STORMCEPTOR HYDROLOGY AND NON-POINT SOURCE POLLUTION REMOVAL ESTIMATES

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Abstract. A model was developed to estimate total suspended solids (TSS) removal in the Stormceptor, an oil/sediment separator. The model was based on a commonly used continuous simulation model (USEPA SWMM) for hydrological processes. The suspended solids' loading was estimated using build-up and wash-off equations. The solids were assumed to be distributed into five particle sizes for settling calculations. Simulations were conducted using various assumptions of loading and settling velocities to determine the sensitivity of the model to assumptions. Simulations were also conducted for a diverse range of geographic areas to determine the sensitivity of the TSS removal rates to regional hydrology. The model was sensitive to the selection of settling velocities and pollutant loading. The model was less sensitive to changes in hydrology although significant changes in hydrology did impact TSS removal estimates.

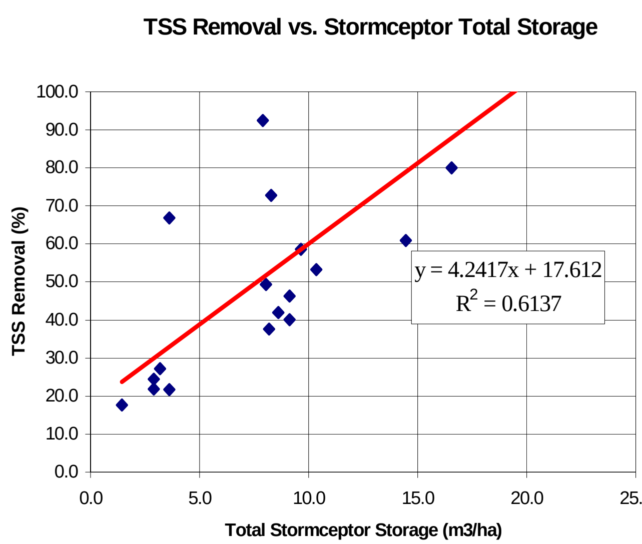
INTRODUCTION

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. Figure 1 shows the performance relationship derived from the Toronto monitoring, which forms the basis for the existing sizing guidelines.

Toronto rainfall time series data (5 minute timestep) were input to 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 were sized according to the 1995 guidelines.

Figure 1: TSS Removal vs. Stormceptor Total Storage



This study was initiated to address concerns about the applicability of the Toronto-based sizing criteria for regional meteorological conditions.

METHODOLOGY

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

The model accommodates the use of either an EMC (event mean concentration) or build-up/wash-off calculations to estimate suspended solids loads. The build-up/wash-off model is more theoretically and physically correct. The EMC method has been shown to provide reasonable estimates of total solids loads (Charbeneau and Barrett, 1998) alone, if the distribution of the load is not important.

The distribution of pollutant load is important for measures that incorporate a high-flow by-pass (commonly known as "first flush" measures). Accordingly, preference is given to the build-up/wash-off calculations 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).

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

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

The maximum pollutant build-up (P) load was adjusted to provide similar long-term solids loading rates (124 mg/l) when compared to the EMC method. 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: Pt = solids remaining on the surface at day t (kg)
Pi = 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 400 µm in size or larger. Smaller particles follow the simple wash-off estimates given by equation 2. The larger particles (≥ 400 µm) require greater runoff intensities to induce wash-off according to the availability factor provided in equation 3.

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

Where: 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.

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

Where: 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 than 400 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). Alterations to the concentration of solids in the separator will vary according to equation 5 (Tchobanoglous and Schroeder, 1987).

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

Where
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.

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

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 concentration in the tank at time t.

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

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.

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

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 that the Stormceptor is only applicable for small drainage areas. 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. In this study, a typical stormwater particle size distribution (USEPA, 1983) was used for analysis (Table 1). The distribution given in Table 1 is
commonly accepted by most regulatory agencies in North America.

The model allows the user to alter the percentages of each size based on site-specific conditions if required. In most areas, it is anticipated that the particle size distribution will not vary significantly since it is primarily related to vehicle wear and atmospheric deposition. There may be certain instances, however, where the native soils

Table 2. Discrete Particle Size Settling Velocities (mm/s)

Particle Size (μm)	S.G. = 1.3 calculated	S.G. = 1.8 calculated	S.G. = 2.65 calculated	USEPA (1983) empirical
20	0.07	0.17	0.36	0.00254
60	0.59	1.57	3.23	0.02540
130	2.50	5.70	11.20	0.12700
400	16.00	37.00	65.00	0.59267
4000	180.00	300.00	450.00	5.50330

S.G. = Specific Gravity

Table 1. Default Particle Size Distribution

Particle Size (μm)	% by Mass
20	20
60	20
130	20
400	20
4000	20

Table 3. PCSWMM 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 Manning's n	0.015
Pervious Manning's 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

contribute loading and the default distribution needs to be altered. The default percentages were used in this study.

Settling velocities were then assessed for each of the particle sizes provided in Table 1. Settling velocities were either calculated or based on empirical literature (USEPA, 1983). The calculation of settling velocities for small particles follows Stokes' law (equation 9) since the Reynolds number (equation 10) is less than 0.3.

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

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)

$$N_R = V_s d p_w/u \qquad (10)$$

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)

If the Reynolds number is greater than 0.3, drag on the particles reduces the settling velocity. An iterative solution was used (solving for the Reynolds number, drag coefficient, and settling velocity until changes in the settling velocity were insignificant) for particle sizes with the Reynolds numbers. The drag coefficient is given by equation 11, and the settling velocity is calculated by equation 12.

$$C_D = 24/N_R + 3/(N_R 0.5) + 0.34 \qquad (11)$$

Where C_D = drag coefficient
N_R = Reynolds number

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

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

Table 2 provides a comparison of the settling velocities used in this study.

The settling velocities based on the empirical USEPA data are 65 to 150 times smaller than the settling velocities based on a specific gravity of 2.65. 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. The use of a higher specific gravity may be justified, however, if the values are considered representative of the settling velocities of fines in a flocculated or coagulated state. Research indicates that there is a high potential for coagulation amongst 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. Coagulation would effectively offset the settling velocity columns in Table 2 (i.e. discrete settling velocity for 60 μm represents coagulated 20 μm particle size).

Numerous field tests on the Stormceptor (Labatiuk, 1996; Ontario MOE, 1999; Bryant, 1995) have indicated a high percentage of fines in the Stormceptor. This empirical evidence lends credence to the coagulated settling theory indicating that the USEPA discrete particle settling velocities may underestimate actual TSS removal rates. Settling velocities based on a specific gravity of 1.8 were chosen in this study as the default or benchmark selection. The solids loading was segmented into the particle size distribution and the concentration of solids in each particle size was tracked individually during the settling calculations.

Meteorological Data. 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 EarthInfo 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 the EarthInfo CD for this purpose. The model uses a 5 minute timestep at all times regardless of the rainfall timestep.

Modeling Parameters. SWMM models catchments and conveyance systems based on input rain, temperature, wind speed and evaporation data. Only rain data were used in these analyses. The default SWMM daily evaporation values (2.5 mm/day) were used. Evaporation data will not be important in this analysis since the catchment's 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 (1%). Table 3 provides a list of the parameters used in the SWMM model.

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

RESULTS

EMC versus Build-up/Wash-off. The suspended solids removal results based on the build-up/wash-off model were compared to those based on an EMC (124 mg/l; USEPA, 1983) to demonstrate the sensitivity of the model to the different solids loading approaches. The use of an EMC assumes an equal concentration of suspended solids in all of the stormwater that is conveyed to the Stormceptor.

Figure 2 shows a comparison of results using an event mean concentration loading and build-up/wash-off loading
given the default particle size distribution and settling velocities based on a specific gravity of 1.8.

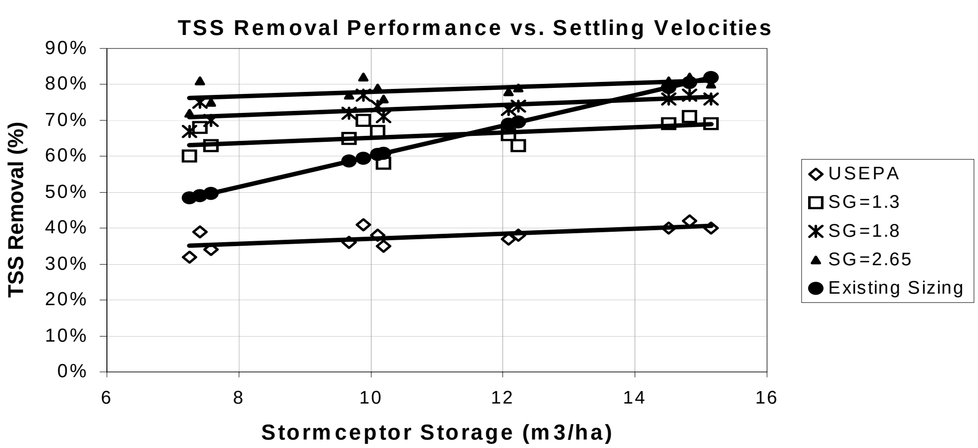


Figure 3 TSS Removal Performance vs. Settling Velocities

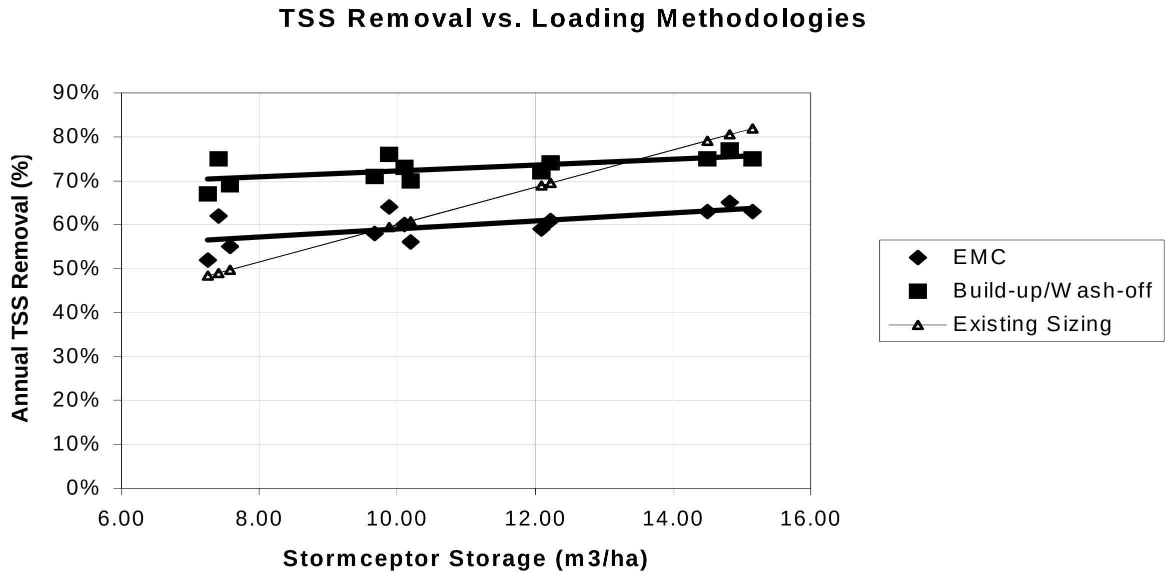


Figure 2. TSS Removal vs. Loading Methodologies

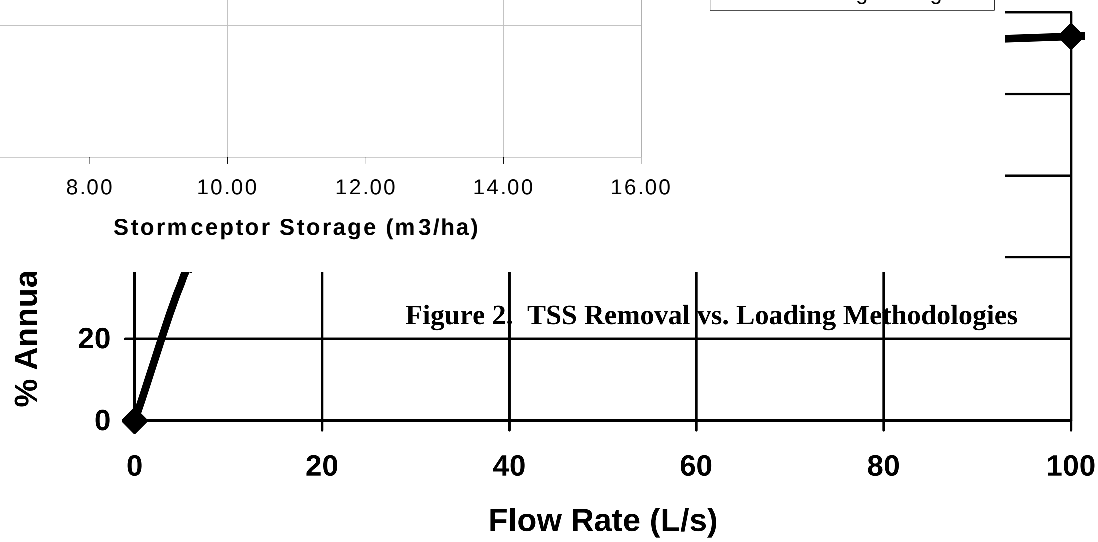


Figure 4. TSS Removal Performance vs. Settling Velocities

The results in Figure 2 show that the TSS removal rates using the EMC approach are lower by 14% when compared to the build-up/wash-off method even though the total loads are similar. This is expected due to the by-pass nature of the Stormceptor. The estimated TSS removals for the existing sizing guidelines which are based on an early field study are lower than both the EMC and build-up/wash-off estimates for low values (50% TSS removal) of separator storage/drainage area and are higher than the other estimates for larger values of separator storage/drainage area (80% TSS removal).

The range of TSS removal values based on computer modeling is smaller than the empirical TSS removal rates. Doubling the size of unit for the same area results in an increase of 30% for TSS removal based on the current sizing guidelines whereas the increase in performance based on the modeling is less dramatic (a 5% to 10% increase in TSS performance). This finding indicates that the modeling results will be less sensitive to changes in the model size for any given drainage area.

Selection of Settling Velocities. A comparison was made regarding the choice of settling velocities using Toronto rainfall data and the build-up/wash-off TSS generation methodology. Figure 3 provides the results of this analysis. The TSS removal estimates using the USEPA settling velocities are an average of 20% lower than the original TSS removal estimates, 29% lower than the estimates using the SG=1.3 velocities and 39% lower than the estimates using the SG=2.65 velocities. These results indicate that the TSS removal performance results are very sensitive to the selection of settling velocities.

Annual Flow Treatment. Numerous regulatory agencies design stormwater quality measures using a “design” event. The design event used generally ranges from the 25 mm storm or annual storm to the 25-year storm. The modified SWMM program was used to calculate the percentage of annual runoff that would be treated (not by-passed) with different by-pass flow rates. This analysis was conducted using the Toronto rainfall for a drainage area of 2.25 ha. Figure 4 shows that the volume of runoff that is treated prior to by-pass quickly becomes asymptotic with increasing treatment flow rate. A device that treats 30 L/s prior to by-pass would treat approximately 80% of the annual runoff. A device that treats 70 L/s (over 2x higher flow rate) only treats 10%

more runoff (90%). Although the relationship between conveyance (% of annual runoff treated) and TSS removal is non-linear, Figure 4 shows that high rate treatment devices are not required for small drainage areas.

The relationship provided in Figure 4 will vary with local meteorological conditions and this is inherently accounted for in the TSS removal modeling.

Regional TSS Removal Performance Analysis. The model was used to compare results from different areas in North America and Australia to determine the effect of regional hydrology on TSS removal performance. All analyses were conducted using 15-minute rainfall data based on the TSS build-up and washoff model and settling velocities for a specific gravity of 1.8.

Table 4 shows the results for various size Stormceptor units with a 2 ha drainage area. The results are plotted in order of decreasing performance expectations. The stations in Table 4 were selected to cover a wide geographic area, provide rainfall on a 15-minute timestep with a 0.25 mm resolution, and provide results

Table 4. Regional Comparison of TSS Removal Performance (2ha)

State/ Province	Location	Stormceptor Model (CDN/USA)					
		300/ 450	750/ 900	1500/ 1800	3000/ 3600	5000/ 6000	6000/ 7200
Colorado	Fort Collins	49%	63%	65%	71%	76%	79%
Alberta	Calgary Forest	48%	63%	65%	71%	76%	79%
British Columbia	Vancouver	48%	65%	66%	71%	76%	78%
California	Davis	44%	61%	63%	69%	74%	77%
Massachusetts	East Brimfield Lake	43%	59%	61%	67%	73%	75%
Ontario	Toronto	43%	58%	60%	66%	72%	75%
New South Wales	Sydney	42%	57%	59%	66%	72%	76%
New York	Rhinebeck	41%	57%	59%	65%	71%	74%
North Carolina	Cataloochee	41%	56%	58%	64%	71%	74%
Queensland	Brisbane	41%	55%	57%	64%	71%	74%
Minnesota	Le Sueur	41%	56%	57%	64%	70%	74%
California	Orange County	39%	57%	59%	65%	71%	74%
Maryland	College Park	37%	53%	54%	61%	67%	70%
Missouri	Miller	34%	50%	51%	59%	65%	69%
Florida	St. Lucie New Lock	30%	43%	44%	52%	59%	64%
Texas	Houston Addicks	27%	41%	42%	49%	57%	61%

representative of large nearby cities. Most data from city airports are recorded hourly, and therefore were not included in the comparison. The results in Table 4 are plotted on Figure 5.

Of the 16 stations analyzed, 12 stations provided TSS removal estimates within ±5% of the Toronto values.

Although the majority of stations provided similar TSS removal estimates, there were areas with significant differences. The performance estimates were lowest for the southeastern United States. This area is well known for it's intense seasonal rainfall distribution. Figure 5 indicates that the TSS removal rates may vary up to 20% under different hydrological conditions on the same land use/site conditions. The use of local or regional rainfall data is therefore appropriate for design purposes.

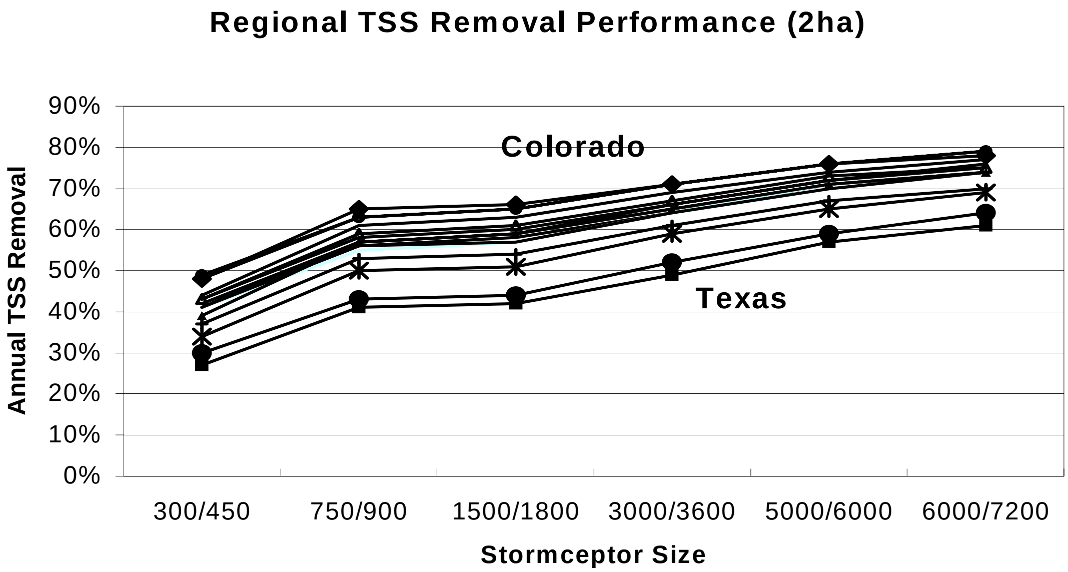


Figure 5. Regional TSS Removal Performance (2ha)

Rainfall Timestep. An analysis was conducted to determine the sensitivity of the model to changes in the rainfall resolution. Results based on hourly rainfall data

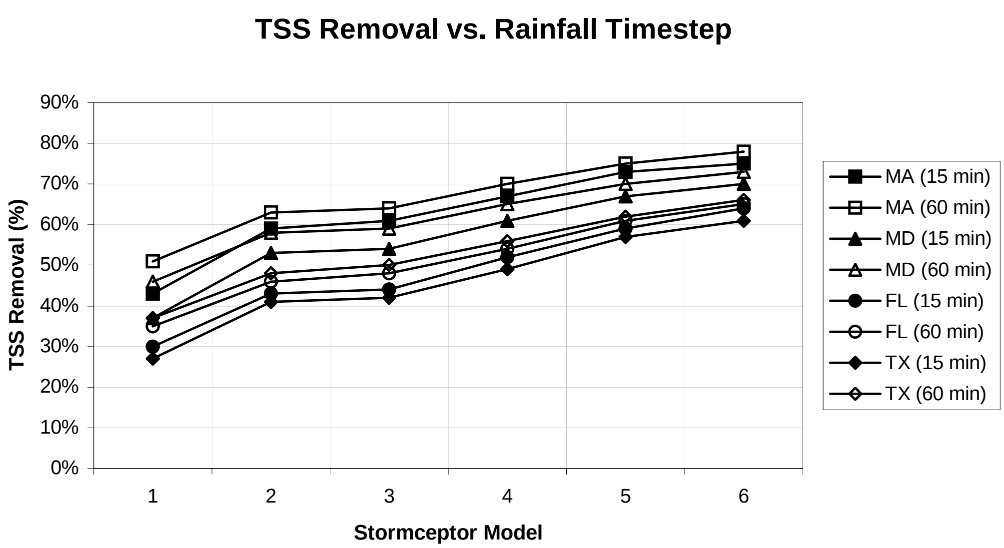


Figure 6. TSS Removal vs. Rainfall Timestep

(0.25 mm resolution) were compared to those based on 15 minute rainfall data to determine the impact of using the hourly data. Hourly data is more readily available than 15-minute data and most large cities have airports that collect rainfall on an hourly basis.

The model reads the hourly data as rainfall that falls during the first fifteen-minute timestep of each hour. This will produce higher intensities since the rain is not distributed correctly over the entire hour. The greater intensity is compensated, however, by the completeness of the hourly records, which translates into a greater number of small rainfall values.

Four areas were analyzed (Rockville, Maryland; Boston, Massachusetts; Miami, Florida and; Houston, Texas). The results of this analysis (Figure 6) indicate that the use of hourly data does not significantly alter the TSS removal estimates for units that are designed to remove over 40% of the annual TSS load. Greater discrepancies can be expected at large ratios of drainage area to separator storage.

CONCLUSIONS

The TSS removal results were sensitive to the selection of settling velocities for the specified particle distribution. Differences in TSS removal of up to 40% were obtained depending on the settling velocities that were evaluated.

Results were also affected by the TSS loading method. The use of an EMC underestimated TSS removal performance by approximately 15% when compared to the use of the build-up and wash-off equations. This difference is expected since the EMC method increases the load that is by-passed and provides higher loads during higher treated flow rates when the detention time and hence settling effectiveness of the unit is reduced.

The model indicates that high percentages of the annual runoff can be treated with low flow treatment devices such as the Stormceptor. The model also predicts that the TSS removal performance is less sensitive to the size of separator than that observed from previous field studies.

Regional hydrology affected the TSS removal estimates provided by the model. Although differences of up to 20% were observed, significant hydrological differences between the sites were needed to obtain this variance. Most of the rainfall station locations tested provided TSS removal estimates similar to those of Toronto where the original sizing guidelines were developed.

Testing of the model with different rainfall timesteps (15 minute versus hourly) indicated that hourly rainfall records can provide an adequate estimation of performance if the rainfall is collected at an adequate resolution (0.25 mm increments).

The modeling indicated that significant TSS removal rates can be achieved using small infrastructure control measures if the drainage area is limited. The results lend credence to the positive field monitoring results obtained to-date for the Stormceptor, and to the concept of small storm hydrology being the predominant parameter for urban stormwater quality design.

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