Stormwater Sand Filter Sizing and Design
A Unit Operations Approach

Ben R. Urbonas, P.E.
Chief, Master Planning and South Platte River Programs,
Urban Drainage and Flood Control District,
2480 W. 26th Avenue, Suite 156-B; Denver, Colorado 80211

ABSTRACT

The use of sand and other media filters are gaining acceptance in the field of urban stormwater structural best management practice. Much work has been done to develop local design guidance such as in the State of Delaware and in Austin, Texas. Also, considerable field testing of these devices has occurred over the last 10 years. This paper consolidates much of the earlier work and provides the technical basis for the design of media filters for stormwater runoff treatment at any location in the United States. The approach utilizes the unit processes known to exist in urban stormwater runoff and within filter devices. The suggested design is based on hydraulic capacity of the filter media, which, in turn, is a function of the total suspended solids removed by the filter.

INTRODUCTION

Sand and other media filters remove constituents from stormwater runoff primarily through a physical process of filtering out particulates from the water. The type of media used and its grain size distribution determine how small of a particle is strained out. Coarser sands have larger pore spaces that have high flow-through rates but pass larger suspended particles. A very fine sand, or other fine media filter, has small pore spaces with slow flow-through rates and filter out smaller total suspended solids (*TSS)* particles. Some media, such as peat-sand mix, may also provide ionic adhesion or exchange for some dissolved constituents which further enhances effluent quality.

Laboratory and field tests have shown (Neufeld, 1996; EPA, 1983; Veenhuis, 1989; City of Austin, 1990) that a filter media consisting of concrete sand (ASTM C-33 mix) provides a good balance between flow-through rates and filtering efficiency. The filter performs like a classic slow sand filter that has been used to treat water for approximately 100 years. Initially the flow-through rates are high, but as the filtrate of fine sediment accumulates on its surface, flow-through rates diminish. In water treatment the quality of the effluent improves as the filtrate layer thickens. This may not be the case with stormwater. Some field tests suggest that the effluent quality improves initially, but may degrade over time, suggesting leaching out of constituents from the filtrate and a need for maintenance.

In water treatment plants, scarifying the “sealed” surface improves the filter’s flow-through rates. Eventually the filter media is removed and replaced. Water treatment filters operate continuously and regular maintenance is a part of the water supply product that is sold to the consumers. However, slow sand filters are rarely used today because they are operationally inefficient and require very large land areas. Instead, multi-media rapid sand filters are the norm in this industry, but they require intense operation and frequent backwashing to keep in operation at design flow-through rates.

Stormwater filters located within a municipality have to operate occasionally, often infrequently. If they are used extensively, there will be a large number of such facilities in any given metropolitan area. As a result, simple economics and pragmatism precludes the use of rapid sand filters for urban stormwater treatment because of their intense operations and maintenance needs. Since there is likely to be a very large number of small filter sites throughout the municipality their operation and maintenance needs become overwhelming. What remains as an option is the use of slow sand filters which require only an occasional cleaning.

The challenge a designer of a stormwater filter faces is to find a design that will provide a sufficient flow-through rate to process most of the runoff events (Urbonas *et al*., 1996a). The filter has to be made as small as possible for cost reasons, while large enough to pass through the design event(s) without backing up water onto streets, parking lots, etc. and creating nuisance or safety problems for a municipality or its private owners.

DESIGN HYDROLOGY AND *TSS* LOAD

Because of the stochastic nature and temporal variability of stormwater runoff, any stormwater media filter will need a detention storage volume upstream of it. This detention volume permits the capture of rapid runoff so as to buffer the flows that have to be processed through the filter. A filter without such a buffer would have to be very large to keep up with the instantaneous runoff rates during rainstorms. The amount of this detention volume is determined by local runoff characteristics. To deal with the stochastic nature of the runoff process, typically a *design storm* is selected. Also, the rate at which the runoff from this *design storm* is allowed to drain through the filter determines its size. This detention capture volume needs to be emptied out in a reasonable amount of time to provide volume for the next storm runoff event that may follow.

After an extensive literature search of practices in the United States in the 1980's, Urbonas and Ruzzo (1986) suggested that a capture volume upstream of a sand filter be equal to ½ watershed inch of runoff from the impervious surfaces in the tributary watershed. Subsequent studies of rainfall records in the United States and field performance of BMPs now suggest that, as a minimum, this storage volume be between the runoff from an average runoff producing storm depth (i.e., *mean* storm) shown in Figure 1 (Driscoll, et al., 1989) and the *maximized* volume (Guo and Urbonas 1996; Urbonas, *et al.*, 1996a). The *mean* and the *maximized* volumes are a function of how rapidly this volume is fully drained (i.e., evacuated) from the detention basin, or from the surcharge of a retention pond. If it takes a long time, say 48 hours to fully drain this volume, then the probability increases for another storm to occur before this volume is evacuated and a larger detention volume needs to be provided than would be needed if the design *drain time* for this capture volume is less, say 12 hours.

Guo and Urbonas suggested Equation 1 (Guo and Urbonas, 1996; Urbonas, *et al.,* 1996) that permits an engineer to make a first order estimate of the *maximized* volume P_o. This relationship and the values for coefficient a (see Figure 2) resulted from extensive runoff modeling performed by Guo using rainfall records from different regions of the United States. The author re-examined these rainfall records and has also developed values of coefficient a for the capture of the *mean* storm runoff volumes for use with Equation 1(see Figure 2).

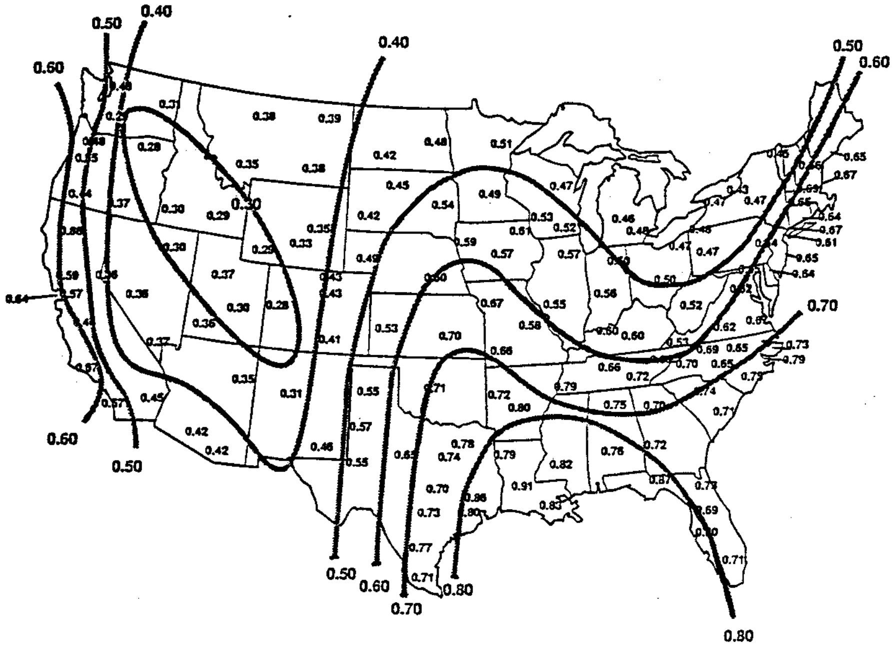
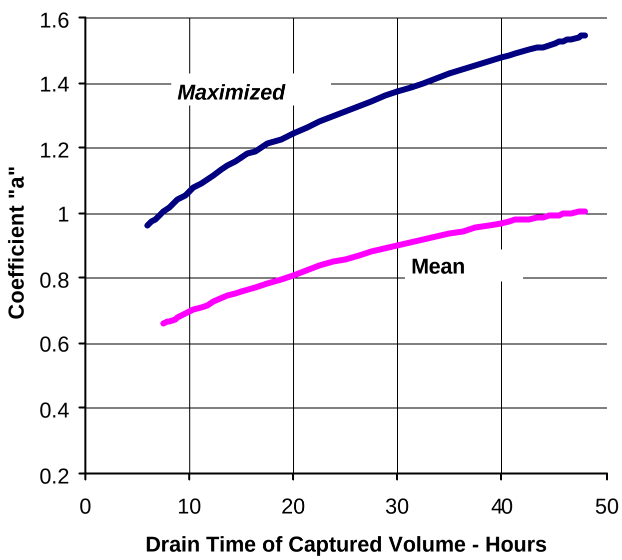


Figure 1. Mean Storm Depths in Inches of Precipitation in United States.
(Ref.: Driscoll, *et. al.*, 1989)



Drain Time in Hours	Determ. Coeff. r^2
12	0.97
24	0.91
48	0.85

Figure 2. Coefficient "*a*" to use in Equation 1.

$$P_o = a \cdot C \cdot P_6 \qquad (1)$$

In which,
- a = coefficient taken for the *maximized* or *mean* runoff volume from Figure 2
- C = catchment's runoff coefficient (see Equation 2)
- P_6 = average runoff producing storm depth from Figure 1, in inches

P_o = water quality capture volume (*maximized* or *mean* as appropriate), in inches
The catchment's runoff coefficient can be estimated using Equation 2 which was developed using rainfall and runoff data from 60 NURP sites across the United States (EPA, 1983).

$$C = 0.858 i_a^3 - 0.78 i_a^2 + 0.774 i_a + 0.04 \qquad (r^2 = 0.72) \qquad (2)$$

In which, i_a = $I_a/100$; fraction of the catchment's total area covered by impervious surfaces
I_a = percent of the catchment's area that is covered by impervious surfaces (use the <u>total</u> percent imperviousness rather than the hydraulically connected portion).

Because the filter's surface accumulates the strained-out materials over time, it is also necessary to know how much runoff can occur over an extended period of time, such as during an average year. This permits an estimate of the average annual load of the constituents in stormwater arriving at the filter and, knowing the filter's removal characteristics, the amount of the constituents removed by the filter during an average year. The annual runoff depth can be estimated using Equation 3.

$$P_A = n \cdot P_6 \cdot C \qquad (3)$$

In which, P_A = average annual total stormwater runoff from the catchment, in inches
n = average number of runoff producing storms per year from Figure 3

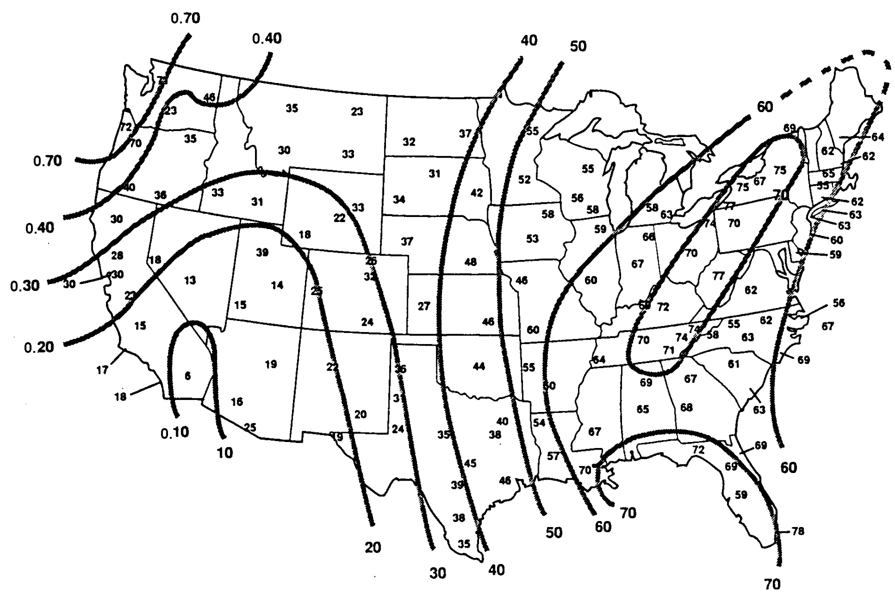


Figure 3. Number of Runoff Producing Storms in United States. (Ref.: Driscoll, *et. al.*, 1989)

Then the average annual load of *TSS* delivered by stormwater to the filter can be found using

$$L_a = \left[\left(A_c \cdot 43{,}560 \right) \cdot \left(\frac{P_A}{12} \right) \right] \cdot \left(\frac{E_s}{10^6} \cdot 62.4 \right)$$

Which can be reduced to:

$$L_a = 0.2265 \cdot A_c \cdot P_A \cdot E_s \qquad (4)$$

In which, L_a = average annual *TSS* load in stormwater runoff from the tributary catchment, in pounds
A_c = area of tributary catchment, in acres
E_s = average *EMC* of *TSS* at the site, in mg/l

This annual load of *TSS*, along with the removal rates by the upstream detention/retention and by the filter, plays a dominant role in determining the size needed for a media filter. In order to proceed further with the design it is necessary to first understand how different detention/retention basin and filter combinations interact in the removal of *TSS* from the water column. Also, it will be necessary to estimate the fraction of the annual *TSS* load, L_a, that will be processed through the filter facility and the fraction that will bypass it.

FILTER CONFIGURATIONS

There are three basic arrangements of upstream design volume storage (i.e., water quality capture volume - *WQCV*), and the filter media. Figure 4 schematically illustrates these configurations. The upstream detention captures and equalizes stormwater runoff rates to those compatible with the filter's flow-through capacity. This design volume temporarily stores the higher rates of runoff and permits stormwater to flow through a filter at rates that it is capable of handling, namely its available flow-through rate. When this design capture volume is exceeded by a larger runoff event, the excess volume ponds on the surface of the catchment immediately upstream of the filter, or it bypasses the filter.

In Figure 4, Case 1 condition represents an arrangement where the filter is preceded by an extended detention basin, namely a basin that is totally evacuated of water after stormwater runoff ends. In Case 2 the filter is preceded by a retention pond with a surcharge extended detention volume above the permanent pool. In this case the permanent pool retains all or some of the runoff within it after storm runoff ends while the surcharge capture volume is totally evacuated after stormwater runoff ends. For Cases 1 and 2 the detained volume is evacuated through a flow control outlet. This outlet is designed to empty out the design capture volume over a desired time period, namely its *drain time*.

The detention outlet can also be oversized and the detention volume's evacuation rate can be governed by the size and flow-through rate of the filter itself. If this is the design condition, the filter will operate similarly to the one shown in Case 3, where at least a part of the detention volume resides directly above the filter's surface. Most common field examples for Case 1 can be found in Austin, Texas. The State of Delaware filter design is best represented by Case 3, as are the field conditions where the filter is incorporated into the banks of a retention pond above the permanent pool's surface. The latter design is commonly used in Florida. Case 3 was the condition tested in Lakewood, Colorado in 1995.

The detention/retention basin upstream of the filter also removes some of the solids since *TSS* can settle before the stormwater reaches the filter. The designer needs to estimate how much *TSS* is removed by the upstream detention/retention basin in order to estimate how much *TSS* may be left in the water column to be removed by the filter. This is not an easy estimate to make since there is much variability in the reported *TSS* removal rates by a detention or a retention basin.

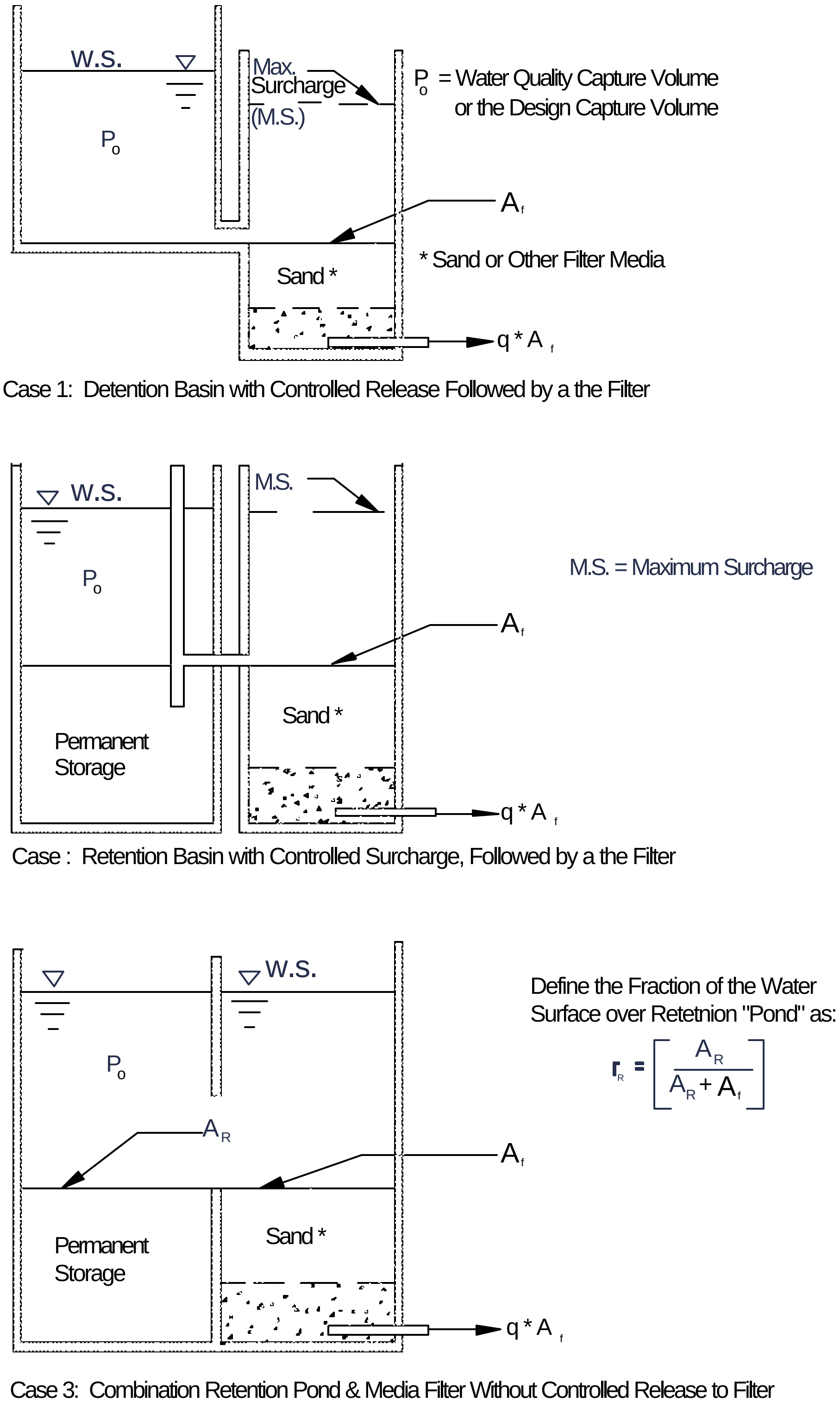


Figure 4. Three possible arrangements for a filter in relation to upstream detention basins.

A conservative design approach suggests that a lower value for *TSS* removals be used for design than the averages reported in literature for detention basins and retention ponds. For the same reason, *TSS* removal efficiencies used for the design of the filter itself should be based on higher removal rates than the average rates reported in the literature. The intent during the sizing of a filter is not to predict actual *TSS* removal rates accurately, but to use reasonable removal rates to arrive at realistic, possibly somewhat conservative filter size. Table 1 provides suggested design *TSS* removal rates for retention ponds and detention basins located upstream of the filter. These removal rates are somewhat lower than the averages reported in the literature. However, if locally collected information differs significantly, the designer should use such locally available data instead.

For Cases 1 and 2 defined in Figure 4 it is possible to assume that the concentration of *TSS* leaving the retention/detention basin can be estimated using :

$$E_{sd} = E_s \cdot \left(1 - \frac{R_D}{100}\right) \tag{5}$$

In which, E_{sd} = average concentration of *TSS* leaving the detention or retention basin, in mg/l
R_D = assumed percent removal rate for the retention or detention basin upstream of the filter bed (see Table 1)

The EMC of the effluent *TSS* leaving the filter after it has passed through retention or detention and the filter bed, is defined as:

$$E_{sf} = \left(1 - \frac{R_T}{100}\right) \cdot E_s \tag{6}$$

In which, E_{sf} = average annual EMC of *TSS* in the effluent from the filter bed, in mg/l
R_T = total system's average percent removal rate of *TSS*

Then the reduction in the EMC of *TSS* by the filter itself can be expressed as

$$E_{sfr} = E_{sd} - \left(1 - \frac{R_T}{100}\right) \cdot E_s$$

In which, E_{sfr} = the change in suspended solids concentration through the filter in milligrams per liter

After substituting Equation 5 into the above relationship and rearranging terms, we get

$$E_{sfr} = E_s \cdot \left(\frac{R_T - R_D}{100}\right) \tag{7}$$

For design purposes it is suggested that the value for R_T be equal to the highest reported rates of *TSS* removals by stormwater filters, namely R_T = 95 percent.

Table 1. Suggested Design Percent Removal Rates by Retention and Detention Upstream of a Media Filters for Sizing Them.

Detention Volume, P_o, Drain Time - T_d in hours	Suggested Percent Removal - R_D	
	Detention	Retention
48	60	90
24	55	85
12	50	80
6	40	75
3	30	70
1	20	50

For Case 3 shown in Figure 4 the above analysis needs to be modified. In Case 3 some of the detention storage volume is directly above the filter media. A first-order estimate of sediment removals ahead of the filter assumes that the water column that is not above the filter's surface acts as an independent retention pond. The water column that is above the filter's surface receives no pretreatment and all the *TSS* in this water is subject to removal by the filter.

Under the Case 3 scenario one can assume that the *TSS* concentration leaving the retention portion of the system can be expressed in terms of retention surface area and the total system surface area. Namely,

$$E_{sd} = r_R \cdot E_s \cdot \left(1 - \frac{R_D}{100}\right) \tag{8}$$

In which, r_R = $[A_R/(A_R+A_f)]$, ratio of the retention basin's surface area to the total system's surface area

A_R = surface area of the retention pond's permanent pool in square feet

A_f = surface area of the filter bed in square feet

Then the reduction in the EMC of *TSS* by the filter bed itself can be expressed by

$$E_{sfr} = E_s \cdot \left[\frac{R_T - r_R \cdot R_D}{100}\right] \tag{9}$$

Note that if all the detention storage is above the filter's surface, such as a basin with a sand filter bottom, $r_R = 0$ and all the *TSS* load is removed by the filter.

FILTER'S FLOW-THROUGH RATE

The classic relationship for water percolating through uniform soil media such as sand can be expressed as

$$q = k_h \cdot I \tag{10}$$

In which, q = flow velocity in inches per hour

k_h = hydraulic conductivity of the soil in inches per hour

I = hydraulic gradient in feet per foot

The relationship breaks down for a slow sand filter as fine sediment accumulates on top of its surface. In fact, field observation and laboratory tests (Neufeld, 1996; Urbonas *et al.*, 1996b) show that the flow-through rate for a sand filter (and other media as well) quickly becomes a function of the sediment being accumulated on the filter's surface. This relationship appears to be not very sensitive to the hydraulic surcharge on the filter's surface. It is represented graphically in Figure 5 and can be expressed mathematically as

$$q = k_i \cdot e^{-c \cdot L_m} \tag{11}$$

In which,
- k_i = empirical flow-through constant (see Figure 5)
- c = empirical exponential decay constant (see Figure 5)
- L_m = cumulative unit *TSS* load accumulated on the filter's surface in pounds per square foot

It is this relationship that is used as the basis for the design procedure described later in this paper. Although the coefficients in Figure 5 are probably indicative of the expected performance for a sand filter, similar sets of coefficients can be developed for other filter media such as sand-peat mixes, etc. Namely, the procedure discussed here should be valid for other filter media provided appropriate empirical flow-through coefficients are employed . Examination of Figure 5 reveals that when the filter bed is new, the flow-through rates far exceed 12 inches per hour. As *TSS* is removed over the storm runoff season and the filtrate accumulates on the filter's surface, the flow-through rate rapidly drops off to approximately 0.9 inches per hour, after which it slowly continues to decrease to approximately 0.6 inches per hour.

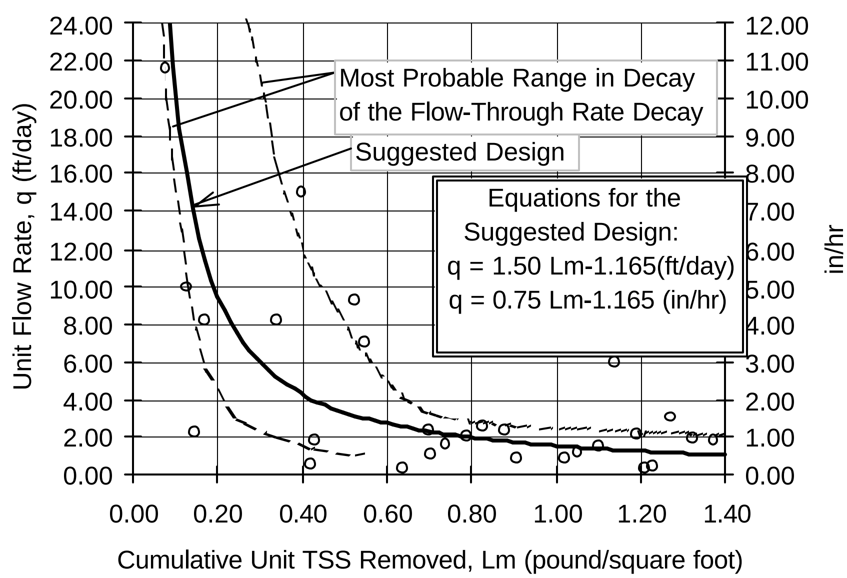


Figure 5. Flow Through Rate vs. Cumulative TSS Removed - Lakewood Sand Filter Test Site

The fraction of all runoff volume from the tributary area that will be treated through the filter facility is, in part, a function of the capture volume (i.e., detention) provided upstream of the filter. This detention volume can be bypassed by larger runoff flows, or the larger flows can first go through the detention basin before overtopping it and bypassing the filter itself. Depending on which condition occurs will also determine the amount of treatment provided to the excess volumes produced by larger storms. If the *maximized* capture volume is provided, approximately 80 to 90% of all runoff volume can be treated by the filter installation. If, however, the capture volume provided is based on the *mean* runoff volume, approximately 60% to 70% of all runoff volume will be fully processed through the filter. Approximate values of coefficient *a* to be used in Equation 1 can be found on Figure 2, which coefficient can be used to find the capture volume for the *mean* storm and the *maximized* storm.

The filter will need to be maintained to stay in operation. Its contaminated and clogged layers will need to be removed and replaced with new media. After a number of such surface cleanings (estimated at five to ten) the entire media filter will need to be replaced because lower pore spaces will also fill. The frequency of maintenance activities play a major, maybe a dominant role in the filter's design. It is appropriate then to define the *TSS* load removals in terms of the frequency of maintenance cycles the facility will experience each year. Also, since the flow-through rate in Equation 11 (i.e., Figure 5) is expressed as a function of the load removed by the unit area, it is appropriate to express the average *TSS* load removed during each maintenance cycle in terms of *TSS* load removed by each square foot of the filter. Thus,

$$L_m = \frac{L_{afr}}{A_{fm} \cdot m} \qquad (13)$$

In which,
- L_m = average *TSS* load removed by each square foot of the filter during each maintenance cycle, in pounds per square foot per cycle
- m = number of times per year the filter is cleaned and reconditioned (i.e., maintenance cycles per year). Use a fraction (i.e., 0.5) if more than one year between cleanings
- A_{fm} = surface area of the filter sized on the basis of *TSS* for load removed, in square feet

SIZING THE FILTER

Rearranging the terms of Equation 13 yields an expression for estimating the filter's area, namely,

$$A_{fm} = \frac{L_{afr}}{L_m \cdot m} \qquad (14)$$

which is one of two filter area relationships that have to be satisfied simultaneously. The other one is the ability of the filter to process the design storm's runoff volume (e.g., maximized volume) within the desired drain time. This condition can be expressed as

$$A_{fh} \cdot q \cdot T_d = P_o \cdot A_c \cdot 43{,}560$$

Rearranging terms the area of the filter is defined as

$$A_{fh} = \frac{P_o \cdot A_c \cdot 43{,}560}{q \cdot T_d} \qquad (15)$$

In which, q = the design flow-through rate through the sand filter's surface, in inches/hour
T_d = the time it takes the volume P_o to totally drain out at the design flow-through rate *q*, in hours
A_{fh} = surface area of the filter based on hydraulic sizing, in square feet

The designer now has to find a filter's surface area that comes close to satisfying the condition

$$A_{fm} \approx A_{fh}$$

namely, the surface areas found using the *load removed* sizing equation and the *hydraulic sizing* equation are nearly identical.

The following design procedure is suggested for finding the required filter's surface area:

DESIGN PROCEDURE

1. *Determine the average EMC of TSS the tributary catchment will produce.*
   Use local *TSS* stormwater characterization data when available. In absence of local data, use the closest regional averages of *TSS* found in stormwater reported in the Nationwide Urban Runoff Evaluation final report (EPA, 1983) or other, more current, data source. This will set a value for E_s for the design.

2. *Calculate the average annual TSS load in stormwater runoff from the design catchment.*
   Use Equation 2 to find the catchment's runoff coefficient, C; Figures 1, 2 and 3 and Equation 3 to estimate the catchment's average annual runoff, P_A; and the value of E_S from Step 1 above, the catchment's tributary area, A_c, and the foregoing estimate of P_A in Equation 4 to estimate the average annual *TSS* load, L_a, being delivered by stormwater runoff to the filter installation.

3. *Select filter-detention/retention configuration and preselect its desired drain time (i.e., time it takes to fully evacuate the capture volume.*
   It is suggested that Case 1 and 2 configurations (City of Austin, 1988) be used for tributary catchments with over one acre of impervious surface, while Case 3 be considered as a filter inlet for smaller sites (Shaver, 1994; City of Alexandria, 1992).

   It is necessary to assume or select the drain time, T_d , for the capture volume being used to size the filter. This is the determining factor for finding the "maximized" or the "mean" volume, P_o, whichever is used as the design water quality capture volume.

4. *Estimate the reduction in the EMC of TSS provided by the filter itself.*
   Based on the filter's configuration being used (e.g., Case 1, 2 or 3 with a value for r_R), select the appropriate value from Table 1 for the removals by the detention or retention portion of the facility and use Equation 7 to calculate E_{sfr}.

5. *Estimate the average annual TSS load removed by the filter.*
   Use Equation 12 to calculate a value for L_{afr}.
   Assume b = 0.90 if a detention volume equal to P_o is provided.

6. *Determine the filter's annual maintenance frequency.*
   Base this on how often the owner is willing and/or able to clean and restore the filter. For example, on the southwest coastal areas of the United States where almost all rainfall

takes place in a six-month period, if the owner is willing to clean the filter at least once a month during the wet weather months, set the value for $m = 6$. If, on the other hand the owner does not want to bother with frequent maintenance and will commit only to cleaning the filter once every two years, set $m = 0.5$.

7. *With the aid of Figure 5 select the acceptable unit TSS load before each cleaning.* Initially it is necessary to assume a value for the unit *TSS* load removed, L_m. by the filter. This value will be used with Figure 5 to make the first estimate of the needed filter's surface area.

8. *Set the water quality capture volume for this installation.* It is recommended that, as a minimum, a volume equal to the runoff from the "mean" average storm (see Figure 1) and the "maximized" volume be used for design. Using the drain time, T_d, assumed in Step 7 and Equation 1 to calculate a value for P_o.

9. *Make first estimates of the filter's area.* Calculate the filter's area, A_{fm}, using Equation 14 and the values for L_a, E_s, and L_{afr} found in Steps 1, 2 and 5 respectively.

   Also, calculate the filter's area, A_{fh}, using Equation 15 and the values for P_o; the catchment's tributary area, A_c; the flow-through rate, q, using Equation 11 based on the value of L_m; and the assumed drain time T_d for P_o assumed in Step 3.

10. *Compare the two filter areas calculated in Step 9.* If the two calculations give significantly different results, say more than 20% different; average the two areas; calculate a new value for the unit load removed by the filter, L_m; find a new flow-through rate using Equation 11 and repeat Step 9. Otherwise choose the larger surface area of the tow after rounding off, as the design area.

    Repeat this process as needed until the two area calculations are within 20% of each other. At that point use the larger of the two as the design surface area of the filter.

EXAMPLES

Example 1. A commercial site near Chicago, Illinois. The media filter will be preceded by an upstream extended detention basin. The known site conditions are as follows:

Step 1:

Tributary Area	A_c	=	1.5 acres
Expected EMC of *TSS*	E_s	=	120 mg/l
Average storm depth (Figure 1)	P_6	=	0.53 inches
Average number of storms per year ≥ 0.1 inches in depth (Figure 3)	n	=	55
Catchment's total imperviousness	I_a	=	85%

Step 2: Using Equation 2 find its runoff coefficient:

$$C = 0.858 \bullet 0.85^3 - 0.78 \bullet 0.85^2 + 0.77 \bullet 0.85 + 0.04 = 0.66$$

Using Equation 3 estimate the average annual runoff from the catchment:

$$P_A = 55 \bullet 0.53 \bullet 0.66 = 19.24\ inches$$

Using Equation 4 calculate the annual *TSS* load from the catchment:

$$L_a = 1.5 \bullet 43{,}560 \bullet \frac{19.24}{12} \bullet \frac{120}{10^6} \bullet 62.4 = 784\ lbs$$

Step 3: Select the filter's design configuration. Since the filter will be preceded by an upstream extended detention basin, we have Case 1 configuration. Also the outlet from the extended detention basin is designed to drain the capture volume in 12 hours.

Step 4: Using T_d = 12 hours, Table 1 gives for a detention basin a suggested removal rate R_D = 50 percent. Then, assuming an overall removal rate for the detention-filter system (i.e., R_T) is 95%, estimate the reduction in total solids concentration produced by the filter itself.

$$E_{sfr} = 120 \cdot \left(\frac{95 - 50}{100} \right) = 54\ mg/l$$

Step 5: Using Equation 12 estimate the average annual *TSS* load removal by the filter itself.

$$L_{afr} = 0.90 \cdot \frac{54}{120} \cdot 784 = 318\ lbs$$

Step 6: Determine the filter's annual maintenance frequency.
For this example assume m = 1 (i.e., once per year)

Step 7: To keep the size of the filter small while not imposing a very frequent maintenance schedule we choose to design the filter to drain at approximately 2.0 inches per hour. This means the corresponding value for L_m = 0.32 pound/square foot is found with the aid of Figure 5.

Step 8: Using T_d = 12 hours, the runoff coefficient from Step 2 and the coefficient from Figure 2 in Equation 1, find the "maximized" capture volume:

$$P_o = 1.12 \bullet 0.66 \bullet 0.53 = 0.39\ watershed\ inches\ (2{,}124\ cu.\ ft.)$$

Step 9: Using Equation 14:

$$A_{fm} = \frac{318}{0.32} = 994\ sq.\ ft.$$

Using q = 2.0 *in./hr.* in Equation 15:

$$A_{fh} = \frac{0.39 \bullet 1.5 \bullet 43{,}560}{2.0 \bullet 12} = 1{,}062\ sq.\ ft.$$

Step 10: Since the two areas calculated in Step 9 are well within 20% of each other, choose the larger of the two and round off. Namely the filter area scheduled for design is:

A_f = 1,060 *sq. ft.*

This design will require, on the average, one cleaning a year, each cleaning consisting of the removal and replacement of the top three inches of the sand bed. After five or more such cleanings, the entire filter bed will probably need to be replaced. A smaller filter could be used with additional cleanings each year. The designer may want to check to see if substantial savings in life-cycle costs could be achieved using higher maintenance frequencies and a smaller filter or using a larger filter with fewer maintenance cycles.

Example 2. Same as Example 1 except use a filter inlet, namely Case 3, with the retention pond's and filter's surface areas equal to each other, namely r_R = 0.5.

Steps 1 through 3 are the same as in Example 1.

Step 4. In Table 1 we find for a retention pond with T_d = 12 hours for its surcharge detention, the suggested TSS removal rate is R_D = 80 percent

then, using Equation 9

$$E_{sfr} = 120 \cdot \left[\frac{95 - 0.5 \cdot 80}{100} \right] = 66 \; mg/l$$

Step 5. Using Equation 12 we find

$$L_{afr} = 0.9 \cdot \frac{66}{120} \cdot 784 = 388 \; lbs.$$

Step 6. Assume m = 1.

Step 7. Using the same reasons stated in Example 1 we choose q = 2.0 *in./hr.* to begin the sizing process, thus

L_m = 0.32 lbs/ *sq. ft.*

Step 8: Same as in Example 1 @ T_d = 12 *hrs.*:

P_o = 0.39 inches (2,124 *cu. ft.*)

Step 9: Using Equation 14:

$$A_{fm} = \frac{388}{0.32} = 1{,}212 \; sq. \, ft.$$

Using Equation 15:

A_{fh} = 1,062 *sq. ft.*

Step 10: Since these two are within 20% of each other, use the higher of the two. After rounding off recommend the following for design:

A_f = 1,200 *sq. ft.*

Again, one cleaning per year will be required to keep it operating as designed.

EXPECTED WATER QUALITY PERFORMANCE

What kind of hydraulic and water quality performance can one expect from a sand filter? The discussion above addressed the design of the filter based on hydraulic performance and how it varies as *TSS* was removed from stormwater runoff by the filter. The designer, planner and decision makers need to understand that stormwater runoff varies from zero to very large discharge numbers. It is a direct function of the precipitation, its duration and the tributary catchment's characteristics.

By providing a capture volume upstream of the filter that is in balance with the filter's flow-through capacity and after accounting for maintenance, it is possible to fully treat a large percentage of the storm runoff producing events through the filter, while treating some of the larger events only in part. The events that produce runoff at rates and volumes that exceed the capacity of the filter's physical plant will receive only partial treatment since the excess runoff will bypass the filter. Thus, the total system's performance is the composite of the filter's effluent water quality and the water quality of the bypass flow.

Hopefully, the worst polluted water will be captured by the filter's detention volume and will be treated through the filter, and only the cleaner "post first-flush" water will bypass the filter. The quality of the bypass water will also be affected by how the upstream detention or retention basin/pond is connected to the catchment's runoff.

If the basin/pond is in line with the flow after its capture volume is exceeded, stormwater will flow through the basin and the excess will overtop it. A properly designed extended detention basin or a retention pond should provide some treatment, through sedimentation, for the water that flows through it. Its efficiency may be diminished, but some sediment will be removed. A poorly designed or undersized basin may provide no water quality enhancement and may, in fact, cause some of the previously deposited sediment to resuspend and be flushed out.

If the detention/retention basin goes off-line when it is full, the excess runoff bypasses it. This arrangement is superior to in-line arrangement for high flows when the facility is not designed to handle high flows without resuspension of the previously settle solids. At the same time, it will generally produce lesser quality runoff during high flow events when the basin is properly designed to handle them.

The exact arrangement of water quality capture volume basin (i.e., retention or detention) in relation to the runoff system and the filter's size determine what one can expect the average annual EMCs that reach the receiving waters. Figure 6 illustrates the two cases, namely overflow of the excess and the bypass of the excess. To make a valid assessment of the average annual EMC for any constituent reaching receiving waters, the designer needs to flow-weight the concentrations of the effluent and the excess runoff from all the storms that occur, on the average, during a year. Namely, for Case 1 shown in Figure 6:

$$E_c = \left(k_T \cdot k_D \cdot E_i\right) \cdot \left(1 - r_{pf}\right) + E_f \cdot r_{pf} \qquad (14)$$

and for Case 2

$$E_c = \left(k_T \cdot E_i\right) \cdot \left(1 - r_{pf}\right) + E_f \cdot r_{pf} \qquad (15)$$

In which, E_c = average annual constituent's EMC downstream of the filter facility's installation, in mg/l

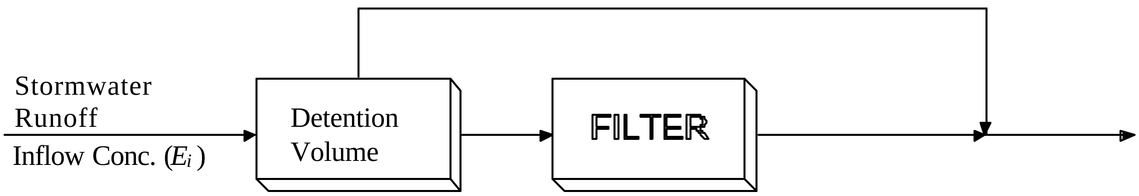
E_i = average annual constituent's EMC in the runoff inflow to the filter system, in mg/l

E_f = average annual constituent's concentration in the filter's effluent, in mg/l

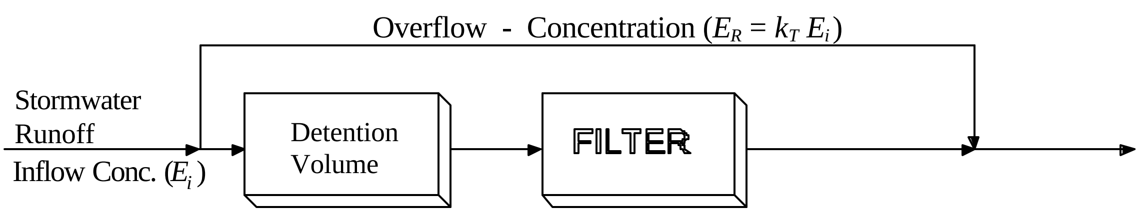
r_{pf} = fraction of the average annual runoff volume from the catchment that flows through the filter

k_D = fraction of the original constituent in the runoff that remains in the overflow water after the detention basin or retention pond overflows

k_T = coefficient of the reported constituent EMCs that represent the post "first-flush" fraction of the average EMC in stormwater runoff



Case 1. All runoff passes through the detention or retention basin upstream of the filter



Case 2. All runoff exceeding detention volume bypasses the filter and the detention/retention basin.

Figure 6. Two possible arrangements for a filter bypass with upstream detention volume.

Currently it is not possible to suggest definitive values for k_D and k_T, which coefficients depend on the constituent being considered and the actual design. However, a literature review suggests the following tentative ranges for *TSS*:

k_D = 0.3 to 0.5

and

k_T = 0.7 to 0.9

If the *maximized* coefficients suggested by Figure 2 for finding P_o are used, one can expect 80 to 90% of all runoff volume to be captured and treated through the filter, namely r_{pf} = 0.8 to 0.9. If, however, the runoff from the mean storm is used as the basis for design, one can expect approximately 60% to 70% of the runoff to be captured and treated through the filter, namely r_{pf} = 0.6 to 0.7.

Table 2 summarizes, after screening out the outliers, the findings of filter tests at four cities in the United States, namely, Alexandria, VA; Austin, TX; Anchorage, AK; and Lakewood, CO. Data for the first three were procured and consolidated into a single report by Bell et al. (1996) and the data for the Lakewood site were obtained by the Urban Drainage and Flood Control District in 1995. Note the high variability in the influent (i.e., stormwater runoff) measured concentrations for the six constituents reported here. Also note that the ratios between the high and the low concentrations are significantly less for the effluent. The variability in the influent appears to be primarily responsible for the large range in the report values of percent removed. However, most common removal rates for each constituent tend to cluster in a narrower range than the maximums. It is suggested that the designer look at the mean effluent (i.e., Out) concentrations in Table 2 to judge the filter's expected performance.

Table 2. Field Measured Performance Ranges of Sand Filters

Constituent	In or Out	Concentration *mg/l*			Percent Removed		
		Low	High	Mean	Low	High	MCR*
TSS	In	12	884	160			
	Out	4	40	16	8%	96%	80-94%
TP	In	0.05	1.4	0.52			
	Out	0.035	0.14	0.11	5%	92%	50-75%
TN	In	2.4	30	8.0			
	Out	1.6	8.2	3.8	(-130)%	84%	30-50%
TKN	In	0.4	28	3.8			
	Out	0.2	2.9	1.1	0%	90%	60-75%
TC_u	In	0.030	0.135	0.06			
	Out	0.016	0.035	0.025	0%	71%	20-40%
TZ_n	In	0.04	0.89	0.20			
	Out	0.008	0.059	0.033	50%	98%	80-90%

*MCR - Most Common Data Range

Returning to the earlier examples will illustrate the above discussion. In Example 1 an extended detention basin was used upstream of the filter. It is relatively easy to design this arrangement so that all runoff will pass through the detention basin and the excess runoff will overtop the pond. Let's further assume that k_D = 0.4 and k_T = 0.9. As a first order estimate we assume that 80% of the average annual runoff volume will pass through the basin and the filter and 20% will overflow the basin. If we assume that the filter will have an average effluent *TSS* concentration of 16 mg/l (see Table 2) then the average annual EMC of *TSS* downstream of the filter installation will be

$$E_c = (0.9 \bullet 0.4 \bullet 120) \bullet (1 - 0.8) + 16 \bullet 0.8$$

$$E_c \;=\; 21 \text{ mg/l}$$

Comparing this to the average EMC for *TSS* in stormwater runoff at that site (i.e., 120 mg/l) this installation will have 82% average annual removal efficiency for *TSS*. As a note of interest, it appears that the filter installation will produce only a marginal water quality improvement in *TSS* concentrations over a well-designed extended detention basin. Also, it appears that the filter's average effluent *TSS* and *TP* EMCs should be equivalent to one(s) produced by a well-designed retention pond. Similar estimates can be made for other constituents using the concentrations listed in Table 2.

Acknowledgments

The author acknowledges the support of the Urban Drainage and Flood Control District and City of Lakewood in the building and testing of this test filter installation.

The help provided by John Doerfer, project hydrologist at the District, for the installation and maintenance of the instrumentation and by Richard Ommert and Curtis Neufeld, both formerly engineering student interns with the District for collecting and analyzing the field data was invaluable. In addition, the cooperation and assistance of Jerry Goldman and Chris Jacobson of the City of Lakewood are also acknowledged. Without their help, the installation, maintenance and testing of this facility would not have been possible.

Special thanks go to Warren Bell, P.E., City Engineer for the City of Alexandria, Virginia for providing his report on their assessment of the pollutant removal efficiencies of Delaware sand filter BMPs. The data accumulated throughout the United States reported by him (Bell et al., 1996) supplemented the data collected by the District helped the author to verify his formulate ideas and interpretations on how media filters function in the field.

The following colleagues reviewed the earlier drafts of this paper: Richard Horner, Betty Rushton, Eugene D. Driscoll, Jonathan E. Jones, Jiri Marsalek, Bill Pisano, William P. Ruzzo, George Chang and James C.Y. Guo. Their generous comments and suggestions helped to improve this paper.

REFERENCES

Bell, W., Stokes, L., Gavan, L.J. and Nguyen, T. 1996 (undated). *Assessment of the Pollutant Removal Efficiencies of Delaware Sand Filter BMPs.* City of Alexandria, Department of Transportation and Environmental Services, Alexandria, VA.

City of Austin (TX). 1990. *Removal Efficiencies of Stormwater Control Structures,* Final Report. Environmental Resource Management Division. Austin, TX.

Driscoll, E.D., Palhegyi, G.E., Strecker, E.W. and Shelley, P.E. 1989. *Analysis of Storm Events Characteristics for Selected Rainfall Gauges Throughout the United States*. U.S. Environmental Protection Agency, Washington, D.C.

EPA. 1983. *Results of the Nationwide Urban Runoff Program, Final Report.* U.S. Environmental Protection Agency, NTIS PB84-18552, Washington D.C.

Guo, J.C.Y. and Urbonas, B. 1996. "Maximized Detention Volume Determined by Runoff Capture Ratio," *J. Water Resources Planning and Management*. Jan/Feb, p. 33-39, American Society of Civil Engineers, Reston, VA.

Neufeld, C.Y. 1996. "*An Investigation of Different Media for Filtration of Stormwater.*" Masters Thesis, Department of Civil Engineering, University of Colorado at Denver, Denver, Colorado.

Urbonas, B. R., and Ruzzo, W. 1986. "Standardization of Detention Pond Design for Phosphorus Removal," *Urban Runoff Pollution.* NATO ASI Series Vol. G10, Springer-Verlag, Berlin.

Urbonas, B., Roesner, L.A., and Guo, C.Y., L.S. 1996a. "Hydrology for Optimal Sizing of Urban Runoff Treatment Control Systems," *Water Quality International*. International Association for Water Quality, London, England.

Urbonas, B.R., Doerfer, J.T. and Tucker, L.S. 1996b. "Stormwater Sand Filtration: A Solution or a Problem?" *APWA Reporter*. American Public Works Association, Washington, DC.

Veenhuis, J.E., Parish, J.H., and Jennings, M.E. 1989. "Monitoring and Design of Stormwater Control Basin," *Design of Urban Runoff Quality Controls.* American Society of Civil Engineers, Reston, VA.