STORMCEPTOR HYDROLOGY AND NON-POINT SOURCE POLLUTION REMOVAL ESTIMATES

INTRODUCTION

The Stormceptor is a water quality separator designed to remove oil and sediment from stormwater. A key feature of the design is an internal high flow by-pass to prevent scouring and re-suspension of previously trapped pollutants. Since the separator is based on treating “the everyday storm”, the effectiveness of the separator is dependent on the distribution of pollution in stormwater and the frequency and magnitude of stormwater flows throughout the year.

In 1995, sizing guidelines were derived for the Stormceptor based on field monitoring of sludge accumulation over time in Toronto, Ontario, Canada. The accumulation data was used to derive estimates of annual total suspended solids (TSS) removal. Two key assumptions were made in the 1995 analysis to estimate TSS removal: a TSS loading rate of 185 mg/l (United States Environmental Protection Agency (USEPA) Nationwide Urban Runoff Program (NURP) median, 1983); and a sludge water content (75% water). Actual Toronto rainfall data combined with the NURP TSS concentrations provided estimates of annual TSS loading.

Toronto rainfall time series data (5 minute timestep) were put into a continuous hydrologic simulation model (Storm Water Management Model (SWMM) Version 4.3) to determine the percentage of annual runoff treated based on these sizing criteria. The analysis of Toronto rainfall indicated that 80% - 90% of the annual runoff would be treated if the Stormceptor was sized according to the 1995 guidelines.

This study was initiated to develop sizing criteria that could be used for areas with hydrology that differ from Toronto and to incorporate field monitoring data that has been conducted on the Stormceptor since 1995.

METHODOLOGY

A computer simulation model was developed based on the USEPA SWMM Version 4.3. Solids build-up, washoff and settling calculations were added to the hydrology code to estimate suspended solids capture by the Stormceptor.

Rainfall from the City of Toronto (5 minute timestep, 0.25 mm resolution, 10 years record, 1987-1996) was agglomerated into 15 minute data for use with the model. Fifteen minute data were obtained for the entire USA from Earth Info on CD ROM.

Stations were selected based on location, period of record, data resolution and completeness within the period of record. Data was also obtained from CSR Humes for various stations throughout Australia. The rainfall data was converted into NCDC format for input to SWMM.

Fifteen minute data were utilized recognizing the small time of concentration that would typically be encountered in most Stormceptor applications. Simulations were also conducted using hourly data to determine the sensitivity of the results to the precipitation timestep. Numerous hourly stations were available on an EarthInfo CD for this purpose. The model uses a 5 minute timestep at all times regardless of the rainfall timestep.

SWMM models catchments and conveyance systems based on input rain, temperature, wind speed and evaporation data. Only rain data were used in these analysis. The default SWMM daily evaporation values (2.5 mm/day) were used. Evaporation data will not be important in this analysis since the catchment area is small (< 10 ha) and has minimal depression storage. The Horton equation was chosen for infiltration. The method of infiltration chosen is unimportant due to the small amount of pervious area simulated in this study (mainly parking lots, etc.). Values of SWMM parameters used in the model are shown in Table 1.

Table 1

SWMM Area Parameters	
Area - ha (ac)	variable
Imperviousness	99%
Width - m (ft)	variable *
Slope	2%
Impervious Depression Storage - mm (in.)	4.7 (0.19)
Pervious Depression Storage - mm (in.)	0.5 (0.02)
Impervious Mannings n	0.015
Pervious Mannings n	0.25
Maximum Infiltration Rate - mm/h (in/hr)	62.5 (2.46)
Minimum Infiltration Rate - mm/h (in/hr)	10 (0.39)
Decay Rate of Infiltration (s^{-1})	0.00055

* The width of catchment was assumed equal to twice the square root of the area.

The distribution of pollutant load is important for measures that incorporate a high-flow by-pass (commonly known as “first flush” measures). Accordingly, build-up/wash-off calculations were employed to correctly distribute the pollutant load with flow recognizing the need to optimize the sizing of small-site stormwater quality measures.

In the model, solids build-up and wash-off are both approximated using an exponential distribution. The distribution of solids build-up is a function of antecedent dry days according to equation 1 (Sartor and Boyd, 1972).

$$P_t = P_i + (PA-Pi)(1-e^{-kt}) \qquad (1)$$

Where:

P_t = solids accumulation up to day t (kg)

P = maximum solids build-up (2.4 kg/ha)

A = drainage area (ha)

P_i = initial solids load on the surface (not washed off from the previous storm) (kg)

k = exponential build-up factor (0.4) (days^{-1})

t = antecedent dry days

An exponential build-up factor (k) of 0.4 was used based on previous literature (SWMM 4.3 users manual). A k value of 0.4 translates into 90% of the maximum solids build-up occurring after 5.66 days. Once the pollutant build-up reaches the 2.4 kg/ha limit additional build-up is not allowed (assumed to be wind re-suspended/driven off the surface). Wash-off is estimated using equation 2.

$$P_t = P_i e_{-}^{kV} \qquad (2)$$

Where:

P_t = solids remaining on the surface at day t (kg)

P_i = initial solids load (from equation 1) (kg)

k = exponential decay factor (0.2) (mm^{-1})

V = volume of accumulated runoff from the surface (mm)

The exponential decay factor (k) of 0.2 was based on a review of previous literature that indicated k values range from 0.03 to 0.55 (Alley, 1981; Charbeneau and Barrett, 1998).

Charbeneau and Barrett (1998) found that the simple wash-off model adequately described observed solids wash-off in Austin, Texas. Other researchers have cited that the wash-off equation (2) is reasonable for fine material but may not be reasonable for larger solids that require a high rainfall intensity for mobilization (Metcalf and Eddy, 1971; Ball and Abustan, 1995). The SWMM model treats wash-off as a function of the runoff rate to account for mobilization. This correction is applied indiscriminately to the entire solids load and does not account for the variation in wash-off rate with particle size. If an “availability” factor is applied to all particle sizes uniformly, the model will underestimate the wash-off of solids with increasing runoff volume if the majority of particles are fine in size. The approach taken in this study was to use an availability factor for particles larger than 150 µm. Smaller particles follow the simple wash-off estimates given by equation 2. The larger particles (> 150 µm) require greater runoff intensities to induce wash-off according to the availability factor provided in equation 3.

$$A = 0.057 + 0.04(r)^{1.1} \quad (3)$$

<u>Where:</u>

A = availability factor

r = runoff rate (mm/h)

Equation 3 is based on research by Novotny and Chesters (1981). The runoff rate is used instead of rainfall intensity recognizing that the wash-off will lag the rainfall based on the time of concentration. The availability factor varies each timestep and is only applied to the runoff volume for that timestep as dictated in equation 4. The availability factor has an upper limit of 1.

$$V = V_i + A(V_t) \quad (4)$$

<u>Where:</u>

V = accumulated runoff volume used in equation 2 (mm)

V_i = accumulated runoff volume prior to current timestep (mm)

A = availability factor (equals 1 for particles smaller or equal to 150 µm)

V_t = runoff volume for current timestep (mm)

The correction in equation 4 effectively re-defines the accumulated runoff volume to be the runoff volume sufficient to mobilize the particles. This methodology requires more accounting in the model but provides a more physically correct wash-off model.

The separator was treated as a completely stirred tank reactor (CSTR). Changes to the concentration of solids in the separator will vary according to equation 5 (Tchobanoglous and Schroeder, 1987).

$$C'V = QC_i - QC_t - r_cV \quad (5)$$

<u>Where:</u>

C' = the change in concentration of solids in the tank with time (kg/m^3s)

Q = flow rate through the tank (m^3/s)

C_i = solids concentration in the influent to the tank (kg/m^3)

C_t = solids concentration in the tank (kg/m^3)

V = tank volume (m^3)

r_c = reduction in solids in the tank (kg/m^3s)

For gravity settling devices r_c can be estimated using equation 6.

$$r_c = V_sC/D \qquad (6)$$

Where:

r_c = reduction in solids in the tank (kg/m^3s)

Vs = settling velocity of solids (m/s)

D = depth of tank (m)

C = concentration of solids in the tank (kg/m^3)

Substituting equation 6 into equation 5, solving the first-order differential equation and integrating provides the general form of the non-steady state solution (equation 7) for the solids concentration in the tank at time t.

$$C = QC_i/(V(V_s/D + Q/V))(1-e^{-(Vs/D\ +\ Q/V)t}) + C_te^{-(Vs/D\ +\ Q/V)t} \qquad (7)$$

Where:

C = concentration in the tank at time t (kg/m^3)

C_i = concentration in the flow influent to the tank (kg/m^3)

C_t = concentration in the tank at the beginning of the timestep (kg/m^3)

Q = flow rate through the tank (m^3/s)

V = volume of water in the tank (m^3)

V_s = suspended solids settling velocity (m/s)

D = tank depth

t = time

Equation 7 was used to estimate the suspended solids concentration in the tank, and in the discharge from the tank each timestep. Equation 7 assumes the suspended solids are completely mixed within the tank volume.

During periods without flow (inter-event periods) the solids are not assumed completely mixed at the beginning of each timestep and the depth of suspended solids in the separator decreases each timestep until all of the solids are removed or there are subsequent flows into the separator. The concentration of solids in the tank during periods without flow was calculated using equation 8.

$$C = C_t\ (1-V_st/\ D) \qquad (8)$$

Where:

C = solids concentration in the tank (kg/m^3)

C_t = initial solids concentration in the tank at the beginning of the timestep (kg/m^3)

V_s = settling velocity (m/s)

t = timestep (s)

D = depth of solids in the separator (m)

The depth of solids (D) in the separator in Equation 8 decreases each timestep based on the settling velocity until all of the solids are removed or there are subsequent inflows to the tank.

The model can be used with either hourly or 15 minute rainfall data. Fifteen minute data is preferred recognizing for small drainage area applications. Small drainage areas have short times of concentration and require data with a suitable timestep. Internally, the model performs calculations with a 5 minute timestep.

The choice of particle size distribution and settling velocities are a key part of the modeling exercise. Different settling velocities can be applied to the same particle size distribution based on the specific gravity of the particles, or to account for the effect of non-ideal settling or the effect of flocculation on settling. Two particle size distributions can be selected in the model. A particle size distribution can be selected that reflects the fines in stormwater (USEPA, 1983; Minton, 1999). This particle size distribution is given in Table 2. The distribution given in Table 2 is commonly accepted by most regulatory agencies in North America. A coarse particle size distribution can also be selected which reflects material larger than or equal to 150 µm. This distribution is given in Table 3. The coarse distribution is provided to allow comparisons with competitors that size their devices based on only the larger particles.

Settling velocities were then assessed for each of the particle sizes provided in Tables 2 and 3. The calculation of settling velocities was based on Stokes' law (equation 9).

$$Vs = g\,(p_s - p_w)d^2/18u \qquad (9)$$

Where:

Vs = settling velocity for particle diameter d (m/s)

g = gravity (m/s^2)

p_s = density of particles (kg/m^3)

p_w = density of water (kg/m^3)

d = particle diameter (m)

u = viscosity of water (kg/ms)

$N_R = S_f V_s d p_w / u$ (10)

Where:

N_R = Reynolds number

Vs = settling velocity for particle diameter d (m/s)

p_w = density of water (kg/m^3)

d = particle diameter (m)

u = viscosity of water (kg/ms)

S_f = shape factor (0.85)

In cases where the Reynolds number (equation 10) was calculated to be greater than 0.3. an iterative solution that accounts for the drag coefficient was used to solve for the settling velocity (solving for the Reynolds number, drag coefficient, and settling velocity until changes in the settling velocity were insignificant). The drag coefficient is given by equation 11, and the settling velocity is calculated by equation 12.

$C_D = 24/N_R + 3/(N_R^{0.5}) + 0.34$ (11)

Where:

C_D = drag coefficient

N_R = Reynolds number

$Vs = (4g(p_s - p_w)d/(3C_D p_w))^{0.5}$ (12)

Where:

Vs = settling velocity for particle diameter d (m/s)

g = gravity (m/s^2)

p_s = density of particles (kg/m^3)

p_w= density of water (kg/m^3)

d = particle diameter (m)

C_D = drag coefficient

A specific gravity of 2.65 is commonly associated with sand-size particles whereas the fines in stormwater are commonly associated with a lower specific gravity due to the organic content.

Research indicates that there is a high potential for coagulation amongst the smaller particles (Ball and Abustan, 1995) which will increase settling velocities and TSS removal rates. Furthermore, historical settling velocity calculations have been based on discrete particle methodologies (vertical settling column tests) that do not account for potential coagulation or flocculation. Numerous field tests on the Stormceptor (Labatiuk, 1996; Ontario MOE, 1999; Bryant, 1995) have shown that a significant percentage of the solids collected in the Stormceptor are fine. In recognition of this, a flocculation equation (13) was used to determine the settling velocity for particles equal to or smaller than 20 µm.

$$V_s = 0.35 + 1.77 P_s \qquad (13)$$

<u>Where:</u>

V_s = Settling Velocity (mm/s)

P_s = Particle Size (mm)

Table 2

Typical Stormwater Particle Size Distribution			
Particle Size (µm)	Percent by mass (%)	Specific Gravity	Settling Velocity (m/s)
20	20	*	0.00035
60	20	1.8	0.00158
150	20	2.2	0.01070
400	20	2.65	0.06500
2000	20	2.65	0.28700

* Flocculated settling velocity based on Equation 13

Table 3

Coarse Stormwater Particle Size Distribution			
Particle Size (µm)	Percent by mass (%)	Specific Gravity	Settling Velocity (m/s)
150	60	2.65	0.01440
400	20	2.65	0.06500
2000	20	2.65	0.28700

The solids loading from the wash-off calculations (2) was segmented into the particle size distribution (Table 2 or 3) and the concentration of solids in each particle size was tracked individually during the settling calculations.

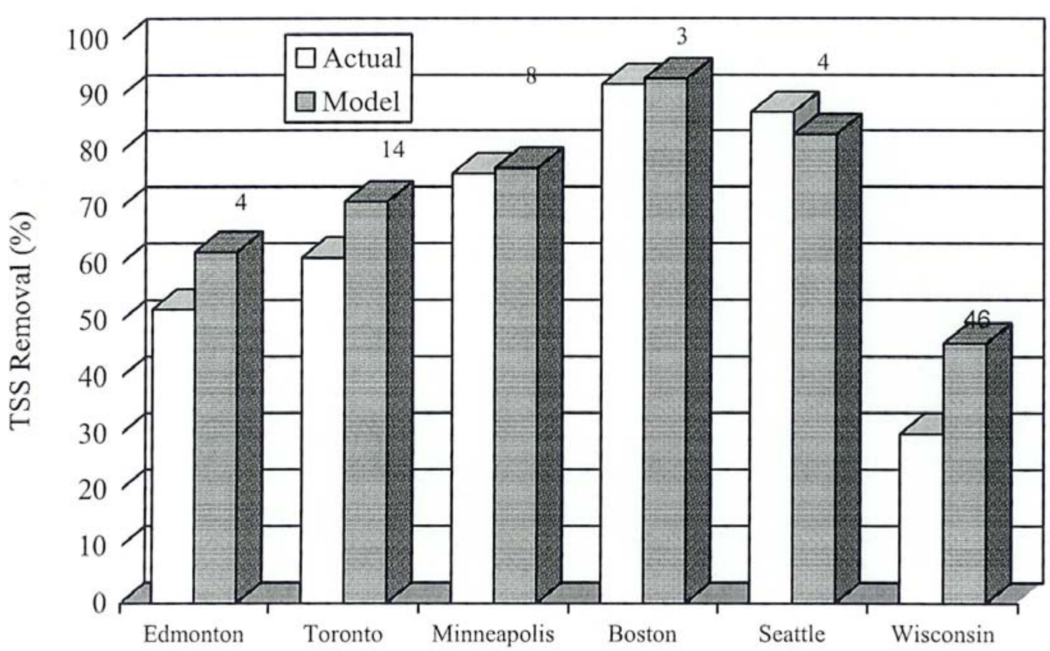
The influent pollution is distributed uniformly in the flow such that during by-pass conditions the amount of pollution in the by-pass is proportional to the flow being by-passed. The total load to the Stormceptor, load removed by the Stormceptor, and load by-passing the Stormceptor are calculated at the end of the simulation to provide an estimate of overall TSS removal. The total volume of water coming to the Stormceptor and bypassing the Stormceptor for the period of record are used to calculate the percentage of annual runoff treated by the Stormceptor.

Results from the model have been compared with field monitoring results. The actual particle size distribution of the sediment in the monitored Stormceptor was modeled to provide the estimates of TSS removal in Figure 1. The modeled TSS removal estimates in Figure 1 are based on the settling velocities given in Table 1 (gradated specific gravity and flocculated settling for less than or equal to 20 µm. The Wisconsin field monitoring was modeled with a power washoff function due to the exposed sand/salt/yard waste/used snow piles. On sites with exposed material, the standard buildup/washoff loading function would be inappropriate.

Figure 1 indicates that the model provides reasonable estimates of TSS removal when compared with actual monitoring performance.

Figure 1

COMPARISON OF MODEL RESULTS WITH FIELD MONITORING
(r2 = 0.97)



REFERENCES

Alley, W., Estimation of Impervious-Area Washoff Parameters, Water Resources Res., 17, 1161, 1981

Ball, J., and Abustan, I, An Investigation of Particle Size Distribution during Storm Events from an Urban Catchment, University of New South Wales, 1995

Ball, J., Jenks, R., Aubourg, D., An assessment of the availability of pollutant constituents on road surfaces, University of New South Wales, 1997

Bryant, G., Misa, F., Weatherbe, D., Snodgrass, W., Field Monitoring of Stormceptor Performance, 1995

Charbeneau, R., Barrett, M., Evaluation of methods for estimating stormwater pollutant loads, Water Environment Research, Volume 70, Number 7, 1998

Henry, D., Liang, W., Ristic, S., Comparison of Year-Round Performance for Two Types of Oil and Grit Separators, Draft paper, 1999

Labatiuk, C., Nataly, V., Bhardwaj, V., Field Evaluation of a Pollution Abatement Device for Stormwater Quality Improvement, CSCE Environmental Engineering Conference, Edmonton, 1997

Minton, G., Protocol for the Acceptance of New Stormwater Treatment Technologies in the Puget Sound Watershed, Draft Proposal Version 4, 1999

Novtony, V., Unit Pollutant Loads, Water Environment & Technology, 1992

Sartor, J. , Boyd, G., Water Pollution Aspects of Street Surface Contaminants, EPA-R2-72-081, U.S> Environmental Protection Agency, Washington, D.C., 1972

Tchobanoglous, G., Schroeder, E., Water Quality, University of California at Davis, 1987

U.S. Environmental Protection Agency, Final Report of the Nationwide Urban Runoff Program, Water Planning Division, Washington, D.C.,1983

U.S. Environmental Protection Agency, Storm Water Management Model, Version 4.3, User's Manual, Washington, D.C., 1988