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Effectiveness of stormwater control measures in protecting stream channel stability

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Abstract

While research on the hydrologic impact of different types of stormwater control measures (SCMs) is extensive, little research exists linking urbanization, widespread implementation of SCMs and channel stability in headwater streams. This study evaluated whether the unified stormwater sizing criteria (USSC) regulations in the state of Maryland, USA, which require the use of both end-of-pipe and distributed, small-scale SCMs, protect channel stability. To achieve this goal, a coupled hierarchical modelling approach utilizing the Storm Water Management Model (SWMM) and the Hydrologic Engineering Center River Analysis System 6.3 (HEC-RAS) was developed to predict changes in streamflow and sediment transport dynamics in a first-order gravel-bed, riffle-pool channel. Storm event discretization revealed that 88% of observed storm events during the 16 years (2004–2020) had durations less than 18 h and that the greatest peak flows resulted from storm events with durations less than 24 h. HEC-RAS simulation results also showed that both channel degradation and aggradation, as high as 1.2 m, will likely occur due to regulations which require the use of 24 h duration design storms with a target stormwater detention time rather than bed material sediment transport limits. Overall, this study provides valuable insights into the complex interactions between SCM practises, flow regimes and sediment transport dynamics in heavily urbanized watersheds. It is recommended that SCMs be designed using a continuous simulation model with at least 10 years of continuous rainfall data. Furthermore, to protect channel stability, the SCM design goal should focus on maintaining pre-development sediment transport regimes across a range of flows.

KEYWORDS

channel stability, HEC-RAS, sediment transport, stormwater control measures, SWMM, unified stormwater sizing criteria

1 | INTRODUCTION

In urban areas, stormwater has historically been conveyed away from its point of origin as quickly as possible and discharged into streams, lakes and other downstream waterbodies (National Research Council, 2009). As a result, the natural hydrology, water quality and aquatic habitats of these receiving waters have been degraded with increasing urban development (Walsh et al., 2005). In response to these impacts, stormwater management (SWM) measures were adopted in the United States in the early 1970s (National Research Council, 2009) and have since continued to evolve and take on various names, interpretations and applications across different regions of the United States and worldwide (Grabowski et al., 2022). Given that the proportion of the global population living in urban areas is expected to rise from 55% in 2020 to an estimated 68% by 2050, primarily due to expansion in cities and surrounding urban regions (United Nations Department of Economic and Social Affairs, 2022), there is an ongoing critical need for innovative and sustainable SWM.

One such sustainable SWM method, the unified stormwater sizing criteria (USSC), was developed by the Center for Watershed Studies with the State of Maryland and adopted in Maryland in 2000 (MDE, 2000). Demonstrating considerable success in urban catchments (Hogan et al., 2014), this unified framework to size stormwater control measures (SCMs) for new developments has been subsequently adopted by eight additional US states (Georgia, Iowa, Minnesota, New York, South Carolina, Texas, Vermont and West Virginia). It is important to distinguish between the terms used: 'stormwater management (SWM)' refers to the broader category of strategies and practices implemented to manage runoff, encompassing both structural and non-structural approaches, whereas 'SCMs' specifically denotes the constructed infrastructure designed to detain, treat and manage runoff at specific sites. Central to the USSC is the emphasis on distributed, decentralized SCMs, designed for the detention and treatment of runoff. The USSC also encourages the implementation of non-structural SWM practices, such as cluster development (Brown et al., 1988) and riparian buffer protection (Bhattarai & Parajuli, 2023). Collectively, these practices are also known as low impact development (LID) (Prince George's County (MD), 2000). A key design requirement of USSC is for decentralized SCMs to capture and treat runoff from 90% of the average annual 24 h rainfall, known as the water quality volume (WQ_v) (MDE, 2000). Nested within the WQ_v is the recharge volume, Re_v, the purpose of which is to maintain groundwater recharge rates that existed prior to development. To protect receiving streams from channel erosion, 12 or 24 h extended detention of the runoff generated from a 1 year, 24 h design storm event, called the channel protection volume (Cp_v), is also required. Structural SCMs, such as ponds and wetlands, provide a gradual release of this stored volume with the goal that the pre-development frequency of bankfull discharge in the downstream channel is maintained following development. In some cases, developers may also be required by local jurisdictions to control runoff from the 10 year and 100 year, 24 h design storms and release it at predevelopment rates to reduce the occurrence of out-of-bank flows and extreme flood damage, respectively. Both of these optional peak flow reduction requirements specify the use of the Natural Resources Conservation Service (NRCS), TR-55 Graphical Peak Discharge Method (Natural Resources Conservation Service, 1986), using a 'forest in good hydrologic condition' as the predeveloped site characteristic.

Numerous modelling and monitoring studies conducted in the Mid-Atlantic region of USA have demonstrated the hydrologic effectiveness of USSC in mitigating peak stormflow, increasing baseflow and outperforming traditional end-of-pipe SWM practices (Bhaskar et al., 2016; Hopkins et al., 2020, 2022; Rhea et al., 2015; Sparkman et al., 2017; Woznicki et al., 2018). However, due to gaps in observed data records, these studies primarily analysed cumulative measurements, such as daily, monthly or annual variations in the rainfall-runoff response, rather than focusing on the sub-hourly or sub-daily changes in runoff characteristics. Headwater streams, particularly in urban environments, typically experience changes in streamflow of up to four orders of magnitude within an hour or less after a rain event due to a high connectivity with anthropogenic structures (Bhat et al., 2010; Johnson et al., 2022). Analysis of daily streamflow data can thus significantly overestimate the hydrologic performance of SCMs in attenuating peak streamflow due to information loss in aggregating rainfall-runoff data. The duration of flood hydrographs in small urbanized watersheds can be on the order of hours; thus, flood peaks are minimized when averaged over a day, leading to an incomplete understanding of how well SCMs reduce and attenuate peak flows. Miller et al. (2021) presented findings that cast the hydrologic effectiveness of USSC in a less favourable light compared with the studies mentioned above. However, their results, which indicate a significantly lower efficacy of USSC in attenuation of the hydrograph peak, can be attributed to their focus on rainfall-runoff data from pulse rain events and the fact that their study watersheds had a very high percentage of impervious cover, exceeding 45%.

Hopkins et al. (2020) recently compared hydrologic metrics of a catchment with a high density of infiltration-focused distributed SCMs to a paired catchment with centralized, storage-based SCMs. The authors concluded that the catchment equipped with infiltration SCMs provided higher peak flow attenuation and reduced runoff volume compared with the catchment with traditional centralized SCMs. However, an analysis of the SCMs at the study site revealed that the catchment with distributed SCMs also had multiple centralized SCMs, such as terminal dry ponds with high storage capacities. Moreover, paired catchment studies often use the same rainfall data to represent precipitation metrics, but precipitation patterns often vary significantly across small areas, particularly during intense, convective storms (Cristiano et al., 2017). Given these complexities, evaluating the effectiveness of different types of SCMs at the catchment scale could be facilitated with a model that can predict changes in hydrologic response due to urbanization at higher spatial–temporal resolutions and with explicit representation of SCM configurations for better differentiation of SCM performance (Khan et al., 2020). Considering these intricacies, it is also crucial to note that Li et al. (2017) found that modelling studies often yield more positive results than empirical studies suggesting a need for caution in interpreting such findings.

One of the major SCM design objectives of SWM programmes across the United States is to maintain the stability of receiving stream channels during and following development. However, there is a scarcity of comprehensive research examining the long-term sediment transport dynamics of catchments that incorporate diverse types of SCMs. Traditionally, a stable stream is viewed as one where the flow regime and sediment supply are in a state of quasi-equilibrium over a period of decades or centuries without channel degradation or aggradation (Schumm & Lichty, 1965). Potential changes in channel stability due to urbanization can be assessed using a variety of metrics of geomorphically significant discharges, exceedances of shear stress and/or sediment transport capacity (Doyle et al., 2000; Kermode et al., 2021; Russell et al., 2020). Although these metrics can provide useful insight into the efficacy of SCMs in preserving stream stability, metrics that rely on the calculation of sediment transport capacity assume that the sediment supplied to the channel meets or exceeds the sediment transport capacity (i.e., the channel is transport-limited). However, many urban streams are typically supply-limited (Vietz et al., 2016). Moreover, recent studies have shown that the departure of the threshold discharge for sediment mobilization (Q_c) from theoretical estimates is much higher in urban catchments compared with forested ones (Hawley et al., 2022). Given these challenges, a continuous dynamic sediment transport model calibrated with long-term channel monitoring is needed to accurately characterize the efficacy of SCMs in achieving stream stability.

This study investigates the effectiveness of SCMs in preserving stream stability, with a specific focus on the Maryland USSC. The primary objectives of this study are to evaluate the following two research hypotheses:

1. The combination of distributed, infiltration-focused SCMs and storage-based SCMs to detain peak flows will maintain channel stability.
2. The exclusive reliance on either end-of-pipe, storage-based SCMs or distributed, infiltration-based SCMs will result in channel instability, due to the limited runoff volume reduction capacity of storage-based structures during smaller, more frequent events and the inability of infiltration-based SCMs practices to effectively control large magnitude storm events.

To test these hypotheses, a sequential, hierarchical modelling approach employing a catchment model and a reach-scale sediment transport model was applied at a selected study site that has extensive monitoring by multiple agencies before, during and after development, as documented by Hopkins et al. (2022).

2 | DATA AND METHODS

2.1 | Study site

This study focused on a small, urbanized, headwater catchment (~0.9 km^2) located in Montgomery County, Maryland, USA, within the Piedmont Physiographic Province (Figure 1a). The entire catchment falls within the Clarksburg Special Protection Area (CSPA), a designated area subject to strict development guidelines for the protection of high-quality or unusually sensitive water resources (designated use IV-P, Recreational Trout Waters and Public Water Supply). 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. Serving this development is a high density of SCMs (SCM density is 274 per km^2), built in accordance with the USSC.

Promulgated by the Maryland Department of the Environment (MDE) (MDE, 2000), the USSC regulations require the storage and treatment of both the WQ_v and the Cp_v, typically through a combination of infiltration-enhancing, decentralized SCMs and traditional, end-of-pipe practices, such as detention ponds. SCMs in the catchment were placed in treatment trains where outflows from infiltration measures are directed to ponds. Runoff generated from all impervious areas is routed through a SCM before discharging to the receiving stream. Even though the total imperviousness of the catchment increased from 5% to 38% 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; however, matching of pre-development peak flows was not required.

A 425 m study reach was chosen to simulate sediment transport dynamics in the receiving stream (Figure 1b). The alluvial study reach begins downstream of the culvert under Snowden Farm Parkway and extends to an unnamed tributary just downstream of the United States Geological Survey (USGS) stream gage (station # 01644372 Little Seneca Creek Tributary at Brink, Maryland). The adjacent floodplain is forested, and the channel is not constrained by urban infrastructure within the study reach. Intermittent tributaries to the main channel were replaced with stormwater infrastructure upstream of the riparian buffer during construction, from 2006 to 2017. The study reach has a gravel-bed, riffle-pool morphology with a bed slope of approximately 1.1% and bed material ranging from sand to small boulders. Cross-section measurements in 2005 revealed that the channel in the study reach was unexpectedly wide; the bankfull width of 5.8 m (Williams et al., 2022) is typically seen in rural catchments with drainage areas five times larger than that of Tributary 109 (Mccandless & Everet, 2003).

2.2 | Modelling framework

A watershed-level Stormwater Management Model (SWMM version 5.1.013) (Rossman, 2015) was developed to simulate current (post-2017) hydrologic conditions in the watershed. A total of 70 SCMs were explicitly simulated in the model (26 micro-bioretention cells, 10 infiltration trenches, 5 detention ponds, 11 sand filters and 18 underground storage facilities). Micro-scale SCMs such as rain

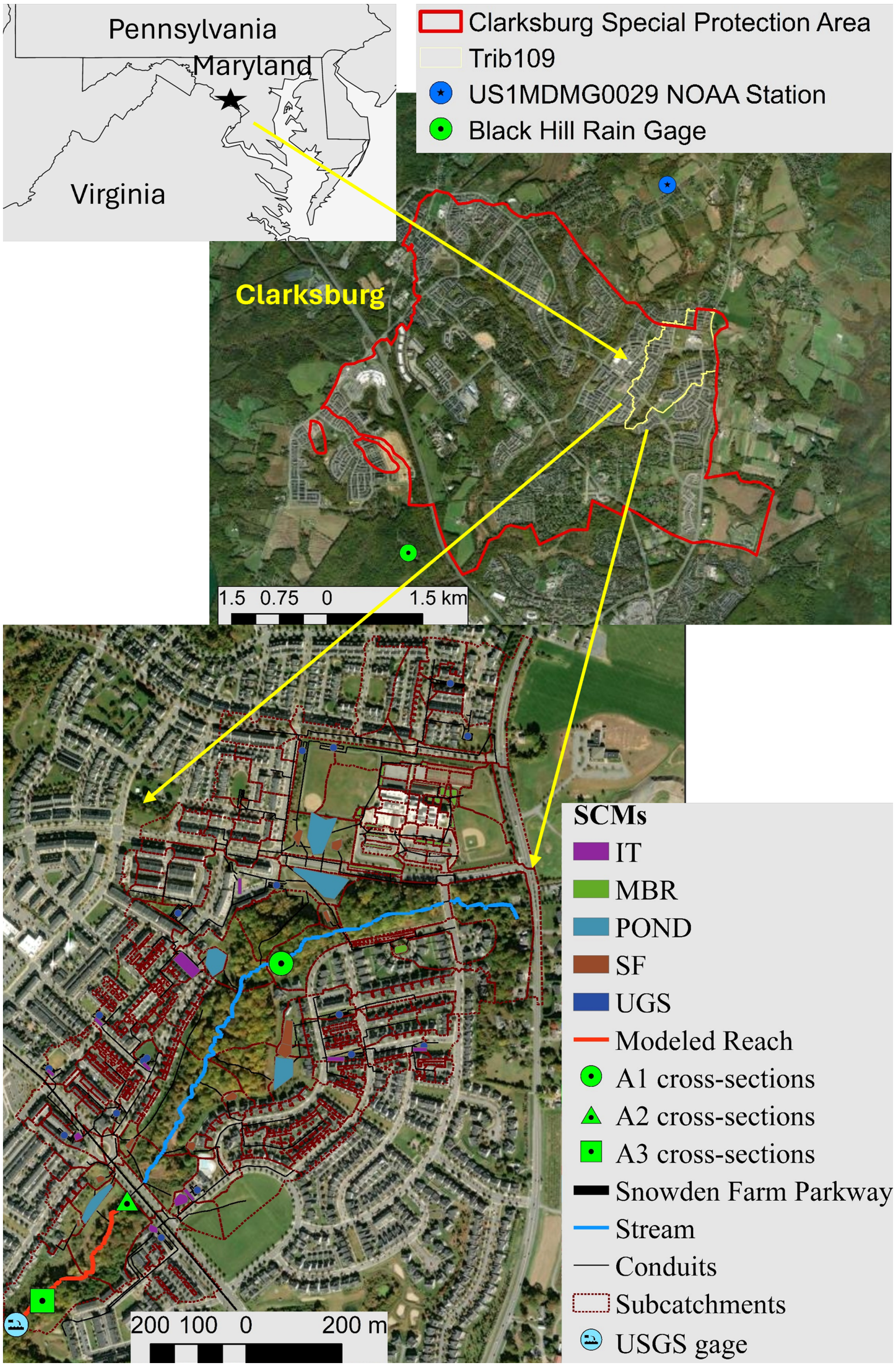

FIGURE 1 Map of (a) location of Tributary 109 site along with the Black Hill rain gauge within the state of Maryland and (b) SWMM model layout. Cross-sections were measured by Montgomery County, MD. IT, infiltration trenches; MBR, micro-bioretention cells; SF, sand filters; UGS, underground storage.

gardens, rain barrels and commercial tree box filters were not simulated to reduce model complexity. Details of the SWMM hydrologic model setup, parametrization and calibration procedures are provided in the supporting information S1 in Data S1. To address the study hypotheses, three additional SWMM models were created by progressively excluding the simulated SCMs from the calibrated model (Table 1). The Ponds SWM scenario model consisted of only the traditional, end-of-pipe SCMs (detention ponds) in the catchment, whereas the distributed SWM scenario model included all of the simulated SCMs except the ponds, representing a SWM scenario where the

TABLE 1 Stormwater management scenario summary.

Scenario name	SCMs simulated in SWMM model
USSC	26 MBR, 10 IT, 5 ED ponds, 11 SF and 18 UGS
Ponds	5 ED ponds
Distributed	26 MBR, 10 IT, 11 SF and 18 UGS
No SCM	No SCMs

Abbreviations: IT, infiltration trenches; MBR, micro-bioretention cells; SCM, stormwater control measures; SF, sand filters; UGS, underground storage.

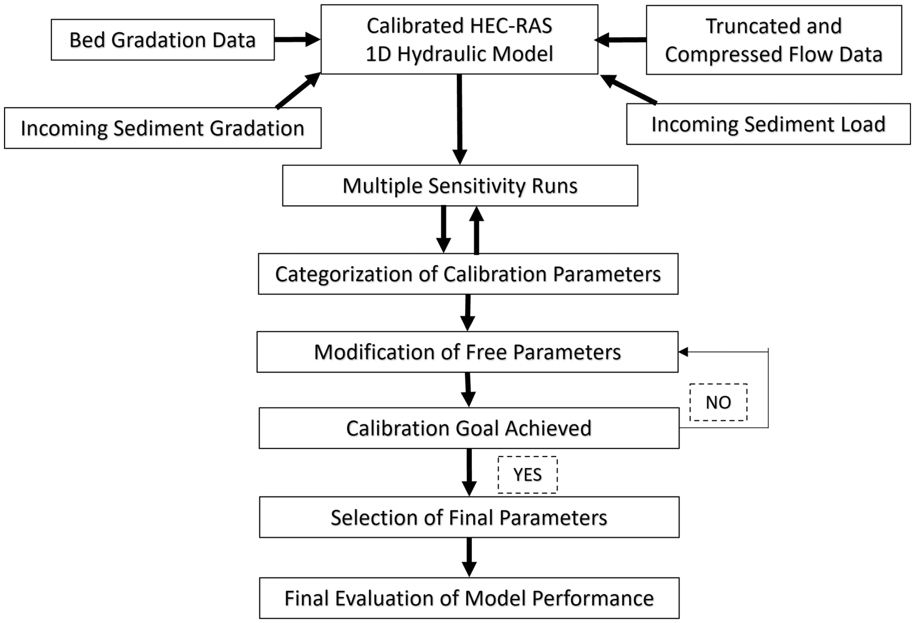

FIGURE 2 Sediment transport model development and calibration framework.

catchment is equipped only with decentralized SCMs. The No SCM SWM scenario had none of the simulated SCMs in the SWMM model and was included for comparison with the SWM scenarios. The calibrated SWMM model (USSC SWM scenario) and the three additional SWMM models were run with 5 min interval local precipitation data obtained from Montgomery County's Black Hill station (Figure 1a), covering the period from water year 2005 to 2020. The resulting 16 year simulated SWMM flow time series at the catchment outfall for the four SWM scenarios were post-processed in *R* to characterize the flow regime (Wickham et al., 2019). Subsequently, the flow data were incorporated into the upstream end of the calibrated sediment transport model after filtering out streamflow values below 0.028 cm (1 cfs). This filtering step was conducted to reduce the computation time of the sediment transport simulations, as bed material transport typically does not occur at low flow rates.

2.3 | Simulating sediment transport

A 1-dimensional (1-D) unsteady hydraulic model of the reach was built utilizing the HEC-RAS version 6.3 to simulate sediment transport dynamics. The channel morphology of the study reach was characterized using cross-section and Lidar-derived 0.91 m digital elevation model (DEM) data collected by Montgomery County, MD (Metes & Jones, 2021). The hydraulic model was calibrated using gage height and discharge data from the USGS streamflow station from water year 2017 to 2020. The calibration effort primarily involved adjusting Manning's roughness to match the water surface elevation at the downstream end of the reach. The roughness factor was calibrated in the fixed channel bed modelling mode before any sediment data were incorporated into the model. Calibration employing an invariant roughness factor did not produce satisfactory results, especially during the high and low stages of storm events. To enhance model performance, a vertical variation of Manning's roughness was implemented to account for a decrease in roughness with increasing flow, which is more suitable for gravel-bed streams (Ferguson, 2010). Following hydraulic calibration, sediment transport was implemented; however, the unsteady sediment transport model failed to provide realistic results, due to model instability that occurred while simulating the highly flashy storm hydrographs (unsteady sediment transport). As a result, the reach was simulated using the quasi-unsteady discharge and sediment transport routines available in HEC-RAS, which produced reliable results based on the calibration goals described later. Sediment model parameterization and calibration are outlined in Figure 2 and described in the following sections.

2.3.1 | Model parameterization

Sediment transport was modelled using the Wilcock and Crowe (2003) method, as the bed material within the study reach is well-graded and contains both sand and gravel. Additionally, since the channel bed is armored, it is best represented with a surface-based transport model such as Wilcock and Crowe. This equation calculates the transport rate of the total bed material load. The active layer method was chosen for the bed mixing method because it is the most appropriate for armoured channels. The thickness of the active layer, which is the top-most layer of the streambed that actively participates in bedload transport (Church & Haschenburger, 2017), is an important parameter in sediment transport modelling because a thinner active layer can significantly reduce the extent of channel degradation. Initially, the minimum and maximum thicknesses were set to 152 mm and three times the channel bed d_{90} (the diameter where 90% of the distribution has a smaller particle size) particle size of 98 mm, respectively, for the entire reach.

The streamflow station located within the reach did not have sediment monitoring data. Therefore, the initial sediment rating curve for the study reach was constructed using suspended sediment discharge data from six nearby USGS streamflow stations in small catchments with urban development (Table 2). These data were collected utilizing continuous turbidity measurements, which were then converted to sediment concentration based on suspended sediment samples from autosamplers. Based on communications with USGS personnel (Porter, 2023), the Teledyne ISCO standard weighted polypropylene intake strainers (9.5 mm i.d., Lincoln, NB, USA) were installed 1–2 m from the streambanks and 6–9 cm above baseflow water level. Because of the small size of the autosampler intakes, sediment sampling was limited to sand-sized (<2 mm) and smaller particles. No bedload transport data were available. Sediment rating curves for each of the six gages were developed using the Sediment Rating Curve Analysis Tool within HEC-RAS version 6.3 (Brunner, 2022), which uses an unbiased power regression method. The sediment load in tonnes/day at 0.028, 1.132, 9.033, 16.991 and 36.811 cm discharges were then estimated for the modelled reach based on the six gage sediment rating curves and the relative channel widths. The median of these values was used to construct the initial total sediment load rating curve for the study reach. Because these values only represent the incoming mass of small sediment particles, this initial sediment rating curve was adjusted during model calibration. The 0.028 cm value was included in the sediment rating curve to improve model stability during calibration, whereas the 1.132 cm discharge was included based on field observations by USGS personnel that gravels on the channel bed were mobile at flows of 1.132 cm. The maximum discharge in the observed post-construction record was 9.033 cm, whereas the 16.991 and 36.881 cm discharges were selected to bracket the maximum peak discharges for the USSC and No SCM SWM scenarios.

Because the largest flood that occurred during the calibration period (2017–2020) had a peak discharge of 9.033 cm, the sediment rating curve beyond 9.033 cm was unknown. In the Maryland Piedmont region, it is common for streams to be supply-limited. To simulate this sediment exhaustion condition during large floods, a second rating curve was constructed, assuming the sediment loads at 16.991 and 36.881 cm were the minimum of the measured loads from the six USGS gages. The initial sediment rating curve without sediment exhaustion was assigned based on the median of the measured loads. The final calibrated sediment rating curves are provided in Figure S1 in the supporting information S2 (Data S1).

To estimate the particle size distribution of the incoming sediment load, bulk subsurface sediment samples were collected from the reach, sieved and weighed. Sediment particles smaller than 0.0625 mm (very fine sand) were not included in the sediment transport model as silt and clay particles are easily entrained and thus have minimal influence on channel stability. The measured subsurface bed gradation was used for the incoming load gradation at a streamflow of 1.132 cm. While little bed sediment transport occurs at low flows, 0.028 cm was included in the sediment load rating curves to improve model calibration and assigned only highly mobile, sand-size fractions. The calibrated incoming sediment load gradation is shown in Figure S2 in the supporting information (Data S1).

2.3.2 | Model calibration

Montgomery County measured one pool and one riffle cross-section, as well as bed surface particle size distributions, annually at three locations along the stream between 2005 and 2017 (locations A1–A3 in Figure 1a). Locations A2 and A3 are in the modelled reach. In 2017, a stream restoration project was completed in the upper third of the modelled reach, just downstream of Snowden Farm Parkway (Williams et al., 2022) (Figure 1b). Following the stream restoration project, only locations A1 and A3 were measured during the period 2018–2021. The stream restoration project was not included in the HEC-RAS model because the project significantly altered the channel geometry and bed materials in that reach.

Due to catchment development, both the catchment hydrology and channel morphology changed (Hopkins et al., 2022). Several measured cross-sections showed signs of aggradation during construction, followed by 0.3–0.6 m of degradation post-construction (Williams et al., 2022). To represent the final built conditions in the catchment, the sediment transport model was calibrated using cross-section data at location A3 from water year 2017 to 2020 and field observations of reach-level changes during the study period (Figure S3). Based on these observations, the following primary goals for the sediment transport calibration process were established: (1) overall sediment mass balance must indicate that the volume of sediment leaving the system should be higher than the incoming sediment at the end of the simulation time period (2017–2020); (2) change in invert elevation should not exceed 0.3–0.6 m; and, the reach bed material size (d_{50}, d_{90}) should increase over the simulation time. The

TABLE 2 United States Geological Survey gauges used in the sediment rating curve development.

USGS gage ID	DA (km^2)	Physiographic Province	Distance from study site (km)	% Imprv	Maximum observed flow (cm)
01646305	5.31	Piedmont	31.0	17.6	10.96
01656903	10.88	Piedmont	39.9	24.6	173.02
01654500	9.63	Piedmont	31.7	14.5	22.03
01645762	7.02	Piedmont	38.0	4.8	35.96
01585075	4.74	Coastal Plain	31.4	12.1	2.52
01589290	8.37	Piedmont	81.0	22.2	8.27

Abbreviations: DA, drainage area; Imprv, imperviousness.

1-D sediment transport model in HEC-RAS is a decadal-scale model and is more robust when used for more than 10 years of calibration and projections. Since a 10 year observed post-construction flow record was unavailable for our study site, the performance of the calibrated model was tested by incorporating the 16 year flow time series from the SWMM hydrologic model for the USSC scenario into the sediment transport/hydraulic/geomorphic model, which achieved the three aforementioned primary calibration goals.

Unlike hydraulic calibration which typically has one calibration parameter (roughness), sediment transport calibration has multiple parameters which can be modified to obtain the expected calibration outcome. Modification of multiple sets of model parameters simultaneously can result in similar calibration outcomes—this phenomenon is called 'equifinality'—a challenge often faced by hydrologic modellers while performing multi-parameter calibration (Beven & Freer, 2001) . To overcome this challenge, a subset of calibration parameters, known as 'free parameters' was isolated to modify while the rest of the parameters were kept fixed throughout the calibration process. These selections were made based on multiple model sensitivity runs, field observations and the HEC-RAS technical reference manual (Brunner, 2022). The categorization of the sediment transport parameters based on these assessments is summarized in Table 3. The free parameters were modified to obtain the calibration goals.

Sediment mass balance and channel profile results of multiple exploratory HEC-RAS model runs with the measured discharge from water years 2017 to 2020 revealed that the simulated bed change was sensitive to incoming sediment load and gradation. Because the maximum measured discharge post-development was 9.31 cm, the calibration sediment rating curve only had sediment loads defined at 0.02, 1.12 and 9.31 cm. In addition to calibrating the sediment rating curve and incoming load gradations, the critical mobility scaling factor (CMSF) was increased sequentially until gravels were mobile only for discharges of 1.13 cm (40 cfs) and greater. The final value of the CMSF was 3.0, which increased the reference shear stress of the Wilcock–Crowe equation. Several studies have concluded that due to the wide range of shear stresses at which gravel-beds become mobile, sediment transport modellers should place more emphasis on choosing a value suitable for the site rather than using a universal value when accurate field measurements of bed load transport are unavailable (Gaeuman et al., 2009; Lamb et al., 2008; Mueller et al., 2005).

TABLE 3 Summary of calibration parameters.

	Sensitivity	
Uncertainty	**Low**	**High**
Low	Incoming flow Bed mixing algorithm	Transport function *Incoming sediment gradation* *Movable bed limits* Bed gradation
High	Fall velocity Active layer thickness	*Incoming sediment load* *Transport function scaling factor*

Note: Free parameters are italicized.

2.4 | Evaluation of simulated flow regime

To compare the simulated stream flows for the SWM scenarios for storm events of varying magnitude and duration, the 16 yearlong rainfall and simulated flow time series were analysed to delineate storm events with a rainfall depth greater than 2.54 mm and an inter-event time greater than or equal to 6 h (Liu et al., 2014). Peak flow magnitude was then extracted from each delineated storm hydrograph. To identify storm events with similar magnitude and duration, storms were discretized into bins based on the rainfall depths of design storms of Maryland (MDE, 2000) and durations in multiples of 2 h, similar to the methods adapted by Amur et al. (2022). The median peak flow within each bin was compared across the different SWM scenarios.

2.5 | Analysis of sediment output results

To evaluate the effects of each SWM scenario on sediment transport dynamics and channel morphology, continuous time series of cross-section shape, longitudinal bed profile and sediment transport rate were exported from the HEC-RAS HDF output files to *R* (Wickham et al., 2019). To quantify and compare changes in channel morphology across the scenarios, two indices were calculated from cross-section data for each of the non-interpolated model river stations (RSs), change in cross-sectional area and change in invert elevation. Channel width in 1-D HEC-RAS does not change over time unless the extent of channel degradation is so high that the final channel invert has reached the bottom of the sediment control volume (typically set at the elevation of a resistant layer such as bedrock). Although multiple RSs did erode to bedrock, channel width did not change. A Shapiro–Wilk test (Shapiro & Wilk, 1965) was performed and showed evidence of non-normality, so a non-parametric paired two-sample test (Rey & Neuhäuser, 2011) was conducted to evaluate statistically significant differences in channel geometry among the SWM scenarios.

In addition to the two indices of channel change, two geomorphically significant discharges were characterized, as described by Doyle et al. (2000), Plumb et al. (2017) and Sholtes and Bledsoe (2016). Effective discharge (Q_{eff}) is defined as the flow that transports the most sediment over long periods of time and was calculated following the methods of Biedenharn et al. (2000) using the time series of water and sediment discharge from HEC-RAS at the cross-section with the least amount of invert elevation change over the simulation time period. Half-yield discharge (Q_{hf}) is defined as the discharge that transports half of the total sediment load over the entire simulation period and was calculated using the method employed by Sholtes and Bledsoe (2016).

The recurrence interval (RI) of these two indicator discharges was then extracted from a flood frequency analysis (FFA) performed using a partial duration series (PDS). Several techniques have been adopted by past studies for the threshold selection for generating PDS; these techniques include graphical, field and analytical methods (Pan et al., 2022). Because of the complexities and limitations associated with each of these methods and the absence of any established method for constructing PDS data, a peak flow threshold was defined for each SWM scenario which resulted in at least five independent flood peaks per year. An automated procedure was developed in *R* to select these peak flows by first identifying flood peaks from the continuous flow time series with a between-flood interval of at least 7 days. Then, a threshold was selected that resulted in approximately five peak flows per year. Several probability distributions were tested to obtain the peak flow and RI relationship. The generalized Pareto (GP) distributions were found to be superior based on the Kolmogorov Smirnov and chi-squared goodness-of-fit tests (Massey, 1951).

3 | RESULTS

Annual rainfall during the simulation period (water years 2005–2020) ranged from 1050 to 1655 mm at the Black Hill rain gauge. Two years (2013 and 2014) experienced annual rainfall totals as much as 37% higher than the National Oceanographic and Atmospheric Administration (NOAA) climate normals (1991–2020) of 1206 mm at the US1MDMG0029 station, situated 3.05 km from the watershed (Figure S4). As described in more detail in the Data S1, the SWMM model demonstrated good overall agreement with observed data, based on model performance evaluation criteria recommended by Moriasi et al. (2015) (Table S2). However, the model overpredicted the maximum flow during both the calibration (2019) and validation period (2020) by 23% and 5%, respectively (see Data S1).

3.1 | Storm event analysis

A total of 1141 storm events were recorded at the Black Hills rain gauge during the study period. The recorded storm events exhibited diverse characteristics, with storm durations and rainfall depths of up to 80 h and 205 mm (8.08 in), respectively (Figure 3). The average and 5 min peak rainfall intensities of the delineated storm events were as high as 112 and 173 mm/h, respectively. Approximately 81% of the storm events had a rainfall total less than or equal to 25.4 mm (1 inch) and the median storm duration was 4 h. These findings highlight that sizing decentralized SCMs to accommodate the runoff from small (<25.4 mm (~1 inch)) storm events, also known as the 'water quality volume' (WQ_v), will provide runoff volume reduction for the majority of storm events.

For storm events with rainfall equal to or less than 25.4 mm (~1 inch), the distributed and ponds scenarios exhibited median increases in peak flow of approximately 125% and 250%, respectively, compared with the USSC scenario (Figure 4). The difference in peak flows arises from the fact that, in the distributed SWM scenario, runoff is

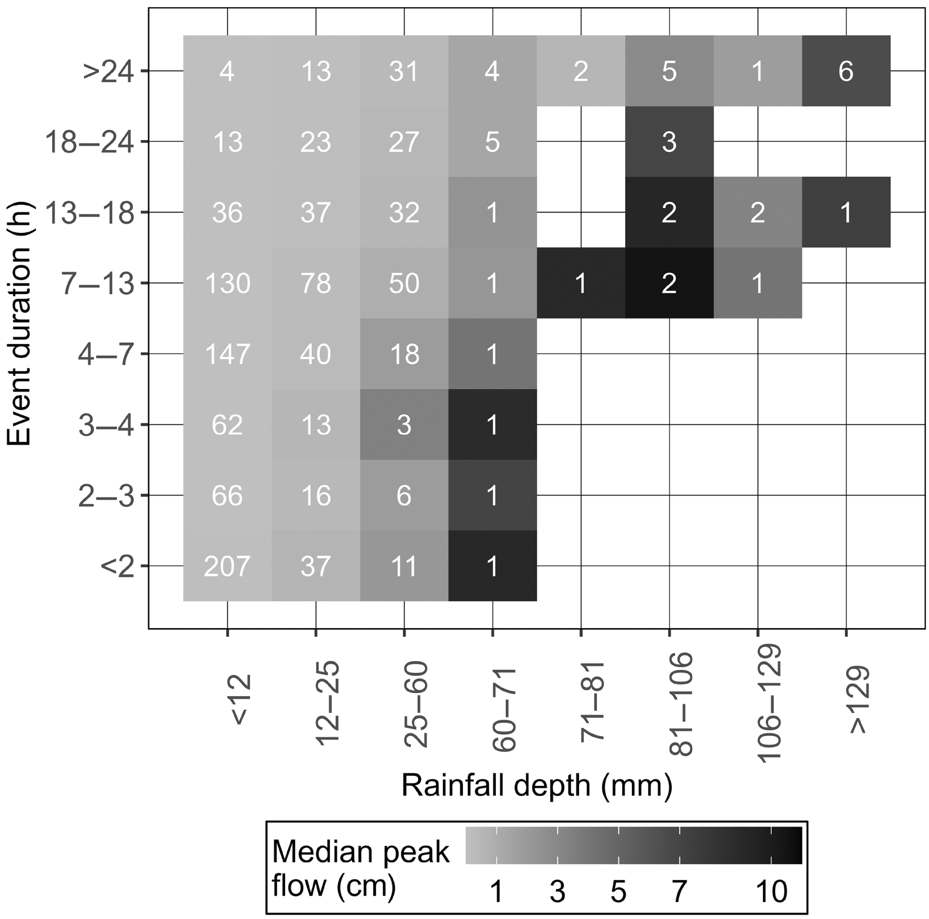

FIGURE 3 Number of storm events within the range of rainfall depth and duration. The shading indicates the median catchment discharge for the unified stormwater sizing criteria (USSC) scenario.

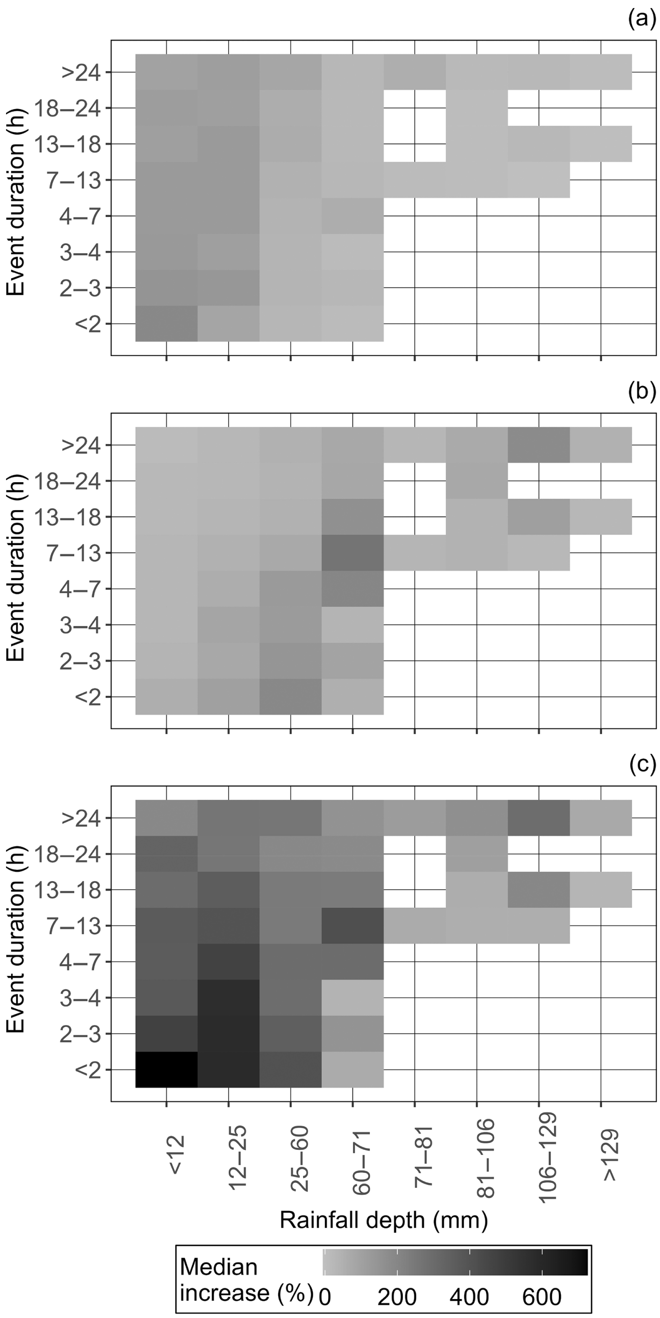

FIGURE 4 The median percent increase in peak flow of the (a) ponds, (b) distributed and (c) No SCM scenarios, as compared with the USSC scenario. SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

stored and infiltrated within the decentralized, infiltration-based SCMs before excess runoff is routed to the stormwater conveyance system. In contrast, the end-of-pipe ponds are not designed with infiltration capabilities and instead have low-flow orifices (low-stage outlets) designed to meet the Cp_v requirements, resulting in the generation of elevated peak flow at the catchment outlet even during small storm events compared with the USSC scenario. In comparison, the No SCM scenario had a median increase in peak flow of 600% relative to the USSC scenario due to runoff being immediately directed to the stormwater conveyance system once the rainfall rate exceeded the infiltration capacities of the local soil. The No SCM scenario demonstrates the effectiveness of USSC regulations in mitigating peak discharges from urbanized areas, particularly from frequent, smaller storms.

A 66 mm (2.6 inches), 24 h storm event is used to size the pond low-stage outlet structure to provide 12 h extended detention of the runoff, as per the Maryland requirements for use III/IV waters, with no outflow from the high-stage outlet structure (MDE, 2000). An examination of recorded storm events with depths ranging from 60 to 71 mm revealed a wide range of durations, with five events falling within the 18–24 h range and four events exceeding the 24 h duration (Figure 3). The resulting peak flows at the catchment outlet for the USSC scenario corresponding to these nine storm events ranged from 0.7 to 9 cm, with peak flows increasing as the event duration decreased and rainfall intensity increased. A similar trend of increasing peak flows with decreasing event duration (increasing intensity) was observed for the USSC scenario for storm events with rainfall depths greater than 71 mm (Figure 3). These results show that the greatest peak flows in heavily urbanized areas, even from catchments equipped with widespread implementation of SCMs, occur for storm events with durations less than 24 h.

Comparison of the simulated results between the distributed and ponds scenarios and the USSC scenario revealed that the median increase in peak flow for storm events with rainfall depths greater than 25.4 mm (1 inch) was greater for the distributed scenario than for the ponds scenario (Figure 4). Median peak discharges of the distributed scenario for these storm events increased by 57% over the USSC scenario, compared with increases of 37% for the ponds scenario ($U = 1836$, $p < 0.001$). This outcome was expected since the SCMs in the distributed scenario were only designed to store runoff from the first 25.4 mm of rainfall, with any overflow bypassing the SCM. Median increases in peak flows when no SCMs were present were as high as 200%. Given that SWM systems are designed to treat more frequent rainfall events (MDE, 2000), it is expected that the effectiveness of these systems will decrease as storm depth and/or intensity increase.

3.2 | Sediment model calibration results

Given the simplifications that occur with a 1-D model and the limited accuracy of sediment transport models, the calibrated model was not expected to exactly replicate the measured change in channel cross-sections; however, the model was successful in replicating the range of invert changes within the reach for the observed timespan of 2017–2020. It is evident from channel profile results that around RS 148 and 537 the channel bed is actively degrading, which replicates observed changes in the channel bed (Figure 5).

The change in channel invert and bed material d_{50} and d_{90} of six RS from the upper, middle and lower sections of the reach throughout the calibration period are shown in Figure 6. It should be noted that the horizontal axis, which denotes the time, only corresponds to those

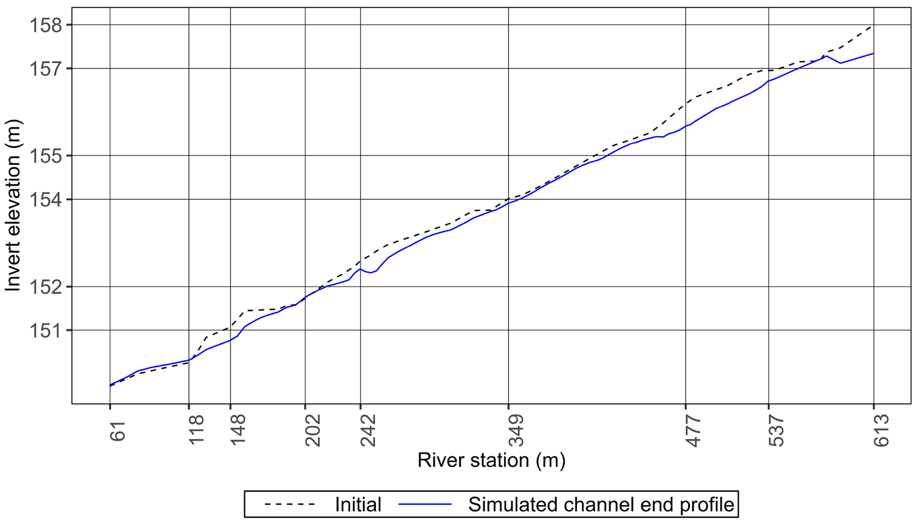

FIGURE 5 Initial and final channel bed profiles during the calibration period (2017–2020).

time steps when the incoming stream discharge was greater than 0.028 cm (1 cfs), which was used as an input to the model. The time series of invert change (total change in the invert since the beginning of the simulation) (Figure 6b) shows the dynamics of the channel bed as the bed scours on the rising limb of the hydrograph at four of the six RSs and then fills as the flood flows recede. For these RSs, the change in bed material gradation reveals that the bed material is coarsening and becoming armored over time. Field observations of loose cobbles on the surface of alternate bars indicate that bed material with a diameter of at least 64 mm is mobilized. At RS 242 and 537, finer sediment is delivered from upstream on the rising limb of the hydrograph, and then is scoured on the falling limb (Figure 6c,d).

3.3 | Predicted long-term changes in the channel profile

Even with the installation of more than 70 SCMs to meet USSC requirements, it is predicted that over the 16 year simulation period, the initial post-development channel degradation observed along Tributary 109 will continue (Figure 7). The overall bed profile for the USSC scenario shows a decrease in bed slope due to a combination of channel degradation and downstream aggradation, indicating the channel is adjusting to the increased runoff from development in the watershed, even with end-of-pipe and distributed SCMs. Immediately downstream of RS 242, the channel narrows, causing backwater effects around RS 242, a reduction in sediment transport potential and deposition of coarse bed material mobilized from the upper section of the reach. The bed coarsens at RS 242 (both d_{50} and d_{90} increase in size) due to the deposition of large clasts, creating a steep riffle at this location (Figure S5b–d). Downstream of RS 242, the channel incises. In the most downstream section, the channel bed erodes to bedrock (estimated as 0.91 m below the initial channel invert elevation, Figure 7), and a knickpoint develops at the downstream end of the reach and migrates upstream over time. It is anticipated that the channel will continue to degrade as this knickpoint migrates upstream over time. Similar channel dynamics were predicted with and without sediment exhaustion at discharges greater than 9.303 cm for the USSC scenario.

Comparison of the final channel profiles in Figure 7 shows that, whereas USSC does not protect channel stability, these stormwater regulations slow down the channel degradation resulting from urbanization without stormwater controls. The central tendency of two indices characterizing the change in channel morphology, channel invert elevation and cross-sectional area, were statistically similar across the SWM scenarios ($\alpha = 0.05$), largely because sediment eroded from one RS was deposited downstream (Figure 8). However, the ranges of changes in invert elevation increased as SCMs were removed from the watershed simulations (USSC = 1.38 m, ponds = 1.66 m, distributed = 1.76 m, No SCM = 2.22 m). For instance, removal of all SCMs from the watershed resulted in 35% of the RSs experiencing either bed degradation or aggradation of at least 0.75 m, whereas in the USSC scenario, the extent of bed change for 75% of the RSs remained within the range of ± 0.5 m (Figure 8a).

3.4 | Impact of SWM on sediment transport dynamics

Channel stability occurs when the incoming sediment load and the sediment transport through the reach are generally balanced or when the channel boundary is resistant to erosion. Sediment transport dynamics of urban gravel-bed streams are influenced not only by variations in flow regimes but also by local sediment supply factors (Downs & Soar, 2021). The modelled incoming sediment load is set by the sediment load rating curve and associated gradation (Figures S1 and S2 of supporting information S2 in Data S1) and is a function of the number, magnitude and duration of flood events. The sediment yield refers to the amount of sediment exported from the downstream end of the reach over the simulation time period. The sediment transport within the reach computed by the model is complex and is influenced by several factors. For instance, the size and

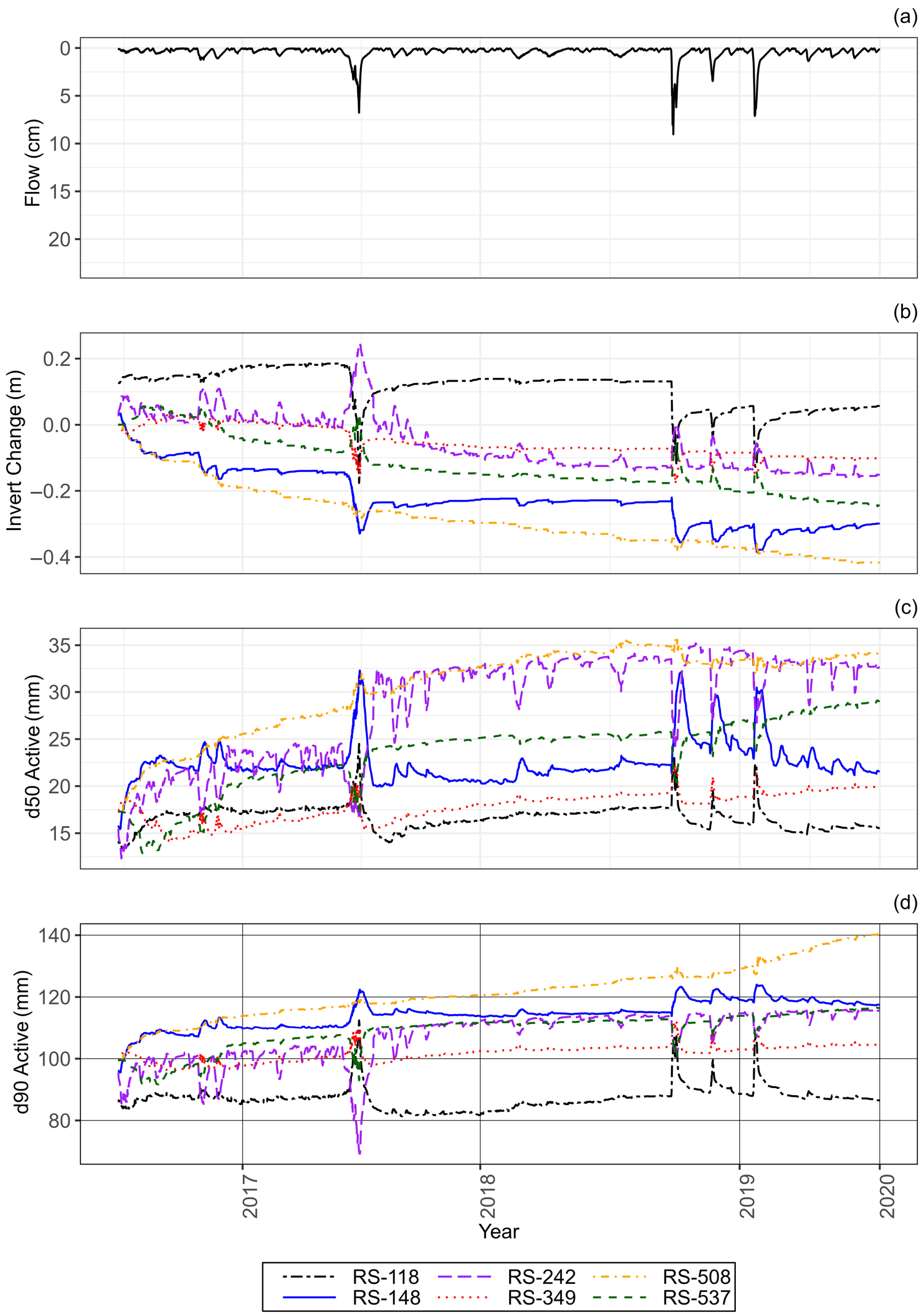

FIGURE 6 Time series of (a) flow; (b) invert change; (c) bed material d50; and, (d) bed material d90 during the calibration period, 2017–2020. The time refers to model time, which only includes stream discharges greater than 0.028 cm. RS, river station.

composition of the sediment within the channel, the stream gradient, and the channel width all influence the sediment transport potential of the individual model RSs.

To illustrate differences in flow and sediment dynamics among the four scenarios, the flow volume input to the HEC-RAS model, total incoming sediment load and total sediment yield for three distinct flow ranges are presented in Figure 9. These flow ranges represent the lowest discharge input to the HEC-RAS model (0.02 cm), the flow at which gravel is mobile (1.13 cm) and flow value at which the water surface elevation reaches the floodplain during the start of simulation for 50% of the RSs (5.89 cm). Although the greatest volume of flow into the reach over the simulation period occurs at discharges less than 1.13 cm, most of the sediment delivery into the reach occurs during flows over 5.89 cm. These two flow ranges have significant impacts on sediment delivery and transport. For instance, despite the total flow volume in the ponds scenario exceeding that in the distributed scenario, the proportion of flow volumes at discharges greater than 5.89 cm is greater in the distributed scenario. As a result, the distributed scenario has a greater incoming sediment load compared with the ponds scenario. Additionally, the non-linear nature of the sediment rating curve leads to a striking difference in the sediment load increase between the No SCM scenario and the USSC scenario, with only a 16% increase in total flow volume resulting in an almost 200% increase in sediment load, due to the increased frequency of discharges greater than 5.89 cm.

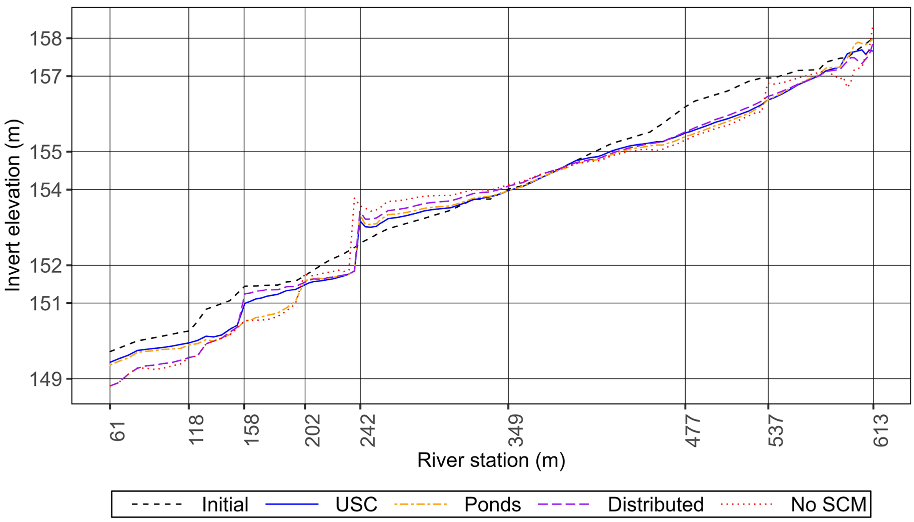

FIGURE 7 Predicted channel longitudinal profile after 16 years under different stormwater management (SWM) scenarios. SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

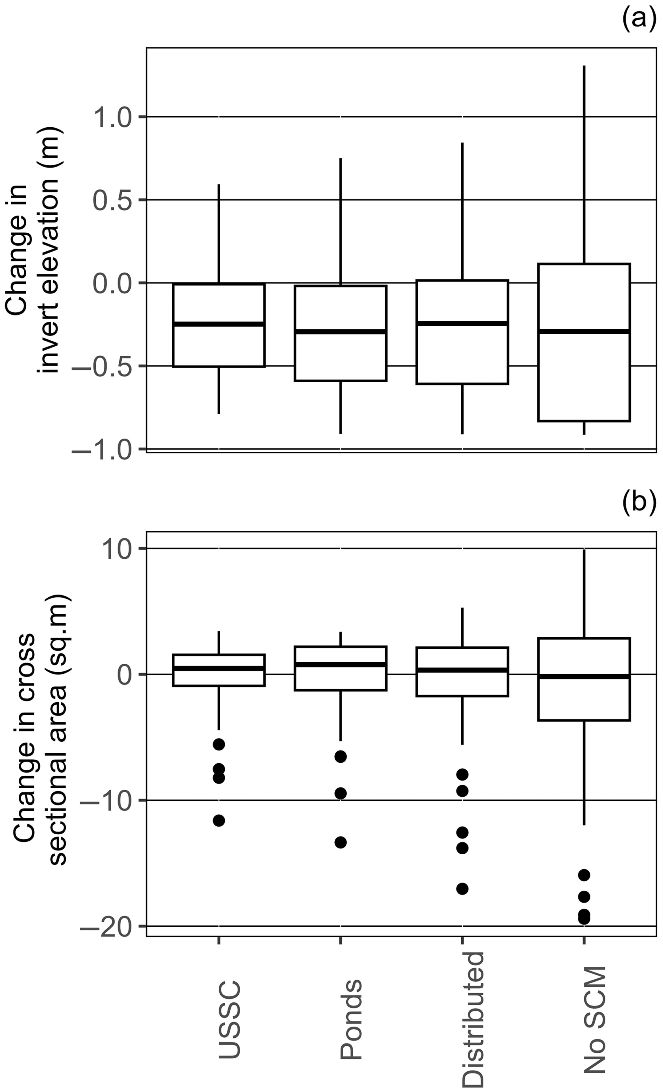

FIGURE 8 Distribution of (a) change in invert elevation; and (b) change in cross-sectional area of modelled river stations for different stormwater management scenarios. SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

Even though there are noticeable differences in incoming sediment load across the different SWM scenarios compared with the USSC scenario, the total sediment yield is similar among the scenarios and is largely occurring at discharges less than 5.89 cm, when the flow is primarily contained within the main channel. Reduced sediment yield occurs at discharges that access the floodplain, indicating that significant sediment storage is occurring on the floodplain. This finding aligns with Trimble's (2009) study on the Coon Creek catchment in Wisconsin, which reported that sediment yield can be very low relative to the incoming sediment load if there is significant floodplain storage. The amount of sediment deposited on the floodplain is likely over-estimated by HEC-RAS, due to the use of the 'veneer' option for floodplain deposition. With this option it is assumed that sediment is deposited evenly across the floodplain and the size distribution of the deposited sediment is the same as that transported in the main channel. These assumptions typically lead to an over-estimation of floodplain sediment storage (Brunner, 2022).

Because of increased flashiness and smaller storm event durations, urban streams typically become unable to transport the larger particles being delivered into the reach during high flow events (Plumb et al., 2017). This phenomenon leads to net deposition in the reach, irrespective of the extent of SCM utilization. This effect is particularly pronounced in Trib 109 given the unusually wide channel. For example, at RS 242, which corresponds to the location of a steep riffle, there was a notable increase in the proportion of boulder-sized particles (larger than 512 mm), rising from 1% to nearly 13%. This increase is attributed to the mobilization of larger bed particles from the upstream portion of the reach.

3.5 | Changes in geomorphically significant flows

Effective (Q_{eff}) and half-yield (Q_{hf}) discharge were obtained from the paired flow and sediment yield time series at the most stable RSs for each of the SWM scenarios (RS 359 for USSC, RS 579 for ponds, RS 391 for distributed and No SCM scenarios). Even though the effective

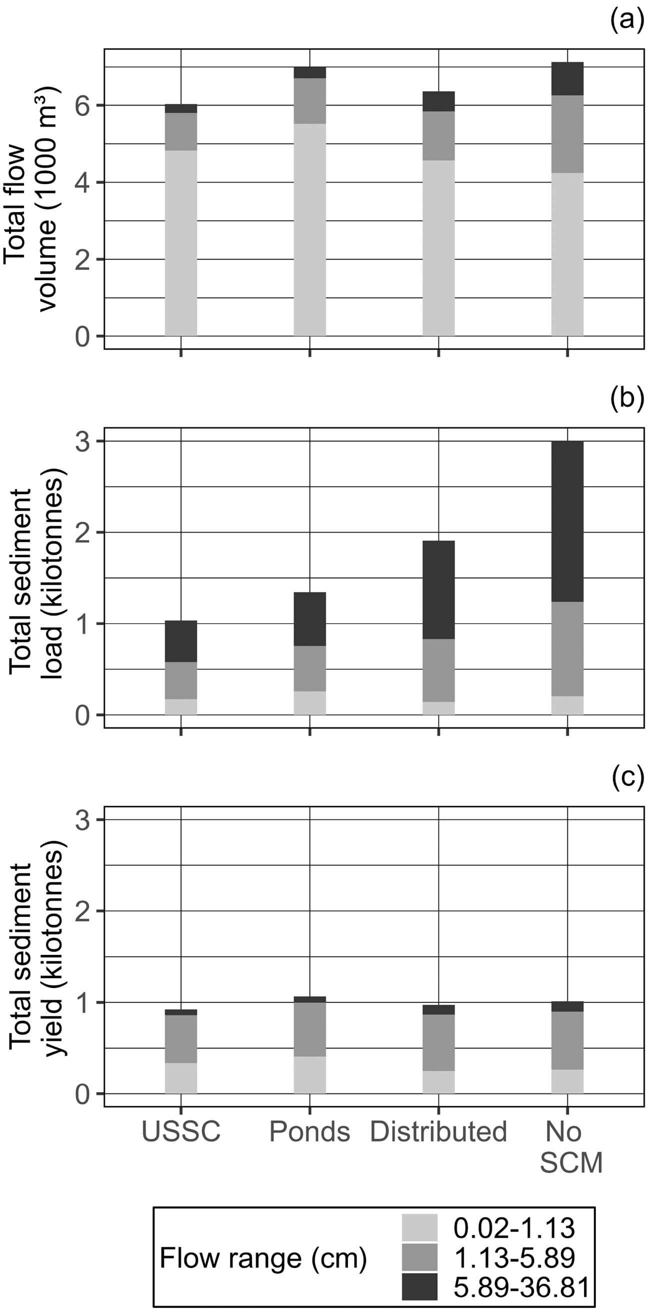

FIGURE 9 Incoming (a) flow volume input to the HEC-RAS model, (b) sediment load and (c) outgoing sediment yield, as a function of stream flow classes. Discharge cutoffs at 1.13 cm and 5.89 cm are discharges at which gravels become mobile and flow accesses the floodplain, respectively. SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

discharge for the USSC and ponds scenarios was similar (Table 4), there was a change in effective discharge and sediment yield-discharge histograms (Figure 10) for the distributed and No SCM scenarios, as compared to the USSC and ponds scenarios. The omission of terminal ponds results (distributed and No SCM scenario) in heavier tails in the sediment yield-discharge histograms, particularly in the higher flow classes, leading to higher Q_{eff} and Q_{hf}, as compared with the USSC and ponds scenarios. Without stormwater ponds to control higher magnitude storm events, there is an increase in the number of intermediate to high magnitude flows, causing sediment transport to be impacted by both infrequent, high-magnitude events and frequent, low-magnitude floods. The similar shape of the sediment yield-discharge histogram for the USSC and ponds scenarios also shows that even though the removal of distributed SCMs in the ponds scenario caused an increase in the peak flows resulting from storm events with a rainfall depth less than 25.4 mm (Figure 7), the increase in geomorphic work for these small events is negligible.

4 | DISCUSSION

4.1 | A combination of distributed and end-of-pipe SCMs does not maintain channel stability

A coupled, hierarchical modelling approach was employed to evaluate the effectiveness of multiple SCM configurations in maintaining stream stability over a decadal scale. We hypothesized that an urbanized catchment equipped with a combination of distributed and end-of-pipe SCMs, designed according to the USSC requirements, would maintain the stability of the receiving stream. However, results from the 16 year sediment transport analysis show that both channel degradation and aggradation, as high as 1.2 m, could occur even with 100% treatment of watershed impervious areas (Figure 8). This model result is supported by repeated cross-section measurements by Montgomery County which documented an increase in channel depth of nearly 0.31 m within just 4 years following the development of the catchment area (Williams et al., 2022). Although the implementation of SCMs as per USSC slowed the extent of channel change along the study reach when compared with the No SCM scenario (Figure 7), it is predicted the study reach will ultimately be degraded by the urbanization of the upstream watershed (Figures 7–9). This model prediction is confirmed by field observations of increased pool depth and reduced riffle length in the study reach.

The USSC specifies the use of a 24 h design storm duration. However, rainfall-runoff analysis (Figure 3) showed that 88% of the recorded storm events had durations less than 18 h and that the greatest peak flows resulted from storm events with durations less than 24 h. Runoff from these shorter duration events quickly exceeded the infiltration rates of the distributed SCMs and the storage capacity of the terminal storage ponds, resulting in higher peak flows and increased sediment transport, particularly for flows contained within the main channel. Storm event based rainfall-runoff analysis by Amur et al. (2022) also showed that observed hyetographs often have multiple peaks and higher mean intensity than design storms.

The theoretical basis of the channel protection volume in the USSC is that providing extended detention of the channel forming flow (approximated as the runoff from the 1 year RI storm event) will protect channel stability (MDE, 2000). However, the key to

TABLE 4 Values of geomorphically significant flows.

Flow value (cm)	USSC	Ponds	Distributed	No SCM
Effective discharge, Q_{eff}, cm (Recurrence interval, year)	0.63 (0.26)	0.63 (0.24)	0.77 (0.22)	1.92 (0.20)
Half-yield discharge, Q_{hf}, cm (Recurrence interval, year)	1.49 (0.31)	1.66 (0.29)	2.77 (0.29)	3.09 (0.22)

Note: The discharge recurrence interval is indicated in parenthesis for different stormwater management scenarios derived from flood frequency analysis using a partial duration series.
Abbreviation: SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

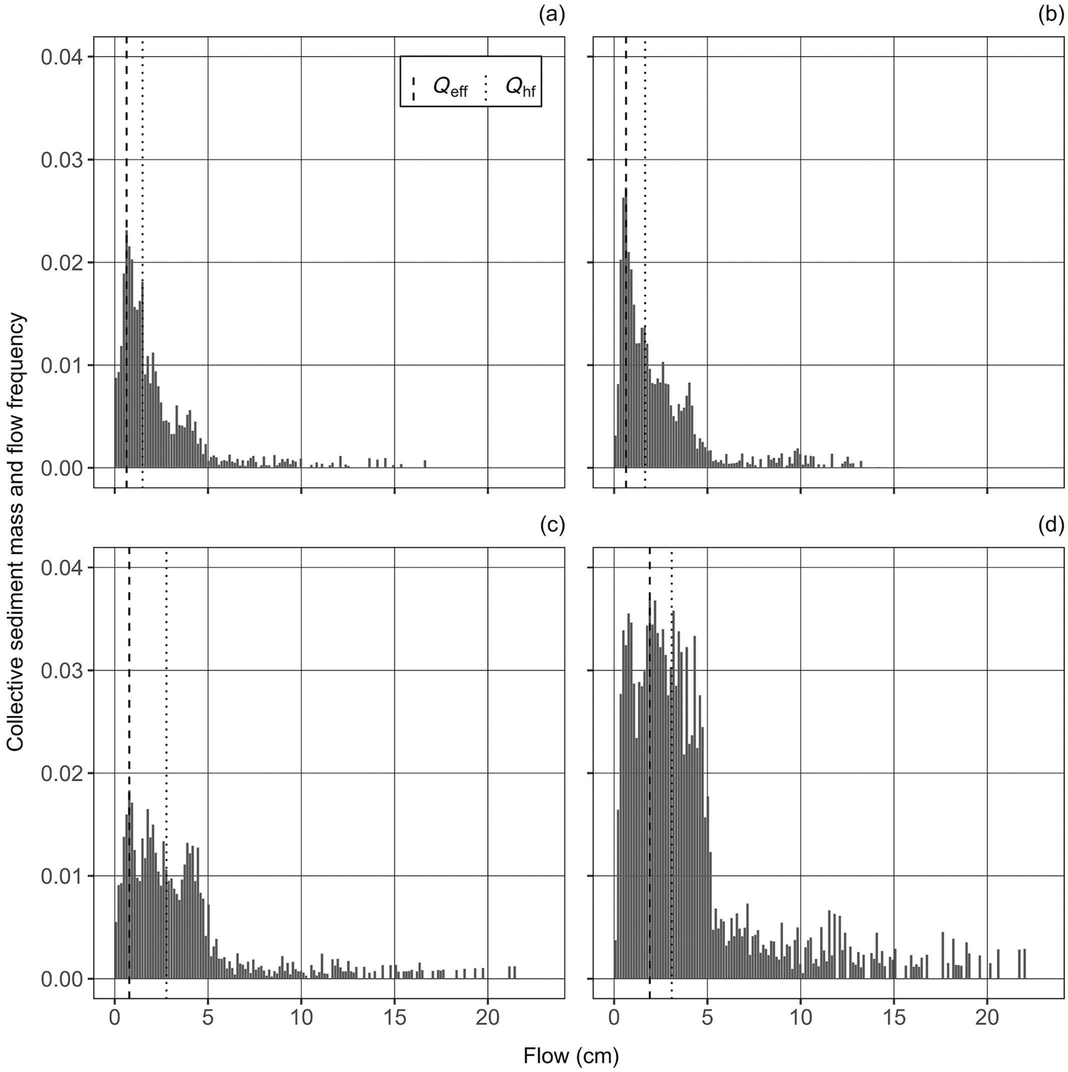

FIGURE 10 Total sediment yield-discharge histogram for (a) USSC; (b) Ponds; (c) Distributed; and, (d) No SCM scenario along with half-yield (Q_{hf}) and effective (Q_{eff}) discharges indicated by vertical lines. SCM, stormwater control measures; USSC, unified stormwater sizing criteria.

maintaining channel stability under an urbanized flow regime is balancing the sediment transport capacity of the channel with the coarse sediment supplied from the watershed (McCuen & Moglen, 1988). Even after reducing the peak flow magnitude SCMs can extend the duration of intermediate flows which are well above the transport threshold. The stability of urban gravel-bed streams is influenced not only by variations in flow regimes but also by the caliper of the local bed sediment, as well as the size and quantity of coarse sediment supplied from the watershed.

4.2 | Exclusive reliance on infiltration or storage-based SCMs worsens stability

Our analysis of storm event delineation and discretization, focused on the simulated streamflow responses of different SWM scenarios, revealed that distributed SCMs are effective in attenuating peak flows for high frequency, low magnitude storm events (less than 25.4 mm). In contrast, end-of-pipe storage SCMs are vital for managing large magnitude events (greater than 25.4 mm, Figure 4). This finding is corroborated by comparative catchment studies using monitoring data from surrounding sites in Maryland (Hopkins et al., 2022; Sparkman et al., 2017). Modelling and empirical studies outside of Maryland also show that distributed SCMs provide better runoff control during small events, as compared with end-of-pipe SCMs (Damodaram et al., 2010; Jefferson et al., 2017; Williams & Wise, 2006). Ultimately, our research supports the hypothesis that exclusive reliance on either infiltration-based or storage-based SCMs leads to channel instability. This result is expected since the combination of both these SCMs was not able to protect the channel from erosion.

Although there was no statistically significant difference in the median change in channel invert elevation among the four SWM scenarios, there was a difference in the range of channel changes (Figure 8). In scenarios that exclusively utilized one category of SCM (distributed versus end-of-pipe), an increased amount of channel change was observed at erosional or depositional hotspots. For instance, the sole use of storage-based SCMs in the catchment resulted in a 250% increase in median peak flows for frequent events (rain totals up to 25 mm, Figure 4a) but resulted in only a 40% increase in cumulative sediment load (Figure 9a). This disproportionality arises because high frequency, low-magnitude events typically produce less geomorphic work per event, as indicated by the similar shapes of the sediment yield-discharge histograms in both the USSC and ponds scenarios (Figure 10a,b). Notably, these small magnitude storm events, interspersed among high-magnitude events, can redistribute sediment within the channel bed, thereby influencing sediment transport rates during subsequent high-magnitude events.

In comparison, the inability of infiltration-based SCMs to contain large magnitude events (Figure 4b) also led to an increased extent of channel disturbance, as compared with the USSC scenario. This is reflected in a significant skewness towards the right tail of the sediment yield-discharge histograms (Figure 10c), resulting in an increase in effective discharge (Q_{eff}), as tabulated in Table 4. This finding underscores that the failure to attenuate peak flows from intermediate to high magnitude storm events by small, distributed SCMs leads to a marked increase in the variability of the flow regime and geomorphic work done on the channel.

4.3 | Factors affecting modelling outcome

In this study, we adopted a coupled, hierarchical modelling approach that provided valuable insights into the complex interactions between the flow regimes generated by four different SWM strategies and sediment transport dynamics. However, it is important to acknowledge that this approach introduces uncertainties that accumulate and amplify in each step across the simulation models. Such challenges are common in dynamic sediment transport modelling, mainly due to the absence of a singular model capable of effectively simulating both watershed and channel processes within a unified platform. As an alternative, data-driven modelling has been considered to address these challenges (Javed et al., 2021). However, the scarcity of actual channel bed data poses a significant obstacle to pursuing this approach. Despite this limitation, the coupled modelling approach employed in this study allowed for a comprehensive comparison of sediment transport dynamics under different SWM scenarios.

Both of the models used in this study have limitations. For example, it has been documented that SWMM overestimates peak flow rates in urban catchments (Nayeb Yazdi et al., 2019; Niazi et al., 2017). This overestimation can influence sediment transport dynamics in the coupled SWMM and HEC-RAS modelling framework. Higher peak flows, as predicted by SWMM, can potentially increase the size and amount of sediment transported in each storm event. However, since field based studies have found that maximum bed sediment transport in small streams often happens before the peak flow of storm events (Thomsen et al., 2020); the effect of this peak flow overestimation by SWMM is anticipated to be minimal.

The development and calibration of the HEC-RAS model for the study reach presented significant challenges, primarily because of the extremely flashy flow regime of the small, urban catchment. Initially, the hydraulic component of the HEC-RAS model was calibrated using the unsteady flow mode. However, this approach led to instability in the sediment transport model for the No SCM scenario because of the increased peak flows. Consequently, the model was ultimately calibrated in the quasi-unsteady mode. This method simplifies hydrodynamics by representing a continuous hydrograph as a series of discrete steady flow profiles. While representing a flashy regime using steady flow profiles might lead to underestimations of the water surface profile, research indicates that both quasi-unsteady and unsteady HEC-RAS models yield comparable results in terms of channel bed degradation and aggradation (Hummel et al., 2012).

The Wilcock–Crowe sediment transport equations used in the model were developed utilizing a channel bed with the largest particles of 100 mm but the channel bed of the study reach has particles as large as 128 mm. Gaeuman et al. (2009) found that Wilcock–Crowe equations may underpredict the transport rate of larger bed particles. This might be the reason why the modelled reach shows areas of channel aggradation. However, many field-based sediment mobility studies have found that gravel particles of urban rivers tend to travel shorter distances, promoting more deposition due to the altered flow regime (Annable et al., 2012; Plumb et al., 2017). The fractional bed load transport of the model includes sediment from the channel bed only and does not consider sediment being transported from bank erosion; however, bank erosion was not observed to be a major sediment source in the study reach. The sediment rating curve was kept the same for all the SCM scenarios but gradual exclusion of SCMs would change the amount of sediment delivery to the reach as they all have different sediment trapping efficiencies (Russell et al., 2019).

5 | CONCLUSIONS

In conclusion, our research has highlighted critical insights into the dynamics of SCMs, flow regimes and sediment transport, particularly in the context of urbanized headwater streams in the State of Maryland. The study findings demonstrate that while current stormwater regulations, such as the USSC, are effective in managing peak flows for a range of storm events. However, because they do not consider changes in sediment transport because of urbanization, they fall short in maintaining long-term channel stability. Specifically, model results, supported by field observations, demonstrate that neither distributed nor centralized SCMs, in isolation or in combination, could fully safeguard against channel degradation.

Based on these findings, we propose two key recommendations for SWM regulations. First, catchment-scale hydrological models that utilize at least 10 years of observed rainfall data should be employed for SCM design rather than using a single 24 h design storm. This modification would provide a more comprehensive understanding of the effect of urbanization and SCMs on catchment flow regimes. Second, SCM design criteria should be revised to consider sediment transport dynamics with the design goal of matching post-development sediment transport to pre-developed conditions. Utilizing spreadsheet-based tools can simplify this process (Bledsoe et al., 2007), making it feasible to estimate total sediment mass transported or total amount of time above a transport threshold without relying on complex models.

These recommendations aim to foster a more nuanced approach to SCM design, one that balances the need for SCM design and review efficiency with the need to protect both human infrastructure and the physical integrity of waters of the United States. It is imperative that future SWM strategies be adapted to the conditions of the receiving stream, integrating considerations of both flow regimes and sediment dynamics following urbanization. These findings and recommendations contribute significantly to the ongoing discourse on sustainable urban water management, emphasizing the need for more comprehensive practices in SWM.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in HydroShare at https://www.hydroshare.org/resource/66c7547f746142cba6e769d7b3efaddf/.

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SUPPORTING INFORMATION

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