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Environmental Quality and Installations (EQI) Green Range Research Program

Modeling the Performance of Sand Filters for Removing Runoff Suspended Sediment

Mark S. Dortch

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Abstract

Geotextile tubes filled with sand are being evaluated for filter treatment of runoff containing lead and other metals stemming from firing small arms on military training ranges. Such filter tubes trap total suspended sediment (TSS) in the runoff, thus removing most of the metals, which are adsorbed to the sediment. Mathematical models were developed within two Excel workbooks to assess sand filter performance for a cascade of filters capturing runoff from the impact area of small arms firing ranges. One of the workbooks assesses filter cascade characteristics for a single design storm, while the other workbook assesses filter characteristics for a continuous, steady rainfall so that the useful life of the filters, as impacted by clogging, could be estimated. Model computations include the approach depth of flow, including filter overtopping, and the flow rate through each filter over time for specific storm events. The time history of effluent TSS concentration and the TSS trapped within each filter are also computed, as well as the TSS removal coefficient and hydraulic conductivity of each filter. The models provide useful general performance information. In order to provide more specific performance information, laboratory experiments with site-specific sand filter material and runoff TSS are required to determine three filter parameters that can be used as part of the model input.

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Preface

This study was funded by the U.S. Army's Environmental Quality and Installations (EQI) Green Range Research Program. The work reported herein was conducted by Dr. Mark Dortch of MSD Engineering Consulting under contract to Los Alamos Technical Associates, which was under contract to the US Army Engineer Research and Development Center (ERDC). Dr. Dortch prepared this report.

The study was conducted under the general direction of Dr. Beth Fleming, Director, Environmental Laboratory (EL); Dr. Jack Davis, Deputy Director, EL; Dr. Warren Lorentz, Chief, Environmental Processes and Effects Division; and Dr. Dorothy Tillman, Chief, Water Quality and Contaminant Modeling Branch. Dr. Elizabeth Ferguson was Technical Director of military environmental research, and Jerry Miller was Program Manager for the EQI Green Range Research Program.

Dr. Jeffery P. Holland was Director of ERDC. COL Jeffrey Eckstein was Commander. This report is approved for unlimited distribution.

Unit Conversion Factors

Multiply	By	To Obtain
inches	25.4	millimeters
inches	0.0254	meters
liters	1,000	cubic meters
hectares	10,000	square meters

List of Acronyms, Abbreviations, and Symbols

Acronyms and Abbreviations

AOI	area of interest, such as small arms range impact areas
BMP(s)	Best Management Practice(s)
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
EQI	U.S. Army's Environmental Quality and Installations Green Range Research Program
HE	high explosives
MC	munitions constituents, such as metals and high explosives
SAFRs	small arms firing ranges
SCS	Soil Conservation Service
TSS	total suspended solids concentration

Mathematical Symbols

A	catchment surface area for the Rational formula, hectares
b	bulking factor of sediment deposited within the filter, dimensionless
C	TSS concentration within filter, milligrams/liter
C_{ef}	filter effluent concentration of TSS, milligrams/liter
C_{in}	filter influent concentration of TSS, milligrams/liter
C_r	empirical runoff coefficient of the Rational formula, dimensionless
d_{10}	effective sand particle size and the size for a sieve that passes 10% by weight of sand sample being sieved, millimeters
H_f	height of the filter, meters
H_L	head loss of flow through the filter, meters
dH/dL	head loss gradient across the filter, dimensionless
h	water depth immediately upstream of the filter, meters
h_c	water depth immediately upstream of the filter at steady-state stage (steady-stage) following clogging, meters
h_i	water depth immediately upstream of filter i, meters
$\bar{h}$	time-averaged water depth immediately upstream of the filter, meters
I	rainfall intensity for the Rational formula, millimeters/hour
K	saturated hydraulic conductivity of the filter, meters/hour
L	distance across filter along flow path, meters

L_f	thickness or length of flow path of the filter, meters
M_s	mass of TSS deposited within the filter, grams
Q	water flow rate across the filter, cubic meters/hour
Q_p	peak runoff flow rate in the Rational formula, liters/minute
Q_i	water flow rate across filter i, cubic meters/hour
$\mathrm{Q_r}$	runoff flow rate for channel segments between filters, cubic meters/hour
Q_o	runoff flow rate for the AOI, cubic meters/hour
R_a	cumulative average annual rainfall depth, inches
R_c	cumulative rainfall depth for steady-stage clogging, inches
S	channel bottom slope, dimensionless decimal fraction
T_c	steady-stage clogging time, rain days
T_f	effective filter life, years
t	time, minutes and hours
V_i	water volume stored immediately upstream of filter *i,* cubic meters v superficial (Darcy) velocity of flow through the filter, meters/hour
W_c	width of the effective drainage approach channel (same as the filter width), meters
α_1	filter sediment clogging factor, 1/meter
α_2	filter sediment clogging factor, 1/meter
Δh_i	water depth difference across filter *i*, meters
ΔL	distance between filters, meters
Δt	time-step for the solution, hours
ΔV_i	change in water volume stored immediately upstream of filter *i* over a time-step, cubic meters
ϕ	sand porosity or ratio of void volume to total volume within the filter, dimensionless decimal fraction
ϕ_i	initial sand porosity within the filter prior to any clogging, dimensionless decimal fraction
Ψ	sand particle shape factor or sphericity, dimensionless decimal fraction
λ	filter removal coefficient, meter to the (-1)
λ_i	initial filter removal coefficient prior to any clogging, meter to the (-1)
ν	kinematic viscosity of water, square meters/second
σ	specific sediment deposit concentration within the filter pore water, dimensionless
σ_m	sediment deposit concentration within the filter pore water, grams/cubic meter
ρ_s	dry sediment particle density, grams/ cubic meter

1 Introduction

Background

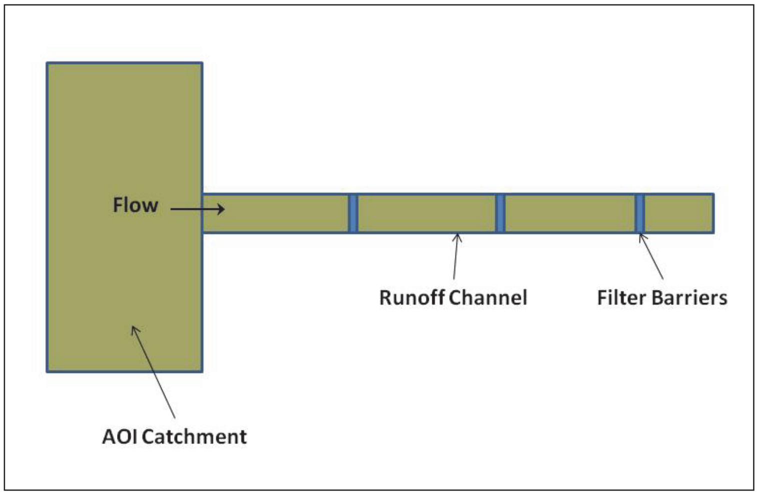
Department of Defense (DoD) firing and training ranges must be managed to protect human health and the environment against exposure to munitions constituents (MC), such as high explosives (HE) and metals. Range management for environmental compliance, referred to here as Best Management Practices (BMPs), can include range use strategies as well as remediation.

Small arms firing ranges (SAFRs) typically include impact berms where fired bullets are trapped and collected. Relatively high concentrations of metals (such as lead and copper) in these bullets build up in the impact soils. Metals that have dissolved into water tend to adsorb relatively strongly to soils. When these soils are eroded, the particulate metals that are adsorbed to soils also move with the runoff.

Methods are sought to reduce or eliminate the presence of metals in runoff from SAFRs. One method being considered uses sand filter tubes or barriers. Sand filters have been used to effectively trap the suspended sediments in urban stormwater runoff, and thus should be effective in removing metals in runoff from SAFRs.

Porous geotextile fabric is used to hold the sand filter material within a tubular shape. As shown in Figure 1, the filter tubes, or filter barriers, can be placed across the drainage path of the catchment encompassing the SAFR or area of interest (AOI). Although this is an apparently rather simple remediation approach, design issues and various unknowns should be considered prior to implementation. Questions concerning the type and size of sand to place in the tubes and how those sand characteristics affect flow and ponding behind the barriers must be addressed. The design should be adequate to pass a design flow without overtopping. Other issues include the spacing between filters, the number of filters required, the total suspended solid (TSS) removal performance and how that changes with time, and the permeability of the filters and how that characteristic changes with time as TSS is trapped within the filters. Eventually the build-up of trapped sediment will render the filter useless for further TSS removal.

Figure 1. Plan view of filter tubes or barriers used to remove suspended sediments in runoff.



Objective

The objective of this work was to develop mathematical models to predict the performance and TSS removal characteristics of the sand filter tubes, including the effects of TSS clogging over time. The intended use of the models is for site-specific design of the filters prior to construction and implementation.

Scope

This report describes the formulation and implementation of these mathematical models, as well as model input requirements. Example application results are also presented.

2 Model Formulation

Due to the relatively low flow velocities through the porous media of the sand filters, laminar flow can be assumed, along with Darcy's law, which states

$$v = K\frac{H_L}{L_f} \qquad (1)$$

where

v = superficial (Darcy) velocity of flow through the filter, meters/hour
K = saturated hydraulic conductivity of the filter, meters/hour
H_L = head loss of flow through the filter, meters
L_f = thickness or length of flow path of the filter, meters

The Darcy velocity is the same as the approach velocity, which is

$$v = \frac{Q}{W_c h} \qquad (2)$$

where

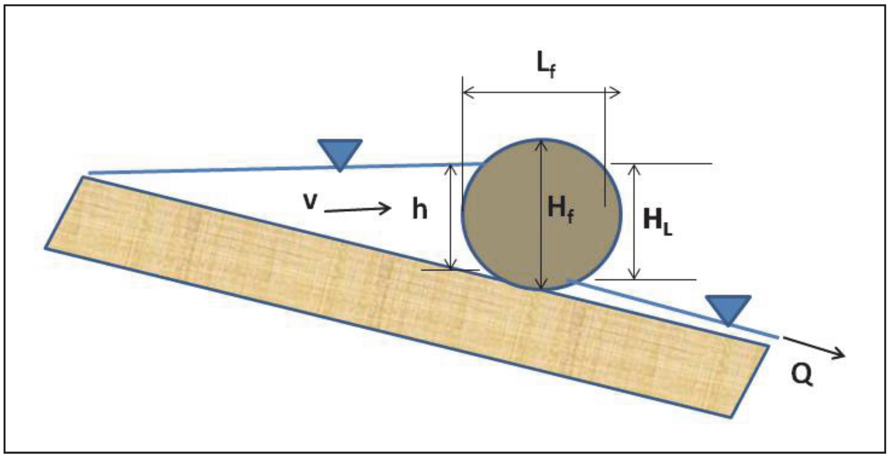
Q = water flow rate through the filter, cubic meters/hour
W_c = width of the effective drainage approach channel (same as the filter width), meters
h = water depth immediately upstream of the filter, meters

For practical purposes, when there is little depth of flow on the downstream side of the filter, H_L approximately equals h as shown in Figure 2. Thus, using Equations 1 and 2,

$$Q = KW_c\frac{h^2}{L_f} \qquad (3)$$

For a single filter, the water flow rate is known and is the same as the runoff flow from the AOI catchment. The approach channel width is also known, as well as the filter thickness L_f and height H_f. The flow depth must be calculated to determine whether or not it is greater than the filter height and whether or not flow overtops the filter. Therefore, K must be estimated.

Figure 2. Flow schematic of filter tube.



The filter hydraulic conductivity K depends on various factors including the filter sand grain size and shape, sand porosity, and the viscosity of water. Additionally, K can vary with time as the filter traps TSS and begins to lose permeability. Various formulae have been proposed for predicting K without the effects of clogging (Hazen 1911, http://web.cecs.pdx.edu/~fishw/UO-Ch14.pdf; Huisman and Wood 1974; Chapuis 2004). These formulae are based on theoretical considerations and are condensed here into the following relation for K (meters/hour):

$$K = 2.355x10^{-4} \frac{\phi^3 \psi^2 d_{10}^2}{\nu(1-\phi)^2} \quad (4)$$

where

ϕ = sand porosity or ratio of void volume to total volume, dimensionless decimal fraction

Ψ = sand particle shape factor or sphericity, dimensionless decimal fraction

d_{10} = effective sand particle size and the size for a sieve that passes 10% by weight of sand sample being sieved, millimeters

ν = kinematic viscosity of water, square meters/second

The particle size d_{10} can be determined from sieve particle size analysis, but it is also related to the grain size uniformity U, which is defined as d_{60}/d_{10}, with U varying between approximately 1 and 5. It is usually desirable for filter sand to have a U value between 1 and 2, but local sands may have a value between approximately 2 and 3 (http://web.cecs.pdx.edu/~fishw/UO-Ch14.pdf). The porosity and shape factor of sand are related to the descriptions shown in Table 1.

Table 1. Shape factor and porosity values for sand (from http://web.cecs.pdx.edu/~fishw/UO-Ch14.pdf).

Description	Shape Factor	Porosity
Spherical	1.00	0.38
Rounded	0.98	0.38
Worn	0.94	0.39
Sharp	0.81	0.40
Angular	0.78	0.43
Crushed	0.70	0.48

The viscosity of water can be related to the water temperature by the following equation:

$$\nu = \frac{1.79E-6}{1+0.03668T+0.000221T^2} \tag{5}$$

where T is the water temperature in degrees Celsius. Based upon the above information, the initial value of K (before clogging) can be readily computed from Equation 4.

Filter clogging occurs due to TSS that has been removed by the filter. The storage of TSS within the filter causes the hydraulic gradient across the filter to increase due to an increase in K. Campos (2002) proposed the following formula to determine the hydraulic gradient (head loss gradient) $\frac{dH}{dL}$ as affected by sediment trapping within the filter:

$$\frac{dH}{dL} = \left.\frac{dH}{dL}\right|_i \left(1+\frac{\sigma}{1-\phi_i}\right)^{1.33} \left(\frac{\phi_i}{\phi_i-\sigma}\right)^{3.4} \tag{6}$$

where the subscript i represents the initial value prior to any clogging, and σ is the current specific deposit concentration of sediment in the filter (non-dimensional), or $\sigma = \frac{\sigma_m}{\rho_s}$, where σ_m is the sediment deposit concentration in the filter pore water, grams/cubic meter, and ρ_s is the dry sediment particle density, grams/cubic meter. The initial hydraulic gradient can be determined from Equation 1 or is equal to v/K for a single filter. The initial porosity is filter-specified based on the sand characteristics.

The TSS mass deposited within a filter M_s is based on mass balance principles and is determined from

$$\frac{dM_s}{dt} = Q\left(C_{in} - C_{ef}\right) \tag{7}$$

where t is time in hours, C_{in} is the TSS concentration entering the filter, and C_{ef} is the filter effluent concentration where both concentrations are in grams/cubic meter or milligrams/liter. The deposit concentration within the filter pores can be determined from the deposit mass divided by the pore volume, as follows:

$$\sigma_m = \frac{M_s b}{\phi W_c L_f \bar{h}} \tag{8}$$

where b is the deposited sediment bulking factor (dimensionless and between 1.0 and approximately 1.5), and $\bar{h}$ is the average water depth immediately upstream of the filter. The average water depth is used since a storm hydrograph results in a rising and falling depth, which affects the deposit concentration. A running average of water depth is used as the hydrograph computations progress over time. The porosity ϕ, as well as all variables in Equation 7, varies over time during a storm hydrograph. Porosity can be computed from the following equation:

$$\phi = \frac{\phi_i}{1 + \frac{\sigma_m}{\rho_s}} \tag{9}$$

The filter TSS removal coefficient λ is empirical since it is affected by the sand filter material, characteristics of the TSS, and potentially other factors; it eventually decreases from an initial value over time due to trapping of TSS within the filter. Although the removal coefficient will eventually approach zero due to clogging, it actually increases with flow time initially (Ives 1987), since the initially trapped sediment helps to temporarily increase the trap efficiency. Campos (2002) proposed the following equation to determine the filter TSS removal coefficient λ as affected by TSS trapping within the filter:

$$\lambda = \lambda_i + \alpha_1 \sigma - \frac{\alpha_2 \sigma^2}{\phi_i - \sigma} \tag{10}$$

As before, the subscript *i* represents the initial value, and α_1 and α_2 are empirical clogging factors that depend on the type of sand and other properties with values for the first factor varying between approximately 6 and 248 m^{-1} and the second between approximately 26 and 970 m^{-1} (Campos 2002). It is possible for the filter coefficient to become negative for high values of deposit concentration. Thus, the value of λ is forced to be zero or greater within the model.

The specific TSS concentration gradient can be determined from a first order removal process (Ives 1987), as follows:

$$\frac{\partial C}{\partial L} = -\lambda C \tag{11}$$

where λ is the filter TSS removal coefficient (per meter) and C is the TSS concentration within the filter. The TSS effluent concentration exiting a filter at any given time, C_{ef} (grams/cubic meter), can be determined from the following integration of Equation 11:

$$C_{ef} = C_{in} \exp\left(-\lambda L_f\right) \tag{12}$$

where L_f (meters) was defined previously as the thickness of the filter (see Figure 2). The most recent time updates of λ and C_{in} are used in Equation 12. The influent concentration for a filter C_{in} is assumed to be constant for the most upstream filter and is specified by the user, but C_{in} can vary over time due to the storm hydrograph for filters downstream of the most upstream filter.

3 Model Implementation

The overall solution procedure can proceed over time by first solving for the approach depth of flow h from Equation 3 using the initial K (determined from Equation 4) and given the approach flow rate Q due to rainfall runoff, filter and approach channel width W_c, and filter thickness L_f as inputs. Knowing the approach flow depth and flow rate, the approach velocity v can be computed from Equation 2. Using the initial filter removal coefficient, the filter initial TSS effluent concentration C_{ef} can be computed from Equation 12. With C_{ef}, Equations 7 and 8 can be solved, yielding the TSS deposit concentration σ_m and deposit-specific concentration σ. With σ_m and σ, the porosity ϕ and filter removal coefficient λ can be updated from Equations 9 and 10, respectively, for use in the next time-step. With the value of σ, Equation 6 can be used to update the head loss gradient. When completing this update, it must be recognized that the initial head loss gradient is actually the present head loss gradient without any sediment trapping; thus, this initial (or non-clogging) value is computed from the ratio of the approach velocity v at the present time to the initial value of K at time zero. The value of K is updated for the next time level by applying Equation 1, which divides the latest value of v by the latest value of the head loss gradient. With the updated K value, the process repeats for the next time level, solving for the updated h, and so on. This procedure has been programmed into an Excel workbook using a first-order accurate Euler time integration with the time-step equal to the simulation duration times 0.0005.

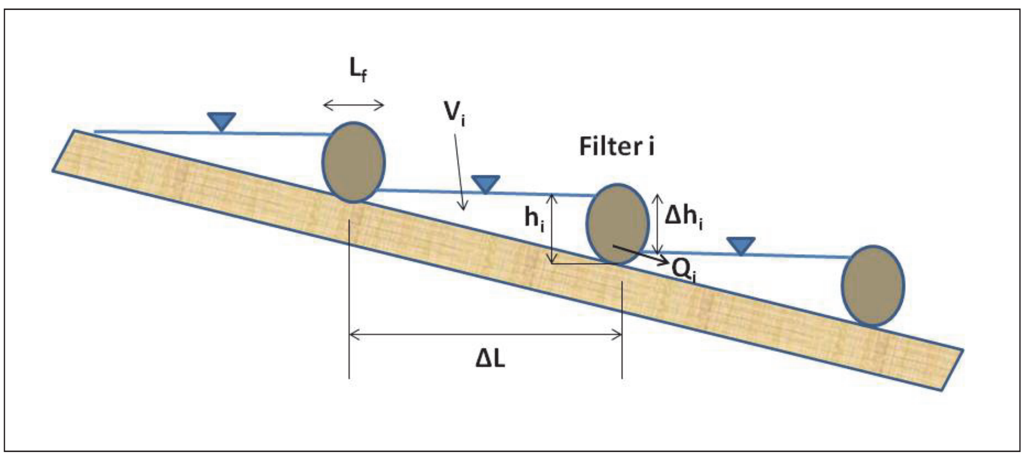
The approach flow rate for a single filter is the rainfall runoff flow rate. The AOI catchment surface areas for SAFRs are expected to be relatively small, e.g., on the order of a few acres. For small catchments, the peak runoff flow rate Q_p (liters/second) can be estimated using the following rational formula (Ponce 1989):

$$Q_p = 2.78\, C_r\, I\, A \tag{13}$$

where C_r is a non-dimensional, empirical runoff coefficient (between 0 and 1), I is the rainfall intensity (millimeters/hour), and A is the catchment surface area (hectares). The coefficient in Equation 13 is 2.78E-7 for flow rate units of cubic meters/second and area in units of square meters. The runoff coefficient is the ratio of the effective rainfall depth (after losses) to the total rainfall depth (before losses). Ponce (1989) provides tables for estimating C_r for urban and rural lands, given the type of cover and soil texture.

The model formulations are actually programmed into two Excel workbooks, one for a single storm event, and one for a continuous steady rainfall. Both workbooks allow up to three filters in succession along the flow path as a cascade, as shown in Figures 1 and 3. The single-storm version can be used to determine if filter overtopping occurs for a design storm, such as the 1-, 2-, 3-, 6-, 12-, or 24-hr storm for a given return frequency, such as 10 years. Rainfall depths for durations from 30 min to 24 hr and return periods from 1 to 100 years are available for the United States (US Weather Bureau (USWB) 1961). The second workbook, referred to as the continuous steady rainfall workbook, was developed to estimate the length of time for clogging to render a filter as ineffective.

Figure 3. Profile view for schematic of a cascade of filters.



Within the single-storm workbook, standard hydrological methods from the Soil Conservation Service (SCS) as outlined by Ponce (1989) are used to develop standardized storm rainfall hyetographs for the United States, given the storm type (one for each of the four standard types depending on location in the United States), the storm rainfall cumulative depth, and the storm duration. The workbook allows storms of 1, 2, 3, 6, 12, and 24 hr in duration. For storms of 1, 2, and 3 hr duration, the rainfall intensity is assumed to be constant over the storm duration. The cumulative rainfall depths corresponding to the storm frequency and duration are used in these three cases.

For storms of 6, 12, and 24 hr, the standard SCS 24-hr rainfall distributions are used based on the four SCS storm types as stated above. The cumulative depth for a 24-hr storm of a given frequency (10-year frequency is recommended) should be used, since the rainfall distribution for each storm type was developed from the 24-hr rainfall. Rainfall intensities corresponding to storm durations shorter than 24 hr are contained within the SCS 24-hr distributions. For example, if a 10-year, 24-hr distribution is used, the 1-hr period with the most intense rainfall within that distribution corresponds to the 10-year, 1-hr rainfall depth. The workbook is set up to handle storm durations of 6, 12, and 24 hr to develop the corresponding rainfall hyetographs. The rainfall distributions for the 6-hr and 12-hr storms are extracted from the SCS 24-hr distributions for each storm type by centering the distribution at the hour that the rainfall is most intense. The hourly rainfall is scaled to ensure that the cumulative rainfall is obtained upon summing all of the hourly rainfall amounts.

For the 1-, 2-, and 3-hr duration storms, the rainfall intensity and runoff flow rate computed with Equation 13 are constant. The runoff flow is assumed to occur only during the storm duration. This assumption is reasonable for small catchments where the time of concentration is much shorter than the storm duration. The time of concentration is expected to be on the order of several minutes for SAFR catchments.

For the 6-, 12-, and 24-hr duration storms, the rainfall intensity varies hourly based on the scaled rainfall distributions as explained above. The hourly rainfall is used to compute the hourly runoff flow rate using Equation 13. As with the shorter duration storms, the runoff flow is assumed to occur only during the storm duration.

Runoff flow rates are computed for the AOI catchment (Q_O) and the channel segments between each filter (Q_r). The Rational runoff coefficient used for the channel segments is the same as that used for the AOI catchment.

For the steady, continuous rainfall workbook, the average annual rainfall depth and the average number of days per year of significant rainfall are model inputs. Rainfall hyetographs are not needed, and time-varying runoff hydrographs are not computed. The runoff flow rate is constant and is based on the average rainfall intensity, which is the average annual rainfall depth divided by the average number of rainfall days per year, with that result divided by 24 hr/day, yielding a rainfall intensity in depth/hour.

Both workbooks handle up to three filters in a cascade of filters. The slope of the ground and the spacing between filters must be taken into account to compute water depths h_i for given storage volumes V_i. With depths, water level (head) differences across each filter Δh_i can be computed. Given head differences, flow rate across each filter Q_i can be computed. The equations relating water storage volume, depth, head difference, and flow rate for a cascade of filters are presented below.

Assuming the channel of the effective drainage path is rectangular, the relationships for water volume stored immediately upstream of filter *i* (V_i) as related to depth (h_i) are as follows:

$$V_i = \frac{1}{2} W_c \frac{h_i^2}{S} \qquad for\ V_i \le \frac{1}{2} W_c \Delta L^2 S \tag{14}$$

$$V_i = W_c \Delta L h_i - \frac{1}{2} W_c \Delta L^2 S \qquad for\ V_i > \frac{1}{2} W_c \Delta L^2 S \tag{15}$$

where ΔL is the distance between filters, S is the bottom slope, and all other terms have been defined previously. Only Equation 14 applies for the first (most upstream) filter. Equations 14 and 15 are solved for depth given the latest value of volume, i.e., the most recent update in time.

The water level difference across filter *i* (Δh_i) is computed from the following relationships:

$$\Delta h_i = h_i \qquad for\ h_{i+1} \le \Delta L S \tag{16}$$

$$\Delta h_i = h_i + \Delta L S - h_{i+1} \qquad for\ h_{i+1} > \Delta L S \tag{17}$$

The above two equations are used for all filters except the most downstream filter, which uses only Equation 16, since storage does not occur below this last filter.

With the depth and water level (head) difference, the flow rate for filter *i* (Q_i) can be computed from

$$Q_i = W_c h_i K \frac{\Delta h_i}{L_f} \tag{18}$$

With the flow rate, the change in water volume stored immediately upstream of filter *i* (ΔV_i) can be computed from the following linear reservoir routing:

$$\Delta V_i = \Delta t \left(Q_{i-1} - Q_i + Q_r \right) \tag{19}$$

where Δt is the time-step, and Q_r is the runoff flow rate between filter *i* and *i-1*. As explained previously, the rational formula is used to compute Q_r using the amount of rain falling on the surface area between the two filters. The surface area between filters is assumed to be $W_c \Delta L$. For the first filter, Q_{i-1} is the AOI runoff Q_o, which is assumed to include any approach channel runoff Q_r. The time-step is determined within the workbooks by multiplying the length of simulation (an input) by a decimal fraction constant of 0.0005 for both the storm event version and the continuous steady rainfall version.

The above equations apply for a given time level. Values must be advanced over time. Given the change in volume for a time level, the volume can be updated for the next time level. The above set of equations can then be solved for the next time level, starting with Equations 14 and 15 and proceeding through Equation 19. The water volume update for time level *j+1* is computed from values at the previous time level *j* as follows:

$$V_i^{j+1} = V_i^j + \Delta V_i^j \tag{20}$$

Both workbooks use the above equation set to advance state variables (flow rate, depth, volume, etc.) over time.

In summary, the main difference between the two workbooks is that the steady rainfall version uses the input for average annual rainfall divided by the input for the average annual number of days of rainfall to compute the steady rainfall rate (intensity) and runoff flow rate. The storm event workbook uses the rainfall depth and duration for a single design storm and computes the time-varying runoff flow rate. The continuous version is run for days (i.e., 100 or more), while the storm event version is run for hours (i.e., 48, 60, etc.).

4 Model Inputs and Outputs

The required model inputs are listed in Table 2. Note that there are only a few differences in inputs for the two models besides the type of rainfall amounts. The single-event version requires storm duration and storm type, whereas the continuous version requires the average number of days per year with rainfall. All of the inputs are fairly easily obtainable with the exception of the filter removal coefficient and the two clogging factors. These three parameters are highly specific to sediments and filter sand at the site. Accurate estimates of the filter removal coefficient and the two clogging factors can be obtained using measurements from laboratory flumes or the field.

Table 2. Workbook input parameters for the filter models.

Input Parameter	Units	Typical Values	Source of Values
Rainfall and Runoff Inputs			
Catchment area	Square meters	Highly variable	Measurement of AOI for site
Design storm rainfall depth (single storm event version)	Inches	Highly variable	USWB 1961; TP 40 is hyperlinked to spreadsheet; depends on duration and return period; recommend 10-yr return period
Design storm rainfall duration (single storm event version)	Hours	1, 2, 3, 6, 12, or 24	Design variable; should evaluate several
Storm type (single storm event version)	Dimensionless	I, IA, II, and III	SCS map of U.S.; map is hyperlinked to spreadsheet
Average annual rainfall depth (continuous rainfall version)	Inches	Highly variable	U.S. Weather Service, U.S. National Climatic Data Center, and other sources
Average number of days per year with significant rainfall (continuous rainfall version)	Dimensionless	Highly variable	U.S. Weather Service, U.S. National Climatic Data Center, and other sources
Rational runoff coefficient	Decimal fraction	0.05 – 0.95	Ponce (1989); tables are hyperlinked to spreadsheet
Total simulation time	Hours (single storm event) or days (continuous rainfall)	24 – 96 hrs 50 – 400 days	User decision; instabilities can occur if time is too long since time-step is a fraction of total simulation time

Input Parameter	Units	Typical Values	Source of Values
Effective Flow Path Channel Specs and Filter Dimensions			
Effective flow path channel width, W_c	Meters	Highly variable	Potential design parameter
Ground slope in direction of flow, S	Decimal fraction	Highly variable	Local measurement
Filter height, H_f	Meters	Highly variable	Potential design parameter
Filter thickness, L_f	Meters	Highly variable	Potential design parameter
Number of filters	Integer	1 - 3	Potential design parameter
Distance between filters, ΔL	Meters	Highly variable	Potential design parameter
Filter Characteristics			
Water temperature	Degrees Celsius	0 - 40	Local measurement
TSS dry sediment density	Grams/cubic centimeter	2.65	Local measurement
TSS concentration in AOI runoff, C_{in}	Milligrams/liter	Highly variable	Local measurement
Sand size d_{10}	Millimeter	Variable	Potential design parameter; the Wentworth grain size chart is hyperlinked to spreadsheet
Sand shape factor (sphericity), Ψ	Decimal fraction	0.70 – 1.0	Potential design parameter; see Table 1; table is hyperlinked to spreadsheet
Sand initial porosity, ϕ_i	Decimal fraction	0.38 – 0.48	See Table 1; table is hyperlinked to spreadsheet
Bulking factor of trapped sediment, b	Dimensionless	1.0 – 2.0 or higher (Spigolon 1993)	Measurements; suggested value of 1.3 for silt
Filter initial removal coefficient for TSS, λ_i	1/meter	2 - 50	Empirical; should be measured for specific filter material and TSS
Filter clogging factor, α_1	1/meter	6 - 248	Empirical; should be measured for specific filter and TSS
Filter clogging factor, α_2	1/meter	26 - 970	Empirical; should be measured for specific filter and TSS

Output from the two workbook models includes time series graphs of the following for each filter in the cascade:

- approach depth (stage) with the filter height noted on the graph
- flow rate with the AOI runoff flow rate noted on the graph
- TSS removal coefficient

- TSS concentration trapped within the filter pore water
- filter effluent TSS concentration
- filter hydraulic conductivity
- TSS mass trapped within the filter

The two graphs of stage and flow rate versus time include the results for all filters on each graph, while the other variables are plotted individually for each filter.

All inputs are entered on the workbook sheet labeled “Inputs.” All output graphs for all filters are presented on the sheet labeled “Outputs.”

5 Model Application

Verification

Model verification is defined as conducting tests to verify that the programmed model is correctly solving the system equations. Most of the equations could be and were checked within the workbooks to verify that the correct solutions are obtained. Various inspections were also conducted to verify reasonableness. Both workbook versions were verified for the hydraulic solutions. This was done by solving for the filter stage for a steady, continuous rainfall rate and comparing the result to the time-varying solutions from the continuous, steady rainfall workbook after reaching a steady-state condition. Since the continuous rainfall workbook is a modified version of the single-event workbook, this verification helped lend credence to verification of the single-event hydraulics. Proper mass balance was also verified by comparing TSS delivered to and removed by a filter.

Example results

Results from the application of both workbooks are presented and discussed below.

Single-event application

A 10-year, 24-hr storm event with 8 in. of cumulative rainfall was evaluated. All of the inputs for this test case are shown in Table 3.

Table 3. Inputs from single-event application.

Input Parameter	Units	Input Values
Catchment area	Square meters	800
Design storm rainfall depth	Inches	8.0
Design storm rainfall duration	Hours	24
Storm type	Dimensionless	II
Rational runoff coefficient	Decimal fraction	0.30
Total simulation time	Hours	60
Effective flow path channel width, W_c	Meters	6
Ground slope, S	Decimal fraction	0.03
Distance between filters, ΔL	Meters	10

Input Parameter	Units	Input Values
Filter height, H_f	Meters	0.5
Filter thickness, L_f	Meters	0.5
Number of filters	Integer	3
Water temperature	Degrees Celsius	10
TSS dry sediment density	Grams/cubic centimeter	2.5
TSS concentration in AOI runoff, C_s	Milligrams/liter	100
Sand size d_{10}	Millimeters	0.5
Sand shape factor (sphericity), Ψ	Decimal fraction	0.90
Sand initial porosity, ϕ_i	Decimal fraction	0.40
Bulking factor of trapped sediment, b	Dimensionless	1.3
Filter initial removal coefficient for TSS, λ_i	1/meter	20
Filter clogging factor, α_1	1/meter	50
Filter clogging factor, α_2	1/meter	400

The flow depth and flow rate results of this application are presented in Figures 4 and 5, respectively. The two figures show the filter-cascade phasing and attenuation of depth and flow over time. Filter 1 is the most upstream filter. Figure 4 also shows the filter height and Figure 5 also shows the AOI runoff hydrograph.

Figure 4. Filter approach depth versus time for each filter compared to the filter height for a single storm event.

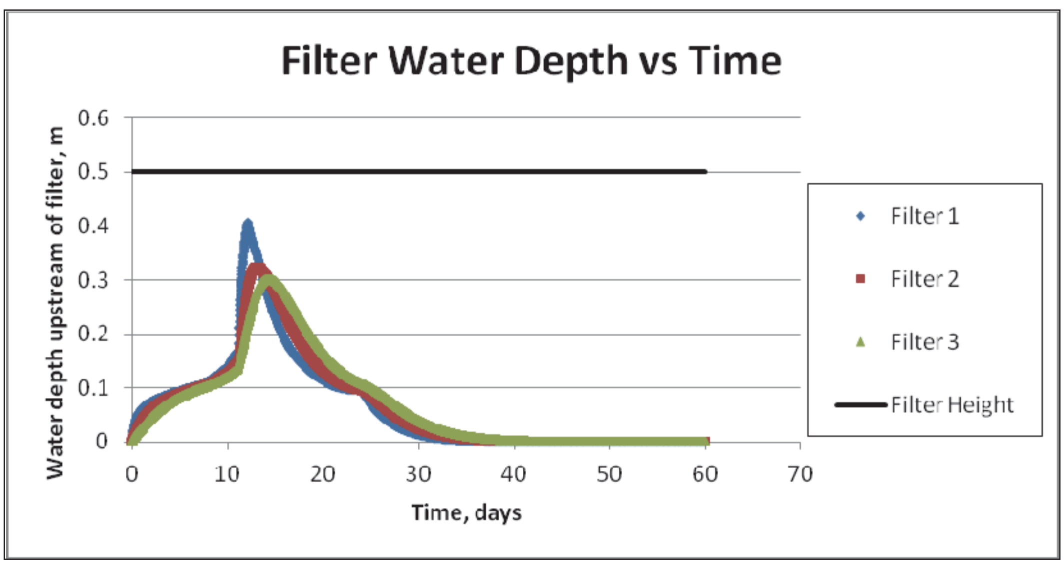
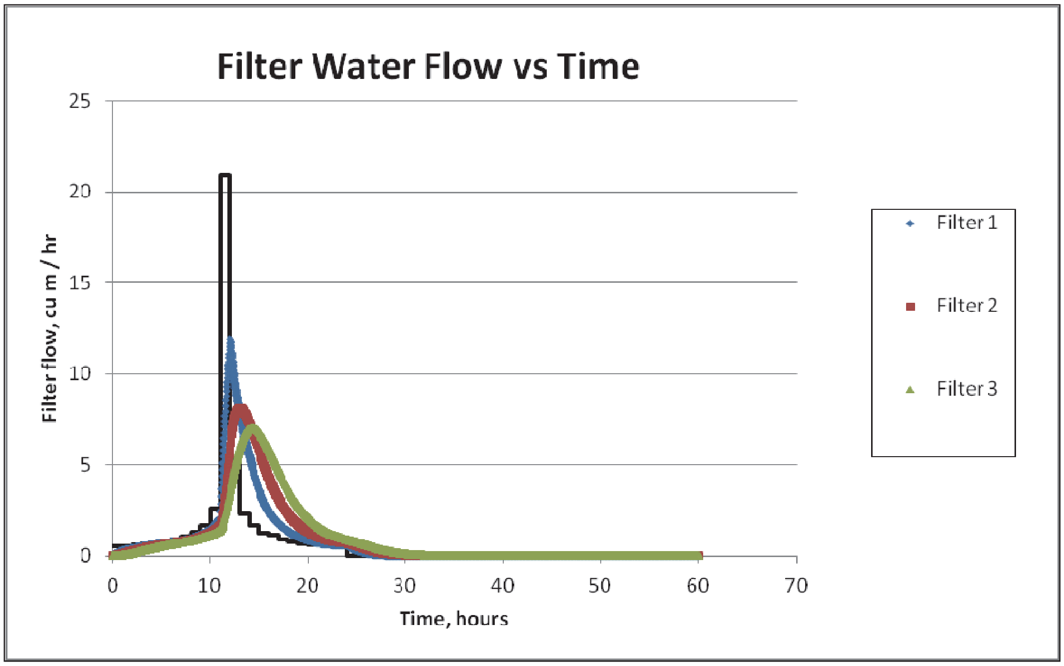


Figure 5. Filter flow rate (cubic meters per hour) versus time for each filter compared to the AOI runoff flow rate for a single storm event.



Filter characteristics for filter 1 (most upstream) are presented in Figures 6 through 10. As stated previously, the filter removal coefficient initially increases with time before starting to decline. The decline has not yet started for this single event. This increase causes a corresponding decrease in the effluent TSS. The trapped TSS increases with time and then levels off due to the termination of the storm routing. Nearly all of the runoff TSS is filtered out of the flow by filter 1. As expected, the hydraulic conductivity drops off somewhat with time.

Figure 6. Filter removal coefficient versus time for filter 1 and single storm event.

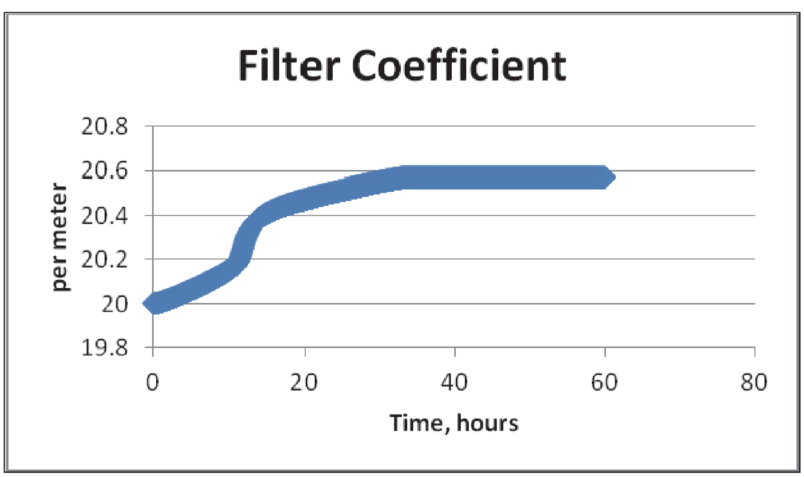


Figure 7. TSS pore water concentration trapped in filter 1 versus time for single storm event.

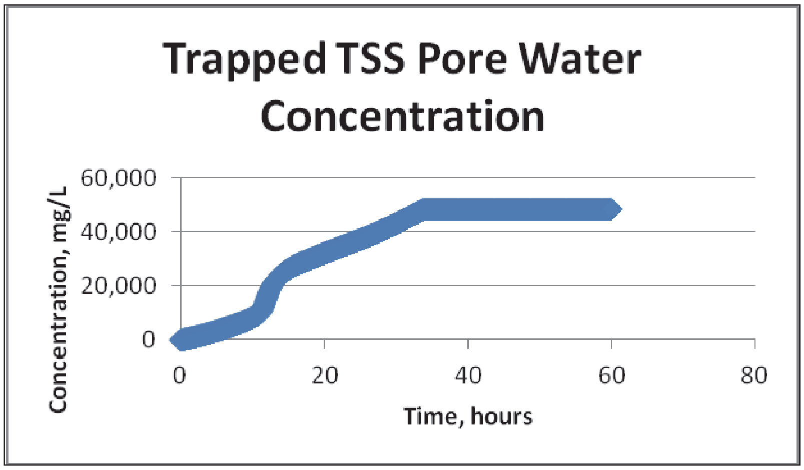


Figure 8. TSS effluent concentration versus time for filter 1 and single storm event.

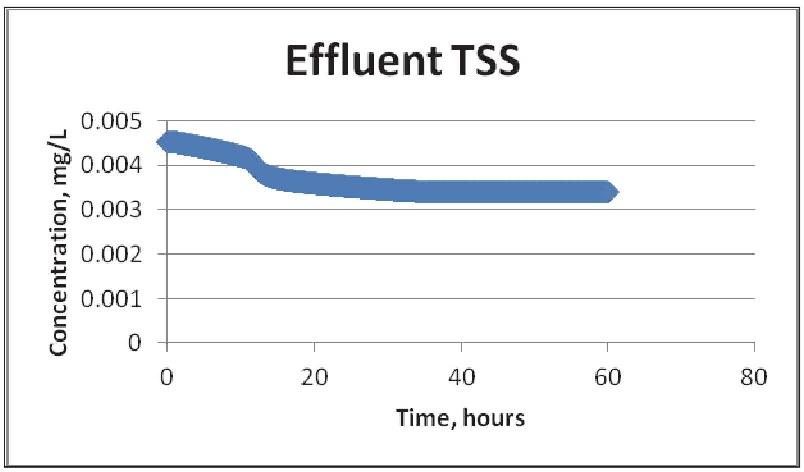


Figure 9. Hydraulic conductivity versus time for filter 1 and single storm event.

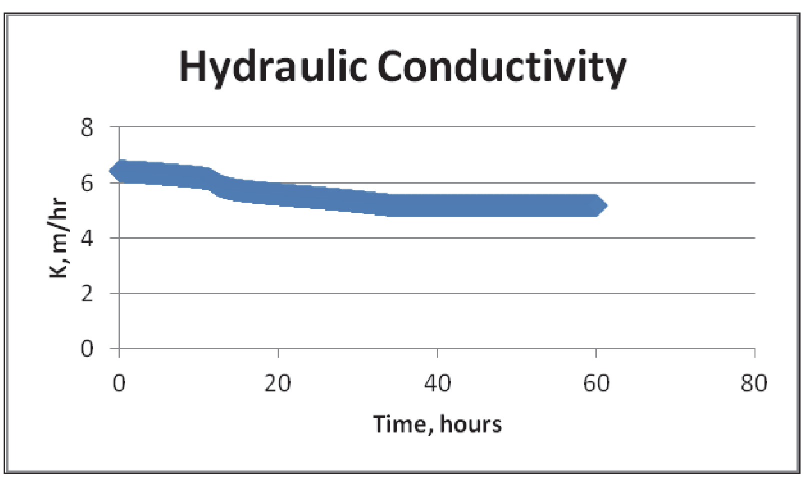
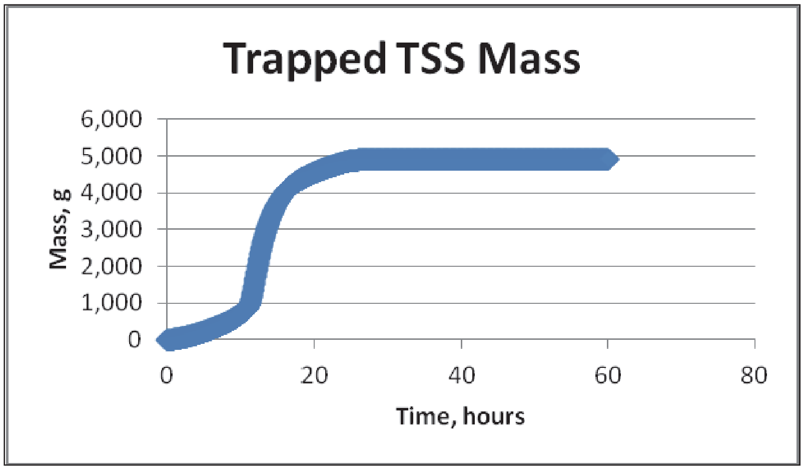


Figure 10. Trapped TSS mass versus time within filter 1 for a single storm event.



The graphs for filters 2 and 3 have the same trends as those shown in Figures 6 through 10, but the values change very little over time since most of the sediment is trapped by filter 1 for the entire storm. Thus, the plots of characteristics for filters 2 and 3 are not presented. The fact that a single storm has little to no impact on the filters downstream of filter 1 was the impetus that led to the development of the continuous rainfall workbook. Thus, the continuous rainfall workbook is designed to determine how much rainfall it takes for each filter to clog to the point of losing its effectiveness.

Continuous steady rainfall application

The conditions shown in Table 3 were imposed for the continuous steady rainfall application, with the exception that the storm type, cumulative rainfall, and storm duration are not inputs; rather, the average annual rainfall depth and number of rainfall days per year are inputs. The input values used for these two inputs were 60 in. and 90 days. The simulation length was set to 120 days. Longer times caused a numerical instability due to the time-step being too large.

The results of this application for filter stage and flow are shown in Figures 11 and 12, respectively. The stage for the first filter approaches a constant value after a period of time. This is due to the steady continuous flow and eventual clogging of the filter up to the steady-state approach depth. The simulation was not long enough for the two downstream filters to become clogged; thus, their flow depths are less than that of filter 1 and are relatively constant for most of the simulation. The effects of clogging are

Figure 11. Filter approach depth versus time for each filter compared to the filter height for continuous steady rainfall.

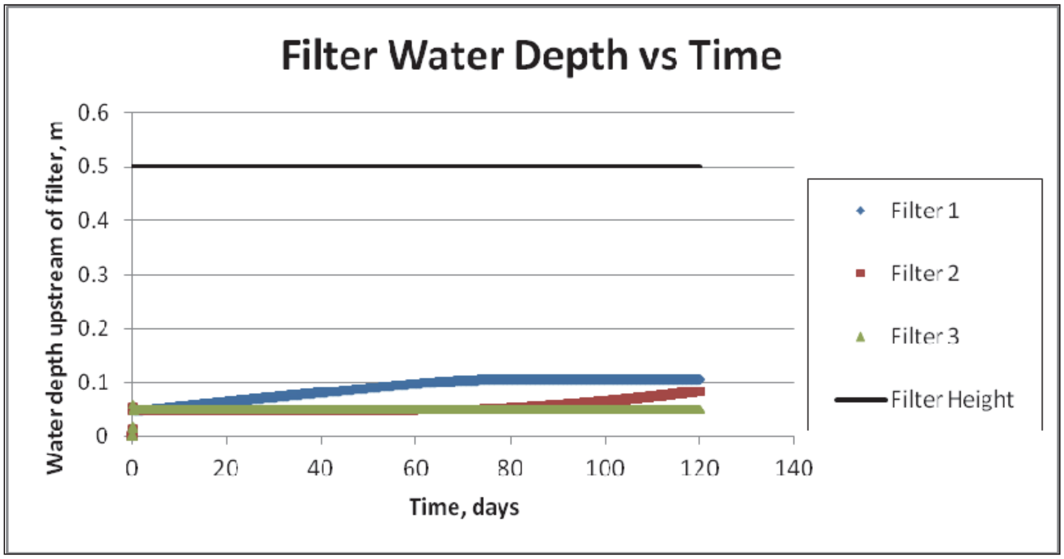
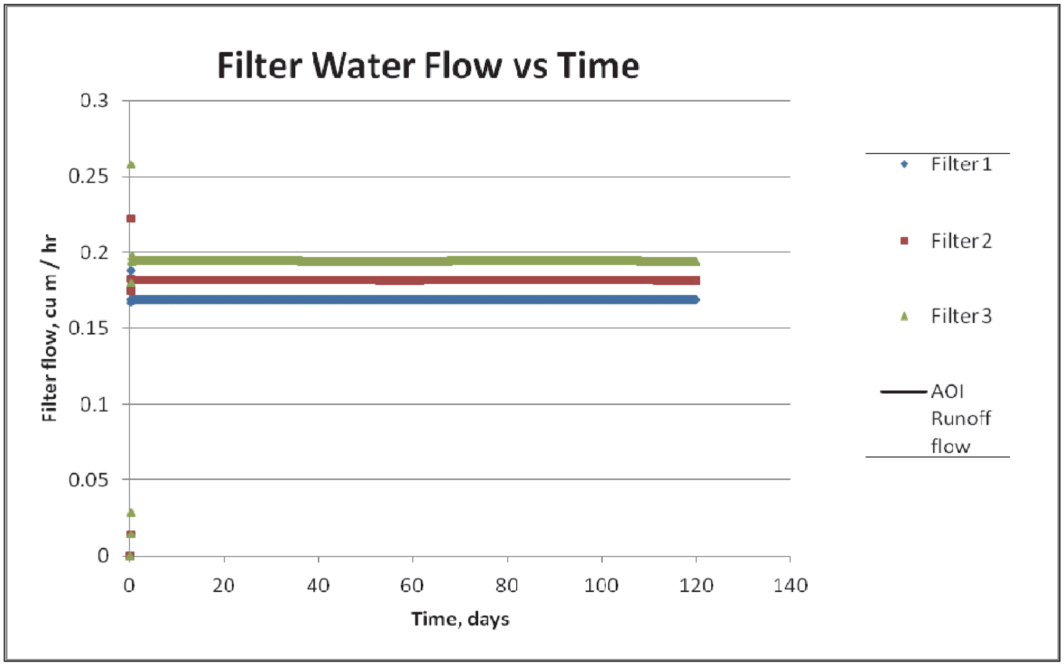


Figure 12. Filter flow rate versus time for each filter compared to the AOI runoff flow rate for continuous steady rainfall.



just beginning to show up for filter 2 near the end of the simulation. By approximately day 70, the first filter has clogged up to the steady flow depth of 0.1 m. However, there is still another 0.4 m of filter height remaining that has not trapped any sediment, but will trap sediment if the stage rises. The model reaches a nearly steady-state condition where the hydraulic conductivity is much lower but still high enough to pass the flow for a depth of 0.1 m. However, at this steady-state condition, essentially no TSS is being removed within filter 1. In reality, it is reasonable to expect that as layers of filter lose permeability, more flow will be able to pass through higher filter layers with greater permeability. The model is not comprehensive enough to capture this transient, layering aspect.

The filter flows are essentially constant over time due to the constant rainfall and associated constant AOI and channel runoff flow rates. Note that the flow increases for downstream filters due to the additional channel segment areas added for each filter. The AOI runoff flow rate is plotted but difficult to see since it is the same as the filter 1 flow rate.

Filter 1 characteristics are plotted in Figures 13 through 17. As mentioned previously, the filter removal coefficient should increase before decreasing, which is the case as shown in Figure 13. It is apparent that the coefficient has approached nearly zero after approximately 70 rain days.

The effluent TSS concentration for filter 1 increases to 50 mg/L after 71.5 rain days, which indicates that filter clogging is having a major impact. After that, the effluent TSS concentration for filter 1 rapidly approaches the influent TSS concentration of 100 mg/L. It should be emphasized that there is still a large portion of filter above the clogged 0.1-m layer that has not experienced any TSS trapping or clogging, but this aspect cannot be fully evaluated with the present model.

Figure 13. Filter removal coefficient versus time for filter 1 and steady continuous rainfall.

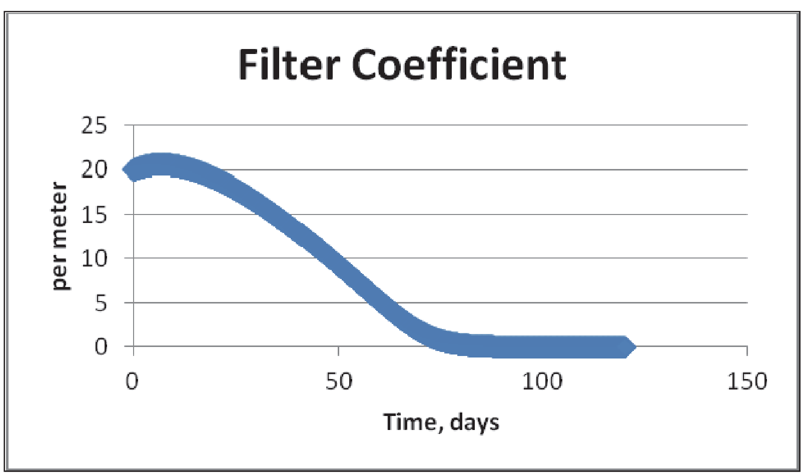


Figure 14. TSS pore water concentration trapped in filter 1 versus time for steady continuous rainfall.

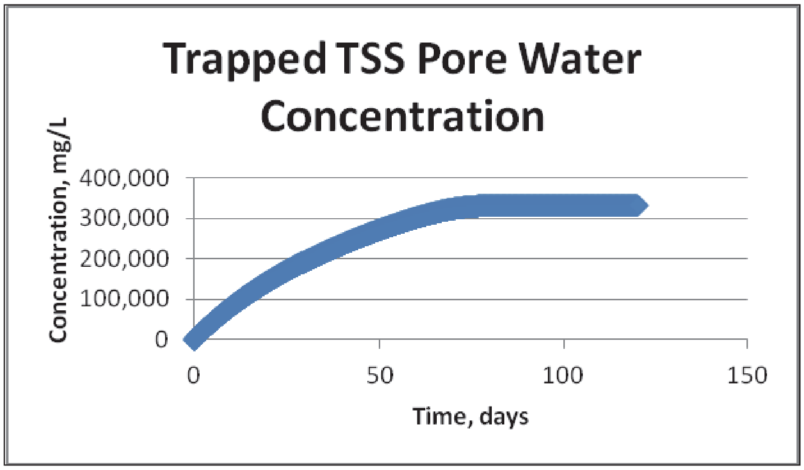


Figure 15. TSS effluent concentration versus time for filter 1 and steady continuous rainfall.

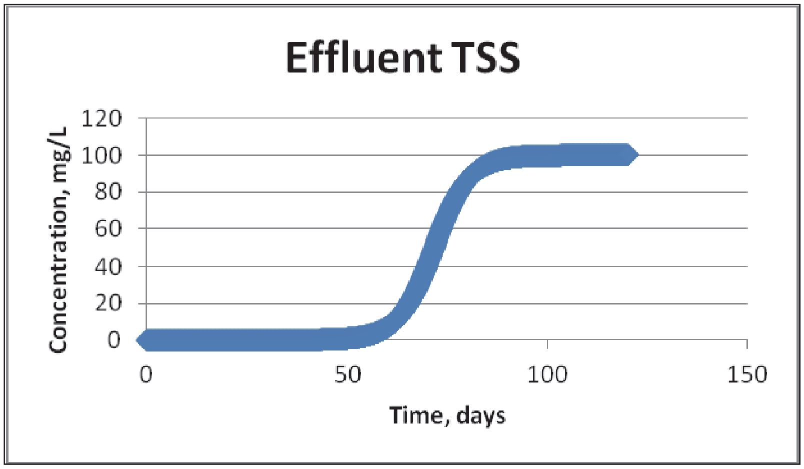


Figure 16. Hydraulic conductivity versus time for filter 1 and steady continuous rainfall.

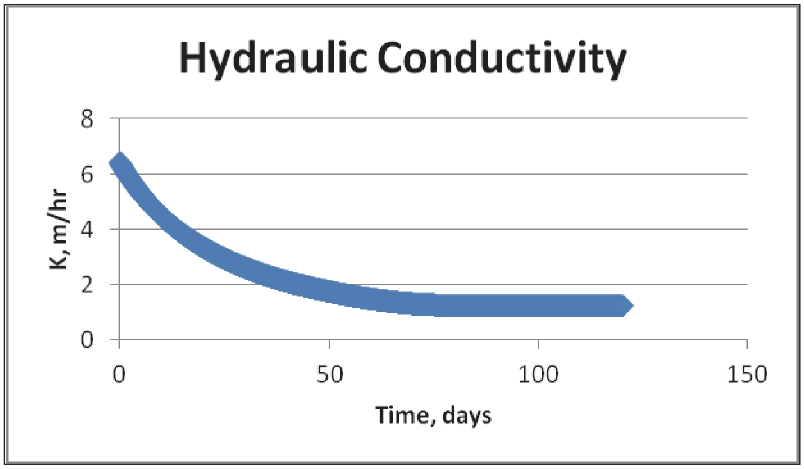
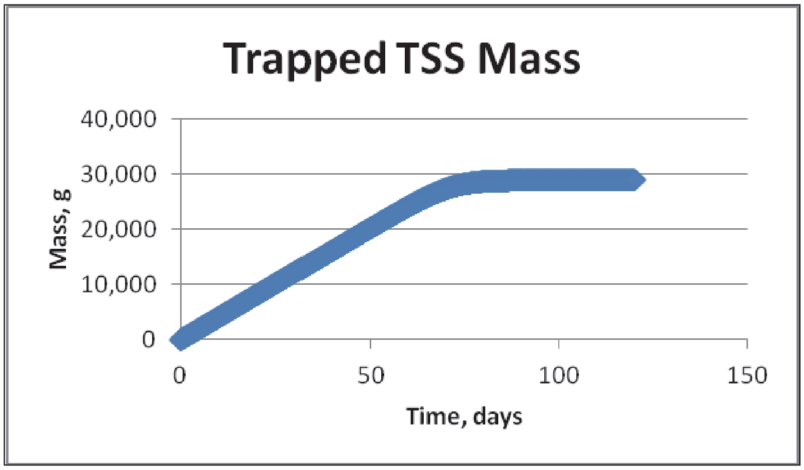


Figure 17. TSS mass trapped within filter 1 for a steady continuous rainfall.



Similar results begin to occur for filter 2, except that the sediment trapping and associated clogging effects are delayed about 70 days until after filter 1 has clogged up to its steady-state stage (steady-stage). The same conditions were run with a higher influent TSS concentration of 400 mg/L to more closely evaluate the subsequent clogging of downstream filters. The higher TSS concentrations shortened the time to reach clogged conditions. For this run, filters 1, 2, and 3 clogged up to their respective stages or depths at approximately 18, 36, and 54 days. Thus, each filter clogged after the same number of rain days following the clogging of its upstream filter. Consequently, the system could be maintained by simply removing the most upstream filter after it has clogged. The above analysis, as well as the model, assumes that all filters have the same filter parameters. As a result, not only is the clogging time the same, but the other filter characteristics (e.g., sediment trapped, trapped sediment concentration, hydraulic conductivity, etc.) reach the same steady-state values following clogging.

The concept of rain days requires some explanation. For this analysis, the rain days value represents the number of days of continuous steady rain falling at a rate equivalent to the average rainfall intensity for the year. This average rainfall intensity is the average annual rainfall depth divided by the number of days per year with significant rainfall. Significant rainfall is a vague term, but it is generally considered to be more than 0.1 in. per day. In the example above, the average rainfall intensity is 0.71 mm/hr. The clogging time (up to the steady-state stage) for the above example is 71.5 rain days, which is defined as the time required for the filter effluent TSS concentration to reach 50% of the filter influent concentration. The cumulative rainfall depth R_c for clogging associated with 71.5 rain days is 47.6 in., which was computed from

$$R_c = \frac{T_c}{365} R_a \tag{21}$$

where T_c is the steady-stage clogging time in rain days (or 71.5 rain days in this example), and R_a is the annual average rainfall depth (or 60 in. in this case). The steady-stage clogging time is 0.79 year (71.5 rain days/90 rain days per year).

The total effective filter life T_f (years) for providing good filtration performance is extrapolated from the steady-stage clogging time,

$$T_f = \frac{H_f}{h_c} T_c \tag{22}$$

where h_c is the filter stage or water depth at steady-state (steady-stage) following clogging. For the above example, the total effective filter life is extrapolated to be 3.7 years (0.79 year x 0.5 m/0.107 m).

With the same filter parameters, each filter within the cascade will have the same total effective life. Also, the filtering capacity of each filter does not appreciably degrade until the filter upstream of that filter has reached its useful life. For high filter TSS removal coefficients, the filters downstream of the most upstream filter serve no TSS removal function as long as the most upstream filter still has removal capacity. For low removal coefficients, the downstream filters do provide additional TSS removal. The model provides the information needed to decide how many filters are needed (up to three filters) to meet a downstream TSS effluent concentration. However, for this type of analysis, it is better to apply the single-event version of the model.

6 Conclusions

Two model workbooks were developed to assess sand filter performance for a cascade of sand filters capturing runoff from an AOI. The models compute approach depth of flow, or stage, and flow rate through each filter over time. The models also compute the time history of effluent TSS concentration and the TSS mass and concentration trapped within each filter's pore water, as well as the TSS removal coefficient and hydraulic conductivity of each filter. One of the workbooks was developed to assess filter cascade characteristics for a single design storm, while the other workbook was developed to assess the filter characteristics for a continuous, steady rainfall so that the useful life of the filters could be assessed.

With three exceptions, all inputs consist of readily available or obtainable information. The three inputs that present the greatest challenge include the filter TSS removal coefficient and the two filter clogging coefficients, since these three are highly variable depending on the type and size of sand filtering material as well as other factors such as the characteristics of the influent TSS. Experimental measurements are required to obtain accurate values for these three empirical coefficients. With values for these three input parameters, the models should prove useful for evaluating filter designs to avoid water over-topping, to predict TSS removal and effluent TSS concentration, and to estimate the useful life of the filters.

TSS removal efficiency should serve as an approximate surrogate for evaluating the removal efficiency of metals, since most of the metal concentration in runoff from SAFRs is associated with particulate metals that are adsorbed to suspended sediments. Runoff can include small colloidal metal particulates that may not be filtered out, but colloidal contributions are expected to be a small fraction of the total runoff mass flux of metal.

For high filter TSS removal coefficients, the filters downstream of the most upstream filter serve no TSS removal function as long as the most upstream filter has removal capacity. For low removal coefficients, the downstream filters do provide additional TSS removal. The single storm event model provides the information needed to decide how many filters are needed to meet a downstream TSS effluent concentration. Model testing indicates that the effectiveness of each filter does not begin to degrade until the immediately upstream filter has reached its effective life.

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14. ABSTRACT Geotextile tubes filled with sand are being evaluated for filter treatment of runoff containing lead and other metals stemming from firing small arms on military training ranges. Such filter tubes trap total suspended sediment (TSS) in the runoff, thus removing most of the metals, which are adsorbed to the sediment. Mathematical models were developed within two Excel workbooks to assess sand filter performance for a cascade of filters capturing runoff from the impact area of small arms firing ranges. One of the workbooks assesses filter cascade characteristics for a single design storm, while the other workbook assesses filter characteristics for a continuous, steady rainfall so that the useful life of the filters, as impacted by clogging, could be estimated. Model computations include the approach depth of flow, including filter over-topping, and the flow rate through each filter over time for specific storm events. The time history of effluent TSS concentration and the TSS trapped within each filter are also computed, as well as the TSS removal coefficient and hydraulic conductivity of each filter. The models provide useful general performance information. In order to provide more specific performance information, laboratory experiments with site-specific sand filter material and runoff TSS are required to determine three filter parameters that can be used as part of the model input.						
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