference for a more thorough treatment of the model development.

The average annual volume of runoff from a catchment (*R*) and the fraction of runoff volume controlled (C_R) by an infiltration facility are given by:

$$R = \theta \frac{h}{\zeta} e^{-\zeta \cdot S_{di}} - \theta \cdot \left(S_n + \frac{h}{\zeta} \right) e^{-\zeta \left(\frac{S_n}{h} + S_{di} \right)} + \theta \cdot \left(S_n + \frac{1}{\zeta} \right) e^{-\zeta \cdot (S_m + S_n)} \qquad C_R = 1 - \frac{P_u}{R}$$

where

$$S_n = h \cdot \left(S_{dp} + S_{iw} - S_{di} + f_c / \lambda \right) \quad \text{and} \quad S_m = h \cdot S_{di} + (1-h) \cdot \left(S_{dp} + S_{iw} \right) + (1-h) \cdot \left(f_c / \lambda \right)$$

and the initial soil wetting volume (S_{iw}) is given by (Guo and Adams, 1998a):

$$S_{iw} = \frac{\left(f_o - f_c \right) \cdot k_d}{(k + \lambda) \cdot \left(k_d + \psi \right)}$$

where *t* is taken herein to be the average rainfall duration (i.e., 3.55 h, from Table 2).

The average annual volume of spills (P_u) is given by:

$$P_u = \theta \cdot E[P]$$

where *E*[*P*] is the expected value of spill volume per rainfall event, and is given by:

$$E[P] = \begin{cases} \frac{h}{\zeta}(B_1 + B_4) \cdot \left\{ 1 - \left[1 + \zeta \left(S_{dp}^* - S_{di} \right) - \frac{\zeta}{h} S_A \right] e^{-\zeta \left(S_{dp}^* - S_{di} \right) + \frac{\zeta}{h} S_A} \right\} + \frac{1}{\zeta} B_5 \\ \quad - \frac{\Omega}{\lambda} (B_2 + B_3) \cdot \left\{ 1 - \left[1 - \frac{\lambda}{\Omega} h \left(S_{dp}^* - S_{di} \right) + \frac{\lambda}{\Omega} S_A \right] e^{\frac{\lambda}{\Omega} h \left(S_{dp}^* - S_{di} \right) - \frac{\lambda}{\Omega} S_A} \right\} & \text{if } S_{dp}^* > S_A / h + S_{di} \\ \\ - \frac{\Omega}{\psi} C_1 \cdot \left\{ 1 - \left[1 - \frac{\psi}{\Omega} h \left(S_{dp}^* - S_{di} \right) \right] e^{\frac{\psi}{\Omega} h \left(S_{dp}^* - S_{di} \right)} \right\} \\ \quad + \frac{h}{\zeta} C_2 \cdot \left\{ 1 - \left[1 + \zeta \left(S_{dp}^* - S_{di} \right) \right] e^{-\zeta \left(S_{dp}^* - S_{di} \right)} \right\} \\ \quad - \frac{\Omega}{\lambda} C_3 \cdot \left\{ 1 - \left[1 - \frac{\lambda}{\Omega} h \left(S_{dp}^* - S_{di} \right) \right] e^{\frac{\lambda}{\Omega} h \left(S_{dp}^* - S_{di} \right)} \right\} + \frac{1}{\zeta} C_4 & \text{if } S_{dp}^* \le S_A / h + S_{di} \end{cases}$$

where

$$S_{dp}^* = S_{dp} + S_{iw} + f_c / \lambda$$

$$A_1 = \left[\frac{\frac{\zeta}{h}}{\frac{\lambda}{\Omega} + \frac{\zeta}{h}} \right] \qquad A_2 = \left[\frac{\frac{\lambda}{\Omega}}{\frac{\lambda}{\Omega} + \frac{\zeta}{h}} \right] \qquad A_3 = \left[\frac{\frac{\psi}{\Omega}}{\frac{\psi}{\Omega} + \frac{\zeta}{h}} \right] \qquad A_4 = \left[\frac{\frac{\psi}{\Omega}}{\frac{\psi}{\Omega} - \frac{\lambda}{\Omega}} \right]$$

$$A_5 = \left[\frac{\frac{\lambda}{\Omega}}{\frac{\lambda}{\Omega} + \zeta} \right] \qquad A_6 = \left[\frac{\frac{\psi}{\Omega} + \zeta e^{-\left(\frac{\psi}{\Omega}+\zeta\right)S_A}}{\frac{\psi}{\Omega} + \zeta} \right] \qquad A_m = \left[\frac{\frac{\zeta}{h}}{\frac{\zeta}{h} + \frac{\psi}{\Omega}} \right] \left[\frac{\frac{\lambda}{\Omega}}{\frac{\lambda}{\Omega} - \frac{\psi}{\Omega}} \right]$$

$$B_1 = A_2 \cdot A_3 \cdot \left[1 - e^{-\left(\frac{\psi}{\Omega}+\frac{\zeta}{h}\right)S_A} \right] \cdot e^{-\zeta \cdot S_{di}} \qquad B_2 = A_1 \cdot A_4 \cdot \left[1 - e^{-\left(\frac{\psi}{\Omega}-\frac{\lambda}{\Omega}\right)S_A} \right] \cdot e^{-\frac{\lambda}{\Omega}h\left(S_{dp}^{*}-S_{di}\right)-\zeta \cdot S_{dp}^{*}}$$

$$B_3 = A_1 \cdot e^{-\frac{\lambda}{\Omega}\left[h\left(S_{dp}^{*}-S_{di}\right)-S_A\right]-\frac{\psi}{\Omega}S_A-\zeta \cdot S_{dp}^{*}} \qquad B_4 = A_2 \cdot e^{-\zeta\left(\frac{S_A}{h}+S_{di}\right)-\frac{\psi}{\Omega}S_A}$$

$$B_5 = A_5 \cdot A_6 \cdot e^{-\zeta \cdot S_m}$$

$$C_1 = A_m e^{-\frac{\psi}{\Omega}h\left(S_{dp}^{*}-S_{di}\right)-\zeta \cdot S_{dp}^{*}} \qquad C_2 = A_2 \cdot A_3 \cdot e^{-\zeta \cdot S_{di}}$$

$$C_3 = A_1 \cdot A_4 \cdot e^{-\frac{\lambda}{\Omega}h\left(S_{dp}^{*}-S_{di}\right)-\zeta \cdot S_{dp}^{*}} \qquad C_4 = A_5 \cdot A_6 \cdot e^{-\zeta \cdot S_m}$$

MODELLING RESULTS

For the purposes of presenting and comparing results, a base case scenario is used herein that employs a catchment area of 1 ha, in addition to the parameter values identified earlier. Given the base case parameter values, the runoff (and pollution) control performance from the hypothetical infiltration facility modelled herein is calculated to be:

- 73.3% using the ASTORM model; and
- 73.7% using the ASWMM model.

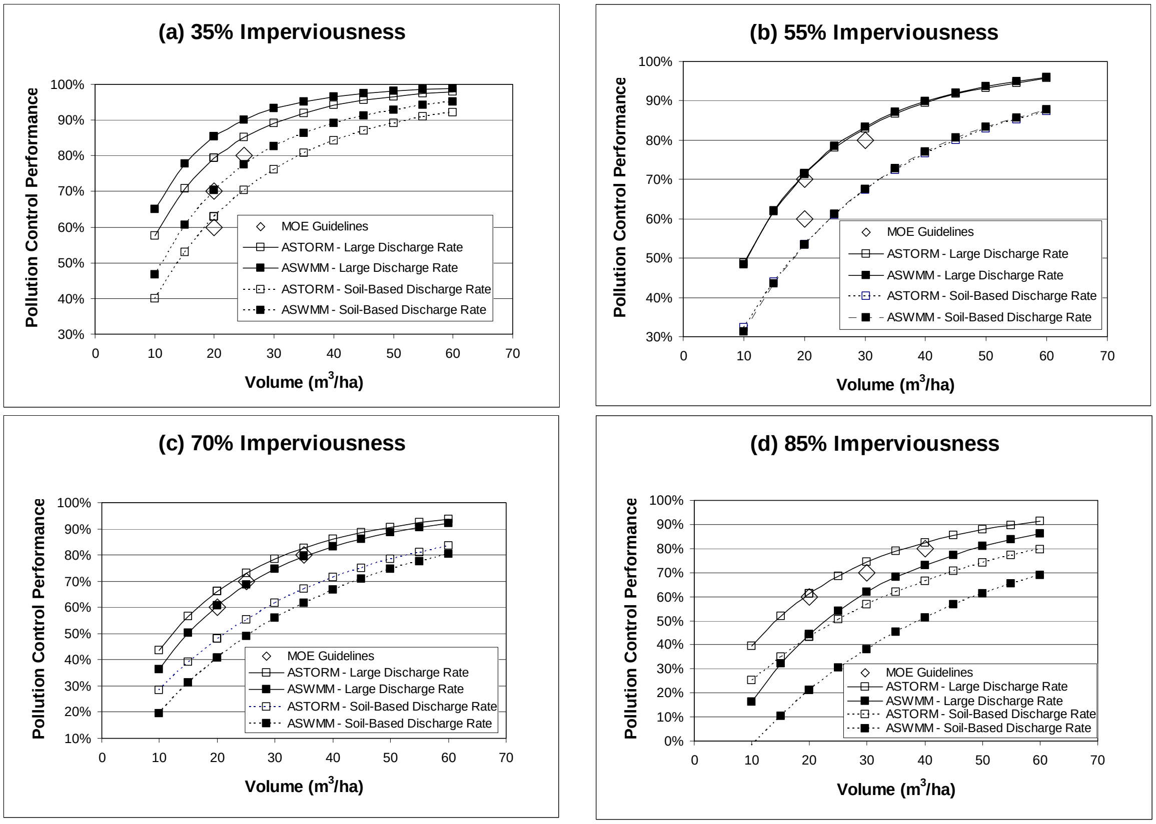
Comparison with Ontario Design Guidelines

First in 1994, then again in 2003, the Ontario government issued guidelines on the design of stormwater management facilities, including infiltration facilities (MOEE, 1994; MOE, 2003), hereinafter referred to as “MOE Guidelines”. In addition to practical considerations in the design of infiltration facilities (e.g., pecolation rates for surrounding native soils, construction details, etc.), these documents indicated the minimum storage volumes required in order to achieve certain runoff (pollution) control performance levels (see Table 4). These storage requirements, in turn, were derived by processing the results of a continuous simulation model (hourly flows and suspended solids loadings) through a model that estimated removal efficiencies from various stormwater management facilities.

The purpose of this section is to compare the MOE Guidelines with results generated using the ASTORM and ASWMM models. For this reason, the input parameters used for the latter models are consistent with those used to generate the values in the guidelines. Plots of performance versus storage volume, comparing the MOE Guidelines with the models, are presented in Figures 2a to 2d (see Soil-Based Discharge Rate curves). From visual inspection of the plots, the analytical models would suggest that larger storage volumes than those specified in the MOE Guidelines would be required to meet the various pollution control targets. The discrepancy increases with increasing imperviousness.

Table 4. Infiltration facility storage requirements (m^3/ha) taken from MOE Guidelines (MOEE 1994; MOE, 2003).

Pollution Control Performance	Imperviousness			
(Suspended Solids Removal)	35%	55%	70%	85%
80% (Enhanced Protection)	25	30	35	40
70% (Normal Protection)	20	20	25	30
60% (Basic Protection)	20	20	20	20



Figures 2a to 2d. Comparison of ASTORM and ASWMM modelling results with the MOE Guidelines.

Review of the available supporting documentation for the MOE Guidelines (Appendix I in MOEE, 1994) does not clearly indicate whether the outflow from the infiltration facilities was indeed considered in the modelling used to arrive at the values reproduced in Table 4 above. In fact, one would expect the percolation rate of the surrounding (receiving) soils to be an important element in the design of an infiltration facility. If it is assumed that the MOE Guidelines were derived not explicitly considering the release rate from the facility (i.e., sufficiently large Ω, regardless of soil), then the comparison of modelling results is as indicated in Figures 2a to 2d (see Large Discharge Rate curves).

Interestingly, the results presented in Figures 2a to 2d for the "large discharge rate" show remarkably good agreement between the MOE Guidelines and the results from the analytical models. Therefore, if the assumption that the release rate was not explicitly considered in deriving the MOE Guidelines, then it would appear that infiltration facilities designed in accordance therewith may be significantly undersized to achieve the desired control levels. The importance of the percolation and, hence, discharge rate used is in the determination of system performance between runoff events. A large discharge rate will result in the facility draining faster, thereby permitting a larger volume of runoff to be treated and, in turn, increasing performance levels; conversely, lower discharge rates increase the expected annual volume of spills or runoff by-passing by the facility since less volume may be available for the next runoff event (see Papa et al., 1999). An appropriate discharge rate for the receiving soils is therefore important for modelling purposes to ensure that the model is not over-predicting performance levels and that the facility is not under-designed as a consequence.

CONCLUSIONS

Analytical probabilistic models for the estimation of pollution control performance of infiltration facilities are presented herein and have been shown to provide a reliable and efficient method for guiding planning and design decisions. The model expressions are in a mathematically closed form thereby permitting the calculations to be performed by hand, or easily automated with programmable calculators or computer-based spreadsheet applications. In addition to their utility in the planning and design of on-site infiltration facilities, the model output can be used directly in regional water budget analyses.

The model results have been compared to design guidelines used in the Province of Ontario, Canada and, based on the findings presented herein, there may be cause to revisit the development of the guidelines to ensure that the performance of these facilities between runoff events is appropriately accounted for.

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