Hydroworks Hydroguard

Sizing Methodology & Calculations

Hydroguard Sizing

Introduction

The design methodology for stormwater quality varies with the type of technology being designed. Storage devices are generally designed based on capturing a volume of stormwater runoff. Filtration devices are designed based on contact time and storage to provide a consistent contact time. Hydrodynamic separators are designed based flow rate/detention time.

Since there is considerable variability of flow rate in stormwater, some companies such as Hydroworks™ are trying to consider this variability in the design of their systems. It is for this reason that Hydroworks has decided to design the Hydroguard based on continuous simulation of rainfall/runoff and TSS loading and removal. This provides the most accurate way to design the system since it takes into account the variability of flow and TSS over time.

Hydroguard Operation

Hydroguard is a stormwater quality treatment structure designed to remove solids and floatable material from urban stormwater runoff. The implementation of water quality treatment structures is one of the six measures identified by the Environmental Protection Agency (EPA) that should be taken to protect and maintain water quality under the National Pollution Discharge Elimination System (NPDES) program. Most urban communities must obtain NPDES permits from the EPA to be in compliance with the Clean Water Act. All urban development must comply with the requirements of the NPDES permit.

Hydroguard is designed to remove solids and floatables during both low and high flow periods. Treatment occurs in separate areas of the device for low flows versus high flows thereby preventing scour of TSS settled in the low flow path during periods of peak flow. This design is unique since most BMPs either treat low flows and bypass high flows or try to treat all flows in the same flow path through the device.

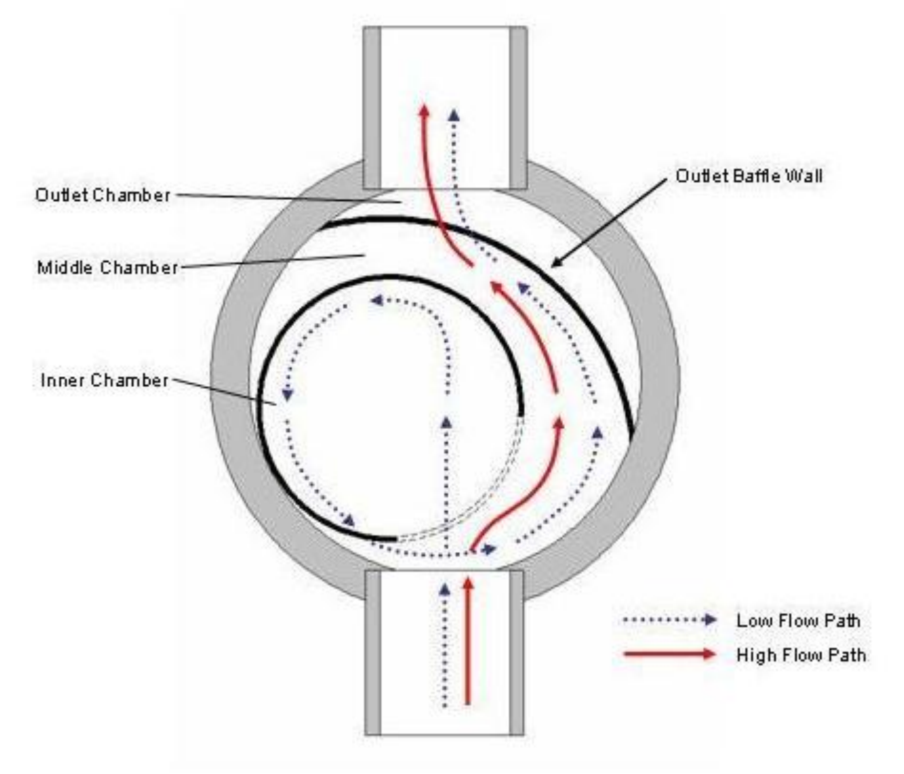
Hydroguard consists of three chambers:

1. an inner chamber that treats low or normal flows
2. a middle chamber that treats high flows
3. an outlet chamber where water is discharged to the downstream storm system

Under normal or low flows, water enters the middle chamber and is conveyed into the inner chamber by momentum. The water strikes the wall of the inner chamber at a tangent creating a vortex within the inner chamber since the inner chamber is offset to one side of the structure.

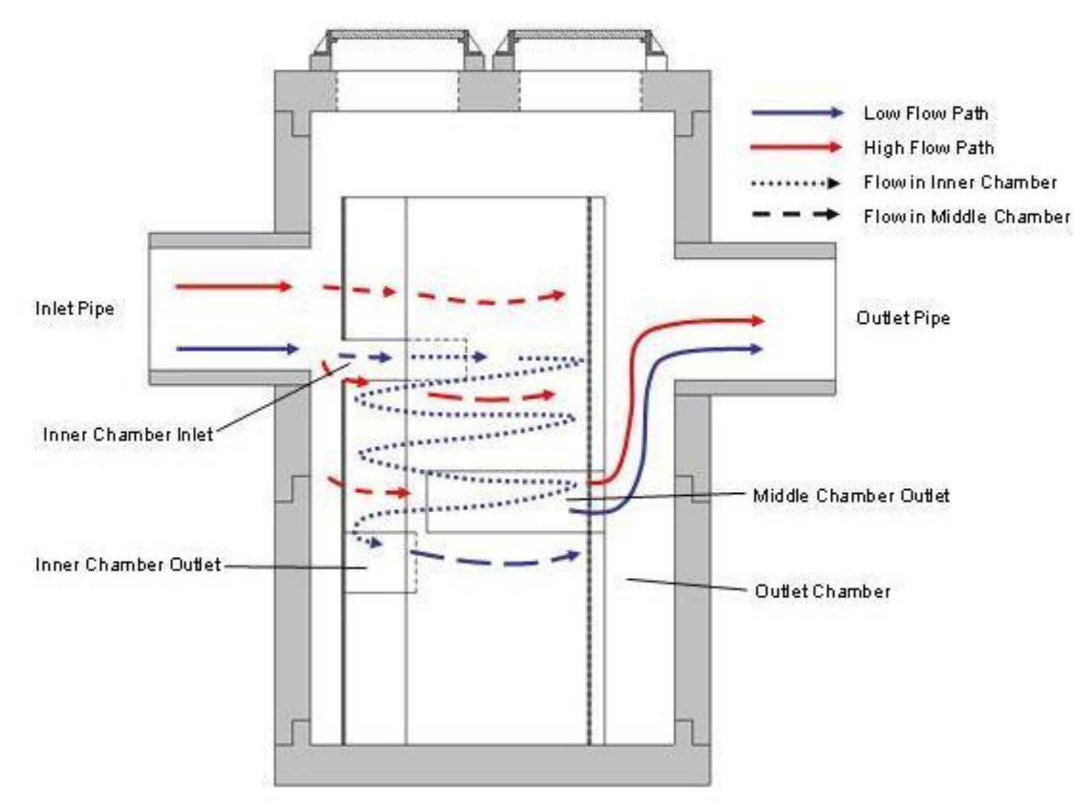
The water spirals down the inner chamber to the outlet of the inner chamber which is located below the inlet of the inner chamber and adjacent to the wall of the structure but above the floor of the structure.

The water leaving the inner chamber continues into the middle chamber, again at a tangent to the wall of the structure. The water is then conveyed through an outlet baffle wall (high and low baffles). Water flowing through the baffles then enters the outlet chamber and is discharged into the downstream storm drain.



Hydroguard Operation – Plan View

During high flows, the flow rate entering the inner chamber is restricted by the size of the inlet opening to the inner chamber. The excess flow is conveyed directly into the middle chamber and flows through the outlet baffle wall to the outlet chamber and downstream storm drain network.



Hydroguard Operation – Profile View

Sizing Methodology

The Hydroguard is sized based on estimated TSS (total suspended solids) removal for local continuous rainfall records. A computer program was developed that calculates stormwater runoff from rainfall records as well as TSS buildup during dry days and TSS washoff during stormwater events.

The TSS conveyed by the stormwater is divided into different sizes (particle size distribution) and settling calculations are performed to determine the TSS removal on a real time basis in the Hydroguard. Settling calculations can be made using Stokes' Law or using a laboratory derived performance rating curve (TSS removal versus flow rate).

The basis for the computer model is the EPA SWMM Model (version 4.4). This model is recognized as a verified model for hydrological calculations. A settling routine that calculates settling for numerous particle sizes based on Stokes' Law or settling based on the laboratory performance curves was added to SWMM since SWMM 4.4 does not have a rigorous settling subroutine.

Fifteen minute and hourly continuous rainfall records were obtained from the National Climate Center through Earthinfo for use as input to the model. The model simulates the runoff from the rainfall and the transport of TSS with the runoff as well as the settling and discharge of TSS from the Hydroguard. The model tracks the mass balance of input TSS, settled TSS, and discharged TSS to determine an overall TSS removal efficiency for the entire period of rainfall records. An overall TSS removal efficiency is calculated for each size of Hydroguard. The size of Hydroguard chosen is based on the desired annual TSS removal efficiency for the TSS particle size simulated.

The remaining sections of this document discuss model inputs and calculations to explain the performance results and sizing recommendations.

Rainfall

The simulation program can use several different rainfall inputs:

- Historical (Local) rainfall records collected at various locations across the US
- Synthetic rainfall events for a single event analysis
- Constant intensity rainfall to analyze performance at a constant flow rate

Historical rainfall records are preferred for design since they the resulting design is based as close as possible to actual operating conditions.

Historical (Local) Rainfall Records

Local or historical rainfall is data collected by municipal, state, and federal governments for a number of years at a particular location. Automatic equipment, such as a tipping bucket rainfall gauge, is used to collect rainfall amounts over time. Rainfall records are collected at several resolutions and frequencies.

Rainfall Resolution

Rainfall can be collected in tenths of inches or hundreds of inches. Rainfall stations selected for use with this program all have rainfall resolutions of one hundredth of an inch. This higher resolution of rainfall more accurately reflects the hydrology of the area being simulated.

Rainfall Measurement Frequency

Rainfall is collected either hourly or every fifteen minutes for national stations across the US. Rainfall stations with a measurement frequency of 15 minutes are preferred for continuous simulation of small areas, the primary application for Hydroguard, since they allow a more accurate calculation of hydrology for short times of concentration. The use of hourly rainfall measurements is less accurate since the distribution of the rainfall throughout the hour must be assumed during the calculations of runoff.

Fifteen minute rainfall was collected wherever possible. Generally, however, hourly rainfall records are more complete than fifteen minute stations since they are collected at areas that use the data on a daily basis (airports, waste water treatment plants, etc.). All of the rainfall records were screened for completeness (how often there were missing records due to equipment malfunction, etc.). A minimum of ten years of data and 70% completeness were used as criteria for 15 minute rainfall stations. A minimum of 20 years of data and 90% completeness were uses as criteria for hourly rainfall stations during the selection process for use with this program. Hourly rainfall stations are included with the fifteen minute stations since hourly records:

- are provided for large urban centers
- cover a large geographic area of each state
- are more complete than most 15 minute stations
- provide long term records (20 – 100 years) for analysis

The hourly data was discretized into 15 minute periods in order to make the data applicable for small drainage areas. Wherever possible a comparison of the intensity distribution was made between an actual 15 minute rainfall file and a nearby hourly rainfall file. The hourly data was then discretized into three equal fifteen minute timesteps per hour (frontal storms) or two equal fifteen minute timesteps per hour (thunder storms) depending on the month, and the thunderstorm months were changed until the intensity distribution curve of the modified hourly data (simulated 15 minute) matched the intensity distribution curve of the actual 15 minute data. Once the months of frontal and thunderstorm rain were defined, this discretization was performed on all the hourly stations in that state. The thunderstorm months were conservatively assumed to be April through November for states that did not have any 15 minute data that met the defined selection criteria.

Area & Imperviousness

The model requires the input of a total drainage area and imperviousness. The imperviousness percentage that is entered should represent the directly connected impervious area (drains directly to a catch-basin and does not flow over pervious areas (i.e. not subject to infiltration).

The calculation of stormwater runoff flow rate depends on the area and imperviousness of the catchment. Impervious and pervious areas will have separate depression storage volumes and surface runoff that will also affect runoff rate. Rainfall falling on pervious areas is also subject to infiltration before surface runoff can occur.

Although both types of areas are subject to evaporation (from the depression storage), evaporation is assumed zero during time periods when rain is falling.

Depression Storage

Depression storage is provided for both the impervious and pervious areas. Depression storage is storage created by imperfections in constant grading, designed undulations in grading, or consolidation due to improper compaction of fill. Depression storage reduces runoff volume and retards runoff timing. Water held in depression storage can either infiltrate (pervious areas) or evaporate (impervious and pervious areas) over time. Typical values of depression storage for uniform grading of grass (0.2 inches for pervious areas) and pavement (0.02 inches for impervious areas) are used as defaults.

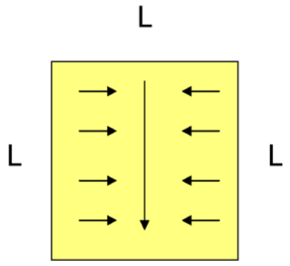
Surface Roughness

The surface roughness, overland flow width, depression storage, and slope affect the timing of surface runoff. Surface roughness can be entered for both the pervious and impervious areas. Typical Manning roughness coefficients are used for the pervious area (n = 0.25) which is assumed to be grass and impervious (0.015) areas which have a roughness value of pavement. These values can be increased (more rough) or decreased (less rough) based on the site specific conditions.

Overland Flow Width

The time of concentration, or how quickly water moves through the drainage area to the Hydroguard, depends on the orientation of the land (i.e. the surface flow path). SWMM uses a width parameter to determine how quickly water moves from the surface to the Hydroguard.

SWMM defines the width of the drainage area as the width perpendicular to overland flow. The definition given in the SWMM manual is a square area with a channel in the middle of the area. Based on this configuration the width would be twice the length of one side of the square. Once a user enters a drainage area, a site width of twice the length is calculated based on a square area. In reality, drainage areas are rarely square and the designer can alter the width parameter to suit the configuration of the drainage system. Care should be taken to ensure that the width of overland flow is entered and not just the width of the area itself.



Width of Flow = 2L

Overland Slope

The overland slope is the slope of the drainage area surface expressed as a percentage. Typical development grading is at 2%, which is the default setting for this parameter in the model.

Evaporation

Evaporation data is used in the model to replenish depression storage (remove water from depression storage) for both the impervious and pervious areas. No evaporation occurs during periods with rainfall. Evaporation is entered as a daily value for each month of the year. The default value of infiltration used in the program is 0.1 in/day for all 12 months of the year. The values for each month can be changed separately by the user to suit the location of interest.

Infiltration

Infiltration of storm water on pervious areas is calculated using the Horton method. The Horton method assumes an exponential decay in the infiltration rate over time from a maximum infiltration rate to a minimum or constant infiltration rate. The maximum infiltration rate would be the rate at which water infiltrates when the soil is dry. The minimum infiltration rate represents the infiltration rate when the soil is saturated. The decay rate represents how fast the soil becomes saturated (the rate at which the infiltration rate decreases from the maximum to the minimum specified rate). Higher values for the decay rate reduce the infiltration rate more quickly (the soil becomes saturated more quickly).

The original Horton method decreases the infiltration rate based on time. An integrated form of the equation is used in this program to make it a function of the accumulated infiltration. This prevents the unreasonable reduction of infiltration rate/capacity during lower intensity rainfall events.

During periods without rainfall, the infiltration rate is allowed to regenerate representing drying of the soil. The rate of regeneration is a function of the infiltration decay rate and a regeneration rate. The program simulates an exponential increase in infiltration rate with time to the maximum infiltration rate. Since the infiltration decay rate is generally set based on how quickly a soil’s infiltration rate is decreased, the regeneration rate provides a variable to allow the user to shorten or lengthen the period of time when the infiltration rate is regenerated without having to alter the decay rate. All of the Horton parameters can be altered in the program except the maximum depth of accumulated infiltration. The maximum depth of accumulated infiltration in the program is 4 inches for the pervious area. If the maximum depth is achieved during any one storm, all of the subsequent rainfall in the storm will be converted to overland runoff. Please contact us at (888) 290-7900 or support@hydroworks.org if you require a different maximum infiltration depth for a particular situation.

Catchbasins

The program collects surface runoff in catchbasins, which then convey the runoff into storm drain pipes. The assumption was made that the number of catchbasins is a function of drainage area. Two catch basins per acre (4 per hectare) are assumed as a default with a minimum number of two catchbasins. This value can be entered as any number by the user to reflect the site conditions.

TSS removal in catchbasins is not simulated. The scouring of TSS from catchbasins is simulated as a function of catchbasin volume, the number of catchbasins in the area, and TSS concentration in the catchbasin. The initial or maximum concentration in the catchbasins is assumed to be 100 mg/l. The sump volume of each catchbasin is assumed to be 4 ft^3 (1.2 m^3). During dry weather periods catchbasin loads are allowed to regenerate to the initial or maximum concentration. The program assumes that the catchbasin loads are regenerated after 5 dry weather days. The SWMM4 manual (EPA, 1992) states that the catchbasin loading is typically insignificant compared to the surface loading from the site itself. However, sites typically served by Hydroworks are small in size and catchbasin loads become more significant as the drainage area gets smaller. The number of catchbasins can be manually changed in the program under the site settings to accommodate site specific situations.

Treatment Flow Rate

The overall treatment rate represents the design flow rate of the incoming pipe. However, the overall treatment rate can be broken down into two components since treatment is defined differently for low flows versus high flows. During low flows the objective of treatment is to remove fine suspended solids. During higher flows the treatment objective is to remove floatables, debris and trash. Therefore, we typically discuss a low flow treatment rate and a high flow treatment rate to distinguish the two removal objectives.

Low Flow Treatment Rate

The low flow treatment rate is the maximum flow rate that can enter the low flow path (i.e. inner chamber for Hydroguard). This value is calculated by the program based on the inlet opening to the inner chamber in the Hydroguard, the inlet and outlet pipe dimensions/capacity, and the headloss for partial pipe flow conditions. The depth and velocity of flow is calculated based on pipe diameter and slope. The velocity is used with the partial flow headloss equation to determine the headloss through the separator. The headloss is added to the effluent flow depth to determine the influent flow depth at the separator.

$H = 1.09\ v^2/(2g)$ Partial Pipe Headloss Equation

The influent flow depth is compared to the inner chamber opening height to determine the maximum flow rate where the entire flow is conveyed into the inner chamber.

High Flow Treatment Rate

The high flow treatment rate is the maximum treatment flow rate through the structure prior to overtopping the high flow baffle (i.e. outlet baffle wall in the Hydroguard). The total flow rate treated by the structure is determined by calculating the velocity from the headloss equation based on the maximum head differential prior to overtopping the outlet baffle. This velocity multiplied by the area of the discharge pipe provides the maximum high flow treatment in the Hydroguard

$H = 1.09\ v^2/(2g)$ Full Pipe Headloss Equation

It is assumed that the drainage piping network will be designed based on gravity flow conditions. Therefore, the treated high flow rate that is calculated is limited to the full flow of the pipe itself. A check is also made for the flow through the outlet baffle wall opening in the Hydroguard to ensure that the maximum flow rate treated by the structure is less than or equal to the flow rate through the baffle opening based on the headloss through the structure. Since the baffle wall is curved and somewhat obstructed by the inner chamber in the Hydroguard, the area for flow through the baffle wall is assumed to be one half of the actual area to be conservative.

Treated Flow Volume

The volume of stormwater that is treated is calculated for the entire simulation period based on the maximum flow rate treated by the structure (Qtot). Each timestep the program compares the influent flow rate to the flow rate treated by the structure (Qtot) and sums the volume of flow treated by the structure. The total volume of flow treated compared to the total volume of flow influent to the structure is expressed as a percentage (the percentage of total flow treated by the structure). Since the flow rate treated by the structure (Qtot) is limited to full pipe flow, water that is not treated by this definition does not necessarily overtop the high flow baffle wall. Water that is not treated represents any one of the following conditions:

- the inlet pipe is surcharged but the water level is still below the high flow baffle wall (the maximum treated flow (Qtot) used in the calculations is limited to pipe full flow)
- the inlet pipe is artificially surcharged since the model assumes the pipe network conveys all of the runoff produced by the area
- the inlet pipe is surcharged and the baffle wall is overtopped (untreated flow)
- the inlet pipe is not surcharged but the inlet pipe is larger than recommended and extends above the baffle wall (baffle wall is overtopped resulting in untreated flow)

The assumption is made that all of the runoff from the site is conveyed by the piping network to the Hydroguard. In many cases flow through the piping network is limited to the 2 year, 5 year, or 10 year peak flow with excess flows being conveyed by the major system (roads). In these cases the model may incorrectly indicate an overflow. The model has inputs for the number of inlets/catchbasins to the minor (piping) system and can correctly limit flows based on the major/minor system design if this information is properly input to the model.

TSS Buildup

TSS buildup is the accumulation of solids on the surface of the site during dry weather days. These solids get washed off during stormwater runoff events to become TSS in the storm drain system.

The TSS buildup can be estimated by three methods:

1. Power Linear
2. Exponential
3. Michaelis-Menton

Three parameter values are input for the buildup:

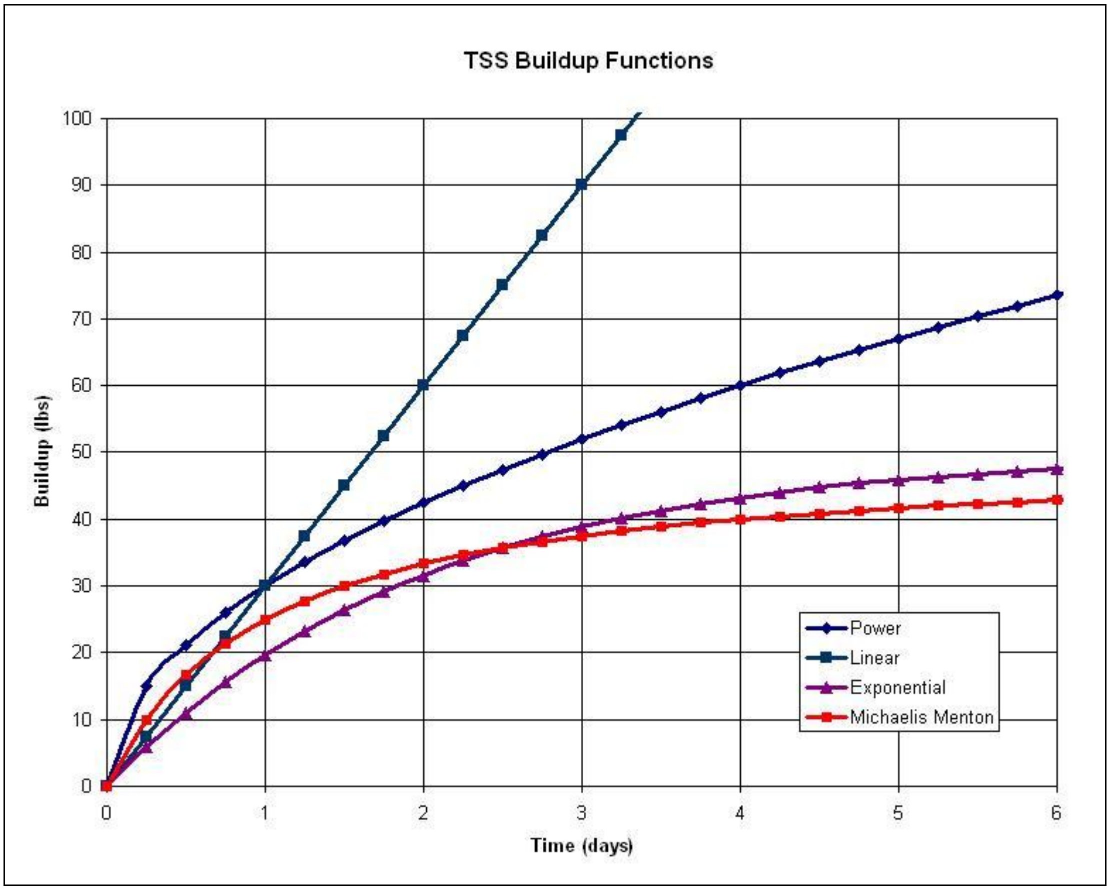
1. Limit (L)
2. Coefficient (C)
3. Exponent (E)

The equations for each of the buildup methods are as follows with t being the time in days:

Power- Linear Load = $C \ t^{E}$ (Linear when E = 1)
Exponential Load = $L\ (1 - e^{(-Et)})$
Michaelis Menton Load = $L\ t\ /\ (E + t)$

The default values are provided for the exponential buildup option only. If the user switches to another buildup method, the three values of Limit, Coefficient, and Exponent should be changed accordingly, especially the Coefficient. The following table provides values of these parameters that were used to derive the following curves.

TSS Buildup Parameters			
Buildup Method	Limit	Coefficient	Exponent
Power (Linear)	50	30	0.5 (1.0)
Exponential	50	60	0.5
Michaelis Menton	50	1	0.5



The different buildup functions can produce significantly different buildup scenarios depending on the parameters that are entered. The power linear buildup provides the fastest buildup of the three methods and would be appropriate for unstable sites or sites where there is an unlimited supply of TSS. The exponential and Michaelis Menton methods provide asymptotic buildup over time (i.e. initially there is a quick buildup and then the rate of buildup decreases slowly to zero) and are more representative of stable post development sites.

The program defaults to the exponential buildup method, however the user must ensure that the appropriate buildup method is selected when making TSS removal estimates.

Street Sweeping

TSS that has built up on the surface of the site can be removed by street sweeping. The National Urban Runoff Program (NURP, 1983) generally found that street sweeping did not have a significant impact on stormwater quality unless performed on a daily basis. The effectiveness of street sweeping depends on many factors:

- Frequency of sweeping

- Type of street sweeper
- Presence of parked cars
- Hydrology (frequency of rain events)

Street sweepers have become more efficient in recent years leading to resurgence in the debate on street sweeping effectiveness. However, the other parameters listed above still have a significant effect on street sweeper effectiveness. Although the effectiveness of a street sweeping program for pollution removal continues to be debated, street sweeping has other benefits (larger immobile particle removal, aesthetics) than just pollution removal.

Street sweeping frequency is the interval in days between sweeping. Street sweeping efficiency represents what percentage of the TSS that has built up on the surface of the site will be removed by street sweeping. Availability represents what percentage of the surface area can be cleaned by street sweeping. For example, if the area in question is a street and parked cars cover 60% of the curb length, the availability could be estimated to be 40%. The efficiency multiplied by the availability provides the overall removal percentage of suspended solids by street sweeping.

The time of year when street sweeping occurs can also be limited by setting the starting month and ending month for street sweeping.

TSS Washoff

TSS washoff is the removal of solids from the surface of the site during rain storms. Washoff is a function of runoff intensity and volume. The Hydroworks Simulation Program provides four methods for TSS Washoff:

1. Power-Exponential
2. Rating Curve with no upper limit
3. Rating Curve limited to the TSS buildup
4. Event Mean Concentration (constant concentration of TSS in the runoff)

Methods 2 and 4 are independent of TSS buildup and therefore TSS buildup is not calculated if either of these methods is selected. This may seem strange when looking at the computer output since it does not appear that there is any TSS buildup to washoff. TSS buildup is assumed to meet the demands of the washoff using these two washoff methods.

Three of the four methods require the input of two values:

- Coefficient (C)
- Exponent (E)

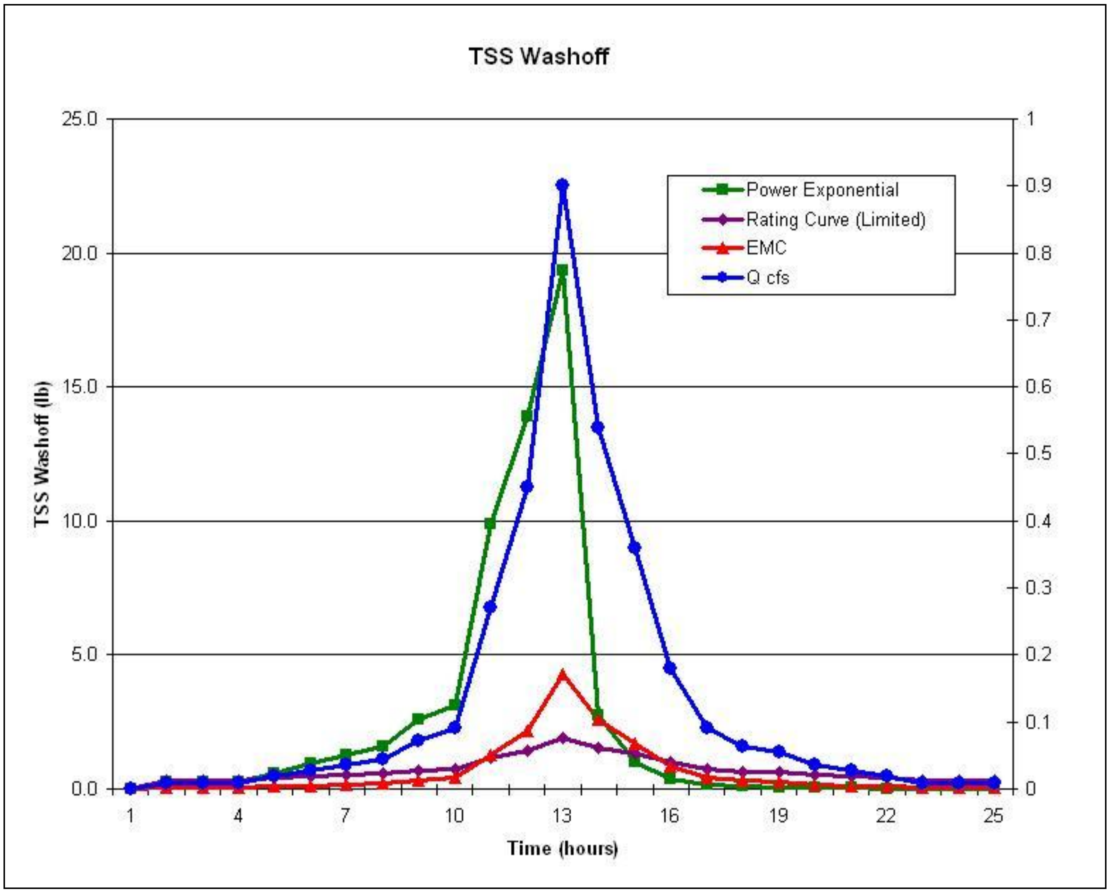
The use of the Event Mean Concentration (EMC) does not require these two parameters. The only parameter required for the EMC method is the concentration of TSS itself in mg/l.

The equations for the different washoff methods are as follows:

Power-Exponential	Load = $\text{Load}_{(t-1)}$ C/3600 r^E t
Rating Curve	Load = (C Q^E) t
Event Mean Concentration	Load = EMC Q t

Where Load is the load washed off the surface of the site during the timestep, Q is the surface flow rate (cfs), t is the time in seconds and r is the runoff rate in in/hr.

The following figure demonstrates the difference in washoff methods for a synthetic storm with a starting load on the surface of the site of 60 lb.



The washoff parameters used to derive the washoff figure above are given in the following table:

TSS Washoff Parameters		
Washoff Method	Coefficient	Exponent
Power Exponential	3	1.1
Rating Curve (Limited)**	1000	0.4
EMC*	2407	1.0

*Values provide an EMC of 85 mg/l. In the program the user enters the EMC in mg/l
** Limited to TSS buildup

The power exponential provides a first flush scenario where most of the TSS is washed off during the rising limb of the hydrograph. The first flush effect is more pronounced as the Coefficient is increased. EMC loading is directly proportional to the flow rate and therefore the highest washoff occurs during the peak flows of a storm event. Washoff form the rating curve is similar to the EMC loading but distributes the load more evenly over the rising limb and recession limb of the hydrograph depending on the value of the Exponent. The rating curve will match the EMC curve as the Exponent approaches 1.0 if the Coefficients are the same.

Power exponential washoff is the default type of washoff in the program. The washoff method chosen, however, should be based on individual site characteristics. If the rating curve washoff method is chosen, the user should review the Coefficient and Exponent values to ensure that they provide reasonable washoff rates.

TSS Removal in the Hydroguard

Suspended solids settling can be estimated using theoretical settling calculations incorporating Stokes' law, Cheng's equation, or by using a laboratory derived performance curve (TSS removal versus flow rate) based on a specific particle size distribution. In order to determine mass or concentration removal, the concentration of suspended solids in the tank at any particular time must be known.

The TSS concentration in a Hydroguard at any one time is based on completely mixed or stirred tank conditions (CST). In a CST changes to the concentration of solids vary based on a continuity of mass (Tchobanoglous and Schroeder, 1987).

$C'V = QC_i - QC_t - r_cV$

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) (settling by Stokes' Law)

For settling based on Stokes' law or Cheng's equation, r_c can be estimated by:

$r_c = V_sC/D$

Where r_c = reduction in solids in the tank (kg/m^3s)
Vs = settling velocity of solids (m/s) (Stoke's or Cheng's)
D = depth of tank (m)
C = concentration of solids in the tank (kg/m^3)

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

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

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

This concentration is used in combination with the volume of discharge and tank volume to calculate the load of suspended solids discharged from the structure and the load removed in the tank by settling, respectively. Simple mass balance calculations are used to ensure that conservation of mass is maintained.

During periods without flow (inter-event or dry weather periods) the tank is not assumed to be completely mixed. The depth of suspended solids in the structure decreases each timestep with settling until all of the solids are removed or there is flow into the structure. The concentration of solids in the tank during dry weather or non-flow periods was calculated as:

$C = C_t (1-V_s t/ D)$

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 structure decreases each timestep based on the settling velocity until all of the solids are removed or there are subsequent flows into the structure.

Particle Size Distribution

The particle size distribution has a significant effect on TSS removal results since settling velocity is not linearly related to particle size. Many stormwater treatment structure vendors and regulatory agencies have their own criteria for the TSS particle size distribution in stormwater. Unfortunately, the particle size distribution varies from site to site. There is no generic particle size distribution that will be suitable for all applications. The best particle size distribution is based on existing data from the site itself. However, in new development applications this is not available and therefore a generic particle size distribution must be assumed.

The default generic particle size distribution used in the program is based on the NJDEP (New Jersey Department of Environmental Protection) laboratory testing protocol for hydrodynamic separators.

Default Theoretical Particle Size Distribution (NJDEP)		
Diameter (μm)	Percentage by Mass	Specific Gravity
8	20	2.65
50	25	2.65
100	15	2.65
250	30	2.65
500	5	2.65
1000	5	2.65

Although the program automatically sets the NJDEP PSD (particle size distribution) as the default to be used, the user has the option of entering any particle size distribution into the program.

Stokes' Law Settling Velocities

Settling velocities are required to determine the suspended solids removal during both dynamic and quiescent timesteps for theoretical settling. Settling velocities for each particle size are based on Stokes' law given a Reynold's number less than 0.3.

Initially the settling velocity and Reynold's number are calculated as follows:

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

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)

$N_R = S_f V_s d p_w / u$

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 Reynold's number is calculated to be greater than 0.3 an iterative solution that accounts for the drag coefficient on the particles is used to solve for the settling velocity (solving for the Reynolds number, drag coefficient, and settling velocity until changes in the settling velocity are insignificant). The drag coefficient and the settling velocity are calculated using the following equations during this iterative procedure.

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

Where C_D = drag coefficient
N_R = Reynolds number

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

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

Cheng's Equation Settling Velocities

Cheng's equation is another option for the calculation of theoretical settling velocities for discrete TSS particles. Previous research (Cheng, 1997) has indicated that it provides better correlation with sedimentation rates measured in the field.

$Vs = \nu/d_p\,[(25+1.2(d_1)^2)^{0.5} - 5]^{1.5}$ Equation 2

$d_1 = d_p\,[(g\,(\rho_s-\rho)/\rho)/\nu^2\,]^{0.33}$

Where Vs = settling velocity
ν = kinematic viscosity of water
d_p = particle diameter
ρ_s = particle density
ρ = water density

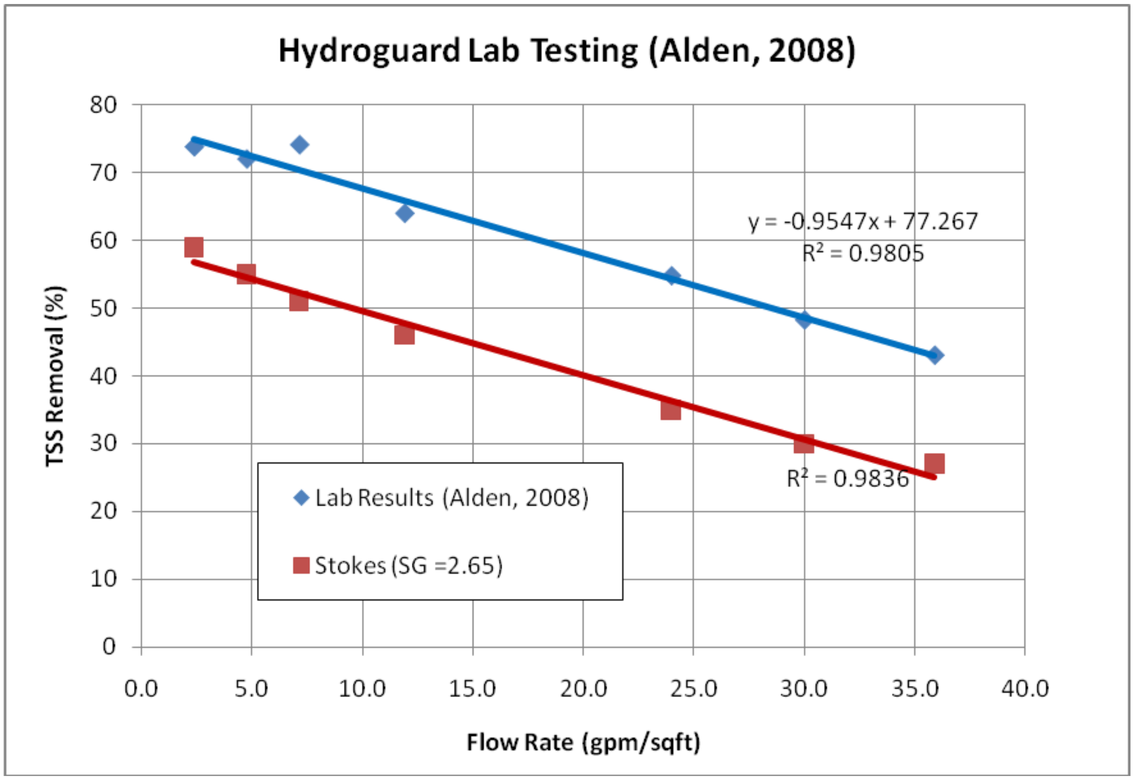
Cheng settling velocities provide values smaller than Stoke's law for particles smaller than 120 µm and settling velocities larger than Stoke's law for particles greater than 120 µm.

Independent Laboratory Testing TSS Removal Calculations

The Hydroworks (SWMM) sizing model was used to simulate the exact flow rates that were independently tested at Alden Labs in 2008 for a full scale HG6. The sizing model can be simulated at a single rainfall intensity to determine the TSS removal performance at a single flow rate. Rainfall intensities were chosen for a 1 acre impervious area to match the flow rates that were tested in the laboratory. The NJDEP (New Jersey Department of Environmental Protection) particle size distribution as measured at Alden labs was input as the TSS particle size distribution and the pipe diameter and inlet pipe slope that was tested at Alden labs was input as pipe parameters in the sizing model.

NJDEP Particle Size Distribution (PSD)	
% Finer (Cumulative)	**Particle Size (µm)**
5	2
10	3
15	5
20	8
25	11
30	15
35	21
40	30
45	40
50	70
60	150
70	190
80	230
90	350
95	510
100	800

The TSS removal results for a HG6 as predicted by the Hydroworks (SWMM) model and the independent laboratory results (Alden, 2008) are shown on the following figure. The use of Stoke’s law in the Hydroworks Sizing Model will underestimate the TSS removal performance measured at the Alden Research Laboratory.



Independent Laboratory Testing vs. Hydroworks Sizing Model (Stokes)

Accordingly, Hydroworks has developed a calculation methodology using the Peclet Number to allow the calculation of TSS Removal using the TSS removal results from the independent laboratory testing (Alden, 2008).

The Peclet number has been used as a dimensionless scaling number for sediment deposition in lakes (Dhamotharan, et. Al. 1981). Others have suggested its use for scaling of TSS removal results for hydrodynamic separators (Dhanak, 2008, Gulliver, Guo and Wu, 2008). The Peclet number is the ratio of convection (convective settling) to diffusion (turbulence keeping particles in suspension). The Peclet number varies with the size of separator, particle size of TSS, and flow rate.

Pe = Vs h d /Q

Where Pe = Peclet number
Vs = settling velocity
h = depth of separator sump
d = separator diameter
Q = flow rate

A particle will be removed in the separator if the Peclet number is equal to, or greater than, the Peclet number calculated for removal of that particle based on the independent laboratory results. The TSS removal value at each flow rate during the independent laboratory testing provides an indication of the smallest particle removed at each flow rate based on the influent particle size distribution. The Peclet number was calculated for the smallest particle removed at each flow rate to generate a relationship between Peclet number and particle size removed in the Hydroguard. The Peclet number is based on the settling velocity of the TSS particle. Settling velocities were calculated using the Cheng equation.

The Alden performance curve indicates that the relationship between TSS removal performance and flow rate is close to linear for the flow rates tested in the laboratory (r^2 = 0.98). A linear regression equation from the Alden TSS Removal curve was used to determine TSS removal results at various flow rates. The input particle size distribution was used with the resulting TSS removal results to determine the smallest particle size removed at each flow rate.

TSS Removal = -15.155 Q + 77.267 Alden Laboratory TSS Removal Results

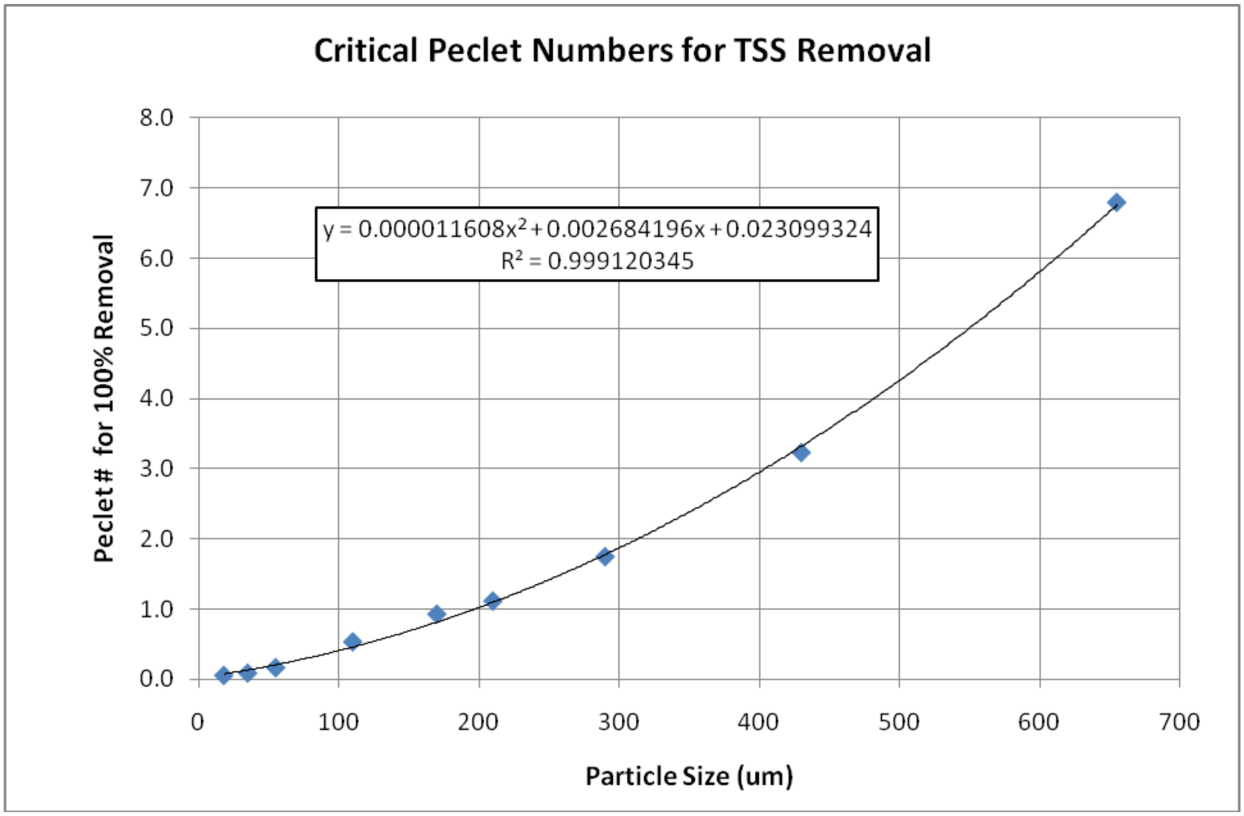
Where Q = flow rate in ft^3/s

The following table provides a range of Peclet Numbers corresponding to TSS removals calculated using the TSS removal equation from the Alden TSS removal tests.

Peclet Number for TSS Particle Size Removed

Flow Rate (cfs)	TSS Removal (%)	Particle Removed	Peclet Number
0.48	70	18	0.053
1.14	60	35	0.085
1.47	55	55	0.163
1.80	50	110	0.532
2.46	40	170	0.928
3.12	30	210	1.114
3.78	20	290	1.745
4.44	10	430	3.231
4.77	5	655	6.797

The following figure shows the relationship between Peclet Number and Particle Size removed.



Critical Peclet Numbers for Particle Removal

The Peclet Number curve indicates that a critical Peclet Number associated with the removal of a specific particle size can be calculated ($r^2 = 0.99$).

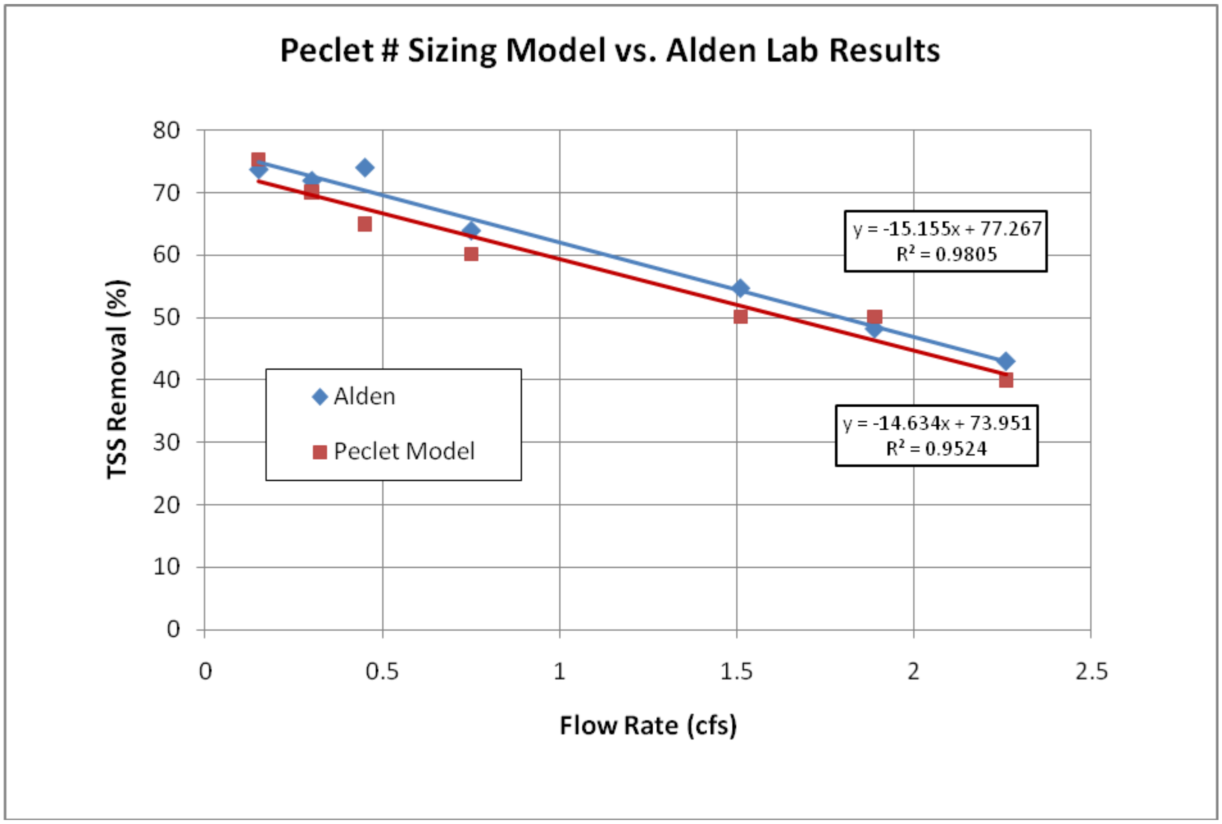
Critical Peclet Number = $0.0000116\ d^2 + 0.002684\ d + 0.023$

Where d= Particle Diameter (µm)
And Critical Peclet Number ≥ 0.050

The Peclet numbers are inconsistent at the lower flow rates due to the fluctuations in TSS removal results at the low flow rates. The results indicate that the smallest particle able to be effectively removed by the separator tested (Hydroguard HG6) during flow periods is 15 µm. Indeed the removal of particles smaller than 15 µm by hydrodynamic separators during flow through periods is not considered realistic due to the potential for these small particles to stay suspended in the water column. Accordingly the fluctuation in TSS removal rates with fine particles is expected at low flow rates due to experimental error and fluctuations in settling velocity for very fine particles. In order to properly account for this phenomenon, a minimum Critical Peclet number of 0.050 was established for any particle to be removed during flow conditions in the separator regardless of flow rate, separator size, and particle size diameter.

The Critical Peclet number curve/equation was used in the settling model to determine a critical Peclet Number for each particle size simulated in the model. For each size of separator and flow rate at any given timestep the Peclet number is calculated for each particle size and compared to the critical Peclet number for that particle size. If the Peclet number calculated at a particular timestep exceeds the critical Peclet number the TSS associated with that particle size for that timestep is considered removed (settled). This calculation occurs for each timestep/flow rate and each particle size such that an overall TSS removal result for the simulation period can be determined.

The calculations of TSS removal using the Peclet Number methodology match the laboratory results (using the tested NJDEP particle size distribution) with a correlation coefficient of 0.96 ($r^2 = 0.91$).



Peclet Number Sizing Compared to Independent Laboratory Results

Erosion

Erosion is simulated in the Hydroworks Simulation Program using the Universal Soil Loss Equation:

L = R K Ls C P

Where:

R = rainfall factor
K = soil erosion factor
Ls = the slope length gradient ratio
C = cropping management or cover index factor
P = erosion control practice factor

Erosion is added to the TSS washoff if the user selects erosion in the simulation. In the default parameters erosion is not selected since it is expected that Hydroworks products will be used on stabilized post development situations. There are numerous cases, however, where soil erosion will be a factor and erosion should be selected for these applications.

The **rainfall factor R** in the Hydroworks Simulation Program is a product of the rainfall energy at each particular timestep (based on the rainfall intensity itself) and the maximum average 30 minute rainfall intensity for the simulation period. The maximum average 30 minute rainfall intensity is assumed to be 4 in/hr. This equates to a 50 year 30 minute rainfall intensity for Trenton, NJ. This rainfall intensity is quite severe and should be reasonable for most locations in the US. Hydroworks should be contacted (888-290-7900 or support@hydroworks.org) if the user wants the design to be based on an alternate 30 minute maximum rainfall intensity.

The **erosion area** will not typically be the entire pervious area of the site. Accordingly, the erosion area is a user input in the program that represents the pervious area that is subject to erosion.

The **flow length** is another input parameter for erosion representing the length of flow from the point or origin to either a flat slope where deposition starts to occur or to a defined channel or storm drain inlet. The flow length is used in a calculation with the overland slope (already entered as a site parameter) to obtain Ls, the slope length gradient ratio.

The erosion (K), cover (C), and control practice (P) factors all range between 0 and 1.0. Conditions that represent higher erosion potential are reflected by higher factors.

The **soil erosion factor K** depends on the type of soil and organic content. Values of K are provided below for reference (OMAF, 2000)

Soil Erosion Factor (K)	
Textural Class	**Average K**
Clay	0.22
Clay Loam	0.30
Coarse Sandy Loam	0.07
Fine Sand	0.08
Fine Sandy Loam	0.18
Heavy Clay	0.17
Loam	0.30
Loamy Fine Sand	0.11
Loamy Sand	0.04
Loamy Very Fine Sand	0.39
Sand	0.02
Sandy Clay Loam	0.20
Sandy Loam	0.13
Silt Loam	0.38
Silty Clay	0.26
Silty Clay Loam	0.32
Very Fine Sand	0.43
Very Fine Sandy Loam	0.35

The **cropping management or cover index factor** is based on agricultural practices as shown below. Exposed soil would have a high C factor.

Cover Index Factor (C)	
Crop Type	**C Factor**
Grain Corn	0.40
Silage Corn, Beans & Canola	0.50
Cereals (Spring & Winter)	0.35
Seasonal Horticultural Crops	0.50
Fruit Trees	0.10
Hay and Pasture	0.02

For pervious areas that are used for agriculture the C factor can be modified by multiplying the C factor given above by a tillage factor (T) to arrive at a composite C factor.

Tillage Method Factor (T)

Tillage Method	T Factor
Fall Plow	1.0
Spring Plow	0.90
Mulch Tillage	0.60
Ridge Tillage	0.35
Zone Tillage	0.25
No-Till	0.25

The erosion **control practice factor (P)** is based on control practices that would help or exacerbate erosion. For example contour farming prevents rill erosion and therefore the P factor is lower for contour farming than farming up and down the slope (that would create rill erosion).

Control Practice Factor (P)

Support Practice	P Factor
Up & Down Slope	1.0
Cross Slope	0.75
Contour farming	0.50
Strip cropping, cross slope	0.37
Strip cropping, contour	0.25

The erosion factor information provided in this document is based on data provided by the Ontario Ministry of Agriculture and Food (OMAF, 2000). More information about the USLE equation can be found at the OMAF website:

http://www.gov.on.ca/OMAFRA/english/engineer/facts/00-001.htm - tab1

TSS Removal Results

TSS (Total Suspended Solids) removal is the comparison of the mass of TSS removed compared to the mass of TSS influent to the treatment structure expressed as a percentage.

The mass of TSS influent to the treatment structure includes any TSS that is contained in any overflow volume. Therefore the TSS removal percentage is an overall result including any overflow or by-pass.

Many state or local agencies have TSS removal criteria for sizing stormwater quality structures (e.g. 80% TSS removal). An overall TSS removal result is provided for each Hydroguard unit based on the user input parameters (area, imperviousness, rainfall station, particle size distribution, etc.). The Hydroguard selected is the smallest size that meets both the flow and TSS removal criteria set forth by the regulating agency.

It should be recognized that some agencies give TSS removal credits/percentages for other stormwater measures (catch-basins, etc.). Accordingly, the Hydroguard may not need to be designed for the full TSS removal criteria (e.g. 80%).

A flow treatment and TSS removal table is provided on the first screen of the sizing program and near the end of the computer output to facilitate the selection of the appropriate Hydroguard model.