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Research article

Stormwater controls for channel stability: Focusing on bed material transport prevents degradation

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ABSTRACT

The hydrologic benefits of catchment-scale implementation of stormwater control measures (SCMs) in mitigating the adverse effects of urbanization are well established. Nevertheless, recent studies indicate that the Unified Stormwater Sizing Criteria (USSC) regulations, mandating the combined use of distributed and storage stormwater controls, do not protect channel stability, despite their effectiveness in reducing runoff from impervious surfaces. The USSC are the basis of SCM design in 11 U.S. states and the District of Columbia. This study employed a calibrated, sequential modeling approach, which integrated a catchment-scale Storm Water Management Model (SWMM) with the Hydrologic Engineering Center River Analysis System (HEC-RAS), to evaluate the effectiveness of two alternative stormwater regulations in preventing channel erosion. A three-step methodology was developed using the calibrated SWMM and HEC-RAS models: (1) establish the pre-development scenario; (2) design SCMs for channel stability under design storm conditions; and, (3) assess regulation effectiveness through continuous simulations. The modeling results revealed that designing stormwater controls using the USSC increased sediment transport for the 1-, 2-, and 5-yr, 24-hr annual recurrence interval (ARI) design storms 2 to 2.7 times the pre-development conditions. SCM designs aimed at matching the sediment transport of the pre-development catchment reduced peak flows 30–70% and prevented knickpoint formation, as compared to designs based on hydrologic targets only. Study results demonstrate that to protect channels from degradation following urban development, the morphology and bed material of the receiving channel must be considered in the design of stormwater controls.

1. Introduction

Urbanization significantly alters the natural hydrology of downstream water bodies and streams in various ways. The transformation of pervious landscapes into impervious surfaces such as rooftops, parking lots, and roads leads to an increase in runoff during storm events, along with pollutants and sediment that are conveyed with runoff (Askarizadeh et al., 2015; Walsh et al., 2016). The Nationwide Runoff Urban Program (NURP) reported event mean concentrations (EMCs in mg/L) for total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) for commercial land use ranged from 0 to 40 (median 1.24), 0.02–19.9 (median 0.3), and 1–4168 (median 98), respectively; and for residential land use, TN, TP, and TSS ranged from 0 to 12.46 (median 1.28), 0.02–1.95 (median 0.16), and 1–2380 (median 102), respectively (Smullen et al., 1999; U.S. EPA, 1983). As the study watershed is tributary to the Chesapeake Bay, TN, TP, and TSS are pollutants of primary interest due to eutrophication concerns.

Originally, stormwater conveyance systems were designed to quickly and efficiently transport the large volume of runoff from urban areas to downstream water bodies, typically without any treatment (National Research Council, 2009). This expedited removal of runoff impacted stream water quantity and quality, prompting urban communities to implement stormwater control measures (SCMs) to infiltrate, store, and treat runoff near its source before discharging it into streams (National Research Council, 2009). Since the 1980s, the strategy for implementing SCMs has shifted from large-scale, centralized, storage-based systems to smaller-scale, multifunctional SCMs distributed throughout urban catchments (Jefferson et al., 2017). In the United States, the design of these SCMs is typically regulated by local and state governments with a focus on three main objectives: 1) reduction of peak flow rates, 2) runoff

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volume detention or reduction, and/or 3) water quality improvement.

In Maryland, from 2000 to 2008, SCM design regulations were based on the Unified Stormwater Sizing Criteria (USSC) requirements developed by the Center for Watershed Protection (Maryland Department of the Environment (MDE) 2009). This framework was subsequently adopted by 11 other states and the District of Columbia. A primary objective of SCM runoff detention in these jurisdictions was to protect downstream channels from erosion through the use of storage-based SCMs like ponds, detention basins, or wetlands. These structures were designed to provide either 12- or 24-hr extended detention of the runoff generated from a 1-yr, 24-hr design storm event (Maryland Department of the Environment (MDE) 2009). This requirement was based on the assumptions that maintaining the frequency of bankfull and sub-bankfull events would protect channel stability and that the bankfull discharge could be approximated by the runoff from 1-yr to 2-yr, 24 design storms and controlled via extended detention alone. Maintaining pre-development peak flows was not required by Maryland regulations. In addition to protecting channel stability using stormwater detention, infiltration-focused SCMs distributed throughout the watershed were required to treat runoff from the first 2.54 cm of rainfall to improve water quality.

In 2009, the Maryland SCM design regulations were updated based on a new SCM design strategy, known as Environmental Site Design (ESD), which places greater emphasis on distributed SCMs, such as bioretention cells, swales, infiltration trenches/basins, and sand filters (Maryland Department of the Environment (MDE) 2009). These design criteria mandate that stormwater runoff storage from a 1-yr, 24-hr storm event be provided for the difference between the runoff volume from a development site and the site with woods in good condition, as per the US Natural Resources Conservation Service (NRCS) National Engineering Handbook, Part 630 (NRCS, 2004). Under this strategy, if the runoff volume storage requirement is met using small-scale, distributed SCMs, then storage-based structural SCMs are not required. However, if distributed SCMs are insufficient to meet the required storage volume, storage-based SCMs must be implemented for the remainder of the runoff volume. Because the ESD regulations do not require separate volumes of runoff storage to meet the water quality and channel stability goals, SCMs design based on the ESD regulations result in a smaller volume of stormwater storage, as compared to the USSC.

The hydrologic benefits of SCMs in mitigating the adverse effects of urbanization are well recognized in Maryland and other regions of the USA (Choat et al., 2023; Hopkins et al., 2020, 2022). However, only a few modeling studies have explored the impact of catchment- or site-scale SCM implementation on channel erosion prevention (Bledsoe, 2002; Bledsoe and Watson, 2001; McCuen and Moglen, 1988; Pomeroy et al., 2008; Tillinghast et al., 2011, 2012). These studies often relied on generic landscapes or design storms for their analyses. Additionally, they typically assumed that the channel sediment supply was equal to the sediment transport capacity. Design storm sediment transport analyses by Bledsoe (2002) and McCuen and Moglen (1988), using generic landscape data, found that SCMs designed with a peak flow reduction approach could increase the frequency of and prolong erosional events in streams. Towsif Khan et al. (2024) performed a decade-scale sediment transport analysis of a headwater stream in Maryland using a calibrated, coupled modeling approach. Their study documented that a system of SCMs designed following USSC would result in the development of knickpoints as well as regions of channel degradation and downstream aggradation as the channel slope adjusted to the catchment hydrology following urbanization with USSC-based stormwater controls.

Streams in urban environments typically have two to three times higher sediment transport capacity than in the pre-development condition (Bledsoe, 2002; Hawley et al., 2022b). Moreover, following urbanization, the sediment supply dynamics are also altered (Russell et al., 2017). Ensuring channel stability in urban streams thus requires that the amount of bed material transported long term is equivalent to the coarse sediment supplied to the stream. Two different SCM design criteria have been used to ensure sediment supply and transport are balanced (Table 1). The first approach calculates the ratio of the total mass of bed sediment transported for the urban or post-development flow condition and the pre-development condition. This ratio is called the "Erosion potential ratio" (E_p (Bledsoe, 2002)) and is calculated as follows:

$$E_p = \frac{\sum_{t=0}^{T} Qs_{post}}{\sum_{t=0}^{T} Qs_{pre}} \tag{1}$$

where Q_s was the sediment transport mass (tonnes) and "post" and "pre" represented the post- and pre-development scenario, respectively, t is time, and T is the total duration for the calculation. Hawley et al. (2022b) monitored a stream in California where the stormwater controls for a new development were designed to achieve $E_p = 1$ for design discharges ranging from 10% of the 2-yr annual recurrence interval (ARI) flow to the 10-yr ARI flow; post-development the channel maintained the pre-development geomorphic trajectory while upstream control reaches continued to erode.

Similar to E_p, the channel effective work can be quantitatively determined as the product of the difference between the applied shear stress and critical stress, the average velocity in the main channel, and the duration of the applied stress. The total amount of time the applied shear stress exceeds the critical shear stress is known as the erosion hour (E_h). The effective work (E_w) is determined as follows:

$$E_w = \sum (\tau - \tau_c) vt \tag{2}$$

where τ is the applied shear stress (N/m^2) on the channel bed at time t, τ_c is the critical shear stress (N/m^2) of the median particle size of the channel bed, v is the average main channel velocity (m/s) and t is the time step (s).

While some previous studies have conducted preliminary modeling analyses of SCM design to reduce channel erosion in generic landscapes (Bledsoe, 2002; McCuen and Moglen, 1988), to our knowledge, no studies have evaluated the effects of SCMs in a real-world site using continuous simulation. Therefore, the aim of this study was to evaluate the cumulative efficacy of a system of SCMs, designed to meet bed sediment-based targets, in protecting channel stability long-term. A sequential modeling approach utilizing SWMM and HEC-RAS, developed by Towsif Khan et al. (2024), was used to achieve these goals. The Stormwater Management Model (SWMM) is a widely used dynamic rainfall-runoff model for simulating urban runoff quantity and quality that is used for both continuous and event-based simulations. (Rosburg et al., 2017; U.S. Environmental Protection Agency (U.S. EPA), 2021).

Table 1
Summary of alternative stormwater control measure (SCM) design criteria.

Attribute	Erosion potential (E_p)	Effective work (E_w)
Key Variable(s) Calculated	Cumulative bed sediment transport in tonnes (Q_s) employing any reach-representative sediment transport equation.	Effective work (E_w) and duration (E_h) of critical shear stress exceedance of a representative bed particle size, typically d_{50} or d_{84}
Design Target	Keep Q_s the same as or less than pre-development conditions for selected design storms or continuous precipitation time series.	Keep E_w and E_h the same or less than pre-development conditions for selected design storms or continuous precipitation time series.
Data Requirements	Grain size distribution of the channel bed. Channel cross-section geometry and bed slope.	Grain size distribution of the channel bed. Channel cross-section geometry and bed slope.
Limitations	Results are highly sensitive to the chosen sediment transport equation. Calculation intensive.	Considers the mobility of selected particle size only.

SWMM incorporates a variety of stormwater control measures (SCMs) and can simulate most if not all of a stormwater conveyance system within the hydraulic model. The Hydrologic Engineering Center River Analysis System (HEC-RAS) is a hydraulic and sediment transport model that is used to simulate natural and man-made channels. It is primarily used in predicting flood elevations, but it has been extended to model sediment transport, including bedload (Brunner, 2022). HEC-RAS was selected for this study because it is widely used in engineering practice and therefore would be more likely to be utilized for SCM design. HEC-RAS has been used successfully to simulate sediment transport in urban and ephemeral streams (Berteni et al., 2018; Hummel et al., 2012) and for stream restoration design (Kassa et al., 2023).

SWMM and HEC-RAS have been coupled previously for real-time flood forecasting applications (Lee et al., 2020); however, little to no published research is available in which these two models were coupled for the purpose of predicting sediment transport and receiving stream stability in small urban streams. Other studies have linked the Soil and Water Assessment Tool (SWAT) and HEC-RAS to simulate channel and floodplain erosion and sedimentation within a 468 km^2 catchment (Song et al., 2015) and SWMM and the River Erosion Model (REM) to evaluate the combined effects of stormwater management and stream restoration on channel erosion in a 280 km^2 catchment (Lammers and Bledsoe, 2019). Considering the focus of many regulatory programs on the stability of small urban streams, further investigation of this application is warranted.

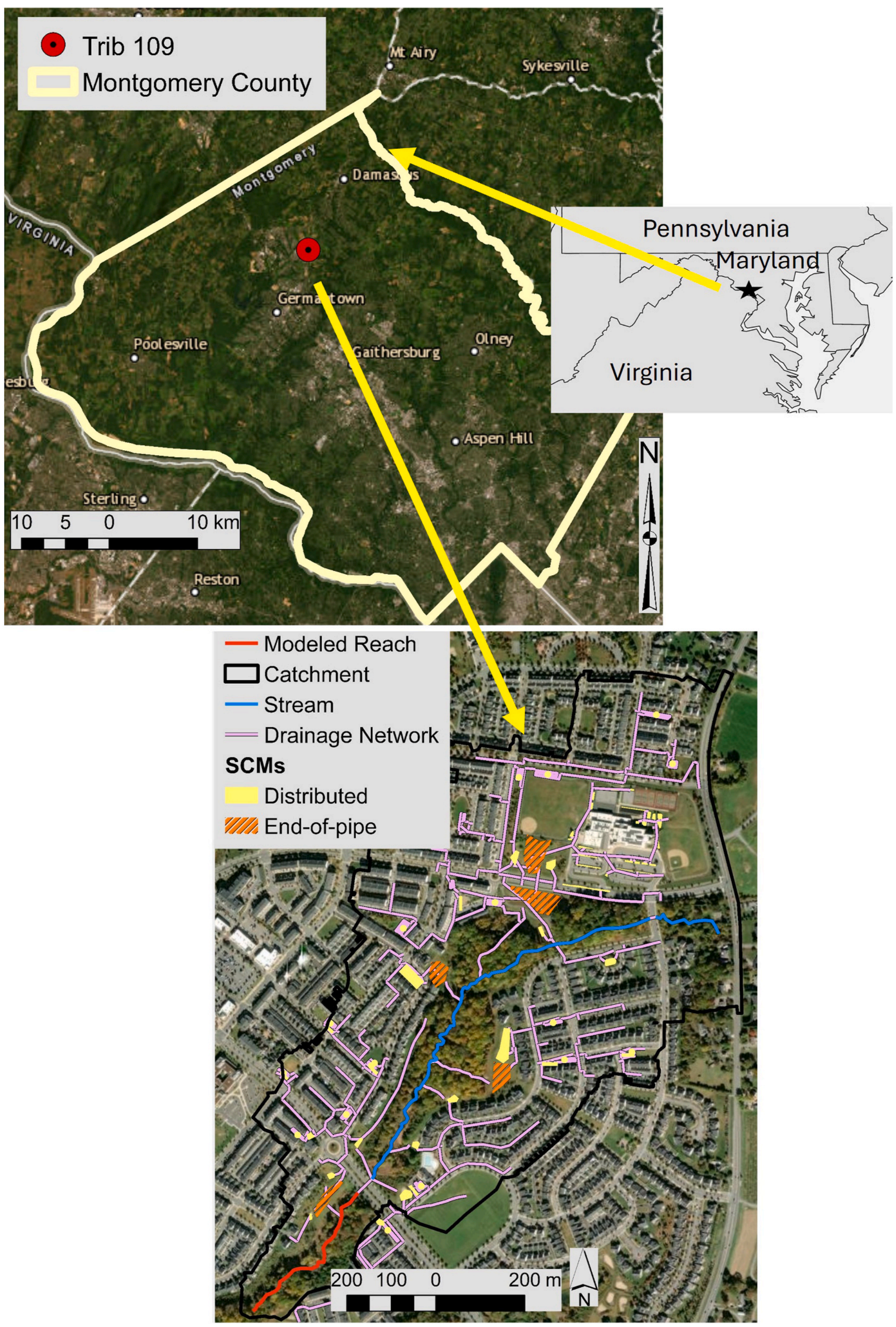

Fig. 1. Location of Tributary 109 (Trib 109) within Maryland and current Google satellite imagery with stormwater control measures (SCMs).

2. Methodology

2.1. Study site and background

We chose a small, urbanized catchment (0.9 km^2) located in Montgomery County, Maryland, USA, within the Piedmont physiographic province (Fig. 1) for our case study. The area is part of the Clarksburg Special Protection Area, an area that is designated by the County as environmentally sensitive and subject to additional protection. Referred to as Tributary 109 (Trib 109), the receiving stream is a single thread, gravel-bed channel with a 1.1% bed slope that has been extensively monitored by Montgomery County and the US Geological Survey (e.g. Hopkins et al., 2020; Williams et al., 2018). The land use and land cover (LULC) of the catchment transitioned from predominately agriculture to suburban development from 2006 to 2017 (Hopkins et al., 2022). The current (post-2017) LULC of the catchment consists of a mixture of detached single-family homes, attached townhouses, and a school. This development has a high density of SCMs (SCM density is 274 per km^2), built in accordance with the USSC. Even though the total imperviousness of the catchment increased from 5 to 45% due to urban development (Hopkins et al., 2022), the directly connected impervious area (DCIA) of the catchment remained close to zero due to the widespread implementation of SCMs. Additional details about this catchment are presented in Towsif Khan et al. (2024).

A sequential modeling approach was developed and applied to examine projected changes in sediment transport and the profile and cross sectional geometry of the 450-m modeled reach (Towsif Khan et al., 2024). The 1-dimensional, quasi-steady HEC-RAS model used a continuous discharge time series from a watershed-scale SWMM model representing the most recent (post-2017) LULC of the area, driven by a 16-yr observed climate time series (2005–2020, Montgomery County Black Hill weather station) (Towsif Khan et al., 2024). Results of that study showed that even with the extensive implementation of USSC and over 70 SCMs, the studied reach will likely degrade over the next two decades in response to catchment urbanization, developing alternating regions of degradation and aggradation that will ultimately reduce the channel slope and sediment transport capacity. The study indicated that SCMs designed with the goal of detaining the runoff volume from a 1-yr, 24-hr design storm for 12 or 24 h will not protect channel stability (Towsif Khan et al., 2024).

2.2. SCM design criteria assessment

Both the E_p and E_w SCM design criteria were evaluated as alternative approaches to the USSC using a three-step approach and the calibrated SWMM and HEC-RAS models from Towsif Khan et al. (2024). First, the pre-development hydrology was estimated using SWMM and the pre-development sediment transport and effective work were calculated based on output from the HEC-RAS model. Second, to determine the post-development sediment transport and effective work under the two proposed SCM design criteria, the outlet structures of the existing extended detention ponds were modified in the calibrated post-development SWMM model and the catchment response to design storms was simulated. The resulting hydrographs were then input into the calibrated HEC-RAS model to determine the post-development sediment transport and effective work for these design storms. The modeled pond outlet structures were adjusted until either the E_p or E_w ratios equaled 1.0 for each design storm. Third, the catchment hydrology under each of these two SCM design criteria was then determined using the two updated SWMM models and measured continuous weather data. Channel response was then modeled to evaluate the impact of the two proposed SCM design criteria on channel stability. These three steps are described in additional detail below.

To establish the pre-development hydrology, a SWMM model was developed for the study catchment utilizing available LULC (Williams et al., 2018) and a 0.9-m resolution digital elevation model (DEM) from the year 2002 (Metes and Jones, 2021). This pre-development SWMM model of the study area was calibrated to a single storm event (July 06, 2006) using discharge data from a U.S. Geological Survey (USGS) stream gage (station # 01644372 Little Seneca Creek Tributary at Brink, Maryland). Due to the short time span between when the gage was established and the initiation of development, only one measured storm event was available for model calibration. The groundwater parameters of the pre-development SWMM model were set to the same values as those of the floodplain in the calibrated SWMM model, which reflected the LULC of the post-2017 period. These parameters were not varied during the calibration of the pre-development model, as the floodplain did not undergo any modifications during the construction period from 2006 to 2017. In this pre-development scenario, all the delineated subcatchments of the pre-development watershed were assumed to be 100% pervious, and their physical properties were obtained from the 2002 catchment DEM.

To determine E_p, Q_s was calculated using the Wilcock and Crowe sediment transport equation (Wilcock and Crowe, 2003) for a range of standard design storms commonly used in stormwater management (e.g. 1-yr, 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, and 100-yr, 24-hr storm events). A time increment of 5 min was used in the calculation of E_p and T was set at two days (48 h) because, in the proposed SCM design scenarios, it took almost two days for the SCMs to drain due to the modification of the SCM outlet structures to further reduce outflows. The channel geometry data used for the calculation of bed material transport amount was a straight channel section from the central portion of the modeled reach, and the channel bed material was the same as that used in the calibrated HEC- RAS model. The 24-hr design rainfall depths were converted to rainfall hyetographs using a Natural Resources Conservation Service (NRCS) Type II storm distribution and the resulting hyetographs were incorporated into the SWMM model of the respective scenarios (pre- or post-development) to generate flow time series for the calculation of E_p. The rainfall depths were obtained from the Maryland Department of the Environment's Stormwater Design Manual (Maryland Department of the Environment, 2009) and are shown in Table 2.

The outlet structures for the five storage SCMs were modified in the post-development SWMM model by changing orifice diameters and weir lengths and increasing the invert elevations to ensure the E_p criterion was met. The exact dimensions of the original (USSC) and alternative outlets are presented in Table OR1.1 in Online Resource 1 and the locations of the redesigned storage-based SCMs are provided in Fig. OR1.1. Additionally, the berm heights of two SCMs immediately upstream of Pond 11AB were raised by 0.4 m in the model to decrease the inflow rate to that pond. During these modifications, care was taken to ensure that the elevation of the riser structure in SWMM did not exceed the elevation of the emergency spillway.

A similar procedure was used modify the modeled SCM outlet structures such that the E_h and E_w were less than or equal to the corresponding values in the pre-development condition for the range of design storms specified in Table 2, following procedures described in Brennan et al. (2018). Under the effective work criteria, the outlet structures of only four of the five ponds were changed in the SWMM model; the berm heights of two SCMs immediately upstream of Pond 11AB were raised by 0.4 m to decrease the inflow rate to the pond, as for the E_p design criterion. Specific details about the outlet configurations are provided in Table OR1.1 in Online Resource 1.

The final SWMM models for the USSC, E_p, and E_w design scenarios were run with the 16-yr measured precipitation record for the 2004–2020 period. Individual storm events were delineated following

Table 2
Design storm depths for stormwater control measure design in Maryland (Maryland Department of the Environment, 2009).

Return Period (yr)	1	2	5	10	25	50	100
24-hr Rainfall Depth (mm)	66	81	106	129	142	160	183

procedures described in Towsif Khan et al. (2024) and the resulting discharges at the catchment outlet were compared. The outflow time series of these three SWMM models were then incorporated into the calibrated HEC-RAS model (Towsif Khan et al., 2024) to evaluate the performance of the SCM design scenarios in protecting channel stability under continuous rainfall. The time series of cross-section shape, longitudinal bed profile, and sediment transport rates were assessed to evaluate the effects of the two potential stormwater regulatory scenarios on sediment transport dynamics and channel morphology.

3. Results

3.1. Unified stormwater sizing criteria performance

Despite the widespread implementation of SCMs designed following the USSC regulations in the Trib 109 catchment, the cumulative mass of bed material transported in the receiving stream after development (USSC Q_s) was almost twice that of the pre-development condition for the 1-yr and 2-yr design storms, resulting in E_p values of 2.13 and 1.91, respectively (Table 3). The E_p of the USSC SCMs were less than 1.00 for design storms with an ARI greater than 5 yrs, indicating the most significant increase in sediment transport amount following development under the USSC regulations was associated with more frequent flows.

The effective work design criterion requires the amount of time stream flow exceeds the d_{50} bed material critical shear stress (E_h) and the amount of effective work (E_w) done by the stream flow on the bed particles for each design storm to equal the pre-development values. For the pre-development scenario, the magnitude and duration of the effective work were zero for the 1- and 2-yr storm events, indicating bed particles equal to or larger than the d_{50} are likely not mobilized during those events. Following development under the USSC regulations, even the most frequent design storm was able to mobilize the median size bed particles, even with the extensive amount of stormwater management infrastructure in the catchment. As shown in Fig. 2a, the peak flow resulting from the 1-yr, 24-hr ARI storm event under the USSC regulations was over twice that of the peak flow for the undeveloped condition. For the 5-yr ARI design storm, E_h decreased 14% while E_w doubled, indicating the storm flows were flashier, with higher peak discharges and shorter durations, than in the pre-development condition (Fig. 2b). All existing ED ponds in the Trib 109 catchment were sized to capture and detain the 1-yr, 24-hr design storm runoff for 12 h; the USSC do not require maintenance of pre-development peak flow rates unless downstream flooding is a concern.

Table 3
Values of erosion potential ratio (E_p), erosional hour (E_h), and effective work (E_w) for the different stormwater management design scenarios. USSC= Unified Stormwater Sizing Criteria. Q_s = total mass of sediment transported per design storm event.

Scenario	Parameter	24-hr Storm Recurrence Interval		
		1-yr	2-yr	5-yr
Predevelopment	Q_s (tonnes)	9.97	18.1	43.2
	E_h (hr)	0.00	0.00	1.75
	E_w (kJ/m^2)	0.00	0.00	34.0
USSC	Q_s (tonnes)	21.3	34.5	59.5
	E_p	2.13	1.91	1.38
	E_h (hr)	0.41	1.08	1.50
	E_w (kJ/m^2)	2.00	20.0	70.7
Erosion Potential	Q_s (tonnes)	11.6	19.3	33.3
	E_p	1.16	1.07	0.77
	E_h (hr)	0.00	0.00	0.42
	E_w (kJ/m^2)	0.00	0.00	7.53
Effective Work	Q_s (tonnes)	11.9	19.1	40.7
	E_p	1.19	1.06	0.94
	E_h (hr)	0.00	0.00	0.83
	E_w (kJ/m^2)	0.00	0.00	32.7

3.2. Erosion potential design criterion performance

By designing the pond outlet structures to meet the erosion potential design criterion, E_p was less than 1.00 for design storms with an ARI greater than 2 years. However, for the 1- and 2-yr design storms, E_p was only reduced to 1.16 and 1.07, respectively. To achieve an $E_p \leq 1.00$ for these two design storms would have required redesign of at least part of the subdivision or the installation of an in-stream storage pond in the catchment. Use of an in-stream pond was considered undesirable from a sediment continuity standpoint and infeasible from a regulatory standpoint.

The E_p design criteria resulted in the peak flow from a 1-yr, 24-hr design storm that was close to the pre-development discharge, but the volume during and duration of the hydrograph recession increased (Fig. 2a). Because urban development ultimately increases the runoff volume, to maintain the pre-development sediment mass transported by the stream, the post-development hydrograph must have lower peak flows and higher recession flows than the pre-development condition. For the 5-yr ARI storm, the E_p peak flow was similar to that from the pre-development watershed, but the duration of the elevated discharge was reduced, resulting in E_h and E_w values that were 76% and 78% lower than the pre-development condition, respectively.

3.3. Effective work design criteria performance

Under the effective work design criteria, peak discharges resulting from the 1-yr and 2-yr ARI design storms were maintained below the flows required to entrain the bed material d_{50}. For the 5-yr storm, E_h was reduced by 50% from the pre-development condition and E_w was nearly equivalent. The peak flow for the 1-yr storm was the same as the E_p scenario since these scenario had the same low and intermediate stage pond outlets. However, for the 5-yr storm event, the peak flow in the E_w scenario was close to that of the USSC because meeting the E_w design criteria only required increasing the high stage invert elevations of two terminal ponds (Fig. 2b).

3.4. Response to continuous rainfall

The 16-yr rainfall time series utilized to evaluate the design scenarios included several high-magnitude storm events. Specifically, there were seven storm events with rainfall depths exceeding those of a 10-yr, 24-hr ARI design storm. The median change in peak flows for all of the storm events for the E_p and E_w scenarios compared to the USSC scenario are provided in Fig. 3.

Under the E_p and E_w SCM design criteria, reducing the size of the low-stage outlets of the storage ponds resulted in a decrease in the median peak flow for both annual and sub-annual storm events (rain totals <71 mm) of between 30% and 70%, but extended the runoff detention for more than 24 h. This prolonged detention in the ponds contributed to an approximately 55% increase in peak flows from the E_w SCMs for three storm events with rainfall depths ranging between 106 and 129 mm (Fig. 3). This increase occurred because all of these events had inter-event time periods of less than 18 h, preventing the ponds from fully emptying before the onset of subsequent storms. In contrast, with the E_p SCMs, where riser elevations were increased for all of the ponds, an increase in peak flows did not occur for any of the storm events. The increased elevation of high-stage outlets during SCM retrofitting enhanced the storage capacity of the five ponds, which delayed overflows during storm event sequences with high rainfall depths and short inter-event times.

3.5. Predicted long-term changes in the channel profile

Using the three SWMM models and the 16-year rainfall record, a time series of stream discharge was developed for each of the SCM design scenarios. These discharge time series were input into the calibrated

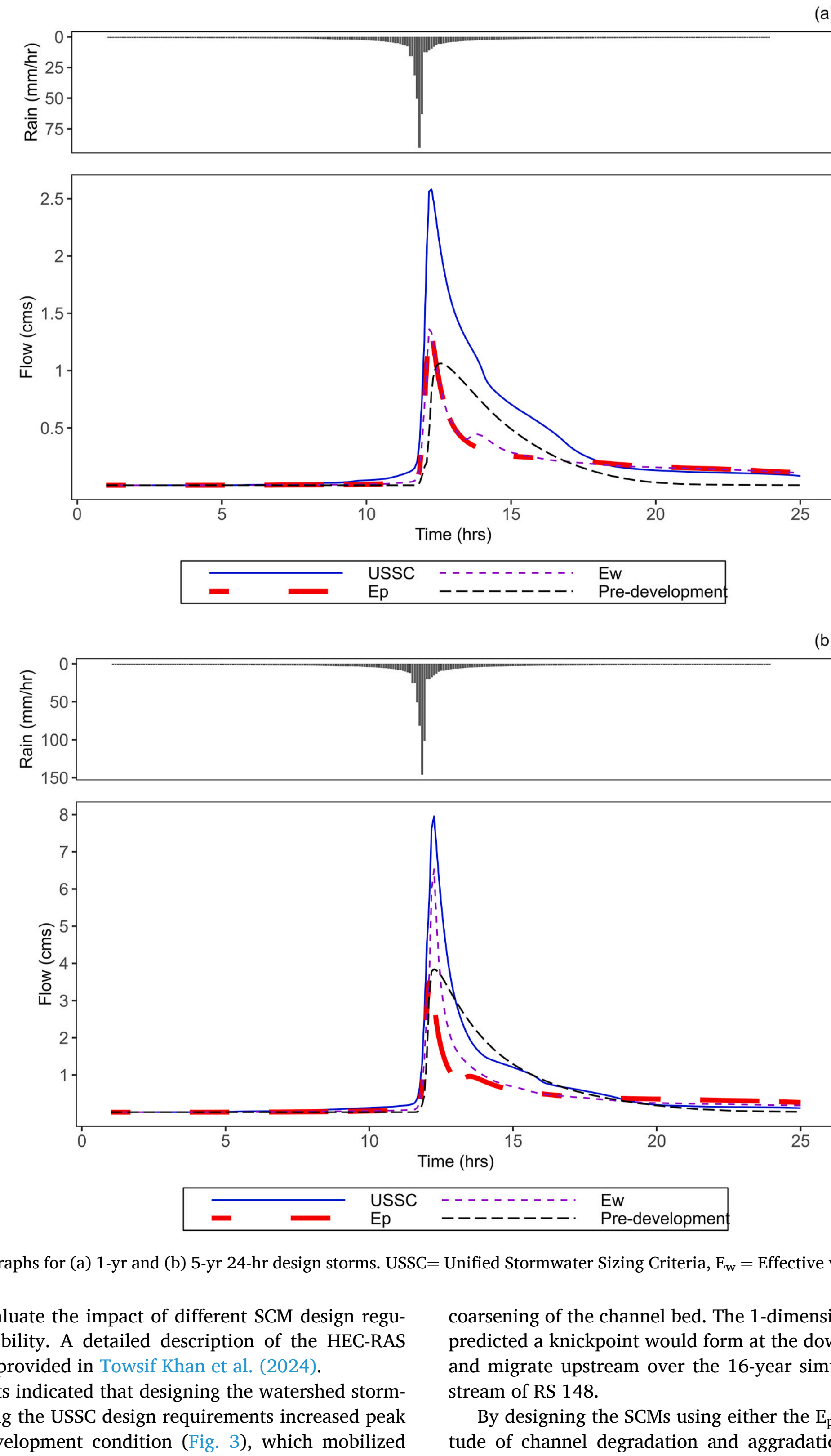

Fig. 2. Simulated hydrographs for (a) 1-yr and (b) 5-yr 24-hr design storms. USSC= Unified Stormwater Sizing Criteria, E_w = Effective work, E_p = Erosion potential.

HEC-RAS model to evaluate the impact of different SCM design regulations on channel stability. A detailed description of the HEC-RAS model development is provided in Towsif Khan et al. (2024).

The HEC-RAS results indicated that designing the watershed stormwater controls following the USSC design requirements increased peak flows over the pre-development condition (Fig. 3), which mobilized cobbles and small boulders present on the channel bed, leading to bed degradation of up to 0.8 m. These particles were subsequently deposited upstream of a channel constriction, resulting in the formation of a steep riffle at River Station 242 (Fig. 4). The pre-development bed particle size distribution, determined by annual Wolman pebble counts (Wolman, 1954), was dominated by gravel, with small amounts of cobbles and a limited number of small boulders (Fig. 5). During smaller storm events following urbanization, sands were selectively transported, causing coarsening of the channel bed. The 1-dimensional HEC-RAS model also predicted a knickpoint would form at the downstream end of the reach and migrate upstream over the 16-year simulation period to just upstream of RS 148.

By designing the SCMs using either the E_p or E_w criteria the magnitude of channel degradation and aggradation observed in the USSC scenario was reduced, as illustrated by the longitudinal profile plot in Fig. 4. Under the E_p and E_w requirements, the low-stage orifices were smaller in diameter than under the USSC requirements, reducing peak flows for storm events with rainfall depths less than 71 mm (Fig. 3). While both the E_p and E_w reduced bed coarsening, as compared to USSC (Fig. 5), changes in the longitudinal bed profile were still predicted to occur in the reach. The extent of deposition at RS 242 decreased from 0.6 m to 0.1 m as compared to the USSC scenario, and the knickpoints

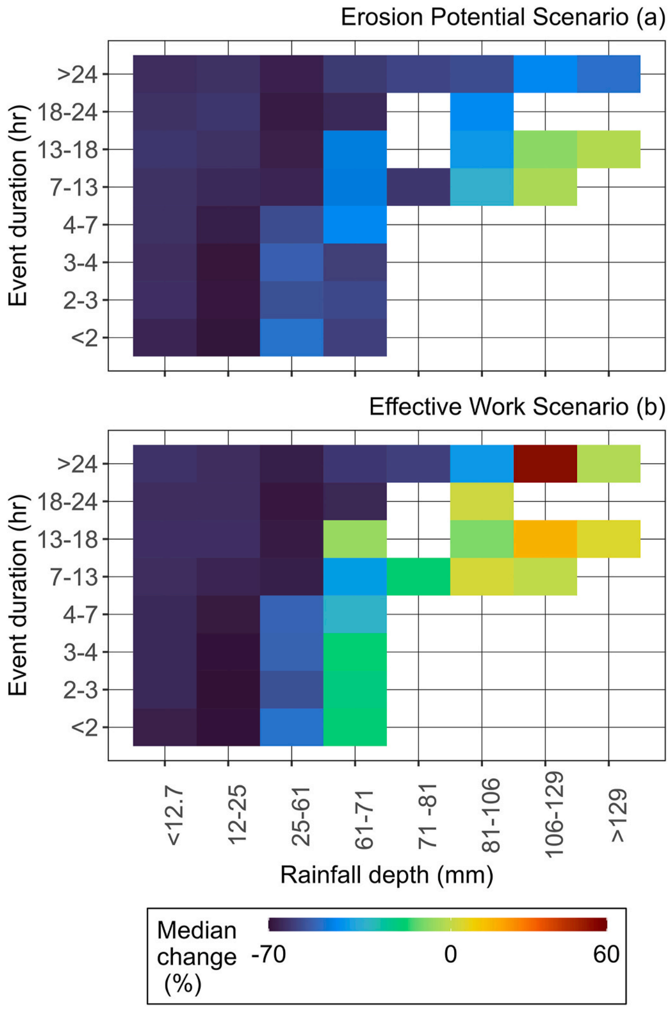

Fig. 3. The median change in peak flow of the a) Erosion potential; b) Effective work scenarios, as compared to the unified stormwater sizing criteria (USSC) scenario. A positive value indicates an increase in median peak flow.

observed near RS 148 and RS 242 in the USSC scenario did not form for the E_p and E_w designs (Fig. 4).

While the SCMs designed following the E_p and E_w criteria reduced the extent of channel change as compared to the USSC scenario, the channel was still predicted to adjust to the upstream urbanization. It should be noted that the design target of $E_p \leq 1$ was not fully achieved in the E_p scenario through redesign of the existing ED outlet structures in the SWMM models. Had the E_p criterion ($E_p \leq 1.00$) been achieved for all of the design storms, changes to the channel bed would likely have been less than those predicted under the E_w design criteria. Additionally, the pre-development channel width was greater than typical; the median bankfull width of the reach was almost five times larger than that of channels in rural catchments with similar drainage areas (McCandless and Everett, 2003). This large deviation in channel width suggests the pre-development channel was likely adjusting to prior impacts when the catchment was developed. As a result of this increased cross sectional area, high flows were contained within the main channel, rather than spreading out over the floodplain, increasing sediment transport for more frequent floods even prior to urbanization.

3.6. *Effect of flow regime on sediment supply and yield*

Gravel bed streams, such as Tributary 109, exhibit a dynamic sediment transport regime closely linked to the flow regime (Downs and Soar, 2021). In HEC-RAS, the incoming sediment load at the upstream end of the modeled reach (sediment supply) is often parameterized by a sediment load rating curve, which quantifies changes in the upstream load with discharge. This load is a function of the upstream watershed and channel characteristics and is often estimated during calibration, due to the challenges in measuring sediment loads directly. For this study, the initial sediment rating curve was developed using suspended sediment measurements at USGS gages in small urban catchments in the mid-Atlantic Piedmont and then calibrated based on observed changes in surveyed cross sections. The particle size distribution of the incoming load was determined by particle size analysis of bulk subsurface bed samples and consisted of sands and gravels, as described in Towsif Khan et al. (2024). Due to backwater effects from a historic upstream driveway and subsequent road following development, larger bed particles (cobbles and small boulders) are no longer transported to the modeled reach.

To demonstrate the differences in flow and sediment dynamics among the three SCM design scenarios, the flow volume input to the HEC-RAS model (for discharges >0.028 cms), total incoming sediment

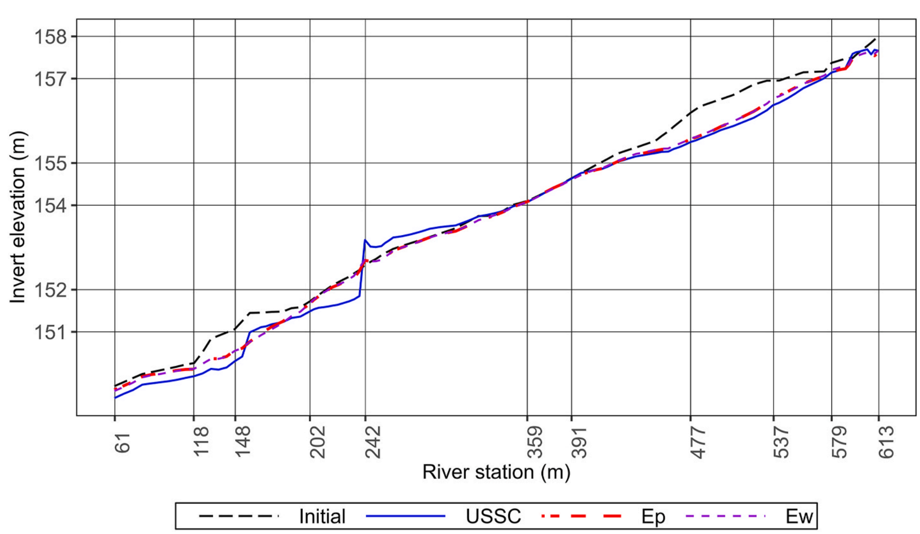

Fig. 4. Predicted channel longitudinal profile for the current climate for the unified stormwater sizing criteria (USSC), effective work (E_w) and erosion potential (E_p) scenarios.

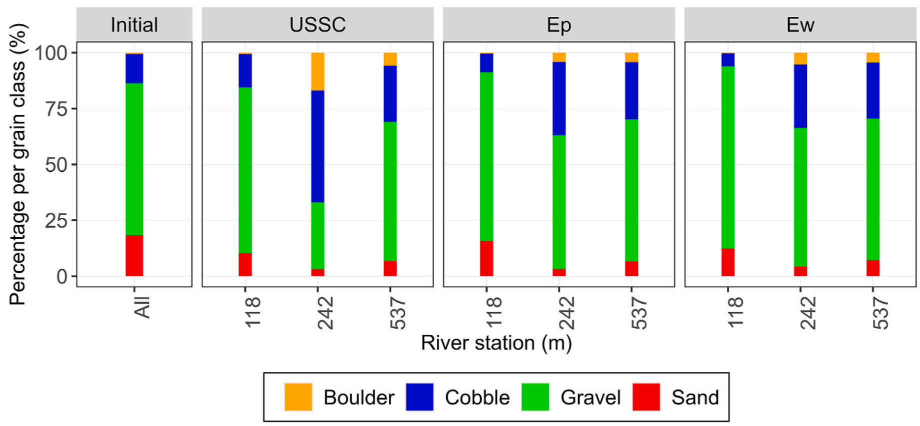

Fig. 5. Bed material grain size distribution for three river stations at the initial condition and after 16 years for the unified stormwater sizing criteria (USSC), erosion potential (E_p), effective work (E_w) scenarios.

load, and total sediment yield for three distinct flow ranges are shown in Fig. 6. These ranges bracket the lowest discharge included in the HEC-RAS model (0.028 cms), the discharge at which gravel was mobilized (1.13 cms) and the average flow at which the floodplain was accessed (5.89 cms). By designing the pond outlet structures following the E_p and E_w scenarios, the stormwater volume was decreased by 41% and 42%, respectively, as compared to the USSC design scenario. The decreased flows reduced the sediment load delivered to the modeled reach by 58% and 38% for the E_p and E_w SCMs, respectively, as compared to the USSC SCMs. While the cumulative flow volume in the E_w scenario was similar to the E_p scenario, the cumulative incoming sediment load was 51% greater due to higher peak flows resulting from storms with rainfall depths above 81 mm (Fig. 3). As shown in Fig. 6, even though discharges less than 1.13 cms transport 80–87% of the overall runoff volume, these flows did not transport the bulk of the bed sediment. Modeled cumulative sediment yields from the reach were 1.04, 0.43, and 0.65 kilotonnes for the USSC, E_p, and E_w SCM design scenarios, respectively; only 10–17% of this exported sediment was transported by flows less than 1.13 cms.

While the reach was still predicted to degrade, by storing stormwater runoff for extended periods and releasing it at less erosive rates, sediment yields from the modeled reach were minimized by implementation of SCMs following the E_p design criterion. It should be noted that the E_p scenario did not fully meet the criterion that $E_p \le 1.00$ for the 1-yr and 2-yr design storms. The E_w criterion ($E_{w.post} \le E_{w.pre}$) was met for all of the design storms; however, SCM designs based on this criterion were less effective in reducing sediment loss, but represented an improvement over the USSC design regulations.

4. Discussion

4.1. Implications for SCM design

Traditionally, the design of storage SCMs focused on matching post-development peak flows to pre-development flows. However, designs based on this criterion did not address the overall runoff volume, causing longer flow durations at erosive levels. In response to this issue, the USSC required the extended detention of runoff from the 1-yr, 24-hr storm event to protect channel stability. This requirement was based on the assumptions that maintaining the frequency of bankfull and sub-bankfull events would protect channel stability and that the bankfull discharge could be approximated by runoff from 1-yr to 2-yr, 24 design storms and controlled via extended detention alone (Maryland Department of the Environment, 2009). Results of this study document that despite the widespread application of both infiltration and storage-based SCMs designed based on USSC requirements, peak flows for the 1-, 2-, and 5-yr, 24-hr ARI design storms in Trib 109 were nearly double those of pre-development conditions (Fig. 2). These modeling results are supported by comparative empirical studies at the catchment scale, utilizing observed rainfall-runoff data (Hopkins et al., 2017). Their study suggested that increasing the number of storage-based SCMs could bring peak flows of frequent storm events closer to pre-development benchmarks. For this study, the USSC outlet structures were redesigned to meet either the E_p or E_w design criteria, which focus on maintaining pre-development sediment transport following development. To meet these criteria, the diameters of the low-stage orifices were reduced and the size and/or invert elevations of the intermediate- and high-stage outlets were adjusted (Online Resource 1), resulting in peak flows at the catchment outlet that nearly matched pre-development levels for the 1-yr design storm. Similar outlet retrofits were conducted in northern Kentucky and resulted in reduced flow flashiness and extended baseflows (Hawley et al., 2017). These studies demonstrate that designing storage SCMs based on a prescribed detention time of a specific runoff volume does not effectively protect against increased peak flows following development.

Ultimately, to minimize channel erosion resulting from urban development, the ability of the stream to transport bed sediment post-development must match pre-development transport rates (McCuen and Moglen, 1988; Hawley et al., 2017). For the USSC design criteria, the predicted sediment transport for the 1-, 2-, and 5-yr, 24-hr ARI design storms was 2–2.7 times the modeled pre-development rates. As a result, the channel is expected to have regions of degradation and aggradation as the channel slope decreases to adjust to the new catchment hydrology (Towsif Khan et al., 2024). Following redesign of the storage pond outlet structures following E_p or E_w design criteria (Online Resource 1), changes in the bed profile were significantly reduced, as compared to the USSC (Fig. 4). Given that urbanization results in increased runoff volume, to maintain the pre-development sediment transport, peak flows must be maintained close to the pre-development rates, while the flows on the hydrograph recession are kept below erosive thresholds to completely drain the storage SCMs without increasing sediment transport. Hawley et al. (2017) reduced the cumulative sediment transport capacity of urban streams in northern Kentucky by 40% by reducing low stage outflow diameters and installing flow bypass structures to handle extreme events. A subsequent study documented that designing stormwater controls to match pre-development sediment transport ($E_p = 1$) was successful at maintaining channel stability following greenfield development (Hawley et al., 2022a).

During the development of Trib 109, the Maryland stormwater regulations were changed from the USSC to Environmental Site Design (ESD). The ESD design goal focuses on achieving a runoff volume from the 1-yr, 24-hr design storm that is equivalent to that from a catchment with a land cover of “woods in good condition” (NRCS, 2004). If the

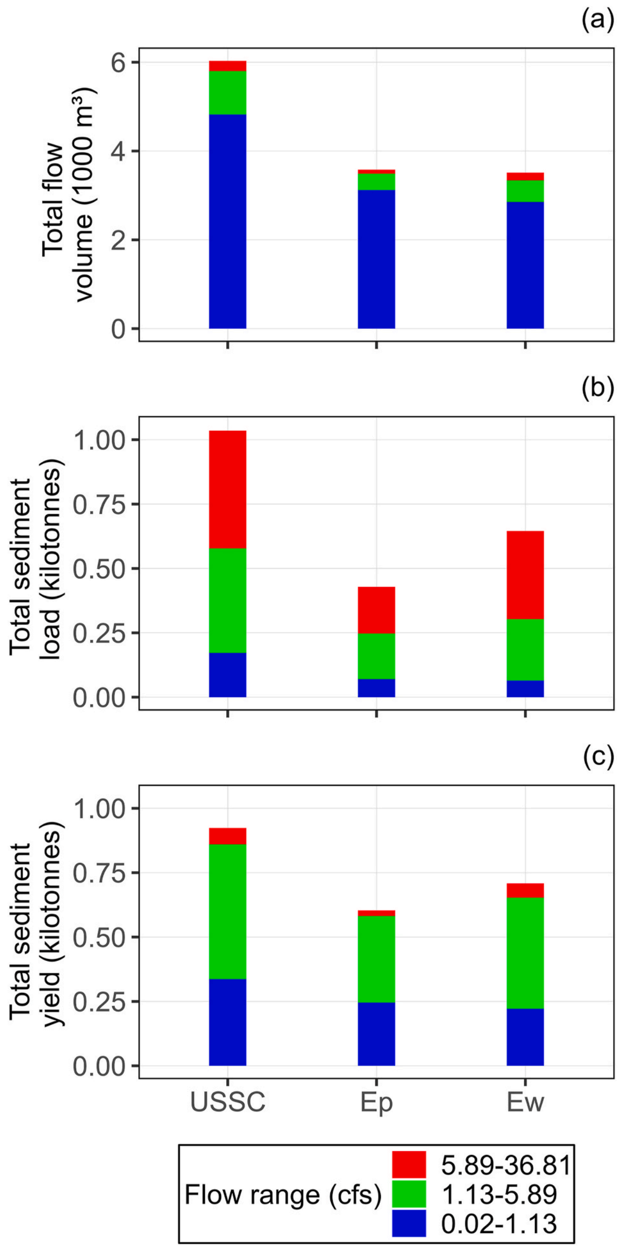

Fig. 6. Flow volumes for discharges >0.028 m^3/s (a), incoming sediment load (b), and sediment yield for the HEC-RAS model (c) as a function of stream flow classes for the unified stormwater sizing criteria (USSC), erosion potential (E_p) and effective work (E_w) scenarios.

runoff volume above that of "woods in good condition" can be stored in distributed, infiltration-focused practices, then storage SCMs are not required. If this requirement cannot be met, then structural stormwater storage can be used for the remaining volume not stored in distributed SCMs. As a result, the volume of storage required by the ESD criteria is less than the amount of storage required by the USSC. Given that Trib 109 is predicted to degrade with the greater USSC runoff storage volume, channel instability is expected to be exacerbated under the current ESD regulations.

4.2. Limitations and future research

The calibrated, sequential modeling approach, integrating a watershed-scale SWMM model with a sediment transport HEC-RAS model, was employed to evaluate the effects of alternative SCM design regulations on the stability of urban streams. This combination of SWMM and HEC-RAS enabled the isolation of the impacts of SCM-modified flow regimes on long-term stream stability. However, several limitations in the modeling approach present opportunities for future research.

The design objective in the Erosion Potential (E_p) scenario to match the cumulative sediment transport amount to pre-development conditions was not fully achieved through redesign of the stormwater storage structures, which involved both reducing the size of low-stage outlets and increasing the height of high-stage outlets. To match pre-development sediment transport when the post-development runoff volume is greater than the pre-development runoff volume, requires that flows be maintained below the discharge that mobilizes bed sediment. A diagnostic analysis of the SWMM model results from design storm simulations indicated that the streamflow at the catchment outlet could not be sufficiently reduced by retrofitting the existing SCMs because a significant proportion of the discharge originated from the forested floodplain. Incorporating a storage-based SCM, such as a wetland, within the channel, was able to reduce E_p to 1. However, such an addition would also disrupt sediment delivery to the downstream channel, which could also lead to downstream channel instability. Moreover, the stream has a designated use of IV-P, Recreational Trout Waters and Public Water Supply, as it contains cold-water streams capable of supporting trout, and installation of any inline pond is prohibited to reduce thermal impacts (Maryland Department of the Environment (MDE) 2009). Therefore, the addition of an in-line storage pond was not included in the study.

This failure to meet the E_p scenario design goal might also stem from the set of calibrated parameter values used to simulate runoff from individual subcatchments in the SWMM model of the post-development conditions. Despite good agreement between the simulated and observed flow at the catchment outlet of the calibrated SWMM model (Towsif Khan et al., 2024a), these parameters might not accurately represent field conditions. This issue exemplifies the concept of equifinality, which is often overlooked in spatially discretized models like SWMM. For example, Worthen et al. (2022) conducted a diagnostic analysis of their SWMM model simulations and discovered at least ten different sets of parameter values which yielded similar calibration metrics. All these parameter sets fell within the range suggested by the SWMM manual. Resolving such issues is challenging due to the scarcity of multiple observed runoff datasets across the catchment, a common limitation in small-scale, high-resolution urban hydrologic modeling.

5. Conclusions

This study evaluated the efficacy of alternative stormwater regulations in maintaining channel stability following catchment development. The study demonstrated that while current SCM designs, as per the USSC, can mitigate certain hydrologic changes resulting from urban development, they fall short in maintaining sediment transport and channel stability at pre-development levels. This limitation is attributed to the focus of stormwater regulations exclusively on hydrologic controls, without directly considering the impact of SCM design on bed material transport within the receiving stream. Importantly, the results of this study are specific to the selected study site, which is representative of streams in the Piedmont area of the eastern US and should not be extrapolated to other regions without consideration of local conditions. This research highlights the complex interplay between urban stormwater management and stream channel dynamics, offering insights for future stormwater control policy.

CRediT authorship contribution statement

S. Towsif Khan: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **T. Wynn-Thompson:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **D. Sample:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Data

Data and model files are available from the corresponding author upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT based on the GPT-4o architecture for grammar checking, improving writing clarity, and troubleshooting errors in R code. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Theresa Wynn-Thompson reports financial support was provided by Maryland Department of Natural Resources. David Sample reports financial support was provided by Maryland Department of Natural Resources. Sami Towsif Khan reports financial support was provided by Maryland Department of Natural Resources. Theresa Wynn-Thompson reports financial support was provided by Chesapeake Bay Trust. David Sample reports financial support was provided by Chesapeake Bay Trust. Sami Towsif Khan reports financial support was provided by Chesapeake Bay Trust. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123651.

Data availability

We are in the process of publishing the models on HydroShare and will provide a doi if the paper is accepted for publication.

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