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Modeling Sedimentation-Filtration Basins for Urban Watersheds Using Soil and Water Assessment Tool

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Abstract

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Introduction

It has long been acknowledged among urban hydrologists that stream flow characteristics of a highly urbanized watershed are strongly related to the increase in impervious cover, which causes increased storm-water runoff and peak flow rates (Rose and Peters 2001; Roesner et al. 2001; Sung and Li 2010; Kim et al. 2011). As concerns grow regarding the environmental impacts of increased urban runoff, many municipalities are now requiring structural treatment devices to maintain the postdevelopment peak flow at a rate that is not to exceed the predevelopment peak flow of the same rainfall event.

Sedimentation-filtration basins (SedFil) mitigate sediment-bound nonpoint source pollution of urban creeks and rivers. SedFils are the primary storm-water treatment device, or best management practice (BMP), actively implemented by the City of Austin, Texas, to control urban storm-water quality. In a SedFil system, storm-water runoff is first diverted into a sedimentation basin in which particulate pollutants are settled by gravity, and is then treated by filter media. As the runoff flows through the filter media, pollutant particles are captured by sedimentation on the surface of filter media (attributable to gravity) or are intercepted as a result of the collision of particles with a filter medium (attributable to momentum or Brownian motion) (Yao et al. 1971).

The City of Austin has developed two design alternatives for SedFils, full and partial types, based on the configuration of the sedimentation basin with respect to the filtration basin (Fig. 1). The full-type SedFil is comprised of a sedimentation basin that is sized to hold a design water quality volume and discharge it into the filtration basin over a set of period. For instance, the City of Austin requires a minimum drawdown time of 48 h for sedimentation basins. Large particles are removed by gravity settling in the sedimentation basin as the flow slows down before entering the filtration basin, which minimizes the clogging potential of the filter media. The partial-type SedFil is comprised of a sediment chamber and a sand filter, which are divided by a gabion wall but are hydraulically fully connected. The sediment chamber is placed in front of the sand filter such that it serves as a partial sedimentation basin. In the full-type SedFil, the sediment chamber and the sand filter are separated by a berm or wall with flow spreading outlets installed (City of Austin 2011). The primary difference between the partial- and full-type systems is that the sedimentation basin in the former design must accept the full water quality volume, whereas both the sedimentation chamber and filtration basin count with respect to the water quality volume in the latter design. Bypass flow is controlled for 100-year storms through diversion structures.

Analogously to other urban runoff treatment devices, the hydraulics and treatment processes of SedFils are not understood very well among urban hydrologists, partially because of the locality of climate and pollutant characteristics, geomorphological complexity, and uncertainties in data. After investigating five SedFils in Austin, Texas, Barrett (2010) found little correlation between

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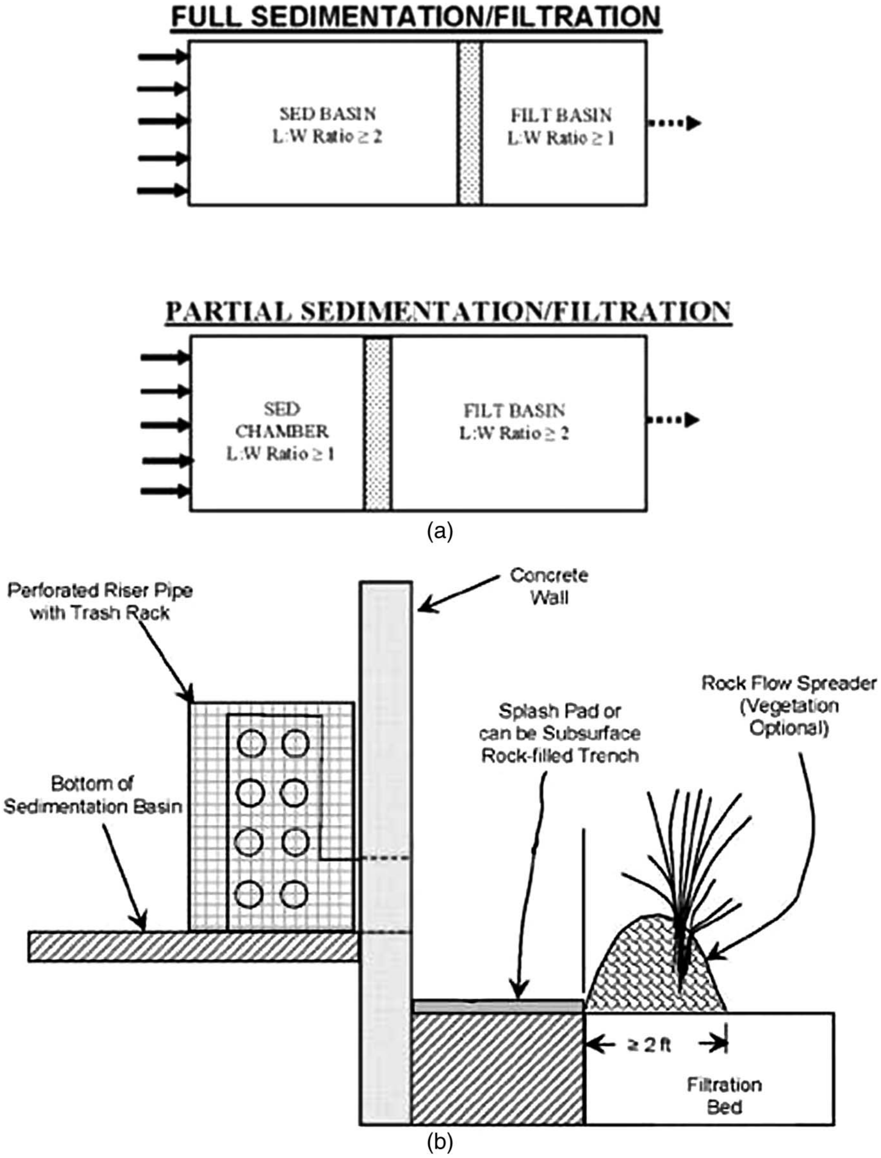

Fig. 1. Schematic of Austin sedimentation/filtration basins [Courtesy of City of Austin (2011)]: (a) configuration of full/partial sedimentation-filtration basins; (b) riser pipe outlet system and flow spreader in full type systems

removal efficiency and discharge pollutant concentration, and suggested that reaction kinetics did not work properly to accurately estimate removal efficiency. In practice, the design criteria and performance evaluation of urban BMPs follow the traditional approach of using design storms and event mean concentration (EMC). For example, after reviewing local SedFil design guidance of the state of Delaware and Austin, Texas, Urbonas (1999) suggests a modified rational equation and an EMC method based on suggested removal rates.

Currently, most urban storm-water models have the capability of modeling infiltration devices (Elliott and Trowsdale 2007); however, only a handful of these models have the capability to model filtration devices. The Model for Urban Stormwater Improvement Conceptualizations (MUSIC) (Chiew and McMahon 1999) has the most advanced algorithm recently developed for modeling stormwater hydraulics in infiltration systems. The MUSIC model divides a filter media into multiple layers. Unsaturated flow is estimated with the Richardson equation and saturated flow is calculated with Darcy's Law (Browne et al. 2008). The noniterative numerical solution of the Richardson equation combined with Darcy's Law allows for rigorous and physically based calculations of water balance in the filter system. MUSIC does not take into account the hydraulic impact of outlet controls, such as perforated orifice pipes, which can easily dominate water movement in the filter. For example, water in the filter media backs up if the filtration rate exceeds the capacity of the orifice pipe. Ultimately, this results in reducing the treatment capacity of the filter in the long term. The water balance model (WBM) (Rowney et al. 1993) also has capability of modeling filtration devices, but is limited with respect to water quantity. In addition, unsaturated flow, which is very common in the central Texas region, is not considered in the WBM model.

In this study, the writers use the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) to model flow through SedFils in Austin, Texas. SWAT has been widely used in rural and suburban watersheds to model water quality, and more than 800 related research articles have been published in peer-reviewed international journals (Arnold 2013). Recently, SWAT was updated to model subdaily hydrologic and water quality processes (Jeong et al. 2010, 2011) in which storm-water runoff is more rigorously estimated separately from the runoff from nonurban areas. These new developments in the SWAT model, along with the development of urban SedFil routines, are expected to be very useful for the planning and design of urbanizing watersheds. The writers nevertheless suspect that the performance of SWAT may be limited with respect to fully urbanized watersheds by its inability to simulate storm sewer systems.

This paper reports the development of physically based algorithms for flow and sediment in sedimentation basins and filtration basins within SWAT. The results were tested on a highly urbanized watershed in Austin, Texas.

Materials and Methods

Model Configuration in SWAT

SedFils are structural BMPs for treating storm-water runoff in urban areas. In accordance with the size of a watershed, there could be hundreds SedFils in the watershed. Subbasins are the routing units for runoff in SWAT. Hydrologic response units (HRUs) are the fundamental modeling units in SWAT and are not spatially identified. HRUs are designated by a collection of land parcels in a subbasin that have homogeneous hydrologic responses in accordance with land cover, soil type, and slope. Therefore, the SedFil algorithm is developed such that the entire runoff or a fraction of urban runoff drains to one or multiple SedFils, and is then treated near the subbasin outlet before it enters the receiving water reach. Specifically, multiple SedFils (as many as 10) may exist in one subbasin, and because SWAT does not consider their physical locations in the subbasin, the SedFils are modeled near the subbasin outlet. Flow and sediment removal through a SedFil basin is simulated dynamically and continuously with a mechanistic algorithm at subhourly time intervals as small as 1 min. The user allocates the percentage of the total urban runoff generated in the subwatershed that drains to each SedFil and any other upland BMPs that may coexist. Therefore, the minimum knowledge that the model requires from the user is the total fraction of urban runoff that is treated by the SedFils in the subbasin. In the model setup, each SedFil may be defined individually, or several SedFils in the vicinity can be aggregated and modeled as a single structure.

The algorithms for sedimentation and filtration basins were coded separately in SWAT to allow for a flexible application of either full or partial type SedFils (see Fig. 2). SWAT estimates subdaily runoff from pervious cover using the Green and Ampt equation (Mein and Larson 1973). The runoff from impervious cover was calculated with an initial abstraction considered. Sediment loads from impervious cover were simulated using the build-up/wash-off algorithm by Sartor et al. (1974). The surface runoff from all HRUs in the subbasin was aggregated, and then routed through the SedFil before entering into the channel. The SWAT SedFil routine requires subdaily weather data and simulation time steps. Only water and sediment were routed through the SedFil routine. Other contaminants such as nutrients or pesticides are beyond the scope of this paper and are not currently available in the SWAT SedFil model.

Design Capacity

In urban watersheds, water quality volume (or the quantity of storm-water runoff to treat) is dependent on the percentage of impervious cover. A larger fraction of impervious cover is correlated with a greater quantity of storm-water runoff. The City of Austin's design guidance for water quality control was used to estimate the design capacity of the SedFils. The City of Austin recommends capturing and isolating at least a minimum volume of storm-water runoff for treatment (City of Austin 2011). The size of a BMP is determined based on water quality volume, which is defined as the first 1.3 cm (0.5 in.) of runoff and an additional 0.3 cm (0.1 in.) for each 10% increase of gross impervious cover over 20% within the drainage area to the control. This can be expressed in mathematical form as follows:

$$V_{wq} = 0.07 \times \left[0.5 + \left(\frac{\text{Impervious area}}{\text{Total drainage area}} - 0.2\right)\right] \times A_d \quad (1)$$

where V_{wq} = water quality volume (cm^3); and A_d = drainage area of the BMP (ha). If a sedimentation basin is constructed with a storage capacity of V_{wq}, it should be able to pass the 100-year storm of Austin, Texas, over the diversion structure without overtopping any sidewalls of the pond. The model uses this guideline to calculate the storage and treatment capacity of a SedFil if it is not provided by the user.

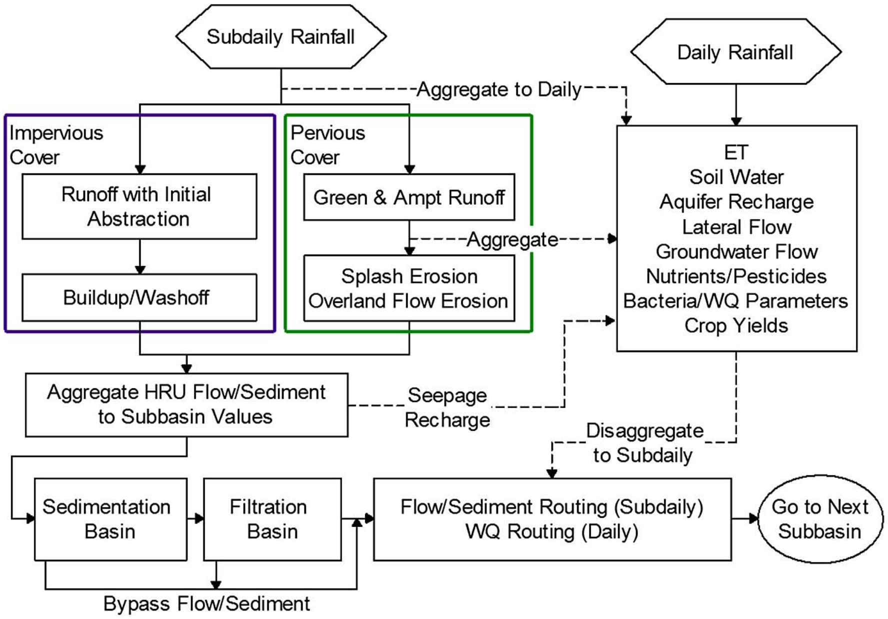

Fig. 2. Schematic of runoff and SedFil processes in SWAT

Sedimentation Basin

A full-scale sedimentation-filtration basin is comprised of sedimentation and filtration basins that are serially connected such that the sedimentation basin works as a pretreatment unit, which reduces sediment clogging in the filtration basin and controls peak flows. The maximum storage of the sedimentation basin is defined by the stage of the emergency spillway. The effluent from the sedimentation basin is discharged into the filtration basin. Discharge from a sedimentation basin is generally controlled by orifice pipes and weirs. Bypass flow was calculated by a weir discharge. A continuity equation for water in the sedimentation basin estimates the water balance every time step:

$$\frac{\partial V_{\mathrm{wtr}}}{\partial t} = Q_{\mathrm{in}} + R - f - E - Q_{\mathrm{sed,pipe}} - Q_{\mathrm{sed,bypass}} \qquad (2)$$

V_{wtr} = total volume of water in the sedimentation basin; Q_{in} = incoming storm-water runoff; R = rainfall; f = infiltration; E = evapotranspiration; $Q_{\mathrm{sed,pipe}}$ = pipe flow at the outlet; and $Q_{\mathrm{sed,bypass}}$ = bypass flow over the emergency weir. Effluent sediment was estimated by the $k' - C^*$ model with the coefficients suggested by Huber et al. (2006) ($k' = 15{,}000$ m/year; and $C^* = 30$ mg/L for total suspended solids), as follows:

$$C_{\mathrm{out}} = (C_{\mathrm{in}} - C^*) \cdot e^{-k'/q} + C^* \qquad (3)$$

where C_{out} = effluent sedimentation concentration (mg/L); C_{in} = influent concentration (mg/L); C^* = equilibrium concentration; k' is a rate constant (m/year); and q = hydraulic loading rate (m/year). This model is a first-order kinetic model that allows the minimum concentration of sediment using C^*.

Filtration Basin

A modified Green and Ampt equation was developed for unsaturated flow simulation in the filtration basin, which allows for consideration of surface ponding when calculating the filtration rate. Saturated flow was computed using Darcy's law. Surface ponding depth, filter media water content, and effluent were estimated based on the mass balance equation (Fig. 3). Moisture content of the filter media was evaluated at every time step and the rate of effluent flow from the orifice pipe was compared with the filtration rate. If the flow from the sedimentation basin exceeds the filtration rate, the excess water is ponded on the surface and saturated flow occurs as the filter media are saturated. Filter flow was controlled by the orifice pipe at the outlet. If pipe flow is smaller than the filtration rate, Darcy (i.e., saturated) flow is controlled by the pipe flow and surplus water backs up on the surface. In contrast, the filter dries out and the flow regime changes to unsaturated flow if the filtration rate is smaller than the pipe flow.

There are two control volumes (CV) defined for calculating water and sediment balance in the filtration basin. The first CV (CV1) is the ponding area above the filter media, and the second CV (CV2) is the filter media that receives inflow from CV1 and drains into the outlet control (Fig. 4). For a partial type system,

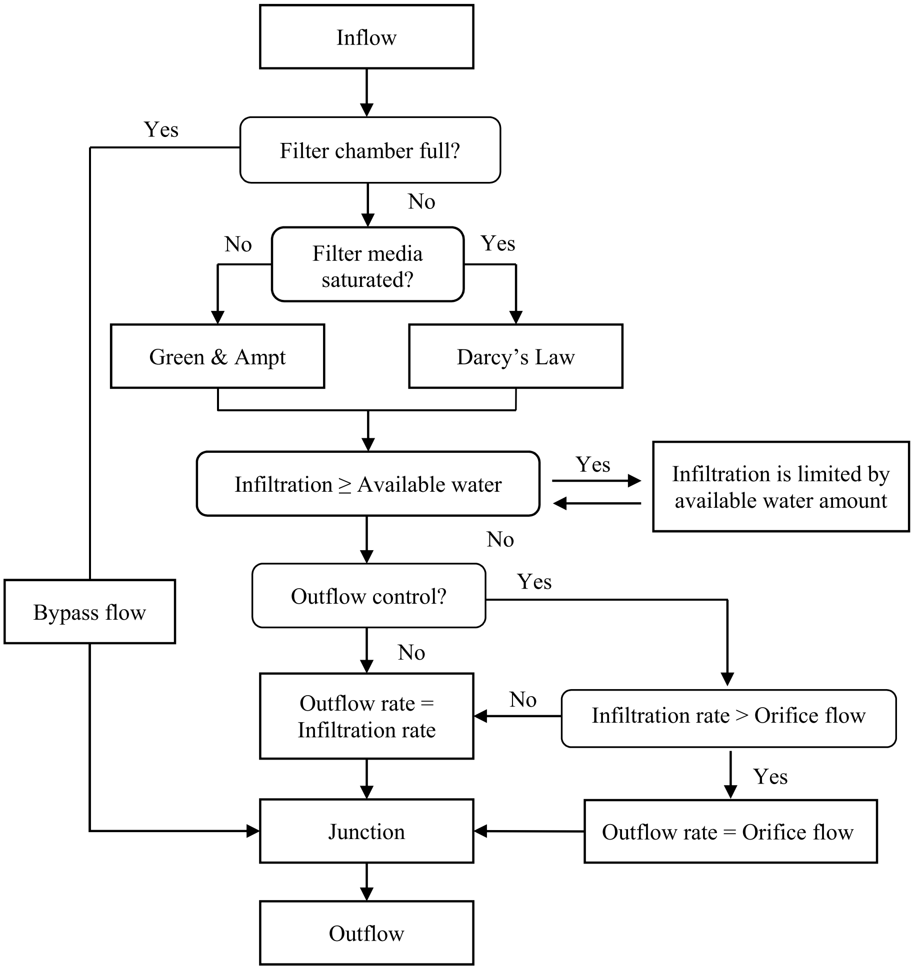

Fig. 3. Schematic view of filter processes

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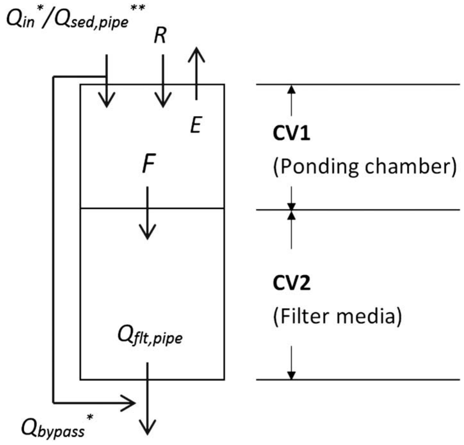

Fig. 4. Water balance components of the filtration basin

CV1 includes the entire storage volume, including the sedimentation chamber. In CV1, storm-water runoff is the primary source and infiltration and bypass flow are the primary sinks. Rainfall and evaporation also affect the mass balance, as shown in Eq. (4). For a full type system, the filtration basin receives flow from the sedimentation basin and bypass flow does not occur, given that the flow is controlled at the outlet of the sedimentation basin.

$$\frac{\partial V1_{\mathrm{wtr}}}{\partial t} = Q_{\mathrm{sed,pipe}} + R - F - E \tag{4a}$$

$V1_{\mathrm{wtr}}$ = volume of water in CV1; and F = filtration rate of the filter media. A partial type system receives storm-water runoff as direct inflow, and therefore excess water bypasses the overflow weir.

$$\frac{\partial V1_{\mathrm{wtr}}}{\partial t} = Q_{\mathrm{in}} + R - F - E - Q_{\mathrm{bypass}} \tag{4b}$$

Q_{bypass} = bypass flow; and Q_{in} = incoming runoff. The second mass balance equation describes the change in water volume in the filter media.

$$\frac{\partial V2_{\mathrm{wtr}}}{\partial t} = F + \frac{\partial SW}{\partial t} - Q_{\mathrm{flt,pipe}} \tag{5}$$

$V2_{\mathrm{wtr}}$ = volume of water in CV2; SW = moisture content in the filter media; and $Q_{\mathrm{flt,pipe}}$ = pipe flow at the filter outlet. The filter media become saturated when the total water content (SW) is equal to the pore volume.

Unsaturated flow occurs in the filter media shortly after the onset of a storm event, before the filter is fully saturated. Runoffs from a series of small events may end up partially soaking the filter media, and the filter is never saturated through the storm events. When a sand filter is unsaturated, capillary forces in the filter medium build up a suction head near the waterfront, which promotes a higher infiltration rate. The Green and Ampt equation is a simplified, physically based model that estimates the infiltration rate in which the media is not fully saturated. Therefore, the Green and Ampt equation is often used in hydrologic models to calculate the quantity of infiltration and surface runoff that is generated by rainfall. Natural soils are typically assumed to have infinite depth, and therefore the hydrostatic pressure that is caused by ponded water on the surface is considered to be negligible (Chow et al. 1988). However, the depth of filtration basins is finite and the water ponding depth is significantly large relative to the depth of the filter at the maximum stage. Therefore, the hydrostatic pressure by the ponded water enhances the infiltration rate at varying degrees with respect to the height of ponded water. Based on this theory regarding the filter hydraulics, a modified equation was developed to account for the contribution of surface ponding to the infiltration rate for unsaturated flow.

Darcy's Law can be used to describe the vertical flow of water through a homogeneous sand filter column. The ponding depth on the surface, length of wetted zone, and the suction head at the wetting front comprise the total head, as follows:

$$f = K\left(\frac{h + l_w + \Psi}{l_w}\right) \tag{6}$$

where f = infiltration rate; h = surface ponding depth; K = hydraulic conductivity at saturation; Ψ = suction head at the wetting front; and l_w = length of wetted zone, which varies from >0 to the filter length. The quantity of water in the sand column increases with infiltration, as follows:

$$F = l_w \cdot \Delta\theta \tag{7}$$

where F = cumulative infiltration; and $\Delta\theta$ = change in water content in the sand column. This equation is valid if l_w is less than the length of the sand column and larger than zero. Substitute l_w in Eq. (7) into Eq. (6), and use the relation $f = dF/dt$ to obtain

$$\frac{dF}{dt} = K\left(1 + \frac{(h + \Psi)\cdot\Delta\theta}{F}\right) \tag{8}$$

Rearrange and integrate to obtain

$$F(t) = F(t-1) + K\cdot\Delta t + (h+\Psi)\cdot\Delta\theta\cdot\ln\left(\frac{F(t) + (h+\Psi)\cdot\Delta\theta}{F(t-1) + (h+\Psi)\cdot\Delta\theta}\right) \tag{9}$$

Eq. (9) is a modified Green and Ampt equation that includes surface ponding in estimating cumulative infiltration, which can be solved numerically by successive substitution. Surface ponding promotes infiltration of water to the sand filter. As shown in Fig. 5, filtration rate is positively proportional to rainfall intensity (or the total head of the ponded water) when surface ponding is considered, whereas the original Green and Ampt equation is insensitive to surface ponding depth. In this particular example, the filtration rate that was estimated with Eq. (9) is more than 50% larger than the filtration rate that was calculated with the original Green and Ampt equation, which is attributable to the added head of ponding water.

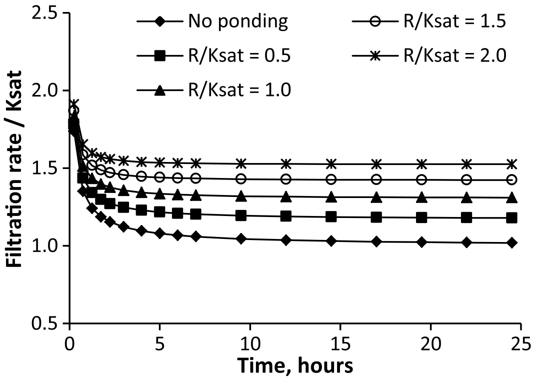

Fig. 5. Infiltration rate is a function of inflow rate when ponding is considered (R = inflow + direct rainfall, $K_{\mathrm{sat}} = 40$ mm/h); baseline (i.e., no ponding) was estimated with the original Green and Ampt equation

The Green and Ampt equation, Eq. (9), is invalid when the filter is fully saturated and Darcy's Law applies to saturated flow conditions.

$$f = K\frac{h+L}{L} \tag{10}$$

L = thickness of the sand filter. The flow regime changes from unsaturated to saturated flow when the sand filter is completely saturated. The model evaluates the percent saturation of the filter every time step using a continuity equation, Eq. (6), and applies either to the modified Green and Ampt equation [Eq. (9)] or Darcy's law [Eq. (10)] to estimate the infiltration rate. For example, in Fig. 6, the infiltration rate decreases with respect to time as cumulative infiltration increases. Once the filter is saturated, the infiltration rate starts to increase in a semi-linear manner, given that the ponding depth on the surface is directly accounted with Darcy's Law. The infiltration rate becomes constant as water flows over the bypass spillway.

The flow rate at the outlet control was estimated with the orifice equation, for which the total head was estimated as the total depth of water in the filter media and ponding surface from the center of the pipe, assuming a square edged configuration (head loss coefficient = 0.6). The City of Austin's design guidelines for water quality controls require all detention units to have an overflow spillway to pass high flows, such as a 100-year storm (section 1.6 of the guidelines). A significant bypass flow over the spillway weir may occur during intense flash storm events. Bypass flow rate was estimated with a general equation for horizontal rectangular weir with both ends contracted (Hwang et al. 2009).

$$Q_{\text{bypass}} = C_{dw} \cdot (L_{\text{weir}} - 0.2h) \cdot h^{3/2} \tag{11}$$

Q_{bypass} = bypass flow rate; C_{dw} is a dimensionless runoff coefficient (approximately 1.84 in SI units); L_{weir} = width of weir (m); and h = head on the weir (m).

Hydraulic conductivity is the primary variable that defines the flow characteristics of a filtration basin for which the value often remains constant in some modeling studies, including the recent work by the City of Austin, i.e., the QUALHYMO model (Rowney 2009). However, the accumulation of solid particles near the top layer is not negligible and thus hydraulic conductivity of the filter decreases with respect to time, which causes reduced treatment capacity. Urbonas (1999) suggests a power function that relates through-flow rate to cumulative total suspended solids (TSS) removed. This model provides a useful insight, but its limitation is that it makes a direct relationship between flow rate and TSS, whereas hydraulic conductivity is not considered. The depth filtration theory (Mays and Hunt 2005; Li and Davis 2008) that is derived from Darcy's Law relates hydraulic conductivity to volumetric specific deposit.

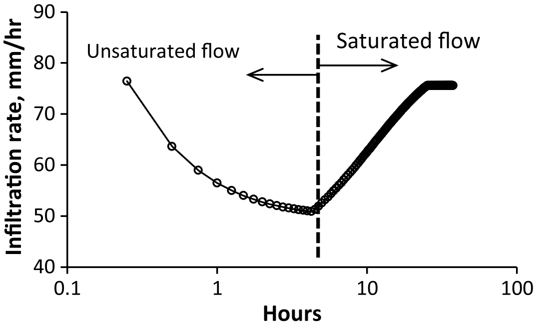

Fig. 6. Infiltration rate varies with respect to time as the flow regime changes from unsaturated to saturated flow (K and $R = 40$ and 80 mm/h, respectively)

$$\frac{K}{K_0} = \frac{1}{(1+\gamma\sigma_v)^2} \tag{12}$$

K = hydraulic conductivity of the filter bed; K_0 = initial hydraulic conductivity of the clean bed; γ is an empirical constant; and σ_v = volumetric specific deposit (the volume of deposited particles per unit filter volume).

Sediment Removal

The single isolated collector model (Yao et al. 1971) estimates sediment removal with respect to clogging of the filter media, attributable to sediment accumulation, was calculated by relating hydraulic conductivity with the volumetric deposit of sediment in the filter media. The single isolated collector model of Yao et al. (1971) estimates particle removal efficiency of the filter.

$$\text{SED}_{\text{out}} = \text{SED}_{\text{in}}\left[1 - \exp\left\{-\frac{3}{2}\left(\frac{(1-\varepsilon)\alpha\eta}{d_c}\right)L\right\}\right] \tag{13}$$

SED_{out} = effluent sediment loads; SED_{in} = quantity of inflow sediment; ε = filter porosity; α = collision frequency (varies from 0–1); η = attachment efficiency; and d_c = characteristic diameter of the filter media particles. The attachment efficiency is the summation of collision efficiencies in terms of sedimentation, Brownian motion, and attractive movement that occurs in the filter between TSS and filter media particles.

Case Study

Study Area

The performance of the SWAT SedFil model was evaluated on the Jollyville sand filter, a typical SedFil in Austin, Texas. The drainage area is 2.81 ha, with approximately 24 m width and 1.2 km length, as shown in Fig. 7. The entire drainage area, 90% of which is connected impervious cover, is urban. The Jollyville sand filter is a partial type SedFil and there is no pretreatment system on the upstream. The total area of the SedFil is 295 m^2 and 15% of the area is a concrete paved sedimentation chamber. Therefore, the net surface area of the filtration bed is 250 m^2. The nominal depth of the filter is approximately 0.5 m. The sedimentation chamber and filtration bed are separated by a wall that has many circular holes near the bottom. Consequently, incoming storm-water flows into the sedimentation chamber, and then moves into the filtration bed. A horizontal rectangular weir was placed at 1.3 m height to allow bypass to the creek. Filtered water drains to the creek through a perforated under-drain pipe at the bottom of the filter. Curb length density is an important parameter for estimating pollutant loading from urban streets such as the Jollyville site. Because the roadways comprise 84% of the drainage area, the curb density and the fraction of connected impervious cover (FCIMP) for the land use type of urban transportation (UTRN) were adjusted to reasonable quantities (see Table 1) based on site conditions.

Data Availability and Model Setup

A SWAT model was developed for simulating the flow and sediment loads to the Jollyville SedFil from the drainage area using ArcSWAT93.7 (SWAT 2009; Neitch et al. 2011) with a

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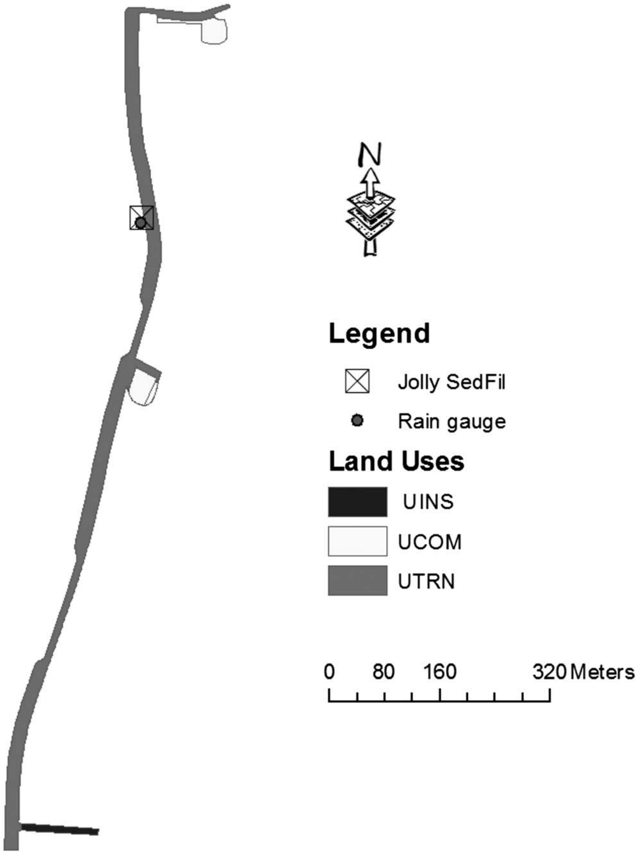

Fig. 7. Jollyville SedFil and its drainage area

15-min simulation time interval. The land use map for 2003 and the 0.6-m (2-ft) contour map, both surveyed by the City of Austin (2013), were used for delineating the watershed in ArcSWAT. Because of the unnatural uneven nature of the urban impervious cover, the contour map was further refined (smoothed) for ArcSWAT delineation before model development. A SWAT model was developed such that the drainage area was comprised of a subbasin and a few HRUs, and the watershed outlet is located at the inlet of the Jollyville SedFil. Therefore, the entire surface runoff generated in the drainage area flows into the SedFil. To calculate the surface runoff from impervious cover, which is 90% of the entire drainage area, an initial abstraction of 6 mm was used (Barrett et al. 1998).

The Jollyville SedFil has been monitored by the City of Austin for flow, sediment, and other pollutants at the inlet and outlet. Flow was recorded every 1 min for 7 years (1995–2002) at the inlet and outlet, but no overflow was measured. Sediment data is available for only for a limited number of storm events. Rainfall data at 1-min intervals, and daily maximum and minimum temperatures, were also collected from an onsite weather gage. The pattern of rainfall at the Jollyville site is relatively mild for the historical weather of Austin, Texas. There were only two events, one in 1997 and another in 1998, which were larger than the 5-year return period storms, and most storms during this period fell below the 2-year return period storms (Fig. 8). The Jollyville SedFil is therefore expected to be highly efficient over a long-term period. Predicted inflow to the SedFil from its drainage area and discharge at the outlet pipe were calibrated at 15-min intervals for a 3-year period (1997–1999), and then validated for 1 year (2001). A grab sampler was used to collect sediment concentration in the discharge from the SedFil. However, measured sediment data were available for two storm events during the study period with 14 sample points. Therefore, the Yao et al. (1971) model for sediment was tested against this measured data for two storm events, but no further validation was attempted because of the lack of good quality data.

Results and Discussion

The proposed SedFil algorithm was tested for flow and sediment removal at the inlet and outlet of the Jollyville SedFil. Although the City of Austin monitored this site for many years, the time series field data were often not of good quality for a long-term analysis. For instance, the total volume of outflow exceeded the inflow volume in many isolated storm events. In addition, sediment data were available for only limited storm events during the study period; therefore, the analyses for the SedFil sediment processes were conducted for only one storm event and not for a long-term period. The recorded 1-min precipitation and flow rates at the inlet and outlet were aggregated every 15 min and were used to calibrate the SWAT 15-min outputs.

Calibration and validation were conducted manually by changing relevant SWAT parameters such as the hydraulic conductivity of filter media, curb density, filter attachment efficiency, and the median particle diameter of sediment particles. The overall statistical efficiency, measured by the coefficient of determination (R^2), and Nash and Sutcliffe Efficiency (NSE) was very good at the inlet (0.82 and 0.59, respectively) and outlet (0.83 and 0.82, respectively), as presented in Fig. 8. The higher NSE value at the outlet relative to the inlet implies that even at this location uncertainty exists in predicted inflow. The well-defined control volume of the SedFil and physically based processes allow for satisfactory results because the highly variable inflow is attenuated in the SedFil. The satisfactory calibration of flow at the inlet implies that SWAT performs well on small urban watersheds at predicting storm-water runoff from urban land uses. However, the results clearly indicate that the predicted low flow points are highly scattered around the unit slope line, and exhibit a slight tendency of overestimation (Fig. 9, left), which is consistent with a previous report by Jeong et al. (2010). Small flows at the inlet were widely spread. This implies high uncertainty in the SWAT overland flow prediction, which was generally underestimated. This may be indicative of connected base flow components that come from outside of the drainage area. The underestimation may also be attributable to the dynamics of

Table 1. Land Use Types of the Jollyville Drainage Area

LU code	Description	Fraction drainage area (%)	FCIMP[a] (%)	Curb length density (km/ha)	Wash-off coefficient (mm^{-1})	Maximum dirt quantity (kg/curb km)	THALF[b] (days)
UCOM	Commercial	11	64	0.28	53.67	200	1.6
UINS	Office	5	47	0.4	41.29	360	3.9
UTRN	Road	84	95	40.28	27.53	340	3.9

Note: LU = land use; UCOM = urban commercial; UINS = urban industrial; UTRN = urban transportation.
[a] Fraction of connected impervious cover.
[b] Number of days for quantity of solids on impervious areas to build up from zero to half of the maximum that is allowed.

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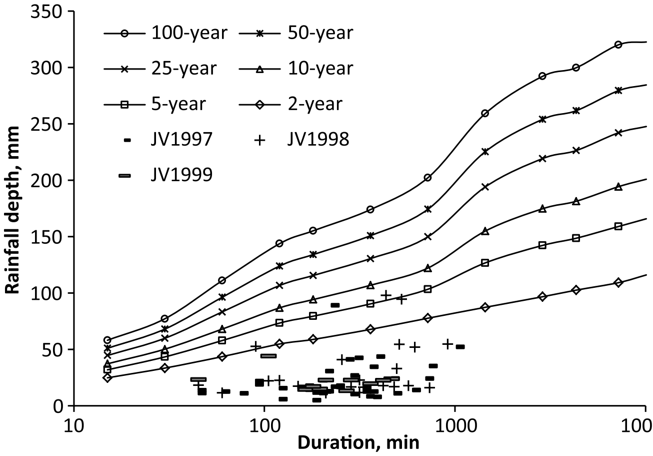

Fig. 8. Event total rainfalls at the Jollyville site for 1997–1999 relative to the intensity-duration-frequency curves of Austin, Texas

sheet flow on pavement surfaces, initial abstraction on impervious cover, or the conduit flow along the underground sewer system. The evaporation rate of impervious cover can be as much as the pan evaporation rate (i.e., potential evaporation rate), whereas the SWAT model estimates the actual evaporation rate based on water availability in the system, temperature, wind speed, and so on, which is typically much smaller than the potential evaporation rate in the central Texas area. The impact of underestimated evaporation should be more distinctive on low than on high flows.

A similar pattern was observed for the flow at the outlet of the SedFil. Because the predicted inflow was inaccurate, the predicted outflow should not be any better and the results clearly reflect this pattern. Because of the inherent variability of flow over impervious cover and underestimation of evaporation from urban impervious cover, it was difficult to determine the variability of the model, especially on the low flow regime. In Fig. 9 (right), the maximum predicted flow rate is presented by the vertically arranged points on the high end. The SWAT SedFil model requires detailed dimensions for storage volume, filter media, and the outlet pipe; therefore, the model was designed to have the maximum outflow rate based on the geometry of the SedFil and the hydrodynamics that occur in the SedFil system. Any surplus inflow bypasses the SedFil over a weir directly to the creek.

The hydrographs of individual storm events present different aspects of the model's performance. The timing of the flow response, peak flow, and rising and receding limbs modeled with SWAT compare well with the observed hydrographs over a long-term period. The calibrated hydrographs that are presented in Fig. 10 are the output of a single SWAT simulation. They are therefore not calibrated for each event but for the entire simulation period (1997–1999) and validated for another 1-year period (2001). The hydrodynamics of the SedFil is well simulated by SWAT if the observed hydrographs are used as a reference. The varying magnitudes of the peak flows that are received at the inlet are attenuated with longer recessions at the outlet, where the range of discharge rate is narrower than at the inlet. The automatic flow loggers and sediment sampler were on and off, and there was no maintenance provided to the SedFil during the study period. Whereas it was expected in this long-term analysis (1997–2001) that the observed data would exhibit evidence of sediment clogging, the Jollyville SedFil data had no indication of clogging in the observed flow data for the 5 years. Sediment deposition was observed by a field operator in the sedimentation chamber after storm events (Roger Glick, personal communication, May 2011), which might have enhanced the long-term performance of the SedFil.

Sediment removal efficiency of Austin sand filters are 90% or higher (Barrett 2003). These reported removal efficiency values were estimated by comparing the sediment concentrations at the inlet and outlet. Even though the sand filters were designed such that they capture the first flush (i.e., the storm-water runoff at the beginning phase of a storm event that contains the most pollutants that were washed off from impervious cover) completely, sediment and other water-bound pollutants bypass the sand filter if overflow occurs. Because the bypass quantity is rarely monitored, the quantity of bypassed pollutants is not addressed in most of the reported performance data of sand filters.

A goal of this paper is to estimate the total quantity of sediment removed, bypassed, and in the effluent for a long-term period such that the performance of the SedFil is accurately evaluated. This was a challenge because there is no continuously monitored pollutant data for a long-term period. At best, an automatic sampler was used to collect a few samples during a storm event. For the case of the Jollyville SedFil, sediment was monitored for only a handful of storm events during the study period. Therefore, the SWAT SedFil model was calibrated for two storm events that occurred in 1997. Next, long-term performance was evaluated using the calibrated model. As presented in Fig. 11, the Yao et al. (1971) model Eq. (13) shows marginal performance with respect to predicting sediment removal ($R^2 = 0.21$ and $\mathrm{NSE} = 0.03$), whereas the statistical measures for flow were much improved ($R^2 = 0.93$ and $\mathrm{NSE} = 0.9$). The increases in the sediment pollutograph during storm events were well predicted, but overall calibration efficiency

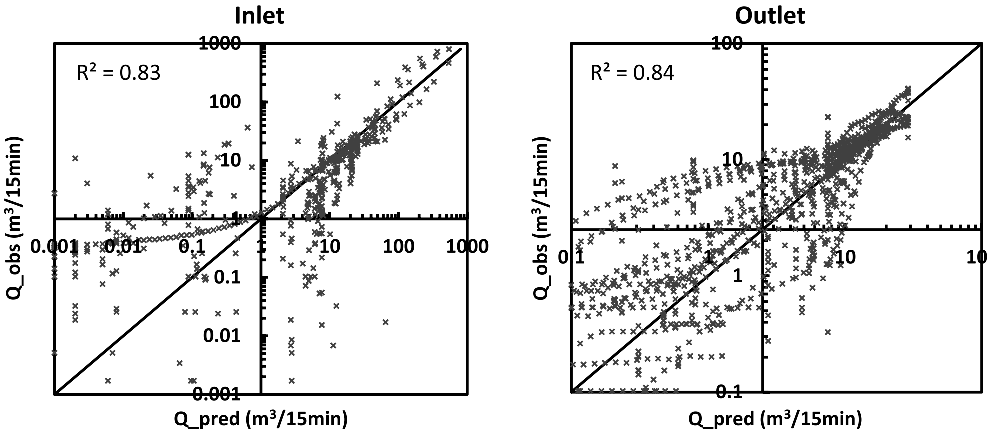

Fig. 9. Simulated 15-min flows relative to observed values at the inlet and outlet of the Jollyville SedFil (1997–1999)

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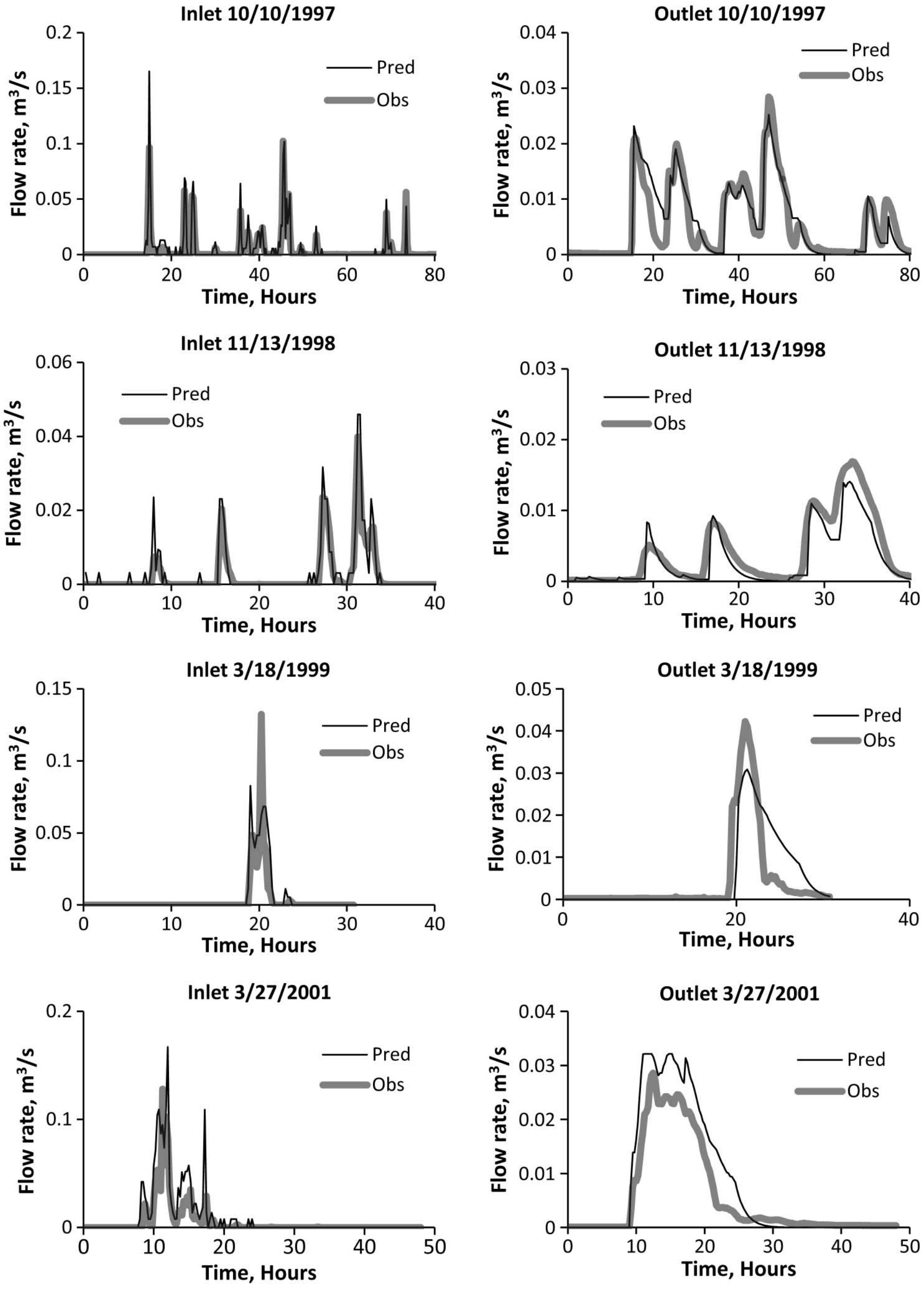

Fig. 10. Selected storm events, showing flow rates at the inlet and outlet of the Jollyville SedFil

was unsatisfactory. Considering that the high concentration at the inlet varied from 60–300 mg/L, the removal efficiency was nearly 99% and the efficiency did not vary substantially with respect to time (<1 mg/L). The parameters and coefficients that were calibrated for the Jollyville SedFil sediment calculation, using Eq. (13), are summarized in Table 2.

Traditionally, the pollutant removal efficiency by BMPs is measured by comparing the runoff concentration before and after passing through the system. Event mean concentration (EMC) is often used to calculate the removal efficiency, as follows:

$$\mathrm{RE} = \left(1 - \frac{\mathrm{EMC_{outlet}}}{\mathrm{EMC_{inlet}}}\right) \times 100 \qquad (14)$$

where RE = removal efficiency. The sediment removal efficiency of the Jollyville SedFil, if calculated with the EMC method, was estimated as 99.7% during the calibration. This estimate does not account for the bypass flow that occurred during these two storm events. The calibrated SWAT model estimated 2,965 $\mathrm{m^3}$ of bypass flow, which accounts for 65% of the total inflow of 4,556 $\mathrm{m^3}$. However, SWAT allows for detail estimation of sediment inflow, removal, and bypass in terms of the total mass at every time step. For estimating the removal efficiency, the sediment that bypassed the SedFil was predicted based on the quantity of bypass flow and sediment concentration in the incoming runoff. Next, the removal efficiency was estimated simply by taking the ratio of the actual inflow sediment (i.e., total sediment inflowing to the SedFil subtracted by the bypassed sediment) and the sediment discharged at the outlet. Primarily because of the large percentage of bypass flow that occurred during this particular storm event, SWAT estimation of the sediment removal efficiency was only 39%, which compares

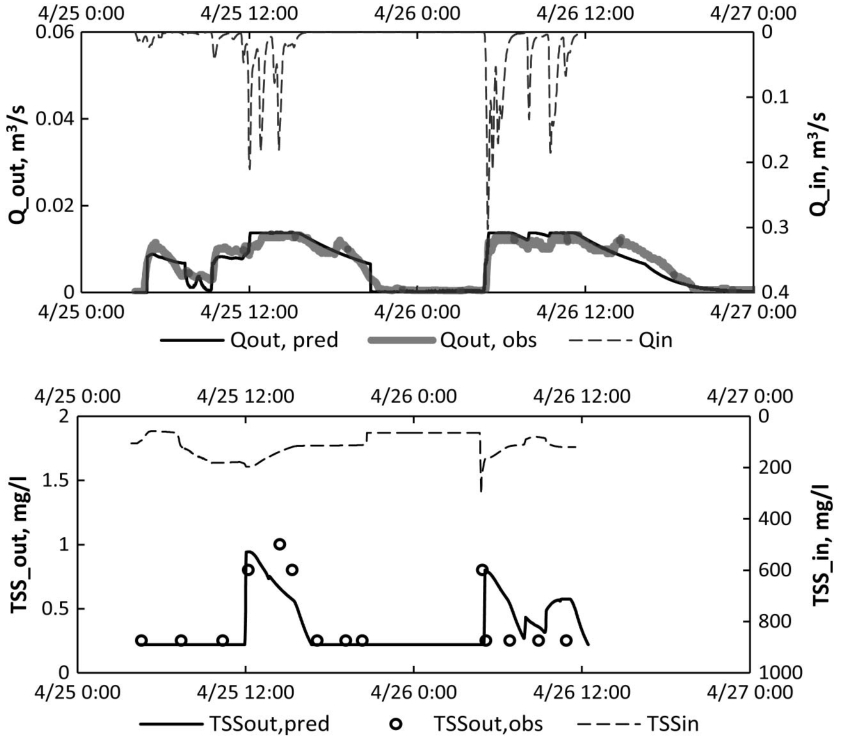

Fig. 11. Estimated flow and sediment concentration at the inlet and outlet

Table 2. Calibrated Sediment Coefficients and Filter Properties

Symbol	Value	Units	Description
d_p	30	μm	Median particle diameter of suspended solids
d_c	760	μm	Median particle diameter of filter media
κ	1.38×10^{-16}	—	Boltzmann constant
T	298	K	Absolute temperature of water
ρ_p	1.4	g/cm^3	Particle density of TSS
ρ_w	1.0	g/cm^3	Density of water
μ	8.91×10^{-3}	g/cm · s	Viscosity of water
ε	0.4	—	Porosity of filter media
α	0.2	—	Attachment efficiency
L	420	mm	Depth of filter

well with the EMC method. Specifically, the estimated total sediment in the inflow was 247.6 kg, the sediment that bypassed the filter was 150.8 kg, and the sediment in the outflow was 0.3 kg. The removed sediment was 96.5 kg, which accounts for a thin layer of particles with 0.2-mm thickness, assuming a sediment density of 1.6 kg/cm^3, although the filtered sediments are generally distributed within the filter media rather than accumulating in a discrete layer on the surface. The estimated thickness of the sediment deposit seems reasonable for two storm events.

In current practice, BMPs are designed at a field scale based on design storms, the minimum retention capacity, and target removal efficiency. At a watershed scale, the BMPs designed using the field scale variables may not function adequately, with respect to maximizing the storm water control (in terms of quantity and quality) and minimizing the impact of the downstream water body. The ultimate benefits of the SedFil routines in SWAT are not only to take advantage of its already validated hydrologic modeling components, but also to evaluate existing or future SedFils in a long-term perspective. A long-term continuous evaluation of a SedFil rather than a few historical storm events should give more accurate data and information to evaluate its performance. Furthermore, the model is useful for optimizing water quality controls with respect to various urban development scenarios.

Continuing on the case study of Jollyville SedFil, the SedFil performance was assessed for a long-term period (1997–2001). The year 2000 was excluded from the analysis because of an issue with data quality. On average, the SedFil allowed for 11.5% of the inflow to bypass the weir, whereas the treatment efficiency for sediment was 97.3%. These data, presented in Table 3, imply that the SedFil was designed appropriately for the drainage area, because the first flush was well-captured by the SedFil and only a limited amount of sediment is released directly to the creek. The removal efficiency, which is defined as the ratio of the sediment removed

Table 3. Long-Term Performance and Water/Sediment Balances

Year	Precipitation (mm/year)	Q_{in} (m^3/year)	Q_{out} (m^3/year)	Q_{bypass} (m^3/year)	Q_{treated} (%)	SED$_{\text{in}}$ (kg)	SED$_{\text{out}}$ (kg)	SED$_{\text{bypass}}$ (kg)	E_{removal}[a] (%)	E_{treated}[b] (%)
1997	1,103	19,863	17,446	2,439	87.8	2,027	34.7	31.0	98.3	98.5
1998	952	16,845	12,314	4,533	73.1	1,707	73.0	49.0	95.7	97.1
1999	401	6,010	5,181	837	86.2	1,122	22.0	19.0	98.0	98.3
2001	1,091	20,610	13,750	6,860	66.7	1,882	102.0	86.0	94.6	95.4
Average	887	15,832	12,173	3,667	78.5	1,685	57.9	46.3	96.5	97.3

[a] Removal efficiency $= (\text{SED}_{\text{in}} - \text{SED}_{\text{out}})/\text{SED}_{\text{in}}$.

[b] Treatment efficiency $= (\text{SED}_{\text{in}} - \text{SED}_{\text{bypass}})/\text{SED}_{\text{in}}$.

and inflow sediment, including the bypassed quantity, was estimated as 96.5%. The estimated removal efficiency compares well with the findings based on field data, in which the estimated removal efficiency was 95% (Barrett 2010). Barrett (2010) did not include bypass flow in estimating the sediment removal efficiency; therefore, the slightly higher efficiency that was found in this research seems reasonably consistent with previous findings.

Summary and Conclusion

A new physically based model of variably saturated flows was developed for simulating flow and sediment in SedFil basins. The integrated SWAT-SedFil model allows for simulation of unsaturated flow in the filtration basin during small storms (or at the onset of storm events) and the transition to saturated flow. Unsaturated flow in the filter media was modeled using a modified Green and Ampt equation, and saturated flow was simulated with Darcy's Law. The transition from unsaturated to Darcy flow occurs if the total volume of water in the filter exceeds the total available pore space. Similarly, the transition from Darcy flow to unsaturated flow occurs primarily during the recession period of storms, in which the outflow rate exceeds filtration rate. Unsaturated flow comprised only a small fraction of flow regimes in large storm events; however, many storms throughout the year are very small storms that will only contribute unsaturated flow in the filtration basin. Therefore, this combined unsaturated/saturated flows approach is beneficial with respect to improving the accuracy of the model, especially in long-term evaluations.

The SedFil model was tested on the Jollyville SedFil, which is located at Austin, Texas. Good results were obtained for flow in the long-term perspective in addition to individual storm events. Partially because of data scarcity, sediment was not comprehensively evaluated but was instead tested for a single event. Based on the results, the developed algorithm for SedFils seems to be functioning adequately. The tool could be used to design SedFils for attenuating nonpoint source pollution in urban landscapes. The integrated version of the algorithm within a watershed scale model can be used to develop many what-if scenarios, and help city managers and policy makers to make appropriate decisions on improving the quality of urban rivers and lakes.

Barrett (2010) suggests that a probabilistic approach may be more appropriate for modeling pollutant removal in sand filters because of the insubstantial correlation between inflow and outflow pollutant concentrations. Therefore, future research will focus on incorporating more methods to improve the model with respect to simulating the mechanism of sediment removal and transport in SedFils.

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