Impacts of Stormwater Management Practices and Climate Change on Flow Regime and Channel Stability

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Abstract

Urbanization increases runoff during storm events due to a reduction in vegetation and an increase in impervious surfaces, which limits the land's capacity to absorb and slow down water. This increase in runoff contributes to channel erosion. While extensive research exists on the hydrologic benefits of various types of stormwater control measures (SCMs), the relationship between urbanization, widespread SCM implementation, and channel stability in headwater streams remains less explored. Additionally, the impact of climate change (CC) on SCMs, with its growing focus due to improved global and regional CC models and data, is a critical area of study. However, most existing studies rely on simplified design storm analyses and unit-area runoff models, and there is a lack of comprehensive research evaluating the long-term, continuous hydrologic response of SCMs under future CC scenarios. This study presents an in-depth evaluation of the effectiveness of SCMs in maintaining channel stability in urbanized headwater streams, with a particular focus on the challenges posed by urbanization and CC. Conducted in a small catchment in Montgomery County, Maryland, USA, the study employs a sequential hierarchical modeling approach integrating the Storm Water Management Model (SWMM) with the Hydrologic Engineering Center's River Analysis System (HEC-RAS). First, the impact of a stormwater management system design following Maryland's Unified Stormwater Sizing Criteria (USSC) on channel stability was investigated. Simulation over 16 years (2004-2020) demonstrated that the majority of storm events were short in duration, with the greatest peak flows resulting from storm events with durations less than 24 hours. However, results indicated that despite the use of multiple SCMs, channel changes, including both degradation and aggradation up to 1.2 m, are likely over a period of 16 years. Study results indicate SCMs should be designed using continuous simulation models to simulate pre- and post-development sediment transport. Secondly, the impact of SCMs and CC on flow regime and channel stability was examined, challenging the previous simplified analyses. The findings highlight that future CC scenarios, characterized by decreased total rainfall but increased intensity, will likely shift watershed hydrology towards a flashier regime, exacerbating channel erosion. To address these shortcomings, a multicriteria design approach for SCMs is required, considering local sediment transport capacity and the complexities of urban catchments under changing climatic conditions. Lastly, evaluation of the impact of proposed stormwater regulations on channel stability using a novel three-step methodology revealed that SCM design goals focused on maintaining pre-development sediment transport or excess shear stress could reduce channel disturbance. Overall, this study illustrates the need for more nuanced and holistic approaches to stormwater management to ensure channel stability, especially in the face of the challenges posed by climatic changes.

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General Audience Abstract

As cities grow, with more buildings and roads replacing green spaces, managing stormwater becomes a crucial challenge. Without enough soil and plants to absorb it, stormwater rushes over these hard surfaces, contributing to stream erosion. This urban scenario sets the stage for my research, which investigated effective ways to handle stormwater in cities to protect small, local streams. The focus of this study was to understand the performance of stormwater control measures (SCMs), which are engineered structures designed to manage this excessive runoff in urban environments. The key question is: Are SCMs effective, especially as we face the impacts of climate change? This research was conducted in a small watershed in Montgomery County, Maryland, using computer simulations to replicate water flow and stream conditions over a 16-year period. The findings reveal that, despite using SCMs, streams can still experience significant changes. This is especially true during intense, short-duration storms that can rapidly increase stream flow and cause channel erosion. With climate change, these problems may increase. Future weather patterns could lead to less frequent but more intense rainstorms. This study suggests that our approach to designing SCMs needs to be more sophisticated, taking into account not only the amount of water running into streams, but also the amount of coarse sediment moving during floods. In summary, this research highlights the need for comprehensive strategies in urban water management to ensure the stability and health of urban streams amidst the challenges of increasing urban development and climatic changes.

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Chapter 1 Introduction

Stormwater Control Measures (SCMs) have long been used in urban areas in the US to mitigate the negative impacts of urbanization (National Research Council, 2009). The effectiveness of SCMs in improving water quality and reducing runoff during storm events has been extensively studied across the US, employing both monitoring data and models (Bell et al., 2020; Jefferson et al., 2017; Li et al., 2017). However, the efficacy of SCMs in protecting downstream channels from erosion has been less frequently explored, owing to the complexity of monitoring sediment transport in urban streams and the challenges in modeling sediment transport dynamics. Despite this, protecting downstream channels from excessive erosion remains a key goal of large-scale SCM implementation.

Many studies have documented an increase in channel erosion following urban development, particularly in urban catchments with minimal SCM implementation (Leopold et al., 2005; Pizzuto et al., 2000; Plumb et al., 2017; Wohl, 2018). Isolating the effects of SCM implementation is crucial to understanding how altered flow regimes affect the rate and magnitude of channel erosion. The altered flow regime due to urbanization differs from that induced by SCMs. SCMs typically store and release runoff at a rate defined by the SCM outlet configuration and shape of the SCM (Bledsoe, 2002). This approach reduces peak flow during storm events but may increase low to intermediate flow at the catchment outlet, potentially exacerbating channel erosion compared to the response due to urbanization alone.

SCM implementation not only influences the flow regime but also significantly impacts sediment supply dynamics to the channel (Russell et al., 2019). The sediment transport capacity of a stream sediment depends on flow and channel structure, whereas the actual sediment transport amount depends on flow, channel structure as well as the sediment supply being delivered to the stream. Both of these collectively determines the response of the channel over time (Wohl, 2018). Thus, understanding the long-term stability of a channel in response to SCM-induced flow and sediment regimes necessitates a sequential flow and sediment modeling platform.

The design of SCMs is traditionally based on empirical evidence from historical long-term rainfall data, assuming past patterns will repeat in the future (Perica et al., 2013). However, US Global Climate Models (GCMs) indicate significant future changes in rainfall amount and timing, with considerable spatial variability (USGCRP, 2018). For instance, the southwest regions of the US can expect a substantial decrease in rainfall during dry seasons, while the north-central and northeastern regions may experience an increase in extreme rainfall events.

The hydrologic performance of SCMs at the catchment level under changing climate conditions shows a notable variance, heavily dependent on the resolution of climate modeling data (Hathaway et al., 2024). Some studies show that urban catchments in the mid-Atlantic regions may see less than a 10% increase in annual rainfall and streamflow (Alamdari et al., 2018, 2020). Conversely, other studies using climate change-induced rainfall-runoff data suggest that, while typical annual cumulative rainfall-runoff may not significantly increase, the rainfall amount for storm events with a recurrence interval (RI) of more than 10 years could rise by up to 60% (Butcher, 2021; Butcher et al., 2023). Given that SCMs in the mid-Atlantic region are designed for high-frequency storm events with an RI of 1-2 years, there appears to be no immediate need to modify design rainfall amounts in this region (Butcher, 2021). Nevertheless, a critical oversight in these studies is their reliance on hourly or daily data applied to generic landscapes on a unit-area basis, which could lead to an underestimation of peak flows in response to intense storm events, especially in urban headwater catchments. These catchments are prone to rapid streamflow changes within an hour due to their proximity to the built environments. Therefore, there is a clear need to develop new methods for assessing the impacts of climate change on SCM-induced streamflow on a more granular, sub-hourly level, utilizing data from actual urban catchments. Additionally, the current focus on individual SCMs, while informative, might not provide a comprehensive understanding at the catchment scale. A broader analysis, considering the effects of SCM regulations and practices on the entire catchment, is essential. This approach is crucial for a holistic understanding of urban hydrology under changing climate conditions. Furthermore, our understanding of how channel morphology will respond in a changing climate remains limited.

1.1 Goal and Objectives

The goal of the research presented in this dissertation is to evaluate the effects of catchment-scale SCM implementation and climate change on the flow regime and stability of urban streams. To achieve the goal, the following objectives will be addressed:

1. Assess the effectiveness of Unified Stormwater Sizing Criteria (USSC) and SCM design regulations of Maryland, in maintaining channel stability in an urban headwater catchment in Maryland.
2. Evaluate the effect of climate change on flood flows and channel stability.
3. Explore the effect of changes to SCM regulations on maintaining channel stability following urbanization.

1.2 Dissertation Organization

Chapter 1 of this dissertation includes a short literature review of SCM design regulations in Maryland and CC impacts on SCM performance and sediment transport. A summary of the research findings of previous works done on the study site is also presented in Chapter 1.

Chapters 2-4 are specific to each of the previously mentioned three main objectives of this research. As each has been prepared for a self-supporting journal article, there is some unavoidable repetition between chapters. Chapter 6 contains the overall conclusions of this research.

1.3 Background

1.3.1 SCM design regulations of Maryland

Maryland was the first state in the USA to adopt stormwater quality regulations (Maryland Department of the Environment (MDE), 2000). Detailed design and placement guidelines for SCMs are provided in the Maryland Stormwater Design Manual (MDE, 2000) which assists engineers and site compliance reviewers. Developed by the Center for Watershed Protection, the initial version of this manual was released in 2000 and introduced the Unified Stormwater Sizing Criteria (USSC), a set of guidelines and standards for designing stormwater management systems. These criteria aim to 1) improve water quality, 2) maintain groundwater recharge, 3) reduce channel erosion, 4) prevent overbank flooding, and 5) safely convey extreme floods. The first three requirements are mandatory, while the last two are optional unless deemed necessary by local approval authorities. The sizing criteria for the optional requirements are not discussed in the dissertation. Maryland stormwater regulations underwent further changes following the passage of the Stormwater Management Act of 2007, which mandated that environmental site design (ESD, similar to low impact development) be fully implemented before structural stormwater practices (typically stormwater ponds) could be used. Although Maryland no longer requires the use of USSC for SCM design, 8 states and the District of Columbia subsequently adopted the USSC.

The SCM sizing criterion for water quality improvement is known as Water Quality Volume (WQ_v). All new developments must incorporate sufficient infiltration-based SCMs to capture and treat runoff generated from 90% of the average annual rainfall (25 mm) through infiltration and evapotranspiration. Mathematically, this volume equals 25 mm of rainfall multiplied by the volumetric runoff coefficient (R_v) and the development footprint area. The R_v is determined using a regression equation where site imperviousness is the sole predictor variable, adapted from the Simple Method approach (Schueler, 1987). The assumption that urban runoff generation is solely a function of site imperviousness oversimplifies the complex interactions with other natural and site factors, as evidenced by field studies (Simpson, 2022; Taleb, 2012). The criteria for maintaining groundwater recharge, termed the Recharge Volume Requirements (R_{ev}), is considered part of WQ_v.

The SCM sizing criterion for maintaining channel stability is called the Channel Protection Storage Volume Requirements (Cp_v). This criterion requires storage-based SCMs at development sites to provide 12 or 24-hour extended detention of runoff, ensuring gradual release such that critical erosive velocities during bankfull and near-bankfull events will seldom be exceeded in downstream channels. The design method for meeting this requirement is based on the Natural Resources Conservation Service Technical Release-55 (NRCS TR-55) document (Natural Resources Conservation Service, 1986) and a simple graphical method formulated by Kalkanis (1980) that determines detention time of ponds (Figure 1-1) . This method involves first calculating the peak discharge of the inflow hydrograph from the contributing drainage area from the graphical peak discharge curves of the NRCS TR-55 method, then determining a storage volume and outflow rate that can provide the required 12 or 24-hour detention. The graphical peak discharge curves of the NRCS TR-55 method were developed based on a combination of rainfall distributions of specific design storms and dimensionless unit hydrographs for on-farm conservation practice design. The second step involves selecting an appropriate peak outflow for the outlet structure of the pond to provide 12 or 24-hour detention. This selection is guided by a detention time versus discharge ratio curve, adapted from older reports (Kalkanis, 1980; Maryland Department of the Environment (MDE), 1987). While many state stormwater regulations in the USA have incorporated these curves to reduce channel erosion, it is important to note that these techniques provide only approximate sizing for storage volumes and single outflow structures. Additionally, the rationale for choosing a 24-hour detention time, as outlined in the stormwater manual, does not fully align with the information in these reports, which emphasize that this detention time for newly designed ponds revolves around the settling behavior of urban pollutants and is not directly associated with limiting downstream channel flow to bankfull or near-bankfull levels. Once the peak outflow is determined from the detention time versus discharge ratio curve, the volume of storage is determined from the detention basin routing curve provided in the NRCS TR-55 manual (Natural Resources Conservation Service, 1986).

In 2009, MDE updated its SCM design regulations and released a revised version of their stormwater management manual. The new SCM design strategy, known as ESD, places greater emphasis on distributed SCMs such as bioretention cells, swales, infiltration trenches/basins, and sand filters. These design criteria mandate that runoff from a 1-year, 24-hour storm event from a development site must be equivalent to that of a wooded site in good condition, as per the NRCS TR-55 manual. Under this strategy, if the runoff reduction requirement is met using small-scale, distributed SCMs, then storage-based SCMs are not required. However, if distributed SCMs are insufficient to meet the requirement, storage-based SCMs must be implemented, and their storage volume should be based on the runoff released from the distributed SCMs. This ESD strategy results in a smaller volume for storage-based SCMs compared to the volume designed under the Cpv criteria, as the volume associated with the Cpv criteria's is based on runoff from the entire site and the runoff treatment provided by upstream SCMs are not considered during the design calculations

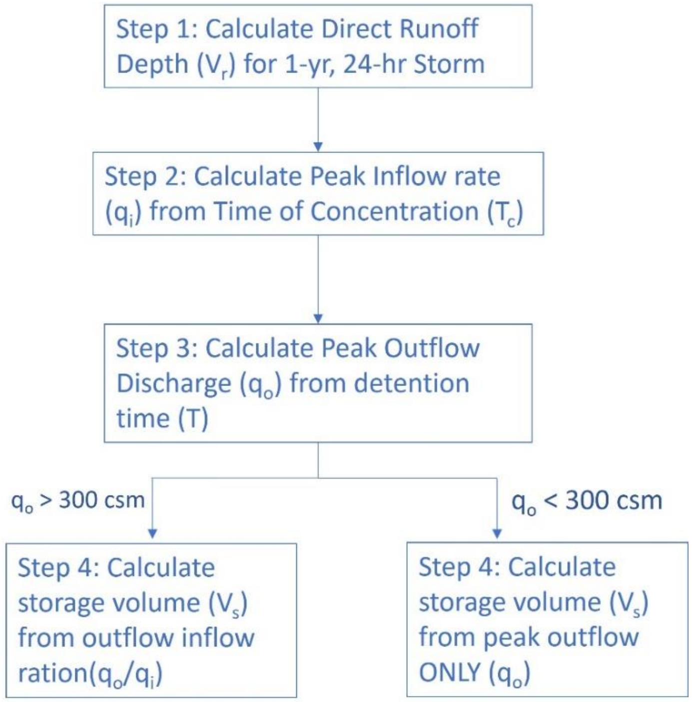

Figure 1-1. Design steps for channel protection storage volume requirements (Cp_V).

1.3.2 Impacts of urbanization and SCM on sediment transport

Urbanization significantly alters land use through anthropogenic activities such as the elimination of vegetation, construction of infrastructure, diversion of streams to supply water, and discharge of wastewater into water bodies. The first two activities increase runoff during storm events, as the reduction in green cover and increase in impervious areas limit the land's ability to absorb and slow down water. Firstly, impervious areas substantially decrease the infiltration of rainfall into the soil, thereby reducing the recharge of groundwater resources. Secondly, these areas capture and channel runoff into a network of subsurface drains and pipes, quickly discharging it into urban water bodies. The impact of urbanization on flow regimes, where water bodies receive runoff from stormwater networks, is now well understood and has been extensively studied (National Research Council, 2009). However, the impact of urban areas treated with stormwater management changes in flow regime and channel morphology is less studied, due to the complexities involved in continuously monitoring flashy urban streams. Documenting the effects of urbanization typically involves repeated cross-section measurements of the channel at various locations over many years (Booth & Henshaw, 2011; Doyle et al., 2000; Olson-Rutz & Marlow, 1992; Pizzuto et al., 2000; Williams, et al., 2022a; Williams, et al., 2022b) and the analysis of sequential satellite imagery or Digital Elevation Models (DEMs) data (Jarnagin, 2010; Jones et al., 2014). These analyses are usually compared with nearby rural streams to assess the impact of altered flow regimes on channel morphology.

Modeling studies have also been used to evaluate the impact of urbanization on sediment transport in urban streams (Beganskas et al., 2021; Fan & Li, 2004; Tillinghast et al., 2011, 2012). These studies involve sediment transport calculations based on observed or simulated flow time series to estimate the frequency of channel bed disturbance. A limitation of these modeling studies is their assumption that urban streams transport sediment at the theoretical transport capacity computed using theoretical threshold discharge (Qc), but recent field studies have indicated that the observed threshold discharge (Qc) for streambed mobilization is much higher than theoretical estimates, especially in highly impervious catchments (Hawley et al., 2022). This finding is surprising, as it is expected that the bed material in urban streams would be mobilized at lower discharges due to amplified rates of streambed disturbance from frequent discharges exceeding critical levels and chronic streambank erosion, which loads fine sediment onto the streambed, making substrates more prone to mobilization.

Increased mobilization of bed material in urban streams post-development, specifically in channels that have stabilized and fully adjusted in response to changes in hydrology and sediment load due to urbanization, has been documented in numerous studies in the US and around the world (Leopold et al., 2005; Russell et al., 2017; Wohl, 2018). While some studies suggest that sediment yield should decrease after urbanization due to reduced sediment generation from paved surfaces (Bledsoe & Watson, 2001; Gurnell et al., 2007; Wolman & Schick, 1967), others have reported elevated sediment yield post-urbanization (Pizzuto et al., 2000; Russell et al., 2018, 2019, 2020; Smith & Wilcock, 2015). Russell et al. (2017) showed that sediment yield from urbanized catchments is likely to increase during construction, then decline, but remain higher compared to forested catchments. These findings were based on summary statistics for sediment yield data worldwide. Russell et al. (2020) found that sediment transport capacity in urban streams was up to three orders of magnitude higher than in forest catchment streams. They also concluded that the increase in this sediment transport capacity is driven primarily by the alteration in flow regime, with very limited contributions from sediment supply from the drainage area. Plumb et al. (2017) demonstrated that both the frequency and magnitude of geomorphically significant flows (threshold discharge, effective discharge, half-yield discharge) increased with urbanization, resulting in a nearly 150% increase in sediment yield. Additionally, they also found the coarse bed material travel distances were shorter in urban gravel-bed streams, as compared to non-urban streams due to higher flashiness and shorter event durations. Annable et al. (2012) reported similar findings in urban gravel bed rivers, concluding that sediment transport dynamics in these rivers are influenced by both flow regime and local sediment supply factors. Pizzuto et al. (2000) found that urban streams in Pennsylvania were about 26% wider than their forested or rural counterparts, with lower sinuosity. However, the extent of channel incision in urban streams was similar to forested ones. Conversely, Hawley & Bledsoe (2013) reported that urban channel enlargement in California was achieved more through increased depth rather than width. Their multivariate regression models, derived using data from both stable and unstable stream, showed that channel enlargement was highly dependent on the ratio of post- to pre-development sediment-transport capacity, explaining 60% of the variance. Booth & Henshaw (2001) observed a range of channel incision rates from less than 20 mm to about 1 m per year in 21 urban channels, with rates not correlating with catchment imperviousness. Channel enlargement, either through widening or incision, appears to be a characteristic response of urban streams following development. In conclusion, urbanization significantly impacts stream channels, often leading to increased runoff, reduced infiltration, and altered sediment transport dynamics. The effects include changes in flow regimes, increased sediment yield, and altered channel morphology, such as enlargement through widening or incision. While the impact on flow regimes is well understood, the specific effects on stream-channel forms and sediment dynamics continue to require further study to fully comprehend the complex relationships between urbanization factors in these environments.

1.3.3 Impact of climate change on urban catchment equipped with SCM

As per the United Nations Climate Action report, climate change (CC) refers to long-term shifts in air temperatures and weather patterns (IPCC, 2033). These shifts may be natural, such as those resulting from variations in the solar cycle, but they can also arise from human activities like burning fossil fuels, including coal, oil, and gas. CC is likely to intensify the hydrological cycle, affecting fluvial, sedimentary, and geomorphic processes on terrestrial landscapes

(USGCRP, 2018). Accurate prediction of these processes' responses to CC requires an understanding of possible future states of the world. The collection of global climate simulations performed by the Working Group on Coupled Modeling (WGCM) provides a standardized set of scenarios for coherent, internally consistent, and plausible descriptions of possible future climatic states (Ii, 2019). The scenario products, known as Global Climate Models (GCMs), are complex mathematical representations of the world's major climate system components and their interactions. Formulating a particular GCM requires consideration of many factors, including the amount of future greenhouse gas emissions. Predictions of how median concentrations of greenhouse gases in the atmosphere will change in the future as a result of human activities (Representative Concentration Pathways, RCPs) affect the projected changes in temperature and precipitation in a GCM. However, the horizontal resolution of all GCMs is 1°, which is too coarse for predicting local scale fluvial and sedimentary responses.

Regional Climate Models (RCMs) are structurally similar to GCMs but provide finer scale resolution of changes in a specific region, both spatially and temporally. The process of creating RCMs, known as downscaling, relies on advanced averaging, weighting, and pattern-scaling approaches, combined with historical observations (Pierce et al., 2014). While advances in these downscaling approaches are ongoing, RCMs still face many of the same uncertainties as GCMs. In some cases, the level of uncertainty can even be amplified during spatio-temporal downscaling (Matonse et al., 2013). Uncertainties may arise from scientific modeling, climate sensitivity, and parametric processes, but natural variability is the primary source of uncertainty in quantifying global CC over the next two decades. Consequently, studies have highlighted the importance of large ensemble simulations in quantifying regional change (Hayhoe et al., 2017). However, due to their exceptionally high computational demands, extensive ensembles of RCM-based projections, especially for predicting future sedimentary responses, are rare. Evaluating the performance of RCMs can be done by comparing downscaled historical simulations with observations from a different time period than the one used to train the model. However, historical records spanning a sufficiently long period are often unavailable for many regions.

The impact of CC on urban flow regimes at regional and local scales is well documented in the mid-Atlantic region of the US, thanks to the recent improved availability of GCMs, RCMs, and associated data (Hathaway et al., 2024). The main theme of these studies is to implement statistical and spatial downscaling of climate data to provide input for hydrologic assessments. The overall approach consists of two main steps: a) post-processing either global or regional climate model (RCM) output (e.g., precipitation, temperature data) via downscaling methods; b) converting the climate-altered precipitation data into streamflow using a calibrated hydrologic model. These calibrated hydrological models typically incorporate SCMs designed under existing climatic conditions. Many studies have also incorporated changes in Land Use/Land Cover (LULC) into these models to evaluate the cumulative impact of CC and LULC (Alamdari et al., 2022; Giese et al., 2019).

Alamdari et al. (2017, 2020) studied the CC effects on streamflow in a 150 km^2 catchment in Virginia, U.S., which had an imperviousness of 18% and was equipped with a wide range of retention-based SCMs. Other small-scale SCMs were not simulated in the model. Alamdari et al. (2017, 2020) used hourly precipitation data of 5 RCMs representing RCPs with radiative forcing values of 4.5 and 8.5 W/m^2, respectively. Results showed that the projected annual streamflow of the RCMs had a wide range of values (median increase of around 6%). In all CC scenarios, both annual and seasonal streamflow were projected to increase, with a greater increase in the RCP 8.5 scenarios. The results also implied that the largest increase in streamflow, on average, would occur in winter, with minimal or no increase in the summer season. Alamdari et al. (2022) investigated the combined the effects of CC and LULC on daily streamflow for a 10 km^2 catchment. They used climate data of 2 GCM-RCM models which were selected from 32 GCM-RCM models based on the methods suggested by Sheffield et al. (2013). Similar to Alamdari et al. (2020), this study also predicted a higher increase in runoff in winter. Their results also showed that annual runoff is expected to be more affected by changes in LULC than changes in climate. Studies conducted outside of the mid-Atlantic region have reported similar results (Nover et al., 2016; Sarkara et al., 2018) but most studies done so far have investigated the impact of CC on annual or seasonal runoff volumes, with no attention paid to other discharge attributes like storm event peak flow, annual peak flows.

Butcher et al. (2021) developed innovative, easy-to-use procedures for generating precipitation intensity-duration-frequency (IDF) curve and found that many locations in the mid-Atlantic regions will likely have minimal changes in total precipitation volume; however, the magnitude (total rainfall amount) of extreme event precipitation is expected to increase in nearly all locations. Their results showed that even though the total annual precipitation depth may decrease for some regions, the runoff generated by a unit area of a generic landscape may increase by up to 60% for events with recurrence intervals (RIs) of more than 10 years. Butcher et al. (2023) further used the aforementioned procedure to generate projected runoff from two different types of SCMs. Their results show that the 90th percentile, 24-hour precipitation event is expected to decrease in all locations of the mid-Atlantic regions while outflow from SCMs in response to more infrequent events (RI > 2 years) is expected to increase, regardless of the GCM-RCM combination. Even though both of these studies used a unit area generic landscape for projected flow, these studies show that the impact of CC on urban flow regimes is heavily dependent on the temporal scale at which the results are analyzed.

1.3.4 Impact of climate change on sediment transport

The nature and extent of sedimentary and geomorphic responses to climate change can be analyzed by studying the influence of both past and future climate processes on fluvial systems. The following sections focus on approaches and findings from studies of anticipated future fluvial system behavior. Various studies conducted over the past few years have predicted the potential impacts of a changing climate on the sediment transport dynamics of fluvial systems. The general methodology of these studies is the implementation of statistical and spatial downscaling of climate data to provide inputs for hydrologic and morphological assessments. The overall approach consists of three main steps: a) post-processing either global or regional climate model (RCM) output (e.g., precipitation, temperature data) via downscaling methods; b) converting the climate-altered precipitation data into streamflow using a hydrologic model; c) simulating sediment transport dynamics using the projected flow data. The current research in this domain has focused on large river basins in general, in support of large infrastructure projects, none of which are within the mid-Atlantic region of the US. A significant research gap exists in assessing the sediment transport dynamics of both small-scale and urban river basins/catchments. Predicting the sediment transport dynamics of these basins is particularly challenging due to uncertainties associated with downscaling RCMs, the lack of historic/current data for calibrating the current condition model, model limitations, and anthropogenic interference, among others.

Multiple types of models, including conceptual, physical, and numerical simulations, have been developed and applied to understand and predict sediment transport dynamics and fluvial system response to environmental disturbances, including climate change (McDowell & James, 2022). Lewicki et al. (2007) reported model results for two scenarios combining land use/land cover (LULC) and climate change to predict changes in bed elevation, slope, grain-size distribution, bedrock exposure, and sediment transport processes of a 30 m long reach in Maryland, USA. They used downscaled precipitation estimates from one GCM to account for climate change and employed a continuous hydrological model to produce climate-altered streamflow. Their modeling results showed that the climate change scenario with urban sprawl generated larger, more frequent storm discharges than the climate change scenario with managed urban growth. The increased storm discharges led to increased bed material transport and bed disturbance, as well as higher suspended sediment concentrations. Moreover, the urban sprawl climate change scenario simulated more mud and bedrock contents in the active layer of the channel bed due to changes in the balance between sediment supply and transport capacity.

Praskievicz (2015) utilized a sequential hierarchical modeling approach to simulate the geomorphic response of three snowmelt-dominated gravel-bed rivers in the interior Pacific Northwest. Their approach was based on discharge and suspended sediment load from a basin-scale hydrologic model driven by three spatially downscaled RCMs. Changes in reach-averaged bed material transport were estimated using Bedload Assessment in Gravel-bed Streams (BAGS) software, and the spatial pattern of erosion and deposition for the three reaches was simulated using the Cellular Automaton Evolutionary Slope and River (CAESAR) model. The BAGS software used flow time series from SWAT and cross-section data as input for determination of reach-averaged bed material transport capacity calculations. Their simulation results showed that the recurrence interval of critical discharge needed to mobilize the d_{50} and d_{90} grains in the channel bed was expected to decrease for the ensemble future scenario, indicating that the bed sediments of the studied rivers were expected to be mobilized more often than at present. The simulated sediment transport increased for one river but decreased for the other two due to an average decrease in precipitation across all scenarios. Due to high computational needs, Praskievicz (2015) simulated the spatial patterns of erosion and deposition through the CAESAR model for a single 5-year run, and the results lacked any coherent spatial pattern. The author's findings suggest that the geomorphic response of the study rivers to climate change is nonlinear and threshold-dependent, with bed material transport both increasing and decreasing within the system.

Brennan et al. (2018) assessed the response of a semi-alluvial, clay-bed creek (urban watershed with a drainage area of 21 km^2) to CC. To obtain climate-altered streamflow, they used spatially and temporally downscaled data from one RCM and incorporated it into a well calibrated (NSE > 0.6) Stormwater Management Hydrologic Model (SWMHYMO) lumped hydrologic modeling platform at a daily timestep. The historic and predicted future erosion potential of one measured cross-section were derived using SWMHYMO's modified erosion index routine, which calculates the cumulative effective work index (CWI) or stream energy expended above the critical value, number of exceedance events, flow volume above threshold, and duration of exceedance. Their results showed CWI increased by 75% (for RCP 4.5) and 139% (for RCP 8.5) based on the measured critical bed shear stress of 3.7 Pa. The mean total exceedance flow volumes and number of above-critical events per year were also expected to increase by the same range for both RCP scenarios in the CC simulation.

Future sediment transport modeling often employs spatially limited simulations over short durations for several reasons. Centennial-scale 1D models struggle to accurately reflect the variability of sediment transport. While CC data with high temporal resolution are available, long-term simulations with high spatial resolutions (2D/3D) are computationally challenging. Additionally, model calibration and validation are difficult due to limited historical data, resulting in underestimation of future conditions (McDowell & James, 2022). Despite cumulative uncertainties from multiple simulations from a hydrologic model coupled with a sediment transport model, these studies show promise for understanding climate-impacted sediment dynamics.

1.4 Study Site

The site chosen for my dissertation is a 0.9 km^2 catchment located in Clarksburg, Montgomery County, Maryland, USA (Figure 1-2). This unnamed tributary to Little Seneca Creek is referred to as Tributary 109 (Trib 109) in the original study of Hogan et al. (2014). The site falls within the Clarksburg Special Protection Area (CSPA), a region recognized for its high-quality or unusually sensitive water resources, such as streams, wetlands, and soils prone to erosion, as well as other environmental features (Jarnagin & Jennings, 2004). The CSPA is located at the edge of the exurban development expanding from the Washington DC metropolitan area and is experiencing rapid development. The CSPA research is an example of Federal-Local technology-transfer partnership, where innovative technologies are researched at the Federal level, and the results are made available locally. The land use/land cover (LULC) of the study site transitioned from agricultural to sub-urban development over nine years (2007-2016) (Figure 1-3). The catchment imperviousness increased from 0 to 45%; however, the effective impervious area remained 0% due to the widespread implementation of SCMs designed as per the USSC requirements. The site has been monitored by Montgomery County and the USGS to evaluate the hydrologic response (Hogan et al., 2014; Hopkins et al., 2020; Loperfido et al., 2014; Rhea et al., 2015), geomorphic response (Jones et al., 2014; Williams, Hopkins, et al., 2022) and ecological function (Hogan et al., 2014; Williams et al., 2021) of the catchment during and after construction. The results of this monitoring have been published in 15 peer reviewed journals and the list of publications is provided in Table 1-1 along with what type of data were employed in the studies. A summary of these results is provided in the following section.

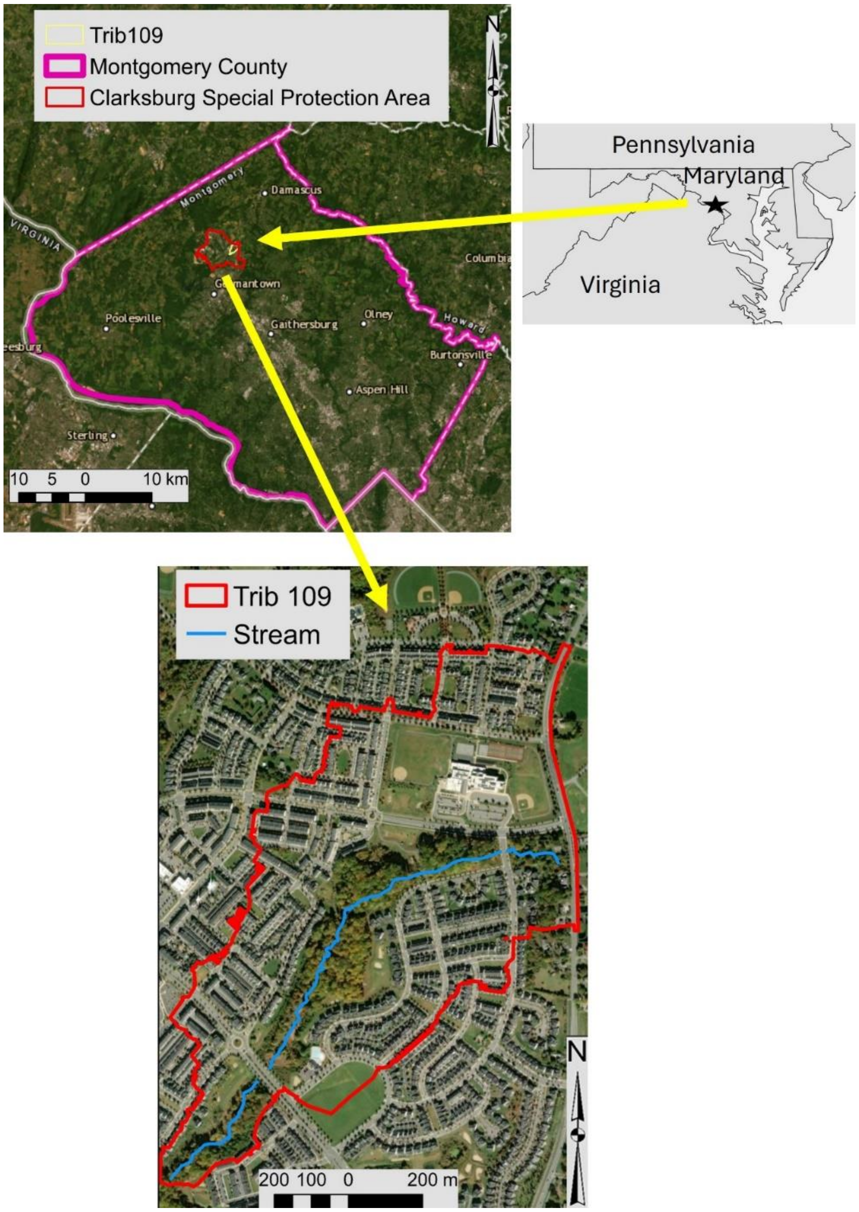

Figure 1-2. Location of Trib 109 within Maryland and current Google satellite imagery of the site.

Figure 1-3. Satellite imagery of Trib 109 during the year of a) 1993, b) 2006, c) 2011 and d) 2013. The red line indicates the catchment boundary following development.

Table 1-1. Summary of prior research on the Tributary 109 catchment.

Citations	**Data used**	**Key Findings**
Hogan et al. (2014), Rhea et al. (2015)	• Temporal LULC data (2000-2010) • 0.9 m LiDAR-based DEM (2002, 2004, 2006, 2008) • Cross-sectional survey data (2005, 2006,2007, 2009, 2010) • Daily Streamflow (2004-2010)	• No change was observed in annual volumetric stream flow, base flow, or storm flow • Channel cross-sectional area changes as high as 0.05 m^2m^{-1} were observed due to deposition after start of construction in 2007 • Surface elevation changed by ~55 cm/m^2 post construction
Jones et al. (2014)	• 0.9 m LiDAR-based DEM (2002, 2004, 2006, 2008)	• Elevation in some areas increased by 2-3 m • Multiple streams were buried and piped during construction. • Some portions of streams werereplaced by swales • Mainstem channel did not undergo any changes
Hopkins et al. (2020)	• 5-min. streamflow (10/2004 to 09/2018)	• Storm event peak flows lower compared to nearby urban catchment with no SCMs • Storm event peak flows and volume still higher compared to forested catchment. • SCMs effective only for storm events with rain less than 20 mm
Williams et al. (2022)	• Cross-sectional survey data (2004-2017) • Pebble count (2004-2017)	• Channel widening occurred immediately after construction • Bankfull depth decreased by an average of 0.25 m from 2004 to 2017 due to deposition • Silt/clay in channel bed increased during construction

1.4.1 Summary of prior research on the Tributary 109 catchment

Hogan et al. (2014) aimed to understand the impact of landscape changes and sediment control best management practices (BMPs) on streamflow, geomorphology, and biological responses in four catchments within the CSPA, including Trib 109. The study involved high-resolution mapping of watershed land-use changes, monitoring stream parameters (daily flow and annual benthic macroinvertebrate) and identifying alterations in stream characteristics due to urbanization and ESC BMP usage. The author's study, which spanned from 2000 to 2010, included a wide range of data as summarized in Table 1-1. Since the construction phase of Trib 109 began at the end of 2007, LiDAR-based DEM analysis revealed that Trib 109 experienced an elevation change of 54.4 cm per square meter of landscape from 2004 to 2008 indicating that a depth of 54.4 cm of earth/soil was removed from the catchment during the construction (Hogan et al. 2014). The magnitude of the annual change in channel cross-sectional area normalized to channel width averaged 0.03 $m^2/m/year$ for Trib 109, which was almost three times that of a nearby forested catchment. Despite substantial changes in geomorphology as a result of land-use change, the study did not find any significant year-to-year changes in storm flow, base flow, or total water yield. This flow consistency might be attributed to the aggregation of daily streamflow data into annual values for these metrics.

Jones et al. (2014) utilized a sequence of 0.9 m LiDAR-based DEM and point cloud data sets between 2002 and 2008 to analyze catchment-scale topographic changes during the early construction phase of Trib 109. Their analysis revealed that the catchment underwent an average of 57 cm of excavation and 71 cm of fill per square meter. However, the 45 m riparian zone did not experience any elevation change during the construction phase. These large-scale elevation changes typically consisted of valley burial and significant cutting on ridgetops. Multiple perennial and ephemeral streams that were tributaries to the mainstem channel were buried by concrete underground pipes and also converted to vegetative swales during the construction phase. Slope analysis across the catchment using the DEM also indicated a transition from relatively smooth profiles to abrupt slope changes within the hillslopes due to land grading.

Williams et al. (2022a) used cross-section and pebble count data at three locations within the mainstem channel to compare geomorphic changes across four headwater catchments, including a forested one. The authors collected annual cross-sectional surveys from June 2006 until January 2018, with the majority of data being gathered during the construction phase, which ended at the end of 2016. The authors' findings showed that the average bankfull depth increased by 0.25 m from June 2004 to December 2017 due to channel incision. The average bankfull width also increased by 0.8 m during the same period due to channel widening. Width and depth ratios at the survey locations showed a trend of widening from 2004 to 2017, indicating the extent of channel widening is more than incising. Williams et al. (2022a) also assessed the correlation between high flow metrics and yearly geomorphic changes, finding a significant correlation for the most upstream cross-section, but not for the most downstream one. Year-to-year geomorphic changes revealed substantial sediment deposition at all surveyed cross-sections along the channel during the construction phase, until the start of 2018. Pebble count distributions at the downstream location showed that the amount of silt/clay almost doubled in 2009, immediately following the start of construction. There was also a trend of increasing gravel in the bed, although the increase was minimal. Overall, the authors' results indicated that all surveyed cross-sections of the catchment experienced a relatively high level of channel disturbance compared to the forested catchment, and the width-normalized standard deviation of all geomorphic metrics was higher, indicating that the channel was responding to upstream construction activities.

Hopkins et al. (2020) used high-resolution (5-minute intervals) rainfall-flow data from four headwater catchments, including Trib 109, to evaluate the responses of streamflow to storm events. The data covered the period from October 2004 to October 2018. The authors' analyzed peak streamflow and runoff amounts for individual storm events, categorizing them based on rainfall depths of 1-10 mm, 11-20 mm, and greater than 20 mm. Their findings showed that both peak streamflow and runoff amount in Trib 109 were lower than those in an urban control catchment with no SCMs for all three storm event categories. However, when compared to a forested catchment, Trib 109 exhibited significantly higher area-normalized peak streamflow and runoff yield for storm events with rainfall depths exceeding 10 mm. This discrepancy suggests that the Water Quality Volume (WQv) requirements of the USSC for Trib 109 were not being met by the existing SCMs. Moreover, the study highlighted the limitations of the SCMs in Trib 109, particularly during larger storm events with rain depths more than 25 mm, emphasizing the need for enhanced management practices to better control runoff, and protect water quality, and ecosystem health. The research contributes to a growing body of evidence on the effectiveness of stormwater management strategies in urbanizing areas and underscores the importance of tailored solutions for different environmental and urban contexts.

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Chapter 2 Effectiveness of stormwater control measures in protecting channel stability of urban headwater streams

2.1 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 sequential hierarchical modeling 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 hours and that the greatest peak flows resulted from storm events with durations less than 24 hours. HEC-RAS simulation results also showed that both channel degradation and aggradation, as high as 1.2 m, will likely occur regardless of the combination of SCMs employed in the catchment. Overall, this study provides valuable insights into the complex interactions between SCM practices, 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.

2.2 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 U.S. 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 U.S. and worldwide (Grabowski et al., 2022). Given that global urban population is expected to increase from 55% in 2020 to a projected 68% by 2050 and much of this growth will be directed towards cities and adjacent urban areas (United Nations Department of Economic and Social Affairs, 2022), the need for innovative and sustainable approaches to managing urban stormwater continues to be a critical need.

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 (Maryland Department of the Environment (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 U.S. states (Georgia, Iowa, Minnesota, New York, South Carolina, Texas, Vermont, and West Virginia). 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-hr rainfall, known as the Water Quality Volume (WQv) (Maryland Department of the Environment (MDE), 2000). Nested within the WQv is the recharge volume, Rev, 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-hr extended detention of the runoff generated from a 1-yr, 24-hr design storm event, called the Channel Protection Volume (Cpv), 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-yr and 100-yr, 24-hr 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 modeling and monitoring studies conducted in the Mid-Atlantic region of the 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, 2017; Woznicki et al., 2018). However, due to gaps in observed data records, these studies primarily analyzed 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. In other words, when daily streamflow data are analyzed, critical details about the rapid fluctuations and peak intensities of runoff during shorter, intense storm events are overlooked. Doing so could lead to an incomplete understanding of how well stormwater control measures perform in real-time situations. Miller et al. (2021) presented findings that cast the hydrologic effectiveness of USSC in a less favorable light compared to the studies mentioned above. However, their results, which indicate a significantly lower efficacy of USSC in attenuation of the hydrograph peak, might 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 the 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's also crucial to note that Li et al. (2017) found that modeling 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 programs across the U.S. 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). While 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 (Qc) from theoretical estimates is much higher in urban catchments compared to 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 modeling approach was applied at a carefully selected study site that has undergone extensive monitoring by multiple agencies before, during, and after development, as documented by (Hopkins et al., 2022).

2.3 Methods

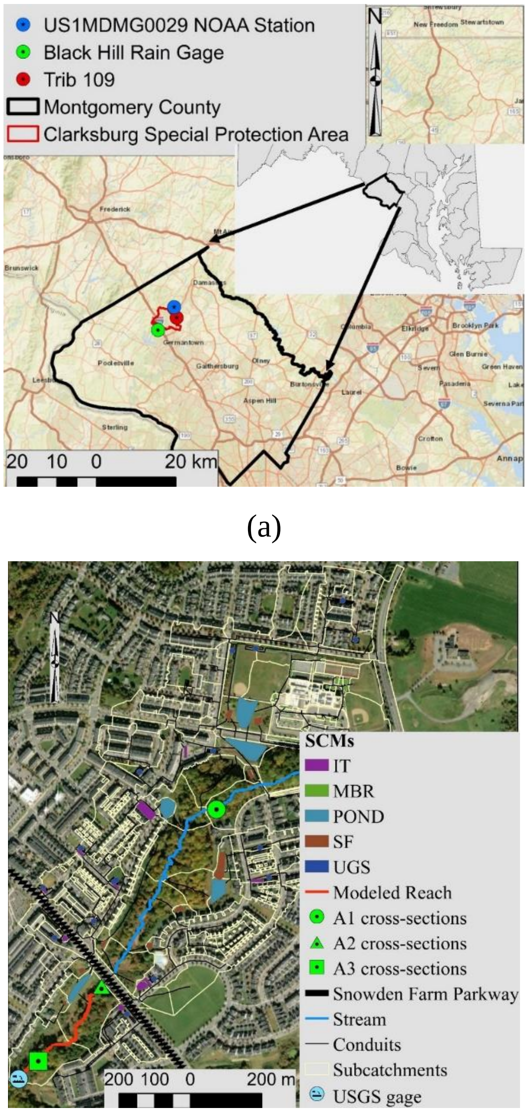
2.3.1 Study Site

This study focused on a small, urbanized, headwater catchment (~ 0.9 km2) located in Montgomery County, Maryland, USA, within the Piedmont Physiographic Province (Figure **2-1**). 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 km2), built in accordance with the USSC.

Promulgated by the MDE (Maryland Department of the Environment (MDE), 2000), the USSC regulations require the storage and treatment of both the WQv and the Cpv, 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 were 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 U.S. 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 -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 (0.012mm to 512 particle size diameter). 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 & Everett, 2003).



(b)

Figure 2-1. 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 (IT= infiltration trenches, MBR=micro bioretention cells, SF=sand filters, UGS=underground storage). Cross-sections were measured by Montgomery County, MD

2.3.2 Modeling 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). Details of the SWMM hydrologic model setup, parametrization, and calibration procedures are provided in Appendix A. To address the study hypotheses, three additional SWMM models were created by progressively excluding the simulated SCMs from the calibrated model (Table 2-1). 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 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 to the SWM scenarios. The calibrated SWMM model (USSC SWM scenario) and the three additional SWMM models were run with 5-minute interval local precipitation data obtained from Montgomery County's Black Hill station (Figure 2-1), 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 cms (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.

Table 2-1. Stormwater management scenario summary (IT= infiltration trenches, MBR=micro bioretention cells, SF=sand filters, UGS=underground storage, SCM=Stormwater control measures).

Scenario name	SCMs simulated in the 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

2.3.3 Simulating sediment transport

A 1-dimensional (1-D) unsteady hydraulic model of the reach was built utilizing the Hydrologic Engineering Center, River Analysis System (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 modeling 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 2-2 and described in the following sections.

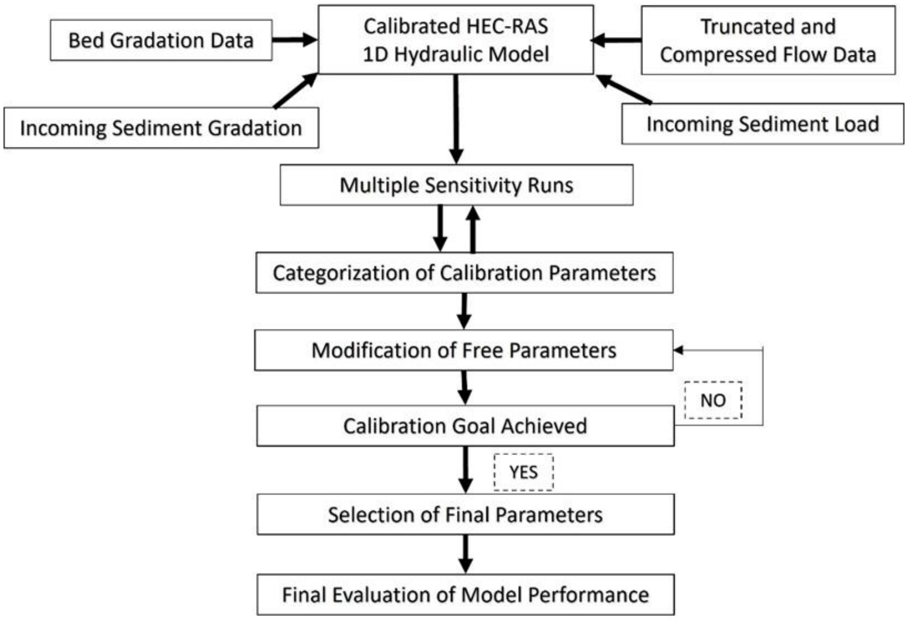


Figure 2-2. Sediment transport model development and calibration framework

2.3.4 HEC-RAS model parameterization

Sediment transport was modeled using the Wilcock and Crowe (2003) method (Wilcock & Crowe, 2003), 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. The Active Layer method (Hirano, 1971) was chosen for the Bed Mixing method because it is the most appropriate for armored 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 modeling 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 d90 (the diameter where ninety percent 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 2-2). These data were collected utilizing continuous turbidity measurements, which were then converted to sediment concentration based on suspended sediment samples from autosamplers. Due to 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 cms discharges were then estimated for the modeled 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 sediment 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 cms value was included in the sediment rating curve to improve model stability during calibration, while the 1.132 cms discharge was included based on field observations by USGS personnel that gravels on the channel bed were mobile at flows of 1.132 cms. The maximum discharge in the observed post-construction record was 9.033 cms, while the 16.991 and 36.881 cms discharges were selected to bracket the maximum peak discharges for the USSC and No SCM SWM scenarios.

Table 2-2. U.S. Geological Survey gages used in the sediment rating curve development. (DA=Drainage Area, Imprv=Imperviousness)

USGS Gage ID	DA (km^2)	Physiographic Province	Distance from study site (km)	% Imprv	Maximum observed flow (cms)
01646305	5.31	Piedmont	31.0	17.6	11.0
01656903	10.88	Piedmont	39.9	24.6	173.0
01654500	9.63	Piedmont	31.7	14.5	22.0
01645762	7.02	Piedmont	38.0	4.8	36.0
01585075	4.74	Coastal Plain	31.4	12.1	2.5
01589290	8.37	Piedmont	81.0	22.2	8.3

Because the largest flood that occurred during the calibration period (2017 -2020) had a peak discharge of 9.033 cms, the sediment rating curve beyond 9.033 cms 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 cms 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 A1 of Appendix A.

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 cms. While little bed sediment transport occurs at low flows, 0.028 cms 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 A2 in the supplementary information.

2.3.5 HEC-RAS 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 2-1b). Locations A2 and A3 are in the modeled reach. In 2017, a stream restoration project was completed in the upper third of the modeled reach, just downstream of Snowden Farm Parkway (B. M. Williams et al., 2022) (Figure 2-1b). 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 material 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 (B. M. 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 A3). 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 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-yr observed post-construction flow record was unavailable for our study site, the performance of the calibrated model was tested by incorporating the 16-yr 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 modelers 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 2-3. The free parameters were modified to obtain the calibration goals.

Table 2-3. Summary of calibration parameters. Free parameters are italicized.

Uncertainty	**Sensitivity**	
	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*

Sediment mass balance and channel profile results of multiple exploratory HEC-RAS model runs with the measured discharge from water years 2017-2020 revealed that the simulated bed change was sensitive to incoming sediment load and gradation. Because the maximum measured discharge post-development was 9.31 cms, the calibration sediment rating curve only had sediment loads defined at 0.02, 1.12, and 9.31 cms. 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 cms (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 modelers 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).

2.3.6 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-yr long rainfall and simulated flow time series were analyzed to delineate storm events with a rainfall depth greater than 2.54 mm and an inter-event time greater than or equal to 6 hrs (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 (Maryland Department of the Environment (MDE), 2000) and durations in multiples of two hrs, similar to the methods adapted by Amur et al. (2022). The median peak flow within each bin was compared across the different SWM scenarios.

2.3.7 Analysis of sediment output results

To allow for evaluating 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, change in cross-sectional area and change in invert elevation. Change in the cross-sectional area was defined as the change in the area between the bank locations at the end of the simulation. Change in invert elevation was defined as the total change in the invert (the lowest elevation station-elevation point between the bank stations of each of the cross-sections) since the beginning of the simulation. 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 river stations did erode to bed rock, 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 & 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 & Bledsoe (2016).

The recurrence interval 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). Due to 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 seven 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 recurrence interval (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).

2.4 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 A4). As described in more detail in the Appendix A, the SWMM model demonstrated good overall agreement with observed data, based on model performance evaluation criteria recommended by N. Moriasi et al. (2015) (Table A2). However, the model overpredicted the maximum flow during both the calibration (2019) and validation period (2020) by 23% and 5%, respectively (see Appendix A).

2.4.1 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 hrs and 205 mm (8.08 in), respectively (Figure 2-3). The average and 5-minute peak rainfall intensities of the delineated storm events were as high as 112 mm/hr and 173 mm/hr, 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 hrs. 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.

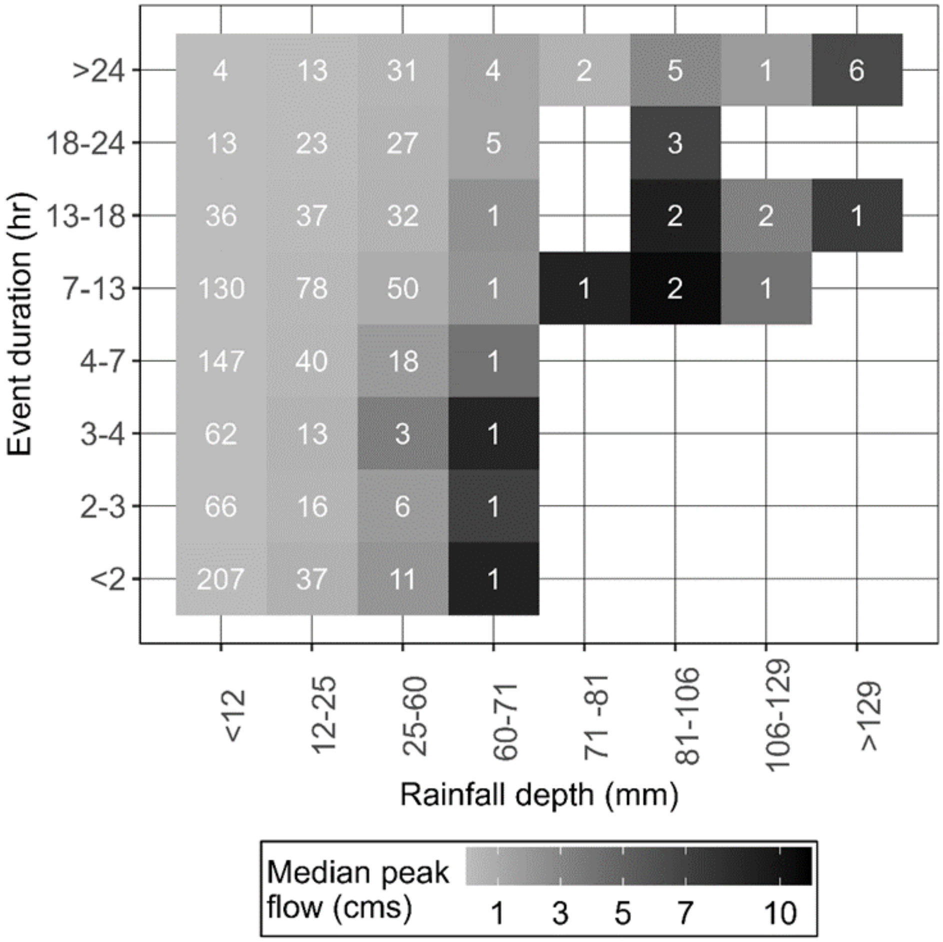


Figure 2-3. Number of storm events within the range of rainfall depth and duration. The shading indicates the median catchment discharge for the unified stormwater sizing criteria (USSC) scenario**.**

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 to the USSC scenario (Figure 2-4). The difference in peak flows arises from the fact that, in the Distributed SWM scenario, runoff is 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 Cpv requirements, resulting in the generation of elevated peak flow at the catchment outlet even during small storm events compared to 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-hr storm event is used to size the pond low-stage outlet structure to provide 12 hr extended detention of the runoff, as per the Maryland requirements for use III/IV waters, with no outflow from the high-stage outlet structure (Maryland Department of the Environment (MDE), 2000). An examination of recorded storm events with depths ranging from 60 mm to 71 mm revealed a wide range of durations, with five events falling within the 18-24-hour range and four events exceeding the 24-hr duration (Figure 2-3). The resulting peak flows at the catchment outlet for the USSC scenario corresponding to these nine storm events ranged from 0.7 to 9 cms, 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 2-3). 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 hrs.

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 2-4). 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 stormwater management systems are designed to treat more frequent rainfall events (Maryland Department of the Environment (MDE), 2000), it is expected that the effectiveness of these systems will decrease as storm depth and/or intensity increase.

2.4.2 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 river stations (RS) 148 and 537 the channel bed is actively degrading, which replicates observed changes in the channel bed (Figure 2-5).

The change in channel invert and bed material d50 and d90 of six RS from the upper, middle, and lower sections of the reach throughout the calibration period are shown in Figure 2-6. It should be noted that the horizontal axis, which denotes the time, only corresponds to those time steps when the incoming stream discharge was greater than 0.028 cms (1 cfs), which was used as an input to the model.

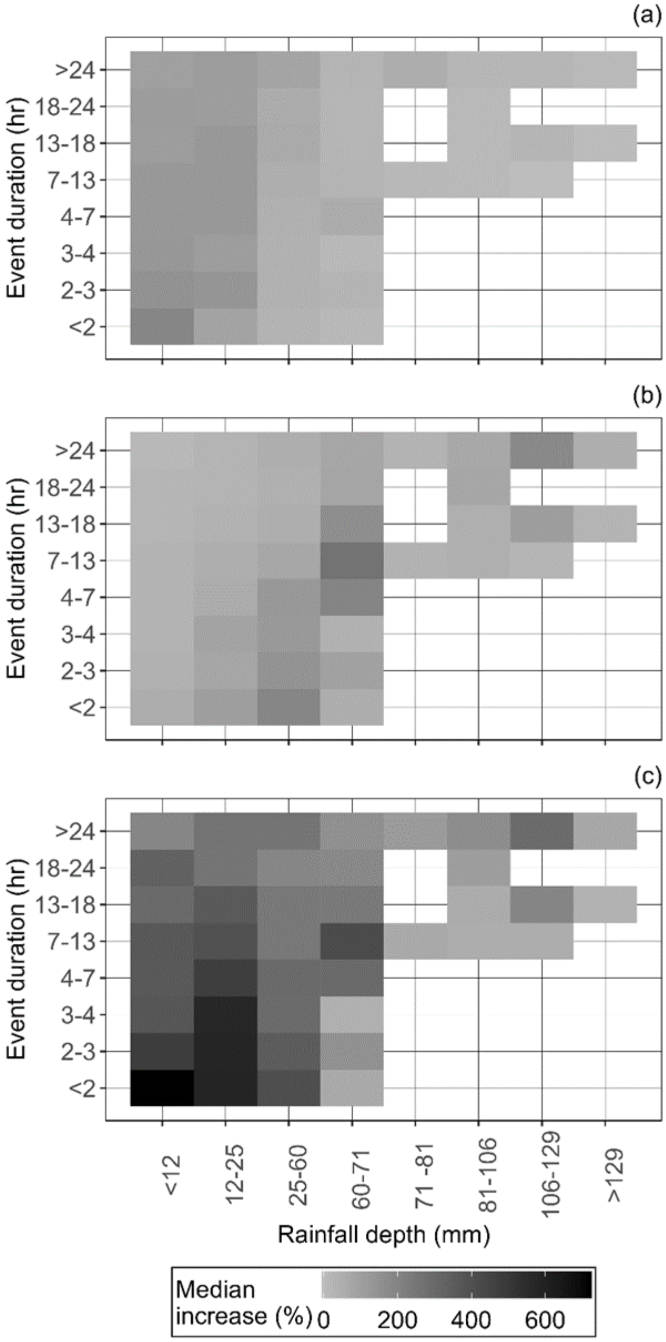


Figure 2-4. The median percent increase in peak flow of the a) Ponds, b) Distributed, and c) No SCM scenarios, as compared to the USSC scenario. (SCM=Stormwater control measures, USSC=Unified stormwater sizing criteria).

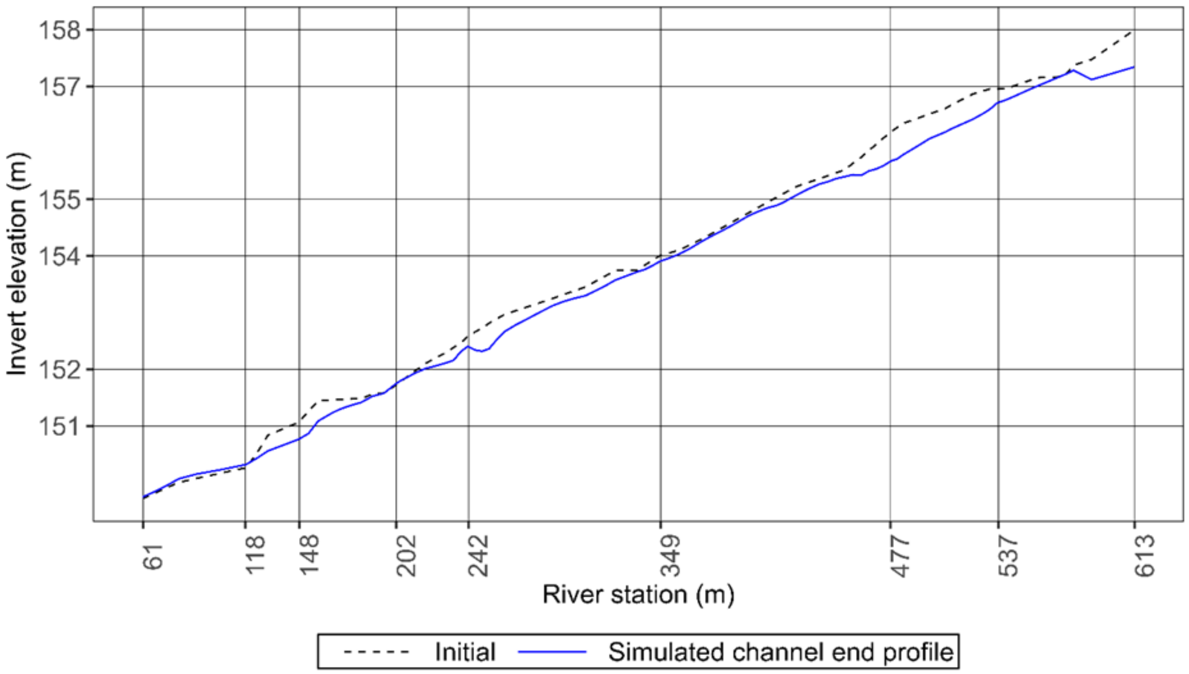


Figure 2-5. Initial and final channel bed profiles during the calibration period (2017-2020).

The time series of invert change (total change in the invert since the beginning of the simulation) (Figure 2-6 b) shows the dynamics of the channel bed as the bed scours on the rising limb of the hydrograph at four of the six river stations and then fills as the flood flows recede. For these river stations, 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 2-6).

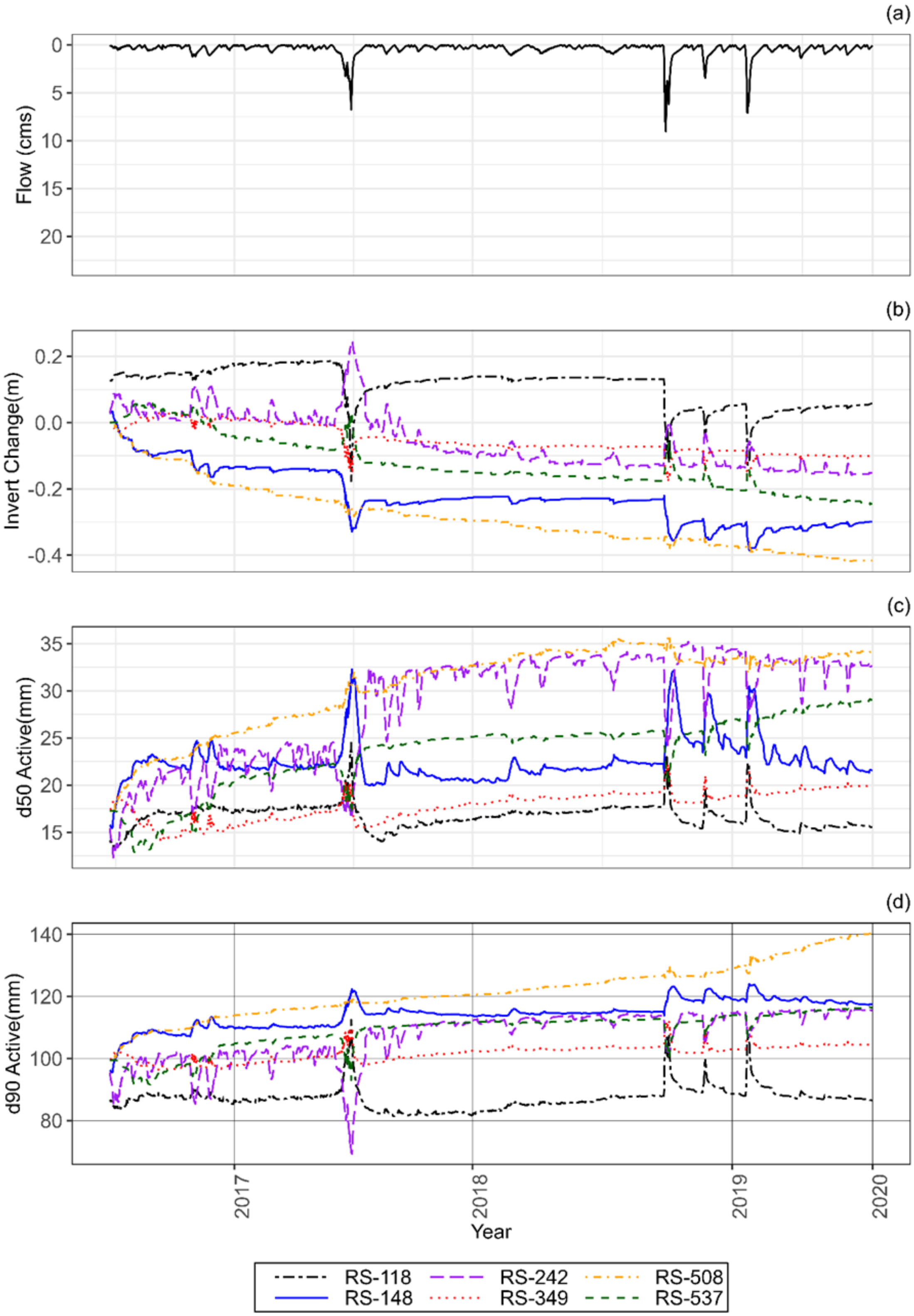


Figure 2-6. Time series of a) flow; b) invert change; c) bed material d_{50}; and, d) bed material d_{90} during the calibration period, 2017-2020. (Note: the time refers to model time, which only includes stream discharges greater than 0.028 cms, RS=River station).

2.4.3 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-yr simulation period, the initial post-development channel degradation observed along Tributary 109 will continue (Figure 2-7). 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 d50 and d90 increase in size) due to the deposition of large clasts, creating a steep riffle at this location (Figure A5b-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 2-7), 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 cms for the USSC scenario.

Comparison of the final channel profiles in Figure 2-7 shows that, while 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 2-8). However, the ranges of these indices 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 river stations 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 river stations remained within the range of +/-0.5 m (Figure 2-8a).

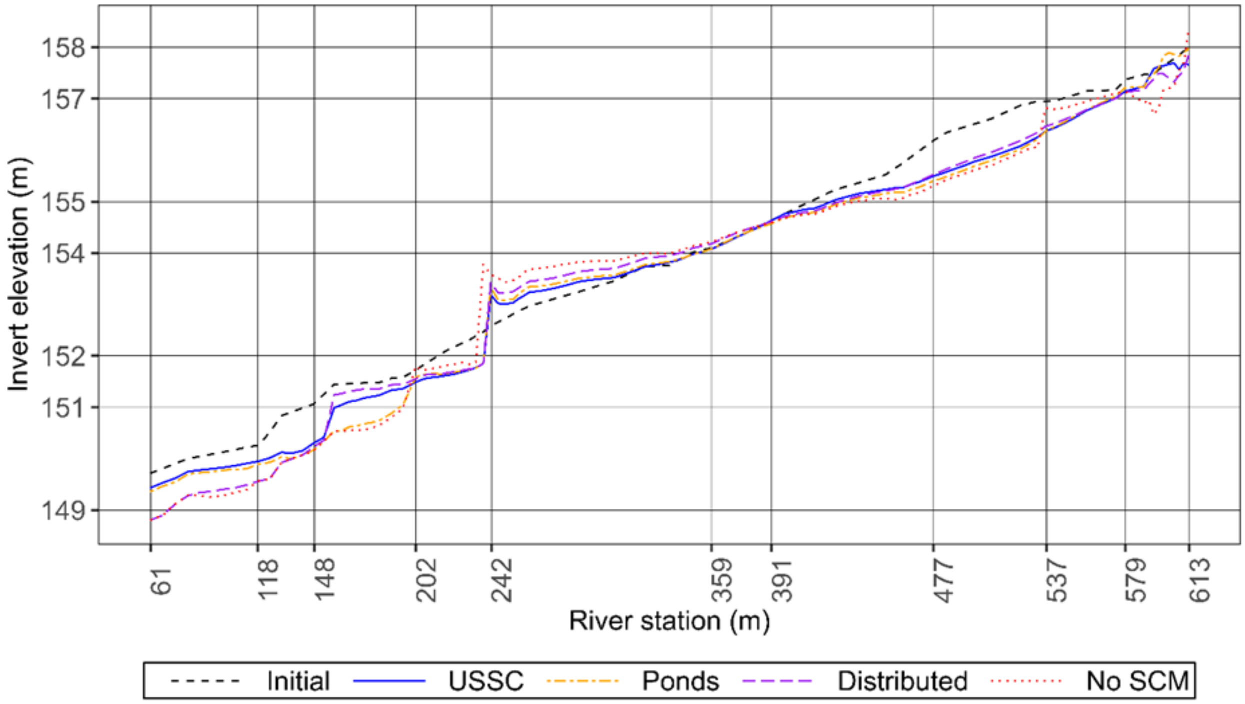


Figure 2-7. Predicted channel longitudinal profile after 16 years under different stormwater management (SWM) scenarios. USSC=Unified Stormwater Sizing Criteria, SCM=Stormwater Control Measures.

2.4.4 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 modeled incoming sediment load is set by the sediment load rating curve and associated gradation (Figure A1 and Figure A2 of Appendix A) 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 composition of the sediment within the channel, the stream gradient, and the channel width all influence the sediment transport potential of the individual model river stations.

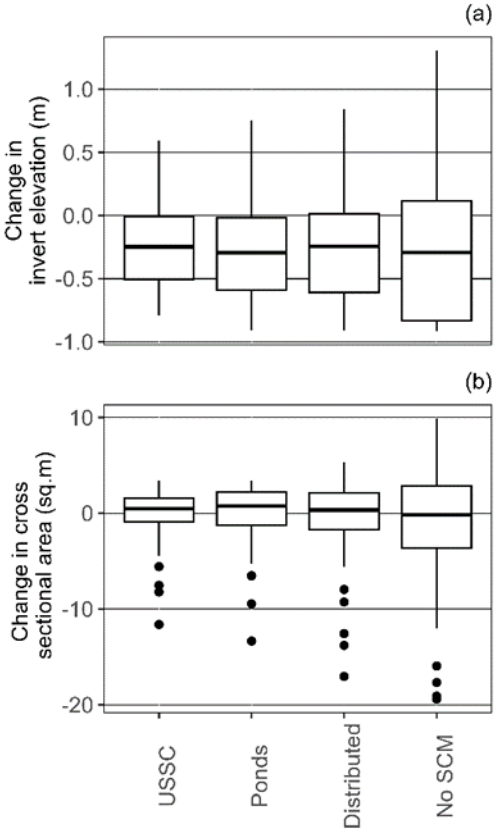


Figure 2-8. Distribution of a) change in invert elevation; and b) change in cross-sectional area of modeled river stations for different stormwater management scenarios. (SCM=Stormwater control measures, USSC=Unified stormwater sizing criteria).

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 2-9. These flow ranges represent the lowest discharge input to the HEC-RAS model (0.02 cms), the flow at which gravel is mobile (1.13 cms), and the flow value at which the water surface elevation reaches the floodplain during the start of simulation for 50% of the river stations (5.89 cms). While the greatest volume of flow into the reach over the simulation period occurs at discharges less than 1.13 cms, most of the sediment delivery into the reach occurs during flows over 5.89 cms. 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 cms is greater in the Distributed scenario. As a result, the Distributed scenario has a greater incoming sediment load compared to 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 cms.

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 cms, 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

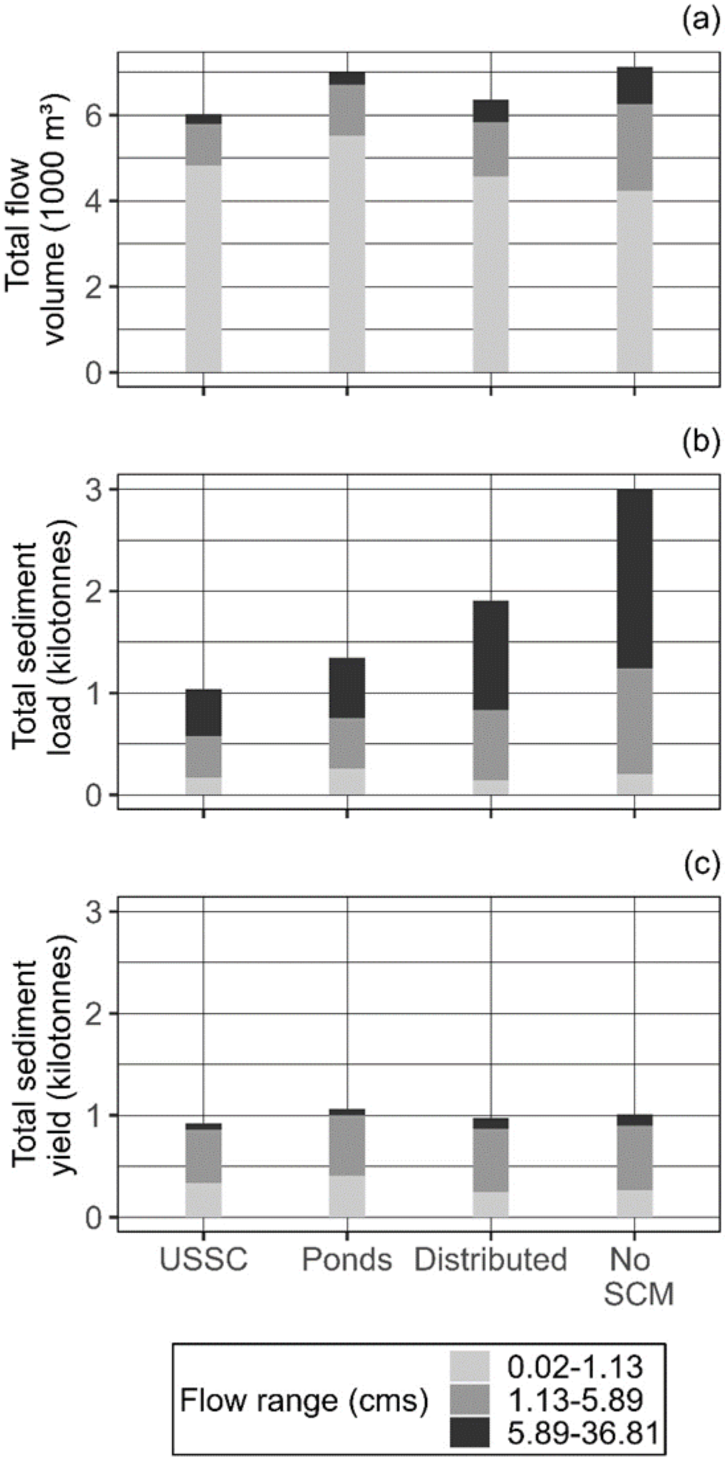


Figure 2-9. Incoming (a) flow volume input to the HEC-RAS model, (b) sediment load, and (c) outgoing sediment yield, as a function of stream flow classes. Discharge cutoffs at 1.13 cms and 5.89 cms are discharges at which gravels become mobile and flow accesses the floodplain, respectively (SCM=Stormwater control measures, USSC=Unified stormwater sizing criteria).

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).

Due to 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.

2.4.5 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 river stations 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 discharge for the USSC and Ponds scenarios was similar (Table 2-4), there was a change in effective discharge and sediment yield-discharge histograms (Figure 2-10) 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 to 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 of than 25.4 mm (Figure 2-4a), the increase in geomorphic work for these small events is negligible (Figure 2-10).

Table 2-4. Values of geomorphically significant flows. The discharge recurrence interval is indicated in parenthesis for different stormwater management scenarios derived from flood frequency analysis using a partial duration series. (SCM=Stormwater control measures, USSC=Unified stormwater sizing criteria).

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

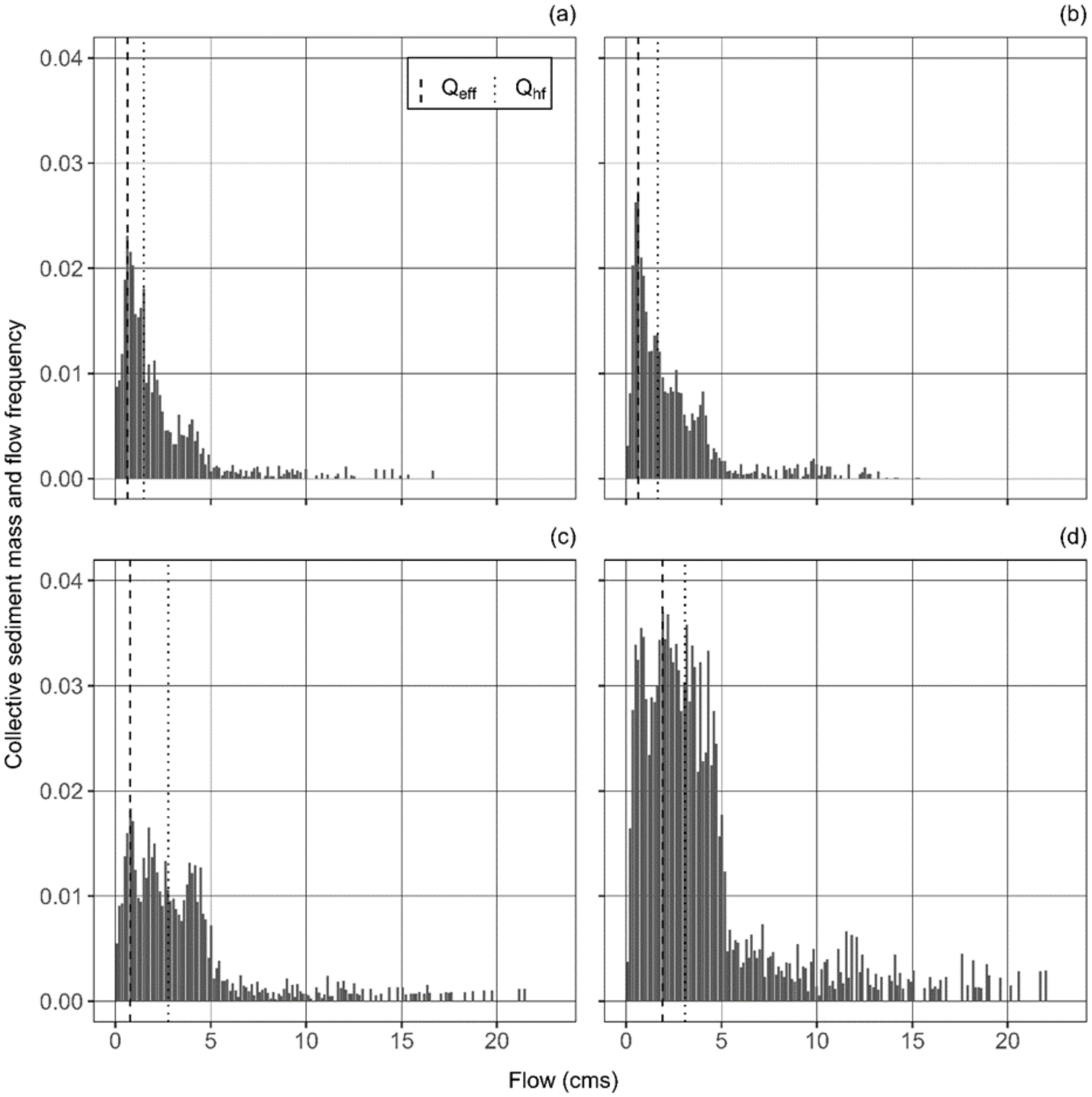


Figure 2-10. Total sediment yield-discharge histogram for a) USSC; b) Ponds; c) Distributed; and d) No SCM scenario along with half-yield (Q_{hf}) and effective (Q_{eff}) discharges indicated by vertical lines. (SCM=Stormwater control measures, USSC=Unified stormwater sizing criteria).

2.5 Discussion

2.5.1 Combination of distributed and end-of-pipe SCMs does not maintain channel stability

A sequential, hierarchical modeling 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 2-8). This model result is supported by repeated cross-section measurements by Montgomery County which documented an increase in channel depth of nearly 0.31 meters within just four years following the development of the catchment area (B. M. Williams et al., 2022). While the implementation of SCMs as per USSC slowed the extent of channel change along the study reach when compared to the No SCM scenario (Figure 2-7), it is predicted the study reach will ultimately be degraded by the urbanization of the upstream watershed (Figure 2-7,8,9). 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-hr design storm duration. However, rainfall-runoff analysis (Figure 2-3) showed that 88% of the recorded storm events had durations less than 18 hours and that the greatest peak flows resulted from storm events with durations less than 24 hours. 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.

Similar discrepancies between observed storm events and design storms 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-yr RI storm event) will protect channel stability (Maryland Department of the Environment (MDE), 2000). However, the key to 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.

2.5.2 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 2-4). This finding is corroborated by comparative catchment studies using monitoring data from surrounding sites in Maryland (Hopkins et al., 2022; Sparkman et al., 2017). Modeling and empirical studies outside of Maryland also show that distributed SCMs provide better runoff control during small events, as compared to end-of-pipe SCMs (Damodaram et al., 2010; Jefferson et al., 2017; E. S. 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.

While there was no statistically significant difference in the median change in channel invert elevation among the four stormwater management scenarios, there was a difference in the range of channel changes (Figure 2-8). 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 2-4a) 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 (Figures 2-10a and 2-10b). 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 2-4b) also led to an increased extent of channel disturbance, as compared to the USSC scenario. This is reflected in a significant skewness towards the right tail of the sediment yield-discharge histograms (Figure 2-10c), resulting in an increase in effective discharge (Q_{eff}), as tabulated in Table 2-4. 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.

2.5.3 Factors affecting modeling outcome

In this study, we adopted a sequential, hierarchical modeling approach that provided valuable insights into the complex interactions between the flow regimes generated by four different stormwater management 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 modeling, 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 modeling 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 sequential modeling 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 sequential SWMM and HEC-RAS modeling 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 due to 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 due to 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 modeled 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).

2.6 Conclusions

In conclusion, our research has highlighted critical insights into the dynamics of stormwater control measures (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 due to 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 stormwater management 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-hr 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 US. Future stormwater management strategies must 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 stormwater management.

2.7 Data availability

The models that were used in this chapter are openly available in HydroShare at: https://doi.org/10.4211/hs.66c7547f746142cba6e769d7b3efaddf.

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Chapter 3 Impact of climate change on storm event-based flow regime and channel stability of urban headwater stream

3.1 Abstract

The projected impact of climate change (CC) on urban stormwater management is well documented due to the recently improved availability of global and regional CC models and associated data. However, most studies are based on simplified design storm analysis and unit-area runoff models but studies on the evaluation of long-term, continuous hydrologic response of extensive stormwater control measures (SCM) implementation under future CC scenarios are limited. Moreover, channel stability in response to CC is seldom evaluated due to the challenge associated with developing a long-term, continuous sediment transport model. The study objective was to evaluate the impact of CC on storm event-based flow regime and channel stability in a small, urbanized catchment (0.9 km2) in Montgomery County, Maryland, USA. This study employed a previously developed and calibrated, sequential hierarchical modeling approach that integrates a watershed-scale Storm Water Management Model (SWMM) with the Hydrologic Engineering Centers River Analysis System (HEC-RAS) to achieve its goal. Ensemble modeling results indicates that conclusions related to CC impacts of SCM-induced flow drawn from simplified, unit area models are different from dynamic, continuous simulations that consider the complexities of real urban catchments and SCM interactions. Despite a general decrease in the total rainfall amount of individual storm events, there is a noted increase in intensity for nearly all future storm events compared to current climatic conditions. This change in storm event-based rainfall pattern is expected to drive the catchment scale hydrology to a flashier regime in the future which in turn is expected to increase the extent of channel erosion compared to the current climate condition. A multicriteria design approach considering the

interplay of multiple SCMs and local sediment transport capacity is thus necessary to ensure channel stability under changing climate.

3.2 Introduction

It is widely recognized that climate change is driving long-term alterations in temperatures and weather patterns globally (USGCRP, 2018). Such variations are expected to intensify the extremes of the hydrological cycle, consequently affecting fluvial (McDowell & James, 2022; Najjar et al., 2010), sedimentary, and geomorphic processes across landscapes (East & Sankey, 2020). Alterations of the hydrological cycle will likely exacerbate the adverse effects of urbanization on urban stream processes due to increased runoff and water temperature (Akinola et al., 2019; Alamdari & Sample, 2019). In response, various innovative and sustainable mitigation measures have been implemented in urban areas to address the combined impacts of urbanization and climate change (CC) on stream processes (Alamdari & Hogue, 2022). These approaches, known under various names such as Green Infrastructure (GI), Low-Impact Development (LID), and Water Sensitive Urban Design (WSUD), and SUDS (Sustainable Urban Drainage Systems), have been adopted to address the environmental challenge of protecting urban waters from development and CC (Bartesaghi Koc et al., 2017). The efficacy of these practices across a range of catchment areas has been extensively documented in numerous studies within the U.S. (Choat et al., 2023). However, a critical gap in these studies is their overreliance on historical precipitation patterns to evaluate the effectiveness of these practices in restoring pre-development hydrologic conditions, without adequately accounting for the effects of CC. Furthermore, existing studies have overlooked a key metric, stream stability, in their assessments perhaps due to the difficulty in predicting or modeling sediment dynamics under changing climatic and land cover conditions.

To effectively isolate the effects of a changing climate on the altered flow regime and sediment transport dynamics within urban catchments equipped with SCMs a continuous, sequential modeling approach is needed. This approach should encompass three main steps: a) post-processing of output from global climate models (GCMs), such as precipitation and temperature data through spatial and temporal downscaling methods; b) translation of the climate-altered data into streamflow projections using a hydrologic model; and, c) simulation of sediment transport dynamics using the projected streamflow data. Current research in this domain predominantly focused on large river basins, generally in support of major infrastructure projects, and often employed a coarse spatial (approximately kilometer scale) and temporal resolution (1 hour or greater) (Goode et al., 2013; Pizzuto et al., 2007; Tian et al., 2020; Verhaar et al., 2010, 2011). As such, there is a significant research gap in the assessment of sediment transport dynamics and SCM-influenced hydrology for small, urban catchments. Predicting sediment transport dynamics in these areas is particularly challenging due to several factors: the inherent uncertainties associated with downscaling GCMs; the scarcity of historic and current data for sediment model calibration; limitations inherent in existing models; and, critically, the complexity involved in accurately simulating small-scale urban rainfall-runoff processes.

Despite the challenges previously mentioned, several recent rainfall-runoff modeling studies have made advances in assessing the effectiveness of SCMs, originally designed based on historical climate conditions, under a variety of spatiotemporally downscaled CC rainfall data sets (Alamdari et al., 2020; Butcher, 2021a; Butcher, Sarkar, et al., 2023a; Giese et al., 2019; Job et al., 2020). These studies suggest that the efficacy of SCMs in managing runoff from increasingly frequent storm events may not diminish in the future under the considered CC scenarios, as the increase in 24-hr rainfall amounts for such events varies (events with recurrence interval upto 2 years), in some cases could be minimal, and may even decrease. Additionally, these studies have shown that the impact of CC on channel erosion could be less severe than anticipated. This conclusion is based on the simplified assumption that climate-induced changes in frequent flows are directly related to stream stability (Bledsoe & Watson, 2001). Consequently, their (Butcher, 2021a; Butcher, Sarkar, et al., 2023b) findings suggest there is no immediate need to adjust local SCM regulations. However, these conclusions are drawn from unit-area rainfall-runoff models that do not account for catchment-scale complexities resulting from changes in subcatchment flood peak timing due to SCM implementation and flow routing through stormwater conveyance systems. Furthermore, Butcher (2021) employed a simplified, semi-quantitative stream stability analysis that does not consider critical factors such as sediment availability, channel shape, slope, and external sediment delivery to the stream (Bledsoe et al., 2007). The latter, in particular, is a major driver of stream instability by numerous field and modeling-based sediment transport studies on urban channels (Masteller et al., 2019; Plumb et al., 2017).

To address the research questions posed within this paper, we aim to build upon existing knowledge regarding the impact of CC on urban stream processes and sediment dynamics. Previous studies have provided valuable insights but have often relied on simplified unit area models. First, we seek to investigate to what extent the conclusions drawn from these earlier studies, based on their simplified models, remain applicable with continuous simulations that consider the complexities of urban catchments. By incorporating long-term CC rainfall data sets into a spatially discretized rainfall-runoff model, we aim to provide a more comprehensive understanding of how changing precipitation patterns and intensities affect urban hydrology. Our model accounts for the presence of multiple SCMs designed according to existing regulations within an urban catchment. This approach allows us to assess how these SCMs perform in the context of evolving climate conditions, including changes in the frequency and magnitude of storm events. Furthermore, we delve into the critical question of how channel stability responds to continuous climate-induced changes in hydrology. Here, we depart from the simplified semi-quantitative stream stability analysis and, instead, employ a continuous calibrated sediment transport model that offers high spatial resolution. This approach allows us to explore the intricate interactions between CC-induced variations in flow regimes, sediment transport dynamics, and channel stability. By considering the complex interplay of factors such as stress history, channel morphology, and external sediment inputs, our study seeks to provide a more nuanced understanding of the potential implications of CC on stream stability within urban environments equipped with multiple SCMs.

By combining high-resolution rainfall-runoff modeling and sediment transport modeling, we aim to contribute valuable insights into the effectiveness of SCMs under evolving climate conditions to provide a more comprehensive understanding of the impacts of CC on channel stability in urban settings. Through these efforts, we hope to provide actionable information for urban planners and policymakers to enhance the resilience of urban catchments in the face of CC.

3.3 Methods

3.3.1 Study site

The site chosen to evaluate channel stability and storm event-based flow regime under changing climate is a small, urbanized catchment (0.9 km^2) located in Montgomery County, Maryland, USA, within the Piedmont physiographic province. The entire catchment falls within the Clarksburg Special Protection Area (CSPA) (Figure 3-1), a designated area subject to strict development guidelines requiring the implementation of both distributed and end-of-pipe SCMs to protect high-quality or unusually sensitive water resources (Jarnagin & Jennings, 2004). The land use and land cover (LULC) of the catchment transitioned from predominately agriculture to suburban development from 2006 to 2017 with total imperviousness increasing from 4 to 45%. The current (post-2017) LULC within the catchment area comprises a blend of detached single-family homes and attached townhouses, complemented by widespread implementation of SCMs adhering to Maryland Department of the Environment's (MDE) 2000 stormwater regulations, which are also referred to as the unified stormwater sizing criteria. These SCMs encompass a range of practices, including conventional end-of-pipe techniques like detention ponds, as well as decentralized SCMs that promote infiltration; the resulting SCM density is 274 per km2 which includes large-scale ponds to small-scale street-side tree boxes. Catchment SCMs were placed in treatment trains where overflows from one SCM were redirected to another SCM before being stored in detention ponds situated close to the main channel. Runoff generated from all impervious areas of the study site was routed through SCMs before discharging to the channel main stem, resulting in a directly connected impervious area (DCIA) of nearly zero. In addition to the structural SCMs, the entire riparian zone of the channel was not developed and can be considered a nonstructural BMP. A 425-m study reach was chosen to simulate the sediment transport dynamics (Figure 3-1). The study reach begins downstream of a culvert and extends to the confluence with another unnamed tributary. All secondary tributaries to the main stem of the channel were replaced with an underground stormwater conveyance system during the construction phase from 2004 -2017. There was also large scale grading during the construction phase prior to 2017 which modified the sediment supply delivery to the reach. However, elevation changes in the forested riparian zone were not observed during the construction phase

(Williams et al., 2022). The study reach has a gravel-bed, riffle-pool morphology with a bed slope of 1.1% and bed material ranging from sands to small boulders.

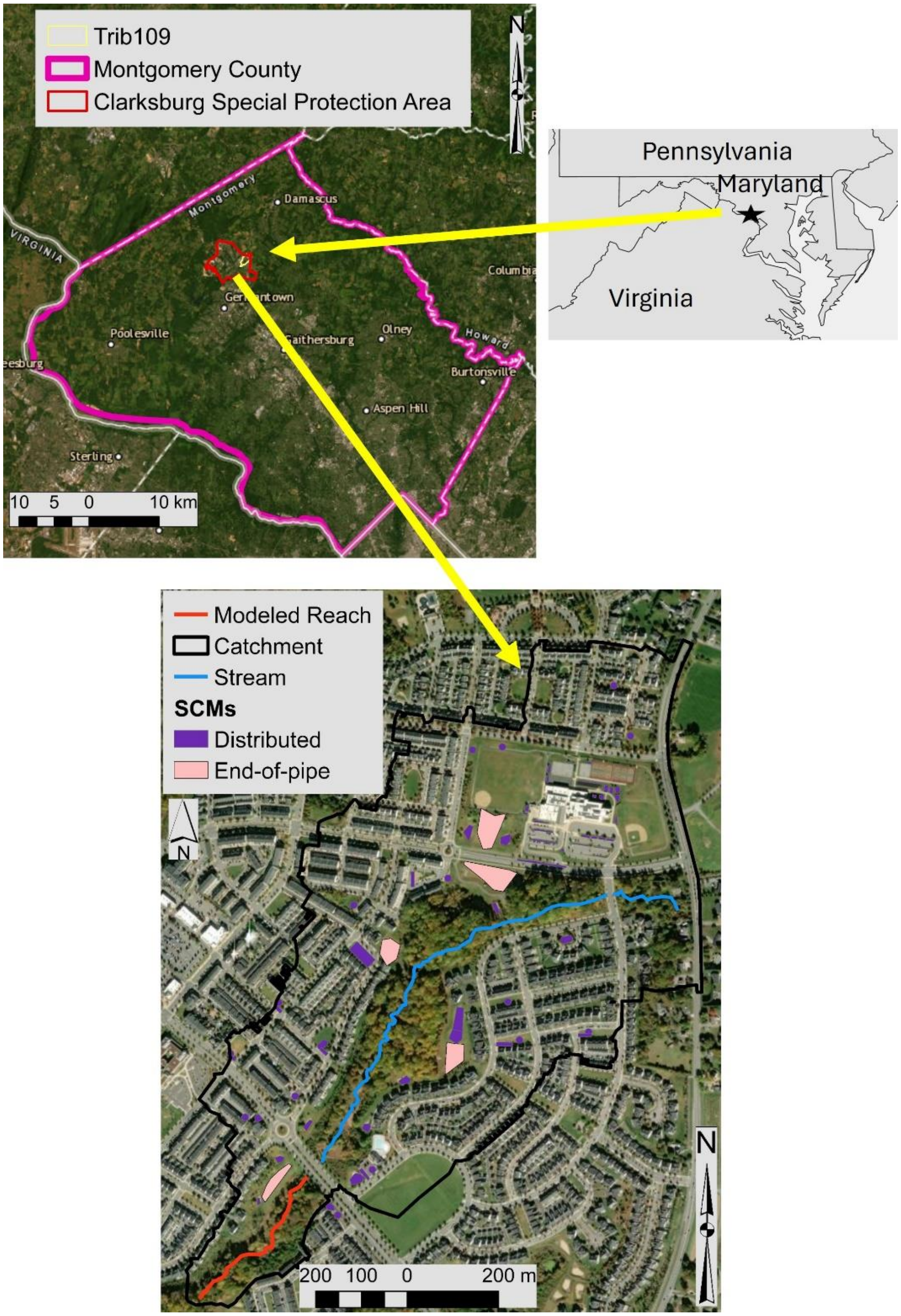

Figure 3-1. Map of Tributary 109 site along with stormwater control methods (SCMs) of the study site.

3.3.2 Input data and model set-up

To evaluate SCM efficacy in protecting channel stability under the current climate, the Storm Water Management Model (SWMM version 5.1.013) and the Hydrologic Engineering Center River Analysis System (HEC-RAS version 6.3) (Brunner, 2022; Rossman, 2015) were utilized in a previous study (Towsif Khan et al., 2024). Details of the model setup and calibration results are documented in Towsif Khan et al. (2024). These paired models were used with rainfall and temperature time series from 16 downscaled CMIP5 GCMs to evaluate the effect of CC on continuous stream flow and sediment transport. This time series included a 5-minute air temperature and rainfall records from water year 2040 to 2099. The selection of these 16 GCMs from the CMIP5 dataset was based on their availability in both Localized Constructed Analogs (LOCA) (Pierce et al., 2014) (Pierce et al., 2014) and Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou & Brown, 2012) downscaling methods. The names of these 16 GCMs are provided in Table B1 of Appendix B. Each of these series in turn contained two series for representative concentration pathways (RCP 4.5 and RCP 8.5) reflecting different future greenhouse gas radiative forcing assumptions. Details about this dataset are described in (Butcher et al., 2023). The rainfall time series of 64 CC scenarios contained values lower than 0.25 mm (0.01 in.) as a result of spatial-temporal downscaling from 24-hr cumulative rainfall depths to 5-min. interval depths. However, due to the inherent limitation of most tipping bucket rain gauges to record trace rainfall below such a low value, these data points were excluded from the analysis. This data filtering process significantly improved the computational efficiency of the SWMM model. Nevertheless, it is important to note that removing these trace rainfall depths led to a reduction in the calculated average annual rainfall by 152 – 180 mm/yr.

The filtered rainfall and temperature time series of the 64 CC scenarios were incorporated into the calibrated SWMM model to obtain streamflow time series under future climate. Two CC scenarios, MIROC-ESM MACA RCP 8.5 and CSIRO-Mk3-6-0 LOCA RCP 4.5, with the highest and lowest rainfall total, respectively, with and without trace rain removal, were incorporated into the SWMM model to compare the effects of the rain time series truncation on the simulated flows. Our findings demonstrated that the cumulative flow volume decreased by approximately 15% as a result of data filtering. However, it is important to note that this filtering had no significant effect on the simulated storm event-based stream flow statistics. Given that sediment transport in gravel-bed rivers predominantly occur during high-flow storm events, this reduction in cumulative flow volume is unlikely to affect the outcomes of our modeling exercise. Additionally, streamflows less than 0.028 cms were excluded from the SWMM flow time series prior to their importation into the calibrated HEC-RAS sediment transport model.

Because sediment transport primarily occurs during storm events, simulated stream flows less than 0.0283 cms (1 cfs) were eliminated to decrease the computation time, given that no bed material transport occurs at low flows. The latest version of HEC-RAS can only utilize input flow time series with less than 40,000 data points, so the truncated flow time series was further compressed. Flows less than 0.283 cms (10 cfs) were grouped while conserving the instantaneous sediment mass delivery at the upstream model boundary and maintaining the total flow duration. This compressed flow time series with irregular flow durations does not conserve the overall flow volume (for flow less than 0.283 cfs) but does conserve the amount of sediment being delivered to the modeled upstream reach. Unlike hydraulics, the sediment transport dynamics in fluvial systems are heavily influenced by the sequence of storm events over longer timespans, a phenomenon called historical contingency (Wohl, 2018). Therefore, to compare the sediment transport dynamics of the CC scenarios with the current climate, the length of the inflow discharge time series must be of the same length. To create a 59-year long flow time series for the current climatic condition, the measured rainfall record from water year 2004 to 2020 at a nearby rain station (Black Hill station) was repeated in series to develop a 59-year long continuous rainfall time series. This synthetic time series was incorporated into the calibrated SWMM model to generate a 59 yr. long continuous streamflow times series for the current climate. The truncated and compressed flow time series for the CC scenarios and the current climate were then incorporated into the calibrated HEC-RAS model, to evaluate sediment transport dynamics and channel stability of the study reach under changing climate.

3.3.3 Storm event and flood frequency analysis

A frequency analysis was conducted for four storm event parameters: storm event peak discharge, total rainfall depth, and average and maximum rainfall intensity to quantify the changes in storm event-based streamflow and rainfall patterns with changing climate. Storm events were identified based on the 5-min. interval rainfall record, employing a rainfall total threshold of 2.54 mm (0.1 in.) and a 6-hr. inter-event period, for both the current climate and CC scenarios. Rainfall attributes of storm events were calculated considering both the rainfall record with and without trace rain removal (< 0.254 mm in 5 minutes). To capture the peak discharge accurately, the end time of each storm event was extended until the streamflow returned to the pre-event baseflow level. This adjustment was necessary due to the typical time lag between the peak rainfall and peak discharge in urbanized streams equipped with SCMs (Hood et al., 2007). Flood frequency analysis (FFA) was performed using a partial duration series (PDS) to provide accurate estimates of peak flows with recurrence interval (RI) less than 5 years, whereas an annual maximum series (AMS) was used for RI of more than 5 years, following the procedures adapted by Towsif Khan et al. (2024).

Several probability distributions were utilized to quantify the changes in the overall shape of the CC peak flow frequency analysis curve (PQDC). A gamma distribution was found to have the superior fit based on the Kolmogorov Smirnov (Goodman, 1954) and chi-squared goodness-of-fit tests (Pearson, 1900). Cheng et al. (2012) also used this distribution to characterize the shape of storm runoff curves from multidecadal streamflow records of 197 catchments across the U.S. The chosen gamma distribution is defined by two parameters: shape and scale. The shape parameter controls the shape of the PQDCs, with a smaller value indicating a steeper slope and flashier flow regime. The scale parameter influences the vertical shift of the curve, with a higher value indicating a stormier flow regime. The probability distribution analysis was performed using the fitdistrplus R package (Delignette-Muller & Dutang, 2015).

3.3.4 Evaluation of sediment transport dynamics

Two indices were calculated (change in cross-sectional area and change in invert elevation) employing methods adapted by Towsif Khan et al. (2024) to quantify and compare the change in channel morphology under changing climate. 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 for each of the two indices to determine if the central tendency of an index for the CC scenario was significantly different from the current climate. A geomorphic work analysis of two characteristic discharges [Effective discharge (Q_{eff}) and Half-yield discharge (Q_{hf})] was conducted for each of the CC scenarios using methods adapted by Towsif Khan et al. (2024). 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). 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 & Bledsoe (2016).

3.4 Results

Similar to previous urban rainfall-runoff studies of projected CC scenarios in the mid-Atlantic region of the US (Alamdari et al., 2020; Butcher, 2021; Butcher, Sarkar, et al., 2023; Giese et al., 2019) we found that the spatiotemporally downscaled GCMs would produce a broad range of aggregated rainfall and simulated runoff amounts at the study site. We have highlighted the results of five representative CC scenarios out of the 64 scenarios evaluated and have provided the upper and lower bounds on the range of CC simulations results to effectively evaluate the results for the complete range of CC simulations in all of the graphical representations of our findings,. These five scenarios were chosen based on the extremes of storm event peak flow distribution (scale parameter of the PQDC) and median change in invert elevations. Additionally, we selected the CC scenario which had the flashiest flow regime defined by the shape parameter of the PQDC. Table 3-1 provides key information on these five CC scenarios and their representation throughout the document.

Table 3-1. Summary of five highlighted climate change scenarios, (GCM = Global Climate Model, DM = Downscaling Method, RCP = Representative Concentration Pathway).

GCM	DM	RCP	Characteristic	Term used to define
CSIRO Mk3.6.0	LOCA	8.5	Greatest Channel Invert Change	Most disturbed
HadGEM2-ES365	LOCA	8.5	Highest Peak Flows	Most stormy
CanESM2	MACA	4.5	Least Channel Invert Change	Least disturbed
MRI-CGCM3	MACA	4.5	Lowest Peak Flows	Least stormy
BCC-CSM1.1	MACA	8.5	Most Flashy	Flashiest

Since the intent of this study was to evaluate the storm event-based streamflow response of catchment scale SCM performance and its impact on stream stability, the results of aggregated rainfall and streamflow metrics are not presented in this paper. Average annual rainfall before and after trace rain removal along with the average annual cumulative streamflow depth is provided in Figure B1 of Appendix B. However, it is worth mentioning that the 16-yr local rainfall record used to represent the current climate condition included annual rainfall totals as much as 37% higher than the NOAA climate normal (1991-2020) of 1206 mm for the US1MDMG0029 station, situated 3.05 km from the catchment.

3.4.1 Projected change in rainfall characteristic of storm events

Three rainfall characteristics (total rainfall depth, average and maximum rainfall intensity) of all delineated storm events were compared for the current climate and all of the 64 CC scenarios. The frequency analysis of these three parameters was conducted using all of the CC rainfall datasets obtained after removing all trace rainfalls (< 0.254 mm in 5 min) (Figure 3-2). The projected total rain depth of all CC scenarios decreased for 98% of the storm events, with a slight increase in the top 1% of the storm events. However, the average intensity of all storm events increased by 150 – 200% due to changing climate, with the amount of change increasing with percent exceedance. This change in average intensity is due to an increase in the peak 5-min rain depth by 50-200% for almost all of the storm events under CC (Figure 3-3). Both results indicate that even though the total rain depth may undergo minimal change due to CC, the storm events will be of shorter duration with higher peak rainfall amounts. The projected increase in increase in air temperature and associated atmospheric moisture holding capacity due to CC also increased the number of cloudburst events. American Meteorological Society defines cloudburst events as storm events with an average rain intensity of more than 100 mm/hr. The existing current climate had no cloudburst event despite it having rain totals higher than the NOAA climate normal (1991-2020). On the contrary, the median number of cloudburst events in the CC scenarios was 6 and each of the CC scenarios had at least 4 cloudburst events (Figure 3-2b).

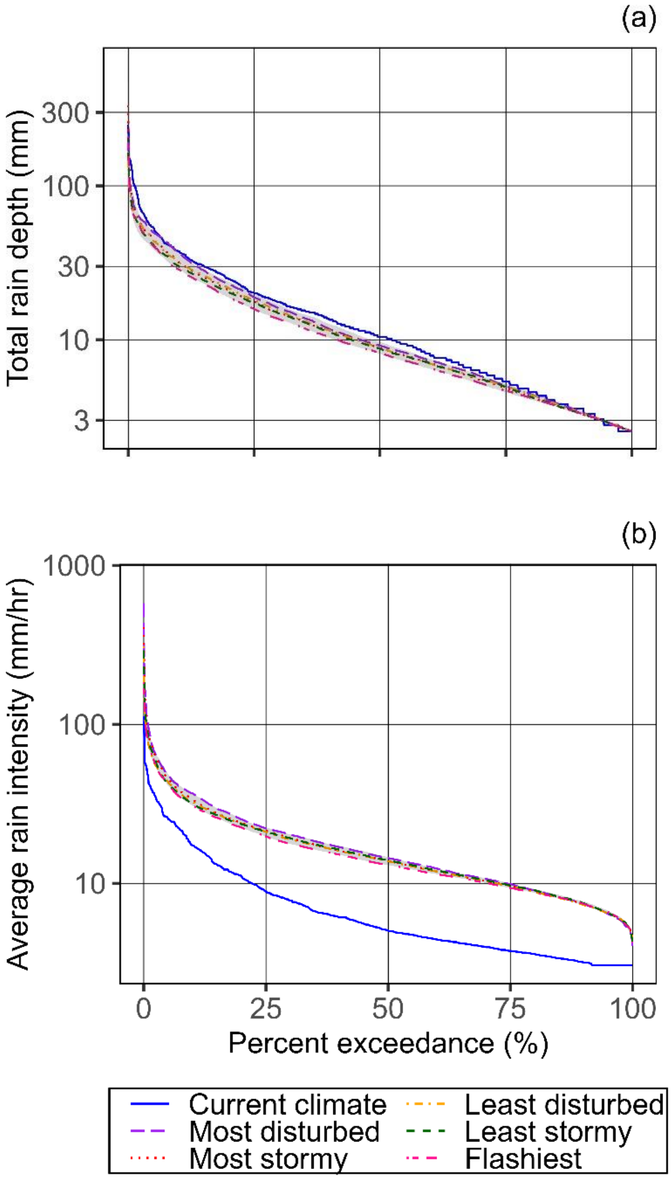

Figure 3-2. Frequency distribution curve of a) total rainfall depth and b) average rainfall intensity of storm events.

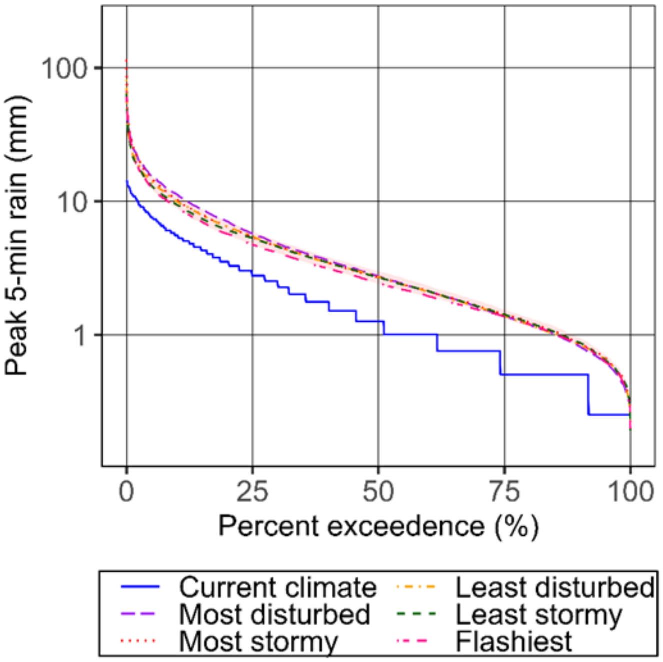

Figure 3-3. Frequency of storm event peak 5-min rainfall depth.

3.4.2 Projected change in storm event-based peak flow

The PQDC frequency distributions developed employing the peak flows of the storm events for the 64 scenarios are shown as a grey band in Figure 3-4, with the five selected CC scenarios and the current climate shown as lines. The Most Stormy and Least Stormy CC scenarios (based on the highest and lowest values of the gamma distribution scale parameter) follow the upper and lower bound of the PQDCs in Figure 3-4, indicating the gamma distribution was adequate to fit the shapes of the curves. The shape and scale parameters of all the 64 CC scenarios along with the five selected scenarios are shown as boxplots in Figure 3-5. The median shape and scale parameters for the CC scenarios are significantly different from the current climate distribution parameters, despite the unusually wet conditions during the measured time period. The shape parameter for the current climate, the inverse of which indicates the extent of the flow regime flashiness, is within the upper 25% of the CC values. Even the Least Stormy and Least Disturbed CC scenarios have flashier flow regimes than the current climate. A similar trend occurs for the scale parameter as well, which indicates the vertical shift of the PQDCs. Even though the median and lower tails of PQDCs shift down due to CC, the upper tails (< 25% exceedance values) shift upward for almost all of the CC scenarios, as compared to the current climate. The logarithmic scale of the vertical axis in Figure 3-4 tends to exaggerate the downward shifts of the curves in the lower tails, but the increase in peak flows from low frequency storm events (<= 25%) is greater than the decrease in peak flows from high frequency storm events (>= 50%) as a result of CC. As a result, this pattern is making the extent of flashiness (denoted by the inverse of the shape parameter of the PQDC, Figure 3-5a) increase in the future for almost 90% of the CC scenarios compared to the current climate condition.

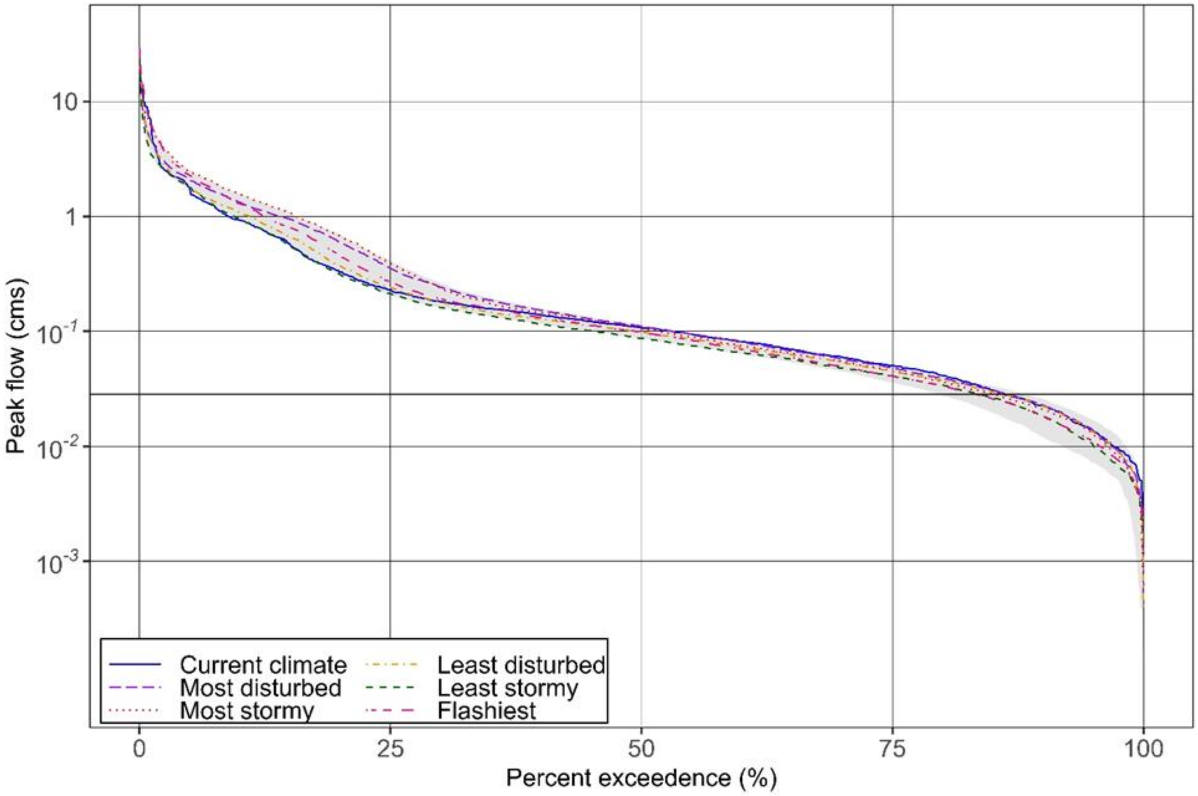

Figure 3-4. Storm event peak flow distribution curve (PQDC) of current climate and climate change scenarios.

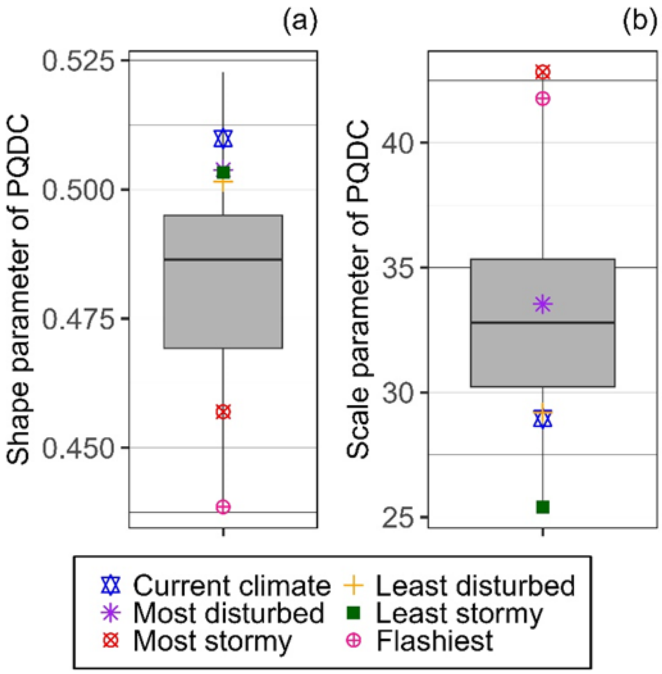

Figure 3-5. Shape and scale parameters of gamma distribution fit of the peak flow distribution curves (PQDC) of the current climate and climate change scenarios.

3.4.3 Projected change in Flood Frequency Analysis (FFA)

Both annual maxima series (AMS) and partial duration series (PDS) were analyzed for the FFA; the peak flows of specific recurrence intervals are presented in Figure 3-6. Consistent with earlier studies of this region (Butcher et al., 2021, 2023), there is a noticeable decline in peak flows for recurrence intervals under 10 years, except in the Most Stormy and Flashiest Climate Change (CC) scenarios, which exhibit higher peak flows at these intervals. Intriguingly, the median peak flow for recurrence intervals of 10 years or more in the CC ensemble results is lower than those observed under current climate conditions, a finding that diverges from previous research in this area (Butcher, 2021; Butcher, Sarkar, et al., 2023). However, this discrepancy is likely because the length of the AMS was only 16 years for the current climate condition, whereas for each of the CC scenarios, it was 59 years.

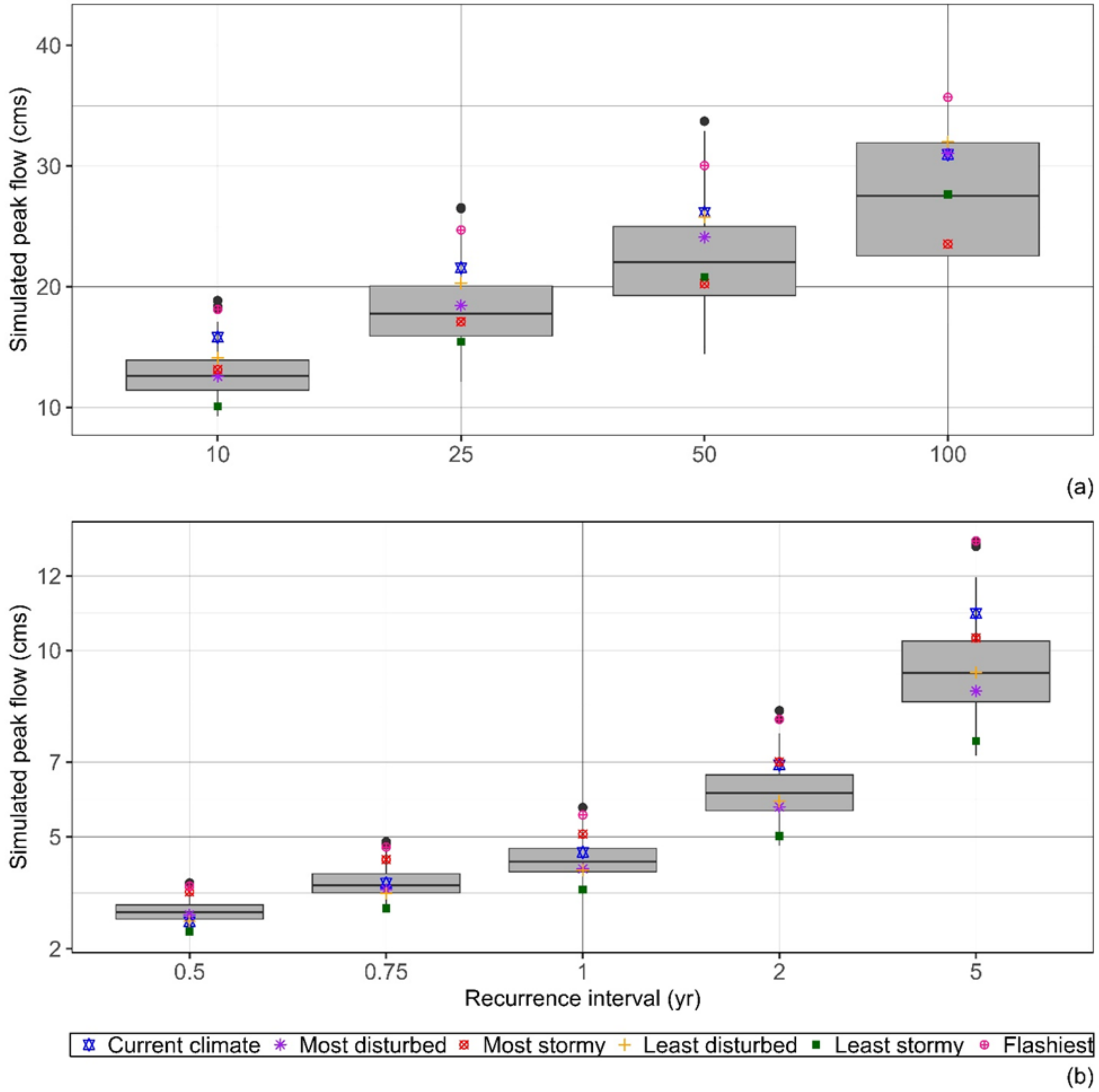

Figure 3-6. Boxplots of simulated climate change scenario peak flows with recurrence intervals of a) 0.5, 0.75, 1, 2, and 5 years, and b) 10, 25, 50, and 100 years.

Moreover, the mean of the AMS of the current climate was significantly higher than the mean of the AMS of the CC scenarios. Both these factors made the peak flows of higher recurrence intervals for current climate conditions very high as per the log Pearson type III distribution.

Studies that performed a comparative analysis of FFA derived from the unequal length of the AMS have also found this issue of overestimation of higher recurrence interval peak flows (Nagy et al., 2017). However, from the simulated AMS of current climate and CC scenarios, it observed that many of the CC scenarios had very high annual peak flows for several years and then had periods of very dry years (Figure 3-7). On the contrary, the AMS of the current climate always had high values with no dry years (Figure 3-7).

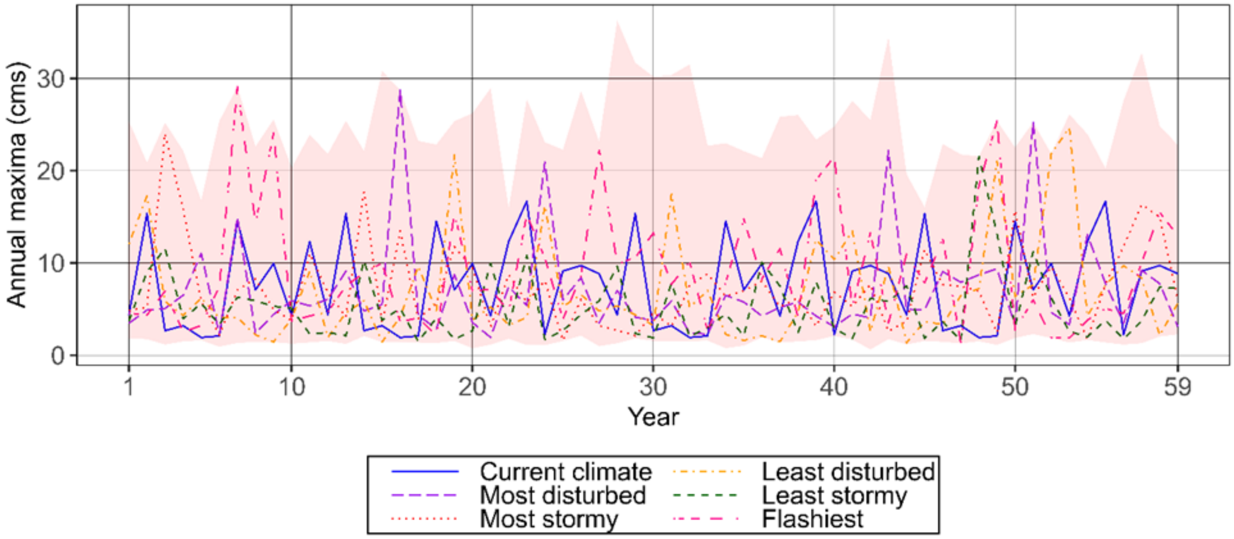

Figure 3-7. Annual maxima series (AMS) of current climate and climate change (CC) simulations. The shaded region shows the range of values from CC simulations.

3.4.4 Predicted long-term changes in the channel profile

Under current climate conditions, even with widespread implementation of SCMs, it is predicted that over the next 59 years, the initial post-development channel degradation observed in the study reach will continue (Figure 3-8). Comparing initial conditions to current conditions, the overall bed profile shows a decrease in bed slope due to a combination of channel degradation and aggradation. This pattern continues for future climate, indicating the channel is adjusting to the increased runoff from development in the catchment. Due to the increased high flows following development, larger bed particles that were stable predevelopment, become mobilized. Model results indicate cobbles (128-256 mm) generally become mobile at flows above 3.4 -4.3 cms, while small boulders (512-1024 mm) are entrained at flows over the range of 7.1-7.7 cms. At RS 242, the channel narrows, causing backwater effects around RS 242, a reduction in sediment transport capacity, and deposition of coarse bed material mobilized from the upper reach. In the most downstream section, the channel bed erodes to bedrock (estimated at 0.9 m below the initial channel invert elevation, Figure 3-8), and a knickpoint forms between RS 158 and RS 118.

Model results indicate that CC will accelerate the long-term channel adjustments predicted under the current climate. Figure 3-8 shows the range of channel bed profiles for the 64 CC scenarios (gray-shaded region). Considering the projected CC, it is anticipated that the magnitude of the largest 25% of peak flows will increase in the future (Figure 3-4), as compared to the current climate. Consequently, the current cobble and boulder particles found in the channel bed, which are typically mobile above discharges of 3.4 and 7.7 cms, respectively, are expected to become mobilized and redeposited in areas of reduced bed shear stress. This process gives rise to the formation of two steep riffles in the channel (RS 536 and 242), altering the channel morphology in response to the increasingly flashy flow regime. Upstream of these two riffles, aggradation is expected to occur, with channel incision occurring downstream. While the exact predicted channel profile depends on the range and sequence of flows for each scenario, the channel is expected to exhibit regions of bed degradation and aggradation as the channel slope decreases in response to the changing hydrology. A boxplot of the median and standard deviation of two indices of channel cross-section change (invert elevation change and cross-

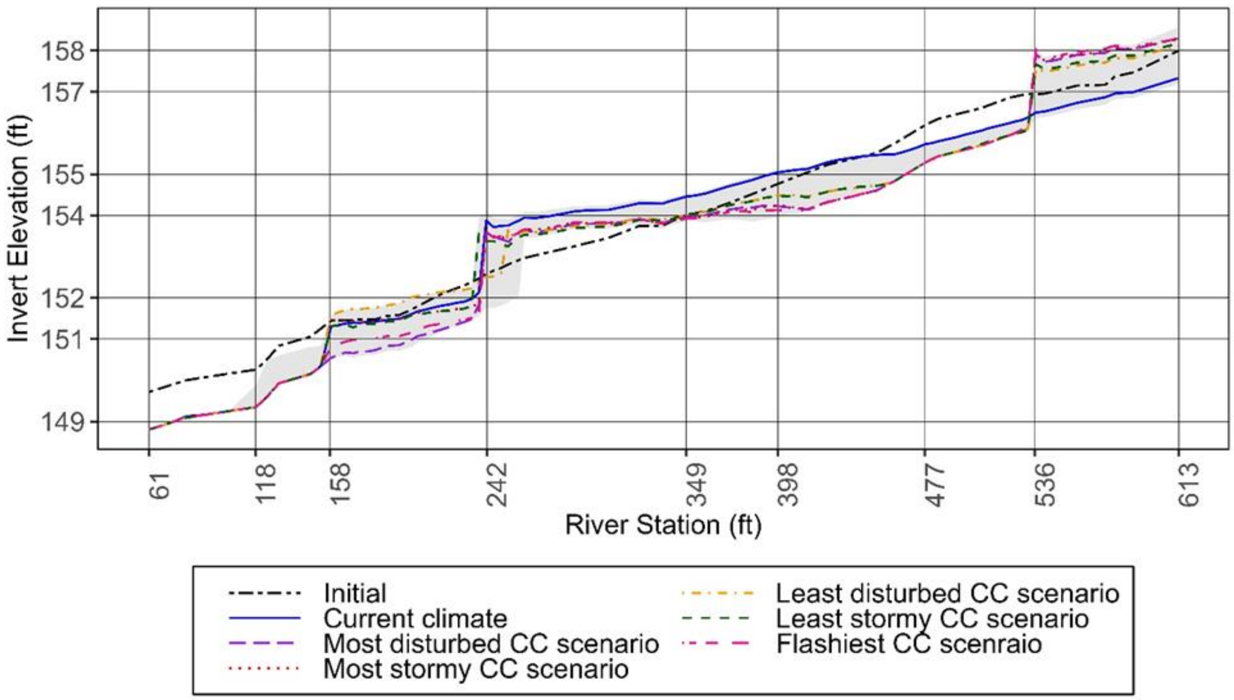

Figure 3-8. Predicted channel longitudinal profile for the current climate, five selected climate change (CC) scenarios, and all CC scenarios (shown as a grey band).

sectional area change) is provided in Figure 3-9. The median invert elevation change, and cross-sectional area change due to erosion is higher in almost 90% of the CC scenarios (Figure 3-9), even the Least Stormy CC scenario experienced more erosion than the current climate condition. The standard deviation of invert elevation for the current climate has also increased due to CC, indicating the extent of both erosional and depositional hotpots along the reach will increase in the future due to the increase of flashiness and shorter event duration of the catchment hydrology.

3.4.5 Impact of climate change on sediment transport dynamics

Channel stability is defined for the purpose of this study as the condition when the sediment supply to the reach is equal to that transport out of the reach. In our case the incoming sediment supply is set by the sediment load rating curve of the calibrated HEC-RAS model (Towsif Khan et al., 2024) and is a function of the number and magnitude of flood events.

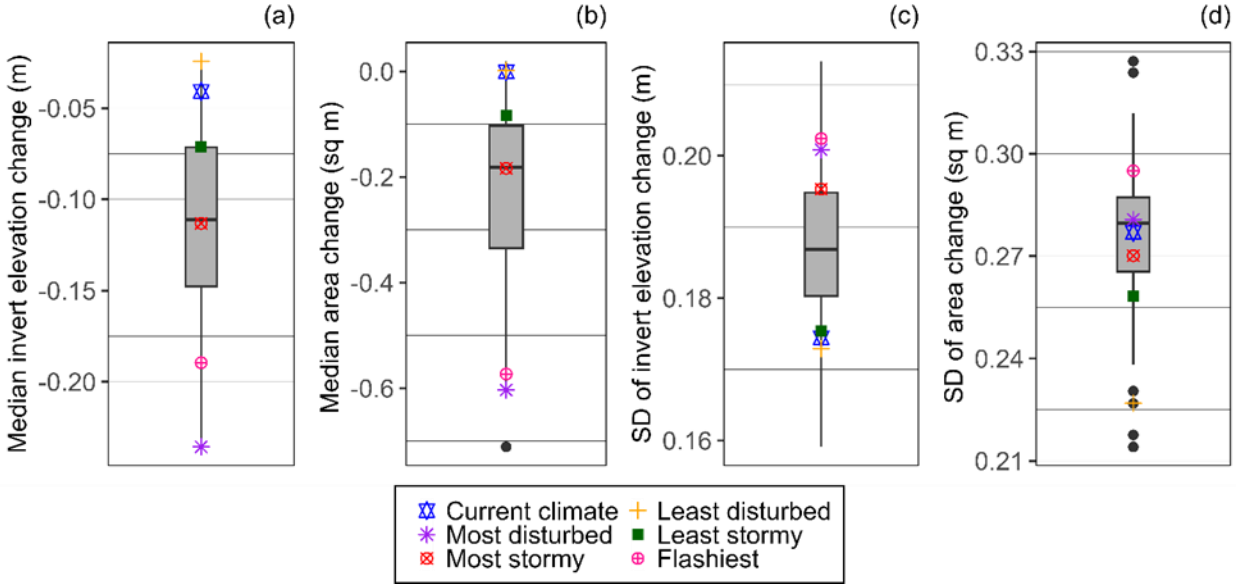

Figure 3-9. Median invert elevation change (a), median cross-section area change (b), standard deviation (SD) of invert elevation change (c), and SD of cross-section area change (d).

On the other hand, the sediment yield, which refers to the sediment amount that left the reach at the downstream end, is computed by the HEC-RAS model and is dependent on the size and composition of the sediment within the channel, the stream gradient, the channel width, and the sediment transport potential of the individual model river stations. The annual incoming sediment supply due to CC is projected to decrease by almost 10 tonnes, with almost 80% of the CC scenarios expected to have a lower sediment supply than the current climate (Figure 3-10a). This is because 70% of the storm events are projected to have lower peak flows in the future due to CC, as evident from the PQDC in Figure 4. Moreover, the incoming sediment load increases at a smaller rate during high flows than during low flows. However, the sediment yield (median of all CC simulations) increased by 1.5 tonnes due to the predicted increase in channel erosion under CC (Figure 3-9a). The sediment yield for all CC scenarios and the current climate condition is much lower than the sediment supply, indicating that even though the channel bed is degrading in some sections, the overall reach is transport-limited, resulting in an increase of overbank deposition within it. Reduced sediment yield occurs at discharges that access the floodplain, indicating that significant sediment storage is occurring on the floodplain. Trimble's (2009) study on the Coon Creek catchment in Wisconsin, showed that sediment yield can be very low relative to the incoming sediment load if there is a very high amount of floodplain storage. Additionally, the amount of sediment deposited on the floodplain is likely overestimated in the calibrated HEC-RAS model. The "veneer" method tends to overpredict floodplain deposition since it spreads a uniform layer of sediment across the entire cross-section with no consideration of diffusion mechanism in the floodplain (Brunner, 2022).

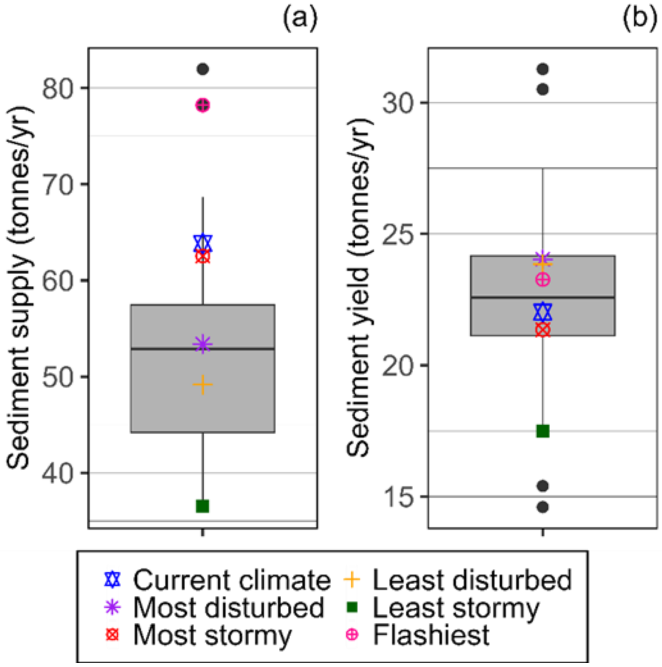

Figure 3-10. Average annual a) sediment supply delivered to the reach, b) sediment yield from the reach, and c) cumulative overbank deposition. CC = climate change.

3.4.6 Predicted 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 least disturbed river stations for each of the 64 selected scenarios along with the current climate condition. The effective discharge calculated for the current climate was 0.63 cms. For 78% of the CC scenarios, the effective discharge increased slightly to 0.77 cms, although this change may have been the result of the flow division method employed to extract the effective discharge values from the magnitude frequency analysis (Biedenharn et al., 2000). In comparison, the Q_{hf} values are expected to increase significantly due to changing climate, with almost 90% of the CC scenarios having higher Q_{hf} than the current climate (Figure 3-11a). The cumulative sediment transport curve (Figure 3-11c) shows the lower flow classes (< 0.5 cms) will transport less sediment, since the peak flows of frequent storm events are expected to decrease substantially due to CC (Figure 3-4).

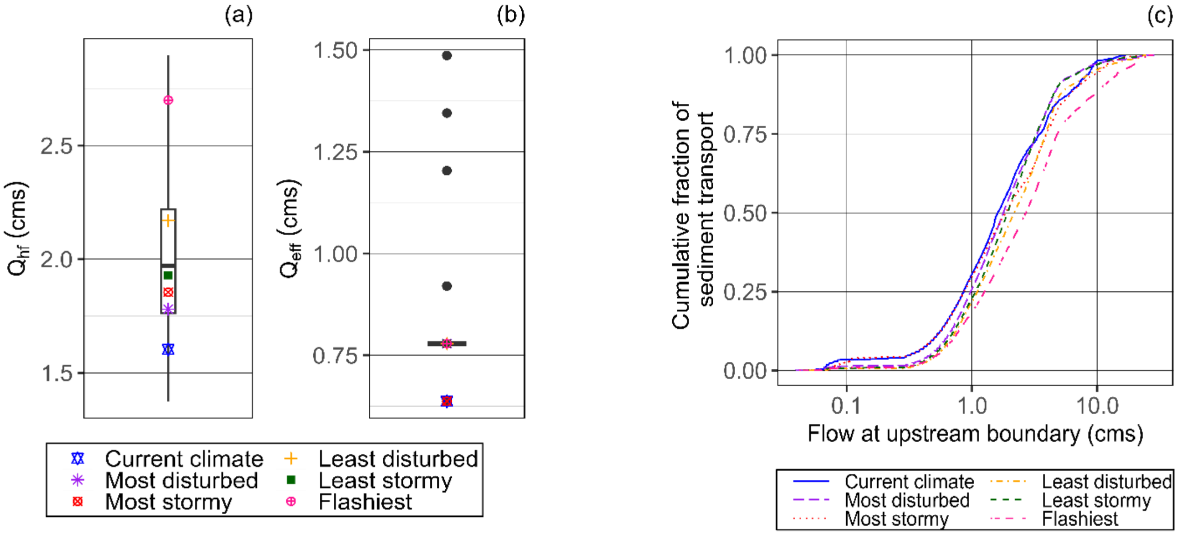

Figure 3-11. Half-yield (Q_{hf}) discharge (a), effective (Q_{eff}) discharge (b), and cumulative sediment transport (c) for the current climate and five selected climate change scenarios.

On the contrary, the proportion of total sediment load transported by higher, less frequent flows will likely increase, as indicated by the rightward shift of the cumulative sediment transport curves for the five highlighted CC scenarios. This pattern indicates that the geomorphic change in the study reach will be governed by the less frequent, high-magnitude flow events due to increased flashiness under the changing climate despite the decrease of cumulative sediment supply to the reach.

3.5 Discussion

A well-calibrated, high-resolution catchment-scale hydrologic model and a reach-scale sediment transport model were implemented with 64 CC scenarios to evaluate the cumulative impact of SCM implementation on stream stability under changing climate conditions. Based on a meta-analysis of results from CC studies (Butcher, 2021; Butcher, Sarkar, et al., 2023) which were done on a unit-area basis and a generic riverscape, we hypothesized that the current observed trend of channel disturbance at the study site would not get worse under changing climate. We made this assumption based on the fact that previous CC rainfall-runoff studies of this region projected small changes in low-magnitude, high recurrence storm events (Butcher, 2021; Butcher, Sarkar, et al., 2023), which typically control channel morphology. However, analysis of the expected changes in channel invert elevation show that the studied reach is expected to degrade over many decades, developing alternate regions of aggradation and degradation due to the changes in watershed hydrology caused by urbanization under both current and future climate conditions. Interestingly, even as the total sediment supply to the reach is projected to decrease in the future due to the decrease in peak flows of 70% of the storm events, the magnitude of channel invert elevation changes will be significantly greater compared to the current climate conditions. It is important to note that these findings and subsequent conclusions are contingent upon the outputs of the GCMs used to derive the precipitation datasets and the reliability of the sediment rating curve and model. Therefore, the applicability of our results may be limited to the specific scenarios and models employed in this study.

3.5.1 Storm event intensification under changing climate

Following the prevailing trends observed in CC impact studies concerning the rainfall patterns in the mid-Atlantic US, our findings align with the consensus that the total precipitation associated with frequent storm events is anticipated to decrease in the future, while there will be a substantial rise in less frequent storm events (Figure 3-2a) (Butcher, 2021; Butcher, Sarkar, et al., 2023). However, a more in-depth analysis of the specific characteristics of individual storm events has unveiled a distinct pattern – the intensity of nearly all storm events is projected to increase in the future, with a maximum amount of 5-min. rainfall during these events potentially increases by 150-200% when compared to current climate conditions (Figure 3-2b,c). This change in storm event-based rainfall pattern is expected to drive the catchment hydrology to a flashier regime in the future (Figure 3-5)..

Empirical studies that have monitored rainfall-runoff dynamics in this region have demonstrated that the peak flow in urban headwater streams is predominantly influenced by the intensity of rainfall rather than the total precipitation depth (Bell et al., 2020; Hopkins et al., 2020, 2022). Given this, one might expect that the peak flow of all storm events would increase under CC. However, our modeling results reveal a different result– while there is indeed an increase in the peak flow of the top 25% of storm events, there is a decrease in the peak flow of the remaining storm events (Figure 3-4). This counterintuitive finding can be attributed to the fact that the top 25% of storm events are typically characterized by rainfall depths exceeding 25 mm (Figure 1a), referred to as the Water Quality Volume (WQv) design rainfall depth as per the stormwater regulations the state of Maryland. The stormwater control measures (SCMs) employed in the catchments to mitigate runoff associated with storm events exceeding 25 mm are designed based on the Natural Resources Conservation Service (NRCS) Type II 24-hour rainfall distribution with an average rainfall intensity of only 2.75 mm/hr, which features considerably lower rainfall intensities than what is observed during all storm events under the CC scenarios. On the other hand, storm events with rainfall depths less than 25 mm are generally managed by smaller-scale distributed SCMs designed primarily based on volume control regulations. Consequently, even though there is an increase in the rain intensity for these smaller storm events under CC, the resulting peak flows did not increase. This phenomenon has shifted the lower half of the PQDC downward, as compared to the current climate conditions (Figure 3-4).

Annual rainfall-runoff metrics, when used to evaluate the impact of climate change, can potentially misrepresent the changing climate dynamics in urban catchments. This issue is evident in studies from the mid-Atlantic region, such as those by Alamdari (2018), Alamdari et al. (2022), and Giese et al. (2019), where the median change in annual rainfall due to climate change, relative to current climate conditions, was within the range of 5-10%. Such a seemingly modest increase in annual rainfall might lead to an underestimation of the severity of climate change impacts in urban landscapes. This underestimation arises particularly because of a shift in the temporal pattern of individual storm events, which are increasingly characterized by high-intensity, short-duration storms. The application of temporally downscaled, high-resolution climate datasets was crucial in identifying these patterns. Additionally, the rising air temperatures and the corresponding increase in atmospheric moisture holding capacity have been linked to the occurrence of cloudburst events in future scenarios for all climate change projections. Although such extreme events have not been observed under the current climatic conditions at our study site, cloudbursts causing urban flash floods have already been reported in various regions of the United States (Rosenzweig et al., 2019). SCMs designed based on the Soil Conservation Service's (SCS) 24-hour rainfall duration are likely to be inadequate in handling such cloudburst events (Hathaway et al., 2024). However, it is important to note that the occurrence of such high-intensity events could also be an artifact of the downscaled climate projections, which tend to increase the uncertainty surrounding extreme storm events (Lopez-Cantu et al., 2020).

3.5.2 Stream stability under changing climate

Recent studies on stream stability employing unit area flow models and generic riverscapes have yielded conclusions that suggest a less severe impact of CC on stream stability compared to current climatic conditions (Butcher, 2021). These conclusions rely on the assumptions that the n-year, 24-hour storm event corresponds to the n-year flood event/peak flow and that the risk to stream stability is low if the 1 or 1.5-year peak flow remains unchanged in a changing climate compared to current climate. However, our comprehensive combined modeling exercises reveal a contrasting perspective. We find that the extent of channel degradation in our study area is expected to increase in the future when compared to current climate conditions, despite a decrease in the 1 or 1.5-year peak flow at the catchment scale (Figure 3-5). In fact, in nearly 80 to 90% of the CC scenarios, there is a notable increase in the median channel invert and cross-sectional area change compared to the current climate condition. This trend arises from several factors. First, while the annual peak flow remains lower in 75% of the CC scenarios, there is a marked increase in the occurrence of high-magnitude events across almost all CC scenarios. Moreover, approximately 25% of the storm events within the CC ensemble exhibit higher peak flows than those observed under current climate conditions (Figure 3-4). These elevated peak flows mobilize larger bed particles within the stream reach, subsequently leading to their redeposition in areas with reduced sediment transport capacity. The shortened transport distances of these larger bed particles can also be attributed, in part, to the flashier and shorter duration of storm events under the changing climate. Previous research by Annable et al. (2012) and Plumb et al. (2017) demonstrated that increased flashiness and shorter event durations due to urbanization lead to frequent yet shorter travel distances for larger bed particles in gravel-bed rivers, consequently resulting in increased topographic variability of the channel bed. In our study reach, this increased topographic variability due to CC is evidenced by the formation of two steep riffles (RS 536 and 242, Figure 3-8), in contrast to the single steep riffle observed under current climate conditions (RS 242, Figure 3-8).

Although the average annual sediment supply to the reach tends to decrease in the future, the median of the average annual sediment yield increases when compared to the current climate. This discrepancy stems from the fact that while sediment supply is influenced by the sediment rating curve and the catchment scale flow regime, sediment yield is also affected by local sediment availability factors at individual river stations. This indicates that the sediment transport dynamics of urban headwater streams are heavily influenced by altered flow regimes due to SCM installation, as well as a range of local sediment supply factors (Berteni et al., 2018; Plumb et al., 2017). Thus, relying solely on peak flows of specific recurrence intervals is likely to yield misleading results regarding stream stability.

Two geomorphically significant discharges were analyzed and compared across the current climate and the five sets of CC scenarios from the paired sediment yield and flow time series of the least disturbed river stations. Much to our surprise, the effective discharge (Q_{eff}), which is the most common geomorphically significant metric used as an indicator for stream stability (Biedenharn et al., 2000), did not change under changing climate when compared to the current condition. This could be attributed to the computational procedure used to determine Q_{eff}, which tends to skew the flow time series histogram towards more frequent events when using high-resolution datasets (Lenzi et al., 2006). However, the median half-yield discharge (Q_{hf}) increased by 50% due to CC, which shows that the geomorphic work of the reach would be influenced by larger, less frequent discharges. Towsif Khan et. al. (2024) also reported such an increase in Q_{hf} for this study reach when all the SCMs were excluded from the catchment. This shift towards episodic, high-magnitude events rather than frequent flows implies that stream stability becomes more influenced by extreme events as flow flashiness increases. This observation is supported by a prior study that reported similar effects when SCMs were removed from the SWMM catchment model (Towsif Khan et al., 2024). Addressing these emerging challenges will be complex, especially considering that under current stormwater regulations, SCMs are seldom designed to accommodate catastrophic rare events due to cost constraints.

3.5.3 Implications to stormwater design regulations

Rainfall-runoff studies and channel stability assessments conducted on a unit-area basis within generic riverscapes in Maryland have indicated that, under the current CC scenario, there is no pressing need to modify the state's stormwater regulations. However, our research, employing continuous sequential models of an existing catchment, presents slightly different findings. In line with previous studies (Butcher, 2021; Nover et al., 2016) we observed a decrease in stream peak flow with CC for storm events with rain depths up to 25 mm, following the Water Quality Volume (WQv) requirements for the Maryland 2000 stormwater regulations.

Nevertheless, our study highlights an urgent need to revise the design regulations related to the Channel Protection Volume (Cpv) criterion. The Cpv criterion is designed to detain runoff from a 1-year, 24-hour storm event for 12 or 24 hours, theoretically controlling bankfull and sub-bankfull discharges post-development. Contrary to the implication of 'volume' in its name, the design procedure for the Cpv depends on calculating a peak flow based on the Soil Conservation Service (SCS) Type II 24-hour rainfall distribution (Natural Resources Conservation Service, 1986) followed by sizing an outlet structure to detain this peak inflow for the specified duration (12 or 24 hrs). While our findings concur with a general decrease in rainfall amounts for most storm events, including those with a 1-year recurrence interval, however, we predict a significant increase in the intensity of nearly all storm events in the future due to increases in maximum 5-min rainfalls and shorter rainfall durations. Furthermore, it is critical to recognize that individual SCMs are often designed without considering the response of other SCMs in the watershed. The peak discharge at any point in a catchment in response to a given storm event is not solely dependent on the peak discharges from contributing sub-catchments, but also on the timing of when those individual sub-catchment peaks converge at a given location in the drainage system (Goff & Gentry, 2006). Designing each SCM individually simplifies the design process, but to effectively protect the stability of small channels, it is imperative to consider the cumulative impact of multiple SCMs on the receiving stream, as well as the sediment transport capacity of the downstream channel. It is thus necessary to consider the complexities of hydrograph timing, as well as discharge peaks and durations due to SCM interactions, and local sediment transport capacity of the channel when designing and implementing stormwater management strategies. A multicriteria design approach considering the interplay of multiple SCMs and local sediment transport capacity, is expected to yield a consistent trend of peak flows at the catchment level in response to the changing climate, given that the total volume of rainfall is less influenced by climate variations.

3.6 Conclusions

A well-calibrated, high-resolution catchment-scale hydrological model and a continuous sediment transport model were utilized with rainfall and temperature data from 64 different CC scenarios to evaluate the impact of SCM implementation on stream stability under changing climate. The hypothesis was that the current trend of channel disturbance would not worsen due to small projected changes for low-magnitude, high-recurrence storm events. However, the models indicate that the studied reach is expected to degrade over a period of decades due to urbanization and CC. The total sediment supply to the reach is projected to decrease, but the magnitude of channel invert elevation changes will differ significantly (decrease due to erosion) from current conditions. These findings depend on the GCMs used for precipitation datasets, limiting the applicability to specific scenarios and models. The study results align with the consensus that total precipitation from frequent storm events will decrease, while less frequent storm events will intensify. Despite a general decrease in total rainfall amount for most events, there will likely be noted increases in intensity for nearly all future storm events.

The design of individual SCMs often overlooks the cumulative impact of development and stormwater management systems on catchment hydrology. The peak discharge at a catchment point depends not just on upstream peak discharges, but also on the timing of these peaks. Effective protection of small channels requires consideration of the cumulative hydrologic impact of multiple SCMs on local sediment transport capacity. Adjusting stormwater regulations to use a multicriteria design approach which considers SCM interactions using a catchment scale model and local sediment transport capacity is essential to protecting channel stability under changing climate.

3.7 Data availability

The models that were used in this chapter are openly available in HydroShare at: https://doi.org/10.4211/hs.b29b912d122d490181f1d98a91f11c8b

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Chapter 4 Assessing the efficacy of stormwater control measure retrofits in maintaining channel stability in an urbanized catchment

4.1 Abstract

The hydrological 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 regulations, mandating the combined use of distributed and end-of-pipe SCMs, fall short of maintaining channel stability, despite their effectiveness in reducing runoff from impervious surfaces. The study objective was to evaluate the effect of SCM retrofits on channel stability in a small, urbanized catchment (0.9 km^2) in Montgomery County, Maryland, USA. This study employed a calibrated, coupled hierarchical modeling approach, integrating a watershed-scale Storm Water Management Model (SWMM) with the Hydrologic Engineering Center River Analysis System (HEC-RAS). A three-step methodology was developed using the calibrated SWMM and HEC-RAS models: (1) establish the pre-development scenario; (2) redesign existing SCMs for channel stability under design storm conditions; and (3) assess scenario effectiveness through continuous simulations. The modeling results revealed that SCM design aimed at matching the sediment transport of the pre-development catchment for design storms can reduce channel disturbance in the receiving stream, as compared to designs based on hydrologic targets only. However, tests of the redesigned SCMs using continuous simulation indicate channel change would still occur as a result of catchment urbanization. Nevertheless, alternate SCM design requirements, such as matching pre-development sediment transport amount show promise for minimizing the impact of urban development on stream channel degradation.

4.2 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 sediments. Originally, stormwater conveyance systems were designed to quickly and efficiently transport this large volume of runoff from urban areas to downstream water bodies, typically without any treatment (National Research Council, 2009). This expedited removal of runoff significantly impacts both the water quantity and quality of urban streams, prompting urban communities to implement stormwater control measures (SCMs) to store, infiltrate, 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 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), 2000). This framework has been subsequently adopted by 11 other states and the District of Columbia. The primary objective of SCM runoff detention in these jurisdictions is to protect downstream channels from erosion through the use of storage-based SCMs like ponds, detention basins, or wetlands. These structures are designed to provide either 12- or 24-hr extended detention of the runoff generated from a 1-yr, 24-hr design storm event so that flows in the downstream channel stay below bankfull or near bankfull levels (Maryland Department of the Environment (MDE), 2000).

The implementation pace of SCMs in urban catchments has surpassed our understanding of their effectiveness in reducing erosion and ensuring channel stability on a catchment scale. The hydrologic benefits of SCMs in mitigating the adverse effects of urbanization are well recognized in Maryland and other regions of the US (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 & Watson, 2001; McCuen & 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. Recent studies using stream bed mobility data have revealed that the actual critical discharge of urban streams is often much higher than theoretical estimates (Hawley, Russell, & Olinde, 2022; Russell et al., 2020). Design storm sediment transport analyses by Bledsoe (2002) and McCuen & Moglen (1988), using generic landscape data, found that SCMs designed with a peak flow reduction approach could prolong and increase the frequency of erosional events in streams. This increased erosion occurs because SCM designs typically do not take into account site-specific critical shear stresses, leading to controlled release rates that extend the duration of erosional events, causing geomorphic instability. Towsif Khan et al. (2024a) performed a decade-scale sediment transport analysis of a headwater stream in Maryland using a calibrated, coupled modeling approach and documented that a system of SCMs designed following USSC did not maintain channel stability following catchment urbanization.

Streams in urban environments typically have two to three times higher sediment transport capacity than in the pre-development condition (Bledsoe, 2002; Hawley, Russell, & Taniguchi-Quan, 2022). Moreover, following urbanization, the sediment supply dynamics are also altered (Russell et al., 2017). Ensuring channel stability in urban streams thus requires a rebalancing of sediment transport capacity by flow mitigation. Bledsoe (2002) conducted preliminary modeling analyses to evaluate the efficacy of SCM in reducing channel erosion. They showed that an SCM designed to provide the same cumulative sediment transport amount as the predevelopment condition needs to be 60% larger than an SCM designed with the peak flow control approach. Hawley et al. (2022a) monitored three urban streams in the USA and in Australia where upstream SCMs were retrofitted to match the sediment transport capacity of the pre-development sediment regime. Their monitoring results showed the streams in the USA, which drained catchments with very low levels of imperviousness, displayed reduced visual evidence of erosion and instability following the SCM retrofitting. However, the stream in Australia, in the catchment with the highest amount of total imperviousness, continued undergoing erosion and bank failure.

This study aims to evaluate the cumulative efficacy of SCMs, designed to meet bed sediment-based targets, in protecting channel stability. While some previous studies have conducted preliminary modeling analyses of SCM design to reduce channel erosion in generic landscapes (Bledsoe, 2002; McCuen & Moglen, 1988), to our knowledge, no studies have evaluated the effects of SCM in a real-world site using continuous simulation. Therefore, the aim of this study was to 1) develop procedures for realistic SCM designs that are based on the transport of bed sediment in the downstream channel and 2) evaluate the effects of these SCM designs in protecting channel stability with a long-term simulation. The sequential modeling approach utilizing SWMM and HEC-RAS, developed by Towsif Khan et al. (2024), was used to achieve these goals because it allows for an explicit representation of a wide range of SCMs in the SWMM model and a reliable representation of the downstream channel in HEC-RAS.

4.3 Methodology

4.3.1 Study site and background

The site chosen to evaluate the impacts of SCM design is a small, urbanized catchment (0.9 km^2.) located in Montgomery County, Maryland, USA, within the Piedmont Physiographic Province. Details about this site are presented in Towsif Khan et al. (2024a, 2024b).

A coupled hierarchical modeling approach was developed and applied inby Towsif Khan et al. (2024a, 2024b) to examine projected changes in sediment transport and channel geometry for the modeled reach draining the catchment. The modeling approach was based on continuous discharge from a watershed-scale SWMM model representing the most recent (post-2017) land use land cover (LULC) of the area driven by an observed climate time series and a range of spatiotemporally downscaled CC precipitation scenarios. Changes in the modeled reach were estimated using HEC-RAS. Ensemble simulation results showed that even with the extensive implementation of USSC and 70 SCMs, the studied reach is expected to degrade further over the next several decades, developing alternate regions of degradation and aggradation due to the changes in watershed hydrology caused by urbanization under both current and future climate conditions. Study results show that the channel will respond similarly under climate change as under the current climate conditions by developing regions of aggradation and degradation that ultimately reduce the channel slope and sediment transport capacity. Stormwater regulations employing the Unified Stormwater Sizing Criteria (USSC) require a 12 or 24-hour extended detention runoff from a developed site for the 1-year, 24-hour storm event. This requirement is based on the assumption that detaining the runoff volume from a 1-yr to 2-yr, 24-hr storm event will protect channel stability. Results from Towsif Khan et al. (2024b, 2024a) predicted that this regulation would not protect channel stability and that climate changes will accelerate the extent of channel degradation, as compared to current climate conditions.

To evaluate the effectiveness of SCM design following criteria based on bed material transport in achieving stream stability following urbanization, a three-step approach was developed using calibrated SWMM and HEC-RAS models. Details of the approach are described in the following sections.

4.3.2 Establishing baseline scenarios

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) (Metes & Jones, 2021) from the year 2002. This model was then used to establish the pre-development baseline conditions of the receiving stream. This pre-development SWMM model of the study area was calibrated to a single storm event (July 06, 2006) using discharge data from the USGS gage. Due to the short time span between when the gage was established and the initiation of development, only one measured storm event was suitable 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 reflects 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. The main purpose of this model was to generate a runoff time series in response to specific design storm rainfall for the calculation of the pre-development cumulative bed material transport amount and effective work criteria, which are described in the following section.

4.3.3 SCM retrofitting for channel stability

Maintaining channel stability following urbanization requires design requirements that address bed material transport in the receiving stream (Bledsoe, 2002; McCuen & Moglen, 1988). Two methods were evaluated at a single cross-section within the reach. The existing catchment SCMs, which were designed following the USSC method, were redesigned to achieve the same cumulative bed material transport amount or effective work as the pre-development condition.

4.3.4 Calculation of erosion potential ratio

To reduce the negative impacts of urbanization, the Erosion Ppotential (Ep) scenario involved redesigning the existing SCMs in such a way that the cumulative bed material transport mass at the catchment outlet did not exceed the pre-development transport mass for a range of standard design storms commonly used in stormwater management (e.g. 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, 24-hour storm events). The ratio of the total mass of bed sediment transported for the urban or post-development flow condition and the pre-development condition is called the “Erosion potential Ratio” (E_{pr}, (Bledsoe, 2002)),

$$E_{pr} = \frac{\sum_{t=0}^{T} Qs_{post}}{\sum_{t=0}^{T} Qs_{pre}}$$

where Qs was the sediment transport mass (tonnes) and “post” and “pre” represented the post- and pre-development scenario, respectively. For this study, Qs were calculated using the

Wilcock and Crowe sediment transport equation (Wilcock & Crowe, 2003). Calculation of E_{pr} facilitated the determination of whether the existing and redesigned watershed SCMs altered the watershed hydrology such that the receiving stream transported the same amount of bed material as before development for a wide range of design storms. A time increment of five minutes was used in the calculation of E_{pr} and T was two days (48 hrs) because, in the redesigned SCM scenario, it took almost two days for the SCMs to drain due to the adjustment of the SCM outlet structures to further reduce peak flows. 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-hour rainfall depth with recurrence intervals of 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year was converted to rainfall hyetographs using a Soil Conservation Service (SCS) Type II storm distribution and the resulting hyetograph was incorporated into the SWMM model of the respective scenarios (pre- or post- development) to generate flow time series for the calculation of E_{pr}. The rainfall depths were obtained from the Maryland Department of the Environment's Stormwater Design Manual (Maryland Department of the Environment, 2000) and are shown in Table 4-1.

Table 4-1. Design storm depths for stormwater control measure design in Maryland (Maryland Department of the Environment, 2000).

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

Outlet structures for all the storage SCMs and the inlet structure of one storage SCM were modified to ensure that the proposed retrofit condition E_{pr} was less than or equal to 1. The exact dimensions of the original and modified outlets are presented in Table C1 of Appendix C and location of the redesigned storage-based SCMs are provided in Figure C1 of the Appendix C. The inlet structure of one storage SCM, which is the outlet structure of two distributed SCMs immediately upstream of it, were raised by 0.4 m. The initial outlet modifications included reducing the opening size of the low-stage outlets and raising the high-stage outlet inverts for all the selected SCMs to decrease E_{pr} as much as possible. During these modifications, care was taken to ensure that the total height of the riser structure did not exceed the height of the emergency spillway. Subsequently, additional intermediate-stage outlets were added to allow the slow release of stored water. The outlet structure modifications of all the existing storage SCMs only reduced E_{pr} to 1.16 and 1.07 for the 1- and 2-yr design storm, respectively. To achieve an $E_{pr} \leq 1.00$ for these two design storms would have required the installation of an in-stream storage pond in the catchment, which was considered infeasible from a regulatory standpoint. E_{pr} for all other design storms were less than 1.00.

4.3.5 Calculation of effective work

To evaluate the susceptibility of the channel to erosion, an effective work analysis was performed for the study watershed employing methods developed by Brennan et al. (2018). The incipient motion of bed particles exists when the force applied by the fluid (applied shear stress) is greater than the minimum amount of force needed to move those particles (critical shear stress). 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 time. The total amount of time the applied shear stress exceeds the critical shear stress is known as the erosion hour (Eh). The effective work (Ew) was assessed at the same cross-section which was used in the Ep scenario as follows:

$$E_w = \sum (\tau - \tau_c) v t$$

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).

Outlet structures for all the storage SCMs and the inlet structure of one storage SCM were modified in such a way that Eh and Ew for the proposed retrofit conditions were less than the corresponding values in the pre-development condition for the range of design storms specified in Table 4-1. The methodology for SCM design to meet the Eh and Ew criteria was the same as for the Ep criterion, except that the riser structures of only two ED ponds were increased, as compared to all five pond riser structures for the Ep scenario.

An outline of these SCM retrofitting methods is provided in Table 4-2 and specific details about the outline configuration modifications are provided in Table C1 of Appendix C.

Table 4-2. Summary of stormwater control measure (SCM) retrofitting scenarios.

Attribute	Erosion potential (E_p)	Effective Wwork (EW)
Key variable(s) calculated	Cumulative bed sediment transport in tonnes (Q_s) employing any reach-representative sediment transport equation.	Effective work (Ew) and duration (Eh) 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 pre-development conditions by retrofitting existing and/or designing new SCMs for selected design storms.	Keep Ew and Eh the same or less than pre-development conditions using adjusted and/or new SCMs for selected design storms.
Data Requirement	• 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.

Attribute	Erosion potential (E_p)	Effective Wwork (EW)
SCM Modifications Required	• Modification of outlet structures (both size and elevation) of all 5 existing ponds. • The berm heights of 2 SCMs immediately upstream of one pond were raised by 0.4 m to decrease the inflow rate to the pond.	• Modification of low-stage and intermediate-stage outlet structures (both size and elevation) of all 5 existing ponds. • The riser structure of 2 existing ponds were increased. • The berm heights of 2 SCMs immediately upstream of one pond were raised by 0.4 m to decrease the inflow rate to the pond.

4.3.6 Evaluation of retrofit scenarios

The SWMM models of the Ew and Ep scenarios were run with the precipitation record of current climate conditions for the 2004-2020 period. The flow time series of these two SWMM scenarios were then incorporated into the calibrated HEC-RAS model (Towsif Khan et al., 2024a) to evaluate the performance of the SCM design scenarios in protecting channel stability under current climate conditions. Table 4-3 provides key information on these two design scenarios and their representation throughout the document. The continuous time series of cross-section shape, longitudinal bed profile, and sediment transport rates were exported from the standard HEC-RAS HDF file of each of these scenarios to R (Wickham et al., 2019) to evaluate the effects of the retrofitted scenarios on sediment transport dynamics and channel morphology.

Table 4-3. Summary of mitigation scenarios. Ew = Effective work, Ep= Erosion potential.

Scenario	Mitigation Actions
Ep	Reduce low-stage outlet diameter Add intermediate-stage outlet Increase high-stage outlet diameter Increase high-stage outlet elevation of five ponds

Scenario	Mitigation Actions
Ew	Reduce low-stage outlet diameter Add intermediate-stage outlet Increase high-stage outlet diameter Increase high-stage outlet elevation of two ponds

4.4 Results

4.4.1 Mitigation scenario performance under design storms

Despite the widespread implementation of SCMs designed as per the USSC regulations, the cumulative mass of bed material transported in the receiving stream following development (Qs_{post}) was almost double that of the pre-development condition for the 1-year and 2-year design storms (Table 4-4). In contrast, the Ep of the existing SCMs was less than 1.0 for design storms with a recurrence interval greater than five years, indicating the most significant increase in sediment transport amount due to urbanization was associated with more frequent flows (Rosburg et al., 2017).

All existing extended detention (ED) ponds in the Trib 109 catchment were sized to capture and detain the 1-yr, 24-hr design storm runoff for 12 hours; the USSC do not require maintenance of pre-development peak flow rates unless downstream flooding is a concern (Figure 4-1). A recent study that compared event-based streamflow metrics from the study watershed with a nearby forested watershed also pointed out the failure of the USSC to maintain pre-development hydrology (Hopkins et al., 2020). Both the Ew and Ep scenarios resulted in the peak flow from a 1-yr, 24-hr design storm peak flow that was close to the pre-development discharge, but the volume and duration of lower flows during the hydrograph recession were increased. 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 baseflows than the pre-development watershed. The 5-yr design storm peak flow for the Ew scenario was higher than for the Ep scenario since the riser structures of only two smaller ponds were raised in the Ew scenario, as opposed to the risers of all five ponds in the Ep scenario. The Eh and Ew for the pre-development, USSC and Ew scenarios are presented in Table 4-4. The magnitude and duration of the effective work for the pre-development condition is zero for the 1- and 2-yr storm events, which indicates bed particles equal to or larger than the d_{50} are not mobilized during those events.

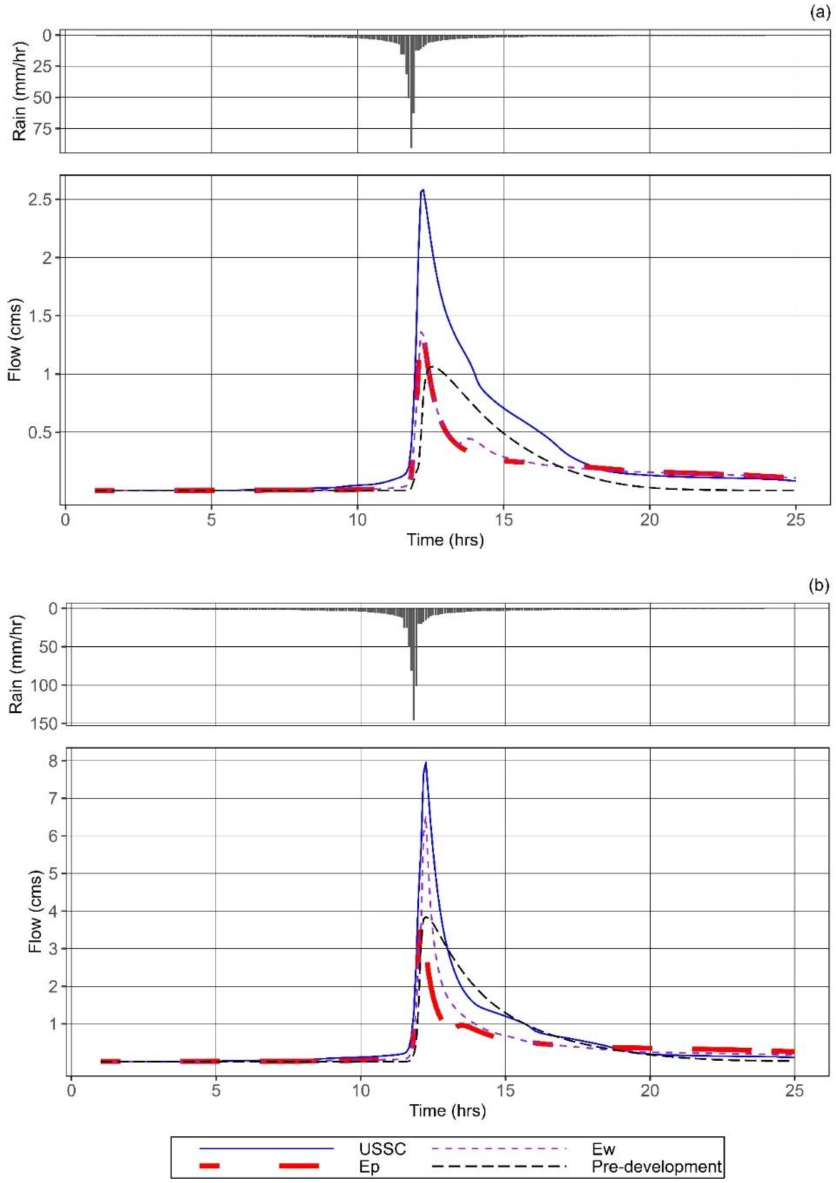
Table 4-4. Values of erosion potential ratio (E_{pr}), erosional hour (E_h), and effective work (E_w) parameters for the different stormwater management scenarios. USSC= Unified Stormwater Sizing Criteria. Qs = total mass of sediment transported per design storm event.

Scenario	**Parameter**	**Storm type** **1-yr., 24-hr.**	**2-yr., 24-hr.**	**5-yr., 24-hr.**
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	34.00
USSC	Q_s (tonnes)	21.3	34.5	59.5
	E_{pr}	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
	E_{pr}	3.45	2.01	1.06
Erosion Potential	Q_s (tonnes)	11.6	19.3	33.3
	E_{pr}	1.16	1.07	0.77
Effective Work	Q_s (tonnes)	11.9	19.1	40.7
	E_h (hr)	0.00	0.00	0.83
	E_w (kJ/m^2)	0.00	0.00	32.7
	E_{pr}	1.00	0.98	0.74

Sediment transport amounts for the pre-development, Ep, and Ew scenarios are presented in Table 4-4. Notably, the peak flows for the 1-year storm in the Ew and Ep scenarios are the same, due to all these scenarios having similar low to intermediate stage outlets in the ponds. However, for the 5-year storm event, the peak flow in the Ew scenario is close to that of the current USSC. This is because the Ew scenario only involved modifications to the high-stage outlets and the riser structure elevation of only two terminal ponds; the elevations of the risers for the three other terminal ponds were same as the USSC scenario.

4.4.2 Changes in peak flows

The 16-year rainfall time series utilized for evaluating the design scenarios included several high-magnitude storm events. Specifically, there were seven storm events with rainfall depths exceeding those of a 10-yr recurrence interval design storm, as depicted in Figure 4-2. The median change in peak flows for all of the storm events for the Ep and Ew scenarios compared to the USSC scenario are provided in Figure 4-3. Details of the storm event delineation process are discussed in Towsif Khan et al. (2024a). In the Ep and Ew scenarios, reducing the size of the low-stage outlets of SCMs led to a decrease in the median peak flow for both annual and sub-annual storm events (rain totals < 71 mm) of between 30% and 70%. This SCM design resulted in the extended detention of stored water in all ponds within the catchment for more than 24 hours. However, this prolonged detention in the ponds contributed to an approximately 55% increase in peak flows in the Ew scenarios for three storm events with rainfall depths ranging between 106 and 129 mm (Figure 4-3). This increase occurred because all of these events had inter-event time periods of less than 18 hours, preventing the ponds from fully emptying before the onset of subsequent storms. In contrast, the Ep scenario, where riser elevations were increased for all of the ponds, did not have an increase in peak flows for any of the storm events. The increased elevation of high-stage outlets during SCM retrofitting enhanced the storage capacity of the five ponds and delayed overflow during storm event sequences with high rainfall depths and short inter-event times.



(b)

Figure 4-1. Simulated hydrographs for (a) 1-yr and (b) 5-yr design storms. USSC= Unified Stormwater Sizing Criteria, Ew=Effective work, Ep= Erosion potential.

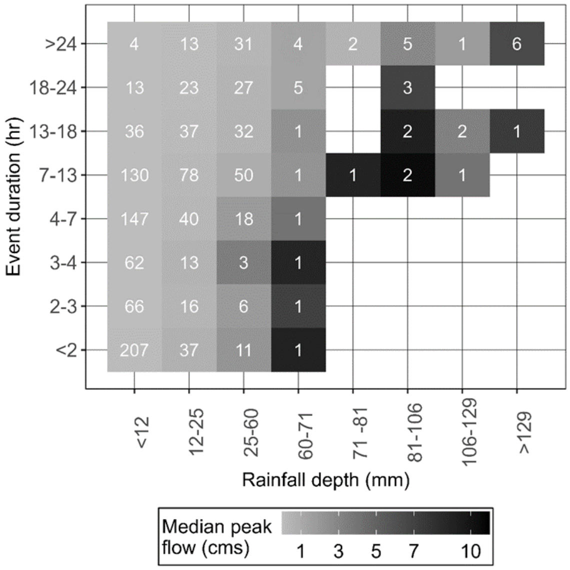


Figure 4-2. Number of storm events with the specified rainfall depth and duration. The shading indicates the median catchment discharge for the unified stormwater sizing criteria (USSC) scenario.

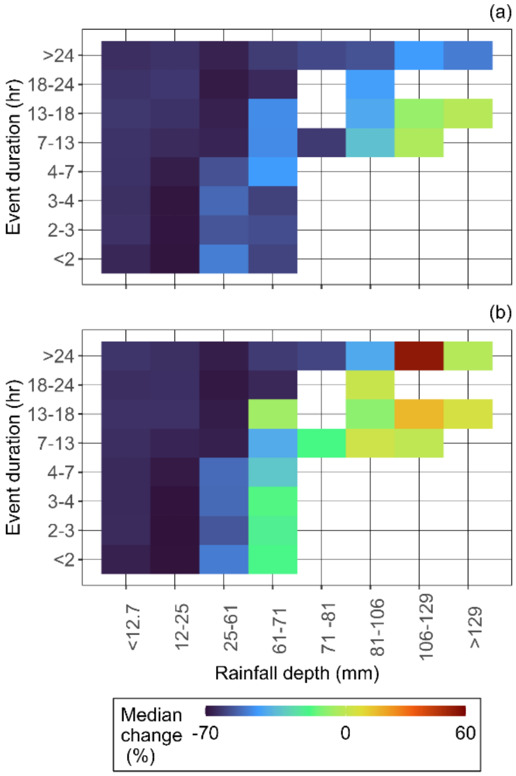


Figure 4-3. The median change in peak flow of the a) Erosion potential; b) Effective work scenarios, as compared to the USSC scenario. (USSC=unified stormwater sizing criteria, a positive value indicates a increase in median peak flow).

4.4.3 Predicted long-term changes in the channel profile

Model results suggest that designing detention ponds using the Ew or Ep criterion would reduce the magnitude of channel degradation and aggradation observed in the USSC scenario, as illustrated by the longitudinal profile plot in Figure 4-4 and by the boxplot of channel dimension change in Figure 4-5. Under the USSC scenario, increased peak flows mobilize cobbles and small boulders, leading to bed degradation of up to 0.6 m. These coarse particles are subsequently deposited upstream of a channel constriction, resulting in the formation of a steep riffle at River Station 242. By designing the outlets of the ED ponds following the Ew or Ep requirement, peak flows for both frequent and infrequent storm events are reduced, as compared to the USSC scenario (Figure 4-3) and bed coarsening is reduced (Figure 4-6); however, substantial bed degradation, ranging from 0.6 to 0.7 meters, is still predicted to occur in much of the reach. The extent of deposition at RS 242 decreased from 0.6 m to 0.1 m as compared to the USSC scenario (Figure 4-5a).

While the SCM designs in the Ew and Ep scenarios reduced the extent of channel change as compared to the USSC scenario, the channel is still predicted to adjust to the upstream urbanization, even with modification of the ED pond outlet structures. It should be noted that the design target of Ep ≤ 1 could not be achieved in the Ep scenario without the addition of an in-line pond just upstream of the study reach. Additionally, the pre-development channel width was greater than typical; the median bankfull width of the reach is almost five times larger than that of channels in rural catchments with similar drainage areas (McCandless & Everett, 2003). As a result of this increased cross sectional area, high flows are contained within the main channel, rather than spreading out over the floodplain, thereby increasing sediment transport at sub-bankfull levels.

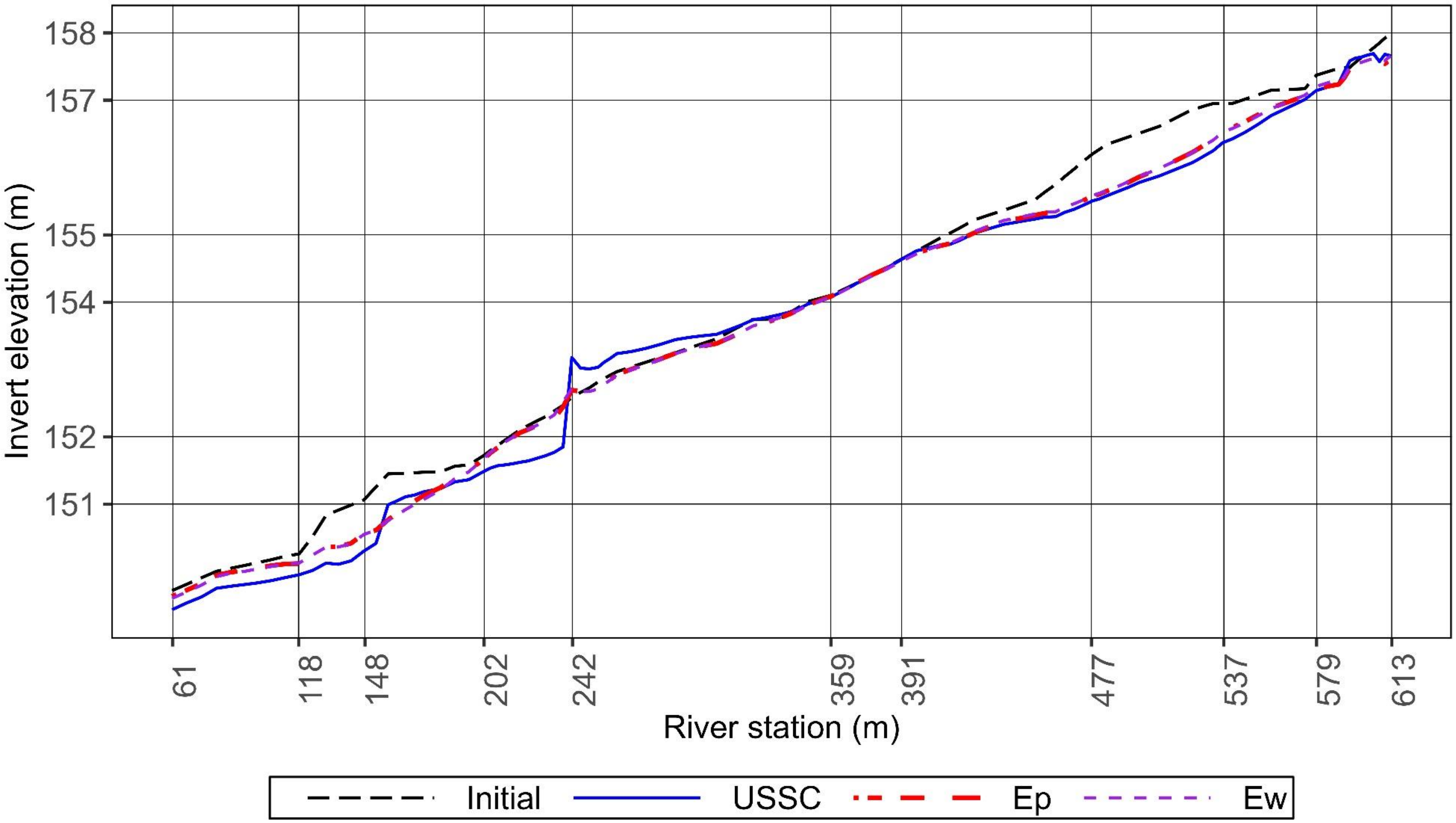


Figure 4-4. Predicted channel longitudinal profile for the current climate for the unified stormwater sizing criteria (USSC), effective work (Ew) and erosion potential (Ep) scenarios.

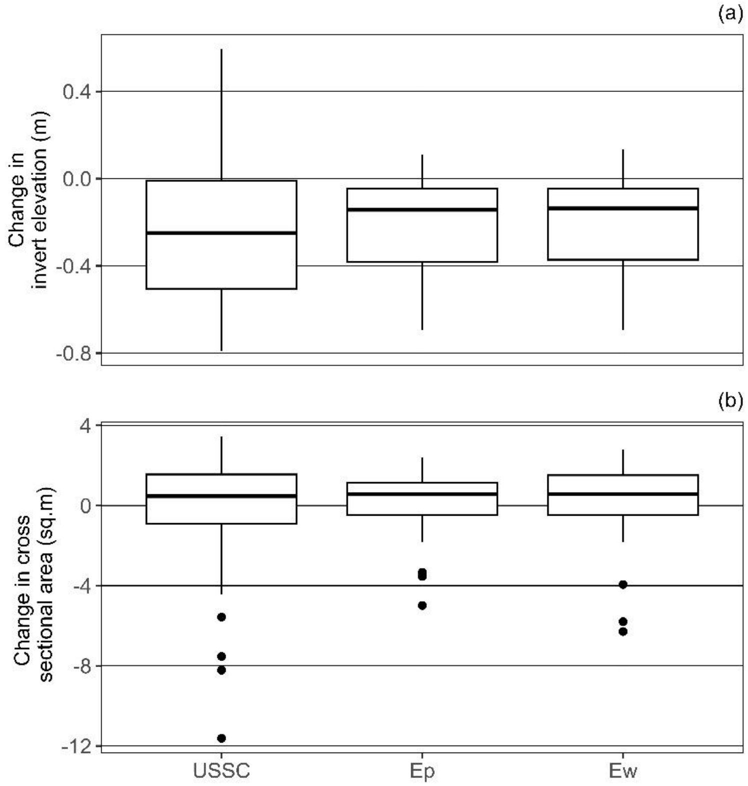


Figure 4-5. Boxplot of changes in a) invert elevation and b) cross-section area after 16 years for the unified stormwater sizing criteria (USSC), erosion potential (Ep), effective work (Ew) scenarios.

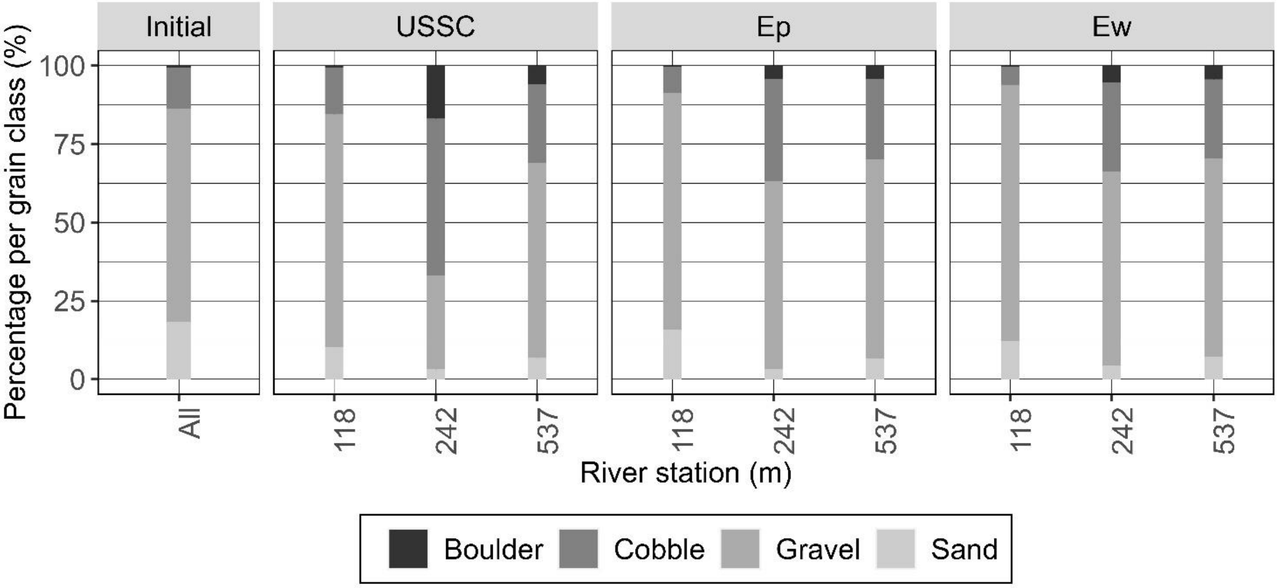


Figure 4-6. Bed material grain size distribution for three river stations at the initial condition and after 16 years for the unified stormwater sizing criteria (USSC), erosion potential (Ep), effective work (Ew) scenarios.

4.4.4 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 & Soar, 2021). In HEC-RAS, the incoming sediment load at the upstream end of the modeled reach (sediment supply) is parameterized by a sediment load rating curve. This load is a function of the upstream watershed and channel characteristics and is often calibrated due to the challenges in measuring sediment loads directly.

To demonstrate the differences in flow and sediment dynamics among the five scenarios, Figure 4-7 presents the flow volume input to the HEC-RAS model (only for discharges > 0.028 cms), total incoming sediment load, and total sediment yield for three distinct flow ranges. These ranges bracket the lowest discharge included in the HEC-RAS model (0.02 cms), the discharge at which gravel is mobilized (1.13 cms) and the average flow reaching the floodplain in the USSC, Ew, and Ep scenarios (5.89 cms). By redesigning the outlet structures of the five ponds, storm discharges were decreased by 42% in the Ep scenario, as compared to the USSC scenario, which decreased the sediment load delivered to the modeled reach by 58%. As a result, the cumulative sediment yield in the Ep scenario exceeded the sediment load by about 0.175 kilotonnes, due to a greater extent of bed degradation within the reach (Figure 4-4). The cumulative flow volume in the Ew scenario was similar to the Ep scenario; however, the cumulative sediment load was higher due to the greater fraction of flows in the range of 5.89-36.8 cms. Similar to the Ep scenario, the cumulative sediment yield in the Ew scenario exceeded the sediment load by 0.105 kilotonnes, due to greater bed degradation within the reach. It should be noted that the Ep scenario did not fully meet the criterion that $Ep \leq 1.0$ for the 1-yr and 2-yr design storms; the addition of an in-line detention pond was required to meet this requirement. However, the Ew criterion ($Ew_{post} \leq Ew_{pre}$) was met for all the design storms. This finding indicates that using design storms with 24-hr durations does not replicate actual precipitation patterns and, as such, does not produce effective SCM designs for urbanized catchments.

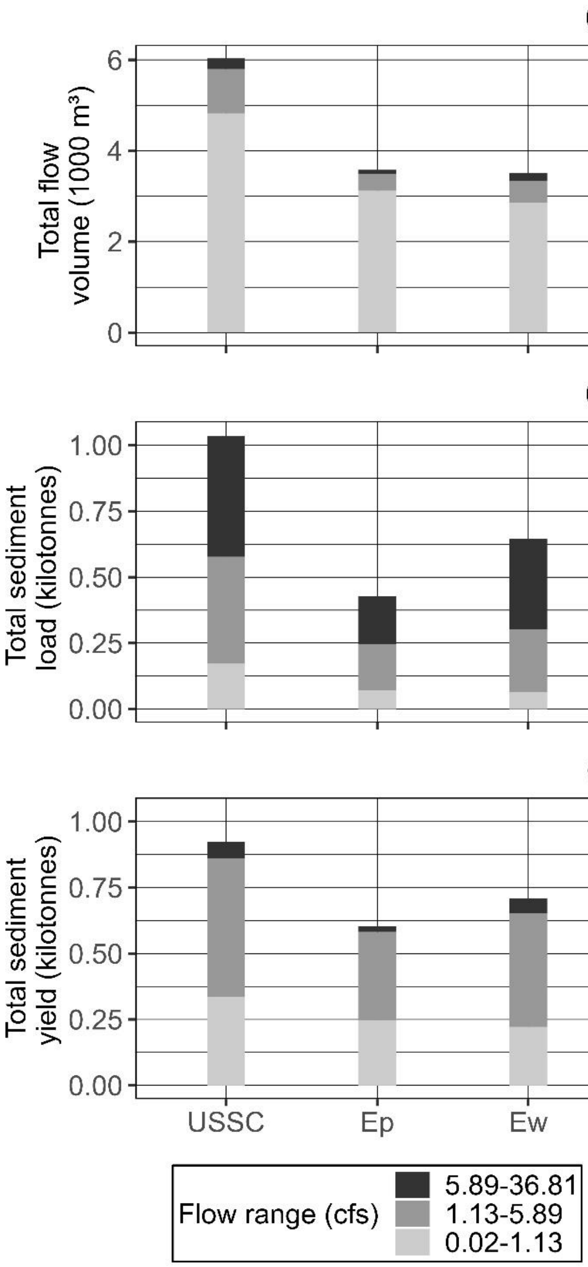


Figure 4-7. Flow volumes for discharges > 0.028 m^3/s (a), incoming sediment load (b), and sediment yield for the HEC-RAS model (c) as a function of stream flow classes for the unified stormwater sizing criteria (USSC), erosion potential (Ep) and effective work (Ew) scenarios.

4.5 Discussion

4.5.1 Implications for SCM design

Despite the widespread application of both infiltration and storage-based SCMs in Trib 109, peak flows for the 1-, 2-, and 5-yr, 24-hr design storm events were nearly double those of pre-development conditions (Table 4-4). Correspondingly, the sediment transport amount within the channel was almost 2 to 2.7 times the pre-development condition. This increase aligns with prior modeling outcomes, as discussed in earlier chapters, which predicted a recurring cycle of significant aggradation and degradation in the channel over a continuous 16-year simulation. Comparative empirical studies at the catchment scale, utilizing observed rainfall-runoff data, corroborated these findings (Hopkins et al., 2017). This study proposed that increasing the number of storage-based SCMs could potentially bring peak flows of frequent storm events closer to pre-development benchmarks. Notably, in both the Ew and Ep scenarios, where the only difference in SCM design was a change in the pond outlet structures, peak flows at the catchment outlet nearly matched pre-development levels for the 1-yr design storm. However, this approach did not entirely mitigate the increased sediment transport. This outcome can be attributed to a significant increase in both the volume and duration of low flows (Figure 4-4). Additionally, the design target of reducing the bed material transport amount to the same as the pre-development condition was not achieved in the Ep scenario through re-design of the existing SCM outlet structures alone. It is important to note that the design objective in the Ew scenario was not focused on the cumulative sediment transport in the channel. Instead, it aimed to maintain the pre-development effective work, defined based on the median bed particle size.

The design objective in the erosion potential (Ep) scenario, to match the cumulative sediment transport amount to pre-development conditions, was not achieved through redesign of the SCM outlet structures alone, which involved both reducing the size of low-stage outlets and increasing the elevation of high-stage outlets. Incorporating a storage-based SCM, such as a wetland, within the channel, could potentially reduce E_{pr} 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 study catchment is designated as a USE III watershed (per Maryland stormwater regulations) 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), 2000). Therefore, the addition of an in-line storage pond was not included in the study.

4.5.2 Limitations and future research

The calibrated, coupled hierarchical 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-induced 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 (Ep) scenario to match the cumulative sediment transport capacity to predevelopment conditions was not achieved through SCM retrofitting for 1- and 2-yr design storm events, which involved both reducing the size of low-stage outlets and increasing the height of high-stage outlets. A diagnostic analysis of the SWMM model results from design storm simulations indicated that the streamflow at the catchment outlet after SCM retrofitting which contributes to higher sediment transport capacity than predevelopment conditions, primarily originating from floodplain runoff. This failure to meet the Ep scenario design goal might 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 a 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. Worthen, Kelleher, & Davidson (2022) conducted a diagnostic analysis of their SWMM model simulations and discovered at least ten different sets of parameter values yielding 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 or flow datasets across the catchment, a common limitation in small-scale, high-resolution urban hydrologic modeling.

4.6 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 on hydrologic control only, 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.

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Chapter 5 Conclusions

In this study, a sequential hierarchical modelling approach was employed to assess the effectiveness of stormwater management practices in safeguarding channel stability within a heavily urbanized watershed in Maryland. Subsequently, this novel modeling approach was employed to assess the impact of CC on storm flows and channel stability. And finally, the modeling approach was used to evaluate the efficacy of alternative stormwater regulationsin maintaining stream stability. The methodology utilized in this research holds the potential for replication in any region worldwide, offering valuable insights into sediment transport dynamics in response to altered flow regimes in catchments equipped with SCMs.

The results obtained from Chapter 2 underscore the critical role of stormwater regulations in preserving channel stability. While significant hydrologic improvements were observed for a wide range of storm events through the combined use of distributed and centralized SCMs, the studied channel experienced instability due to changes in flow regimes post-development. Moreover, the analysis of different SWM scenarios revealed that decreasing the utilization of SCMs could exacerbate the observed instability. Through dynamic sediment transport modelling and geomorphic analysis of indicator discharges, the study revealed that the majority of sediment transport in this urban gravel-bed headwater stream occurs during high-frequency, low-magnitude storm events. By excluding storage ponds from the watershed, the amount of bed sediment transported by less frequent, high-magnitude events increased. Surprisingly, despite their superior performance in peak flow attenuation during high-frequency storm events, distributed SCMs seemed to have a less significant impact on protecting channel stability. To enhance stormwater management and stream stability, it is recommended that catchment-scale hydrological models with a minimum of 10 years of rainfall data be used for designing stormwater control measures (SCMs), rather than relying on a single 24-hour design storm. This approach will offer a more accurate representation of the impact of urbanization and SCMs on catchment hydrology. Additionally, SCM design criteria should be updated to include sediment transport targets, aiming to align post-development sediment transport mass with pre-development levels. This design target can be efficiently evaluated using spreadsheet-based tools for estimating sediment transport.

In the third chapter the sequential modeling approach developed in the second chapter was incorporated with rainfall and temperature data from 64 different CC scenarios to evaluate the impact of SCM implementation on stream stability under changing climate. The results from this chapter indicate that conclusions related to CC impacts of SCM induced-flow drawn from simplified, unit area models are different from conclusions based on dynamic, continuous simulations that consider the complexities of real urban catchments and SCM interactions. Despite a general decrease in total rainfall amount for most storm events, there was a noted increase in intensity for nearly all future storm events compared to current climatic conditions. This change in storm event rainfall pattern is expected to drive the catchment-scale hydrology to a flashier regime in the future. Existing stormwater regulations which rely on just 12 hr. detention of peak flows for specific recurrence interval storm events will thus exacerbate the current observed trend of channel disturbance at the study site under changing climate conditions. A multicriteria design approach considering the interplay of multiple SCMs and local sediment transport capacity is expected to yield a channel that will remain stable in the long term in response to the changing climate.

In Chapter 3, the cumulative efficacy of proposed stormwater regulations in protecting channel stability was evaluated for the same study site that was used in the preceding two chapters. The spatially discretized SWMM model of the study site and as-built drawings of the existing SCMs were employed to develop procedures for realistic SCM design based on proposed criteria. Simulation results showed that the design objective of matching the cumulative sediment transport amount to pre-development conditions was not achieved solely through redesign of SCM outlet structures, although this finding might stem from the set of calibrated parameter values used to simulate runoff from individual subcatchments in the SWMM model. These results showed that future SWMM modeling studies should perform a diagnostic analysis of model simulations to address the parameter equifinality issue. The long-term modeling results of the proposed SCM regulations showed that the extent of channel disturbance was reduced as compared to existing regulations but there were still areas of degradation within the reach.

The results from the three chapters of this dissertation provided a better understanding of the long-term behavior of urban headwater channels currently and in the future. Moreover, the research provided evidence that the existing Maryland stormwater regulations are not protective of channel stability under current or future climate. Nonetheless, future work is needed to improve our overall understanding of modeling, monitoring, and analysis of sediment transport dynamics of urban streams.

Appendices

Appendix A SWMM model development and calibration

A.1 Hydrologic model

A catchment-level Stormwater Management Model (SWMM version 5.1.013) (Rossman, 2015) was developed to simulate the hydrologic conditions in the catchment, specifically focusing on the post-2017 period. SWMM, a 1-dimensional, lumped, physically-based hydrologic model, is capable of simulating both individual storm events and continuous time periods. The model incorporates key hydrologic processes such as surface runoff, infiltration, evaporation, snowmelt, surface water routing (including kinematic and dynamic wave approximations for unsteady flow), surface water storage, groundwater flow, and water quality. SWMM employs a representation of overland flow as a series of nonlinear reservoirs, which are subsequently routed to a link-node network that emulates the urban stormwater conveyance system. Additionally, storage nodes within the model possess the capability of simulating water quality treatment processes. However, it is important to note that while SWMM is able to calculate erosion and washoff of suspended sediment during overland flow, it lacks the capability of simulating channel aggradation or degradation. Therefore, to assess channel stability and related phenomena, a separate model was utilized, as discussed in section 2.2.3-2.2.5 of Chapter 2.

A.1.1 SWMM model construction and SCM representation

The study catchment was delineated into 214 subcatchments based on multiple considerations including stream/conduit network connectivity, the existence of SCMs, and locations where simulated flow outputs were needed for the calibration process (Figure 1b). Topography within each subcatchment was based on a 0.91-m resolution digital elevation model derived from light detection and ranging (LiDAR) data provided by Montgomery County, MD (Metes & Jones, 2021). Hydraulic width was obtained by dividing the subcatchment area by the longest flow length within each subcatchment. Impervious percent within each subcatchment was based on the county-provided geographic information system (GIS data representing impervious structures including roads, buildings, sidewalks, driveways, and parking lots). Guidelines provided within the SWMM documentation were used to assign Manning’s roughness coefficient and depression storage estimates for both impervious and pervious surfaces (James et al., 2010; Rossman and Huber, 2016).The Green-Ampt equation was used to simulate infiltration within the pervious areas and through the simulated SCMs (Heber Green & Ampt, 1911). A shapefile representing the soil saturated hydraulic conductivity was extracted from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff, 2014) and intersected with the subcatchment shapefile to obtain the saturated hydraulic conductivity of the subcatchments. Subcatchment groundwater parameters were determined through calibration utilizing observed baseflow. The following five types of SCMs were explicitly simulated using SWMM :

1.Detention/retention ponds: Six detention ponds were represented as storage nodes in the model using depth-surface area curves and information from as-built drawings provided by Montgomery County, MD. Multiple outfall types, such as weirs and orifices, were incorporated for each pond. The ponds were designed with a multi-stage outlet structure to provide 12-hr extended detention of runoff from the 1-yr, 24-hr storm and to safely convey runoff from the 10-yr, 24-hr and 100-yr, 24-hr design storm events.

2.Sand Filters (SF): A total of 11 sand filters were employed either independently downstream of infiltration basins or in conjunction with detention ponds to provide water quality control and additional storage. Inflows to sand filters were simulated as diversions from the main stormwater drainage network, with smaller diameter pipes capturing the “first flush” of runoff needing water quality treatment. The design of the sand filter outfall structures aimed to ensure containment of the WQv (Water Quality Volume), thus preventing any runoff overflow from 90% of the average annual rainfall, which amounts to 25 mm for the study watershed.

3.Underground storage (UGS): To accommodate limited above-ground space, an underground stormwater storage system consisting of pipes or vaults was implemented. Data from as-built drawings, including length, diameter, slope, and inlet and outlet attributes, were utilized. This system gradually released stored stormwater to local streams or the stormwater drainage network. A total of 17 underground storage systems were incorporated into the model.

4.Infiltration basins/trenches (IT): Infiltration trenches were constructed using underground stone reservoirs to collect stormwater and facilitate slow seepage into the ground. Stormwater diversion from the main stormwater drainage network occurred through smaller diameter pipes, with infiltration trenches functioning as storage nodes with higher seepage capacities than the surrounding areas. The design incorporated overflow pipes to redirect any surplus stormwater back into the drainage network, adhering to the same design procedure employed in the design of the sand filters.

5.Microbioretention (MBR): A total of 26 MBRs, implemented as LID practices within subcatchments, received runoff from smaller subcatchments, primarily rooftops. The attributes of MBRs, such as depth, surface area, soil mixture, storage volume, and under-drainage, were represented using the LID editor in SWMM. Small street tree boxes and a grass swale were not simulated to reduce model complexity.

A.1.2 SWMM model calibration

The model was calibrated using local precipitation and observed instantaneous stream flow data for water year 2020 and validated for 2019. Observed streamflow data were obtained from the USGS streamflow station. These two years were selected mainly because they occurred after the catchment was fully developed (2017), contained fewer data gaps than other years, and had relatively high maximum annual flow rate. Model parameters adjusted during the hydrologic calibration process included subcatchment hydraulic width, Manning's roughness coefficient for impervious and pervious land segments, depression storage for impervious and pervious land segments, and groundwater equation coefficients and exponents. Table A1 provides a list of the adjusted parameters. Based on parameter adjustments made during the hydrologic calibration process, good visual and statistical agreements were obtained between the observed flow at the USGS gage and the simulated flow. Goodness-of fit-statistics (Moriasi et al., 2015) for the calibration and validation periods for the SWMM modeling are provided in Table A2.

Table A1. SWMM parameters adjusted during the calibration process.

Parameter	Definition	Unit	Calibrated Range
Characteristic Width	Characteristic width of the overland flow path for sheet flow runoff is a function of subcatchment area and longest flow path	m	16.15 – 584.3
Impervious Manning's Roughness	Manning's n for overland flow over the impervious portion of the subcatchment	-	0.011 - 0.13
Pervious Manning's Roughness	Manning's n for overland flow over the pervious portion of the	-	0.13 - 0.156

	subcatchment		
Impervious Depression Storage	Depth of depression storage on the impervious portion of the subcatchment	mm	1.905
Pervious Depression Storage	Depth of depression storage on the pervious portion of the subcatchment	mm	5.08 – 5.34
Hydraulic Conductivity	Soil saturated hydraulic conductivity	mm/hr	1.651 – 3.302
A_1	Groundwater flow coefficient	-	0.01
A_2	Surface water flow coefficient	-	0.01
B_1	Groundwater flow exponent	-	1
B_2	Surface water flow exponent	-	0.1

Table A2. Statistics describing the calibration and validation performance of the SWMM hydrologic modeling.

	Calibration (2020)		**Validation (2019)**	
	Observed	**Simulated**	**Observed**	**Simulated**
Peak flow rate (cms)	7.53	9.3	9.57	10.11
Mean flow rate (cms)	0.018	0.018	0.027	0.024
RMSE (cms, daily average)		0.4		0.5
PBIAS (%, daily average)		0.0		16.1
NSE (daily average)		0.70		0.72
R^2 (daily average)		0.71		0.73

A.2 Input Data for HEC-RAS Sediment Transport Model

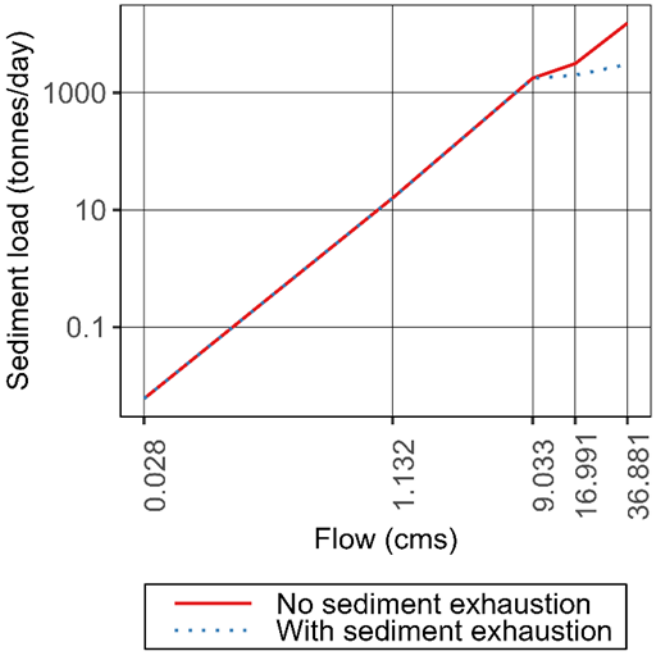

Figure A1. Calibrated inflow sediment rating curve.

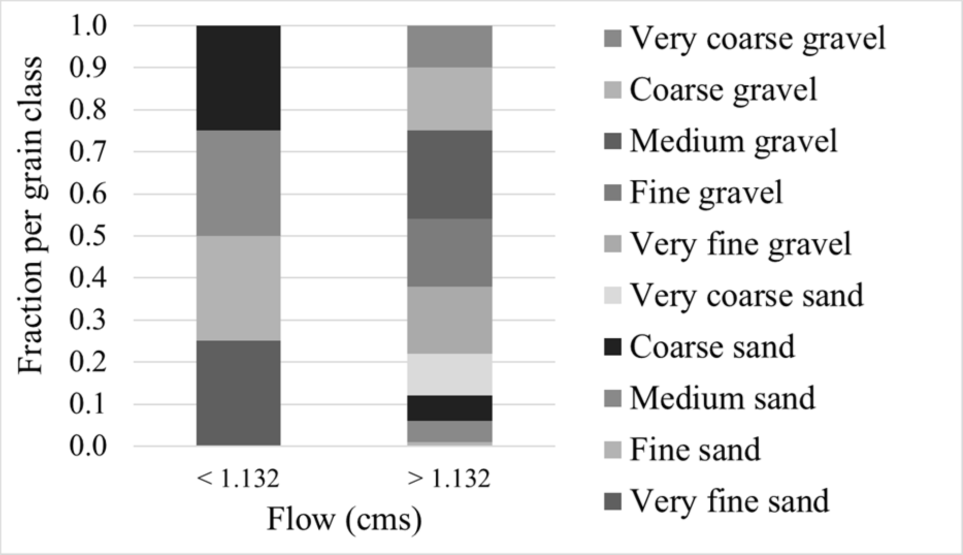

Figure A2. Calibrated inflow sediment load gradation.

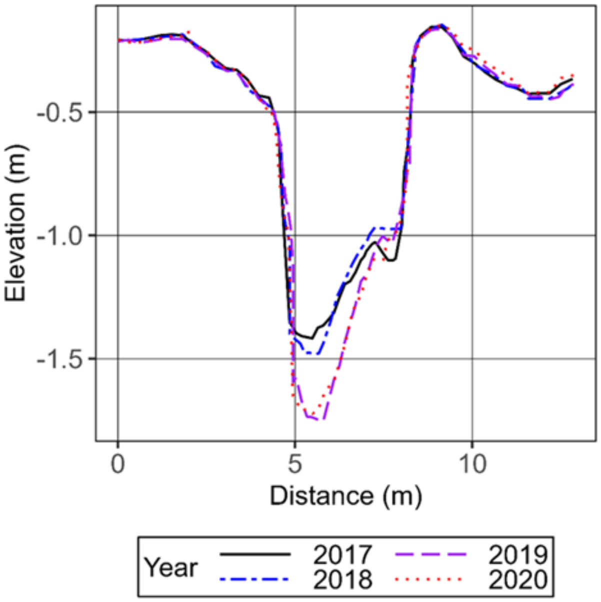

Figure A3. Observed cross-section data for the pool located immediately downstream of the U.S. Geological Survey gage.

A.3 SWMM simulation results

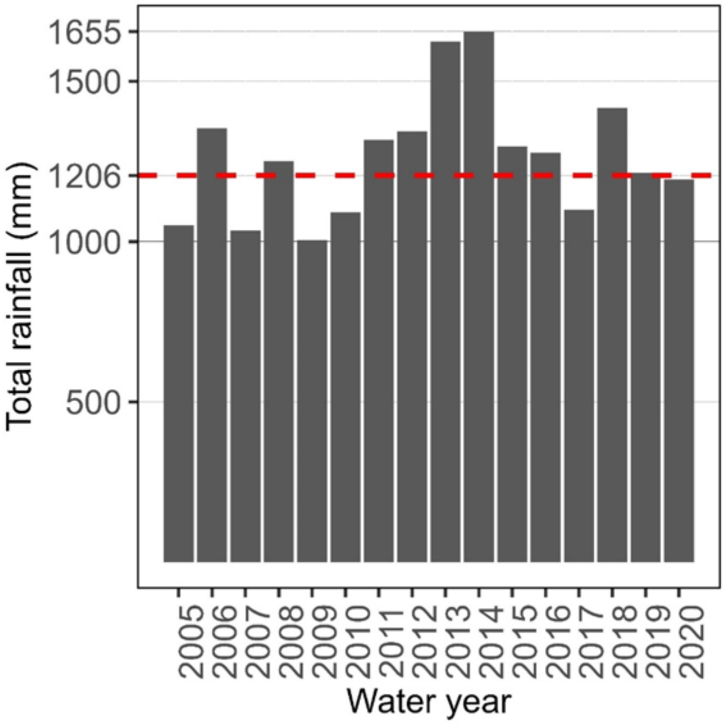

Figure A4. Annual total rainfall (water years 2005 -2020) at the Black Hill rain gauge which was input in the SWMM model along with the average rainfall (water years 1991-2020) for NOAA station US1MDMG0029, situated 3.05 km away from the study site, indicated by the dashed line.

A.3 HEC-RAS Simulation Results

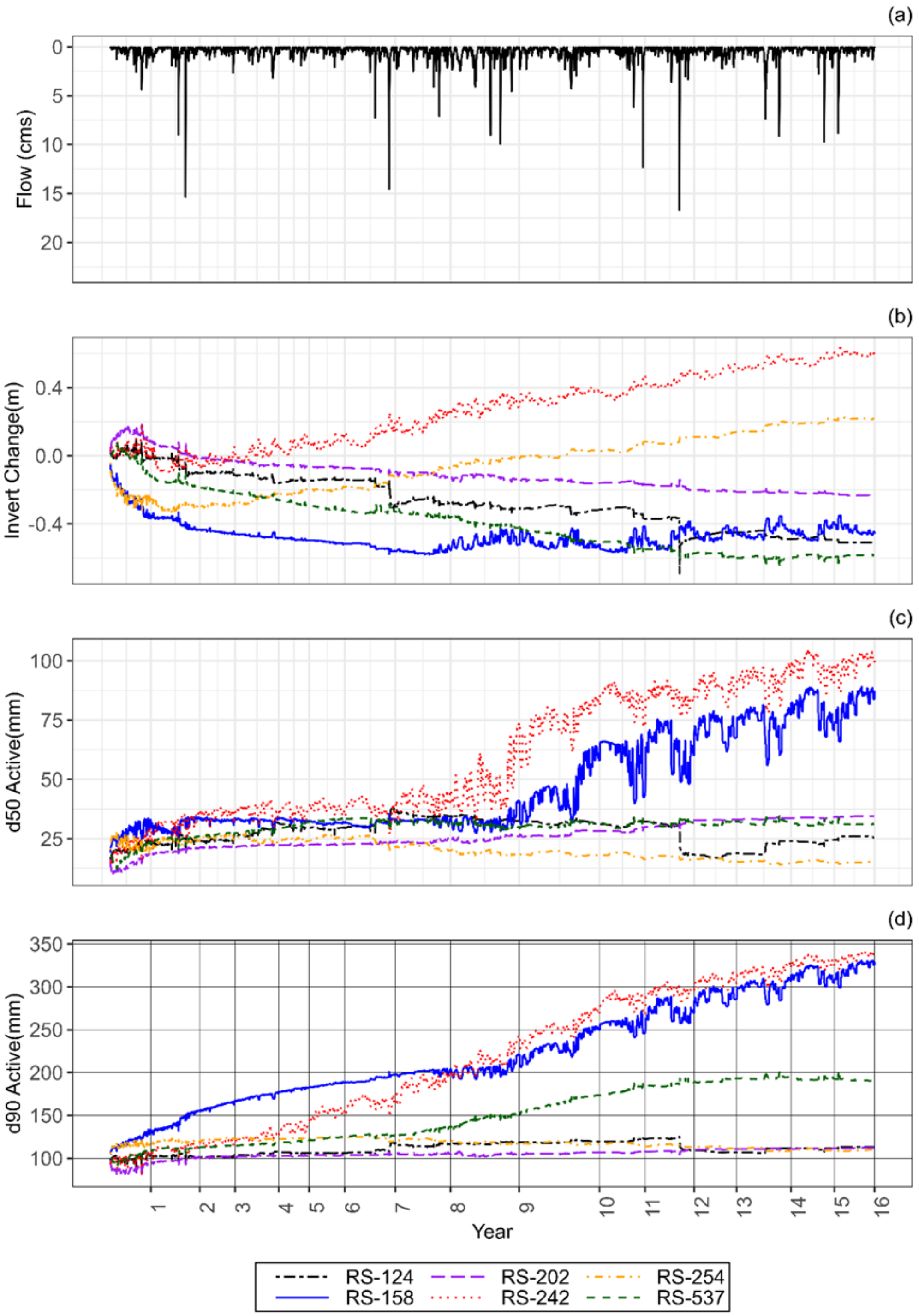

Figure A5. Time series of a) flow; b) channel invert elevation; c) bed material d50; and d) bed material d90 during the simulation period for the unified stormwater sizing criteria (USSC) scenario.

Appendix B Summary of climate change dateset

Table B1. Name and ID of 16 Global Climate Models (GCMs) used in the study.

GCM ID	Model Name
bcc-csm1-1-m	Beijing Climate Center Climate System Model version 1.1, moderate resolution
CanESM2	Second generation Canadian Earth System Model
CCSM4	Community Earth System Model
CNRM-CM5	Centre National de Recherches Météorologique
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization Mark 3.6.0
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model, ESM2M Version
HadGEM2-CC365	Hadley Centre Global Environmental Model version 2 - Carbon Cycle 365-day version
HadGEM2-ES365	Hadley Centre Global Environmental Model version 2 - Earth System 365-day version
IPSL-CM5A-LR	Institut Pierre Simon Laplace Climate Model 5A - Low Resolution
IPSL-CM5A-MR	Institut Pierre Simon Laplace Climate Model 5A - Medium Resolution
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate - Earth System Model - CHEMistry version
MIROC-ESM	Model for Interdisciplinary Research on Climate - Earth System Model
MIROC5	Model for Interdisciplinary Research on Climate version 5
MRI-CGCM3	Meteorological Research Institute Coupled Global Climate Model version 3
NorESM1-M	Norwegian Earth System Model version 1 - Medium resolution

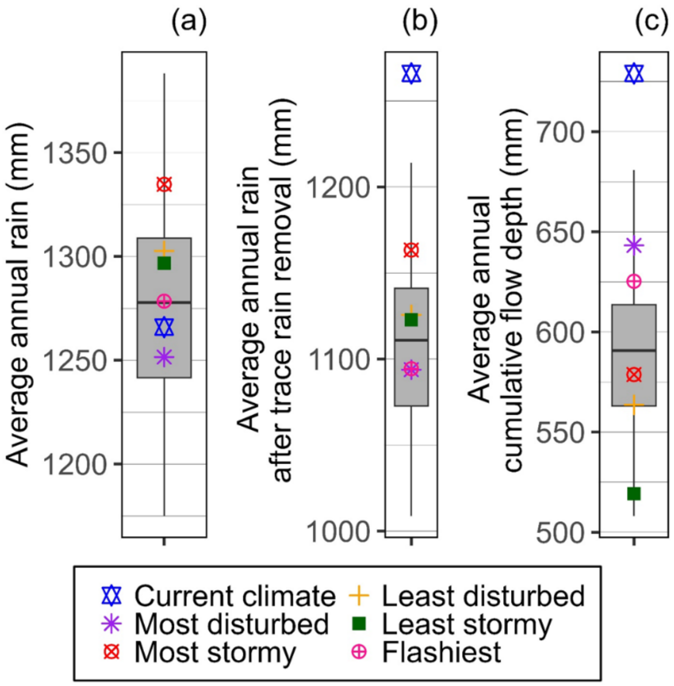

Figure B1. Boxplot of average annual rain (a), average annual rain after trace rain removal (b), average annual cumulative flow depth (c) of current climate and climate change scenarios.

Appendix C Summary of SCM modifications

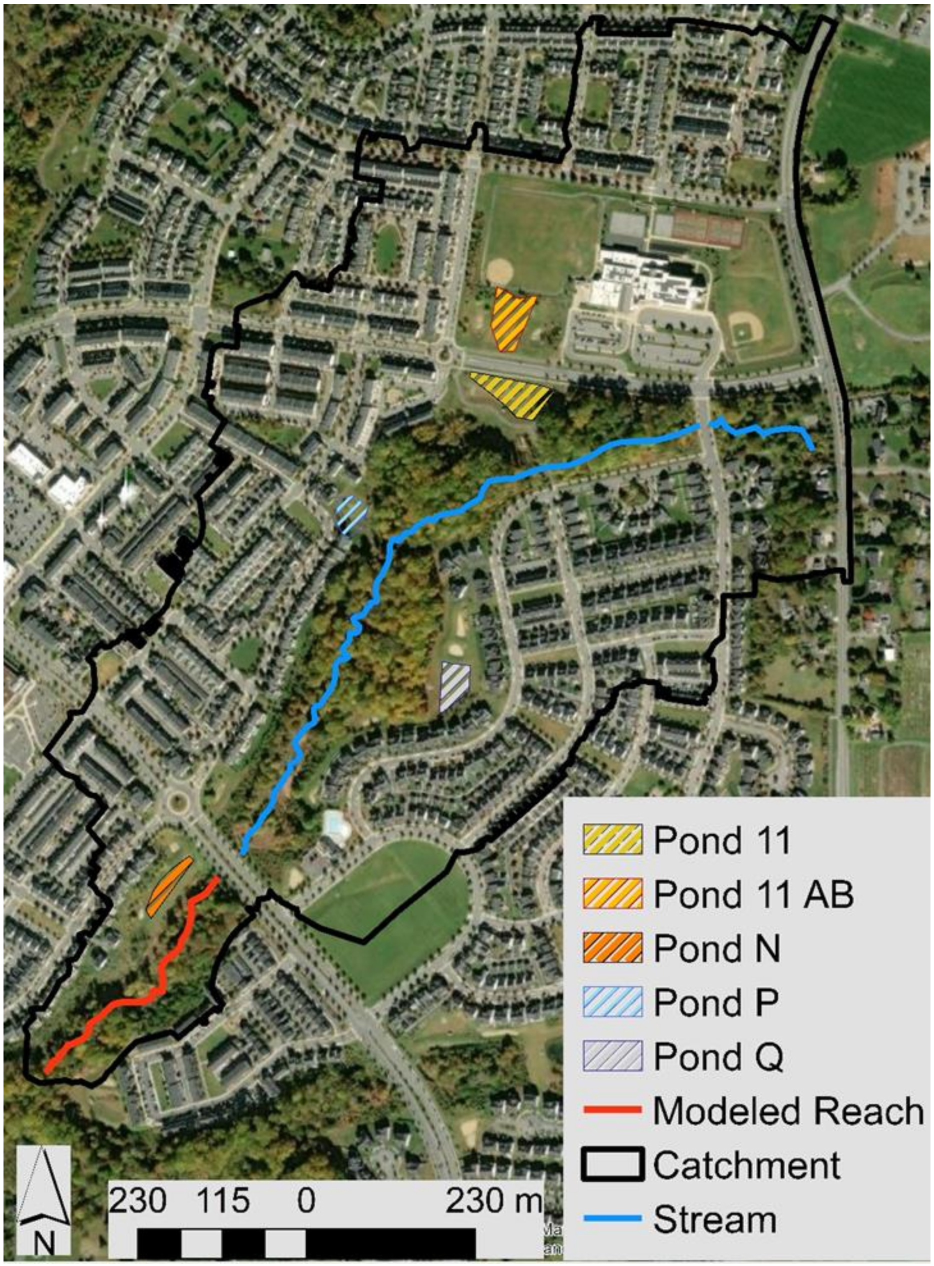

Figure C1. Location of storage based SCMs (ponds) which were retrofitted within the study site. SCM=Stormwater Control Measures.

Table C1. Weir opening dimension (length and height) and orifice diameters (Ø) of outlets in the SWMM model of perspective SWMM models. The number within the parenthesis indicates the offset of the outlet from the base of the pond riser structure. Unified stormwater sizing criteria (USSC), Erosion Potential (Ep) , Effective work (Ew).

SCM ID	**High-stage Outlet (Weir)**			**Intermediate Stage Outlet (Orifice)**		**Low-stage Outlet (Orifice)**	
	USSC	**E_p**	**Ew**	**USSC**	**Ew and E_p**	**USSC**	**Ew and E_p**
Pond 11AB	1.6 m × 0.7 m (1.24 m)	1.6 m × 1.6 m (2.5 m)	1.6 m × 0.7 m (1.24 m)	-	-	-	-
Pond 11	3.3 m × 0.7 m (2.4 m)	9.1 m × 0.7 m (3.81 m)	3.3 m × 0.7 m (2.4 m)	Ø 0.3 m (0.6 m) Ø 0.3 m (0.6 m)	Ø .07 m (0.7 m) Ø .1 m (1.5 m) Ø .1 m (7.1.5 m)	Ø 0.1 m (0)	Ø 0.07 m (0)
Pond P	5.4 m × 0.3 m (1.42 m)	5.4 m × 0.3 m (2.4 m)	5.4 m × 0.3 m (2.6 m)	-	-	Ø 0.1m (0)	Ø 0.07 m (0)
Pond Q	5.4 m × 0.6 m (1.8 m)	5.4 m × 0.60 m (2.6 m)	5.4 m × 0.6 m (2.4 m)	Ø .1 m (0.38 m)	Ø .07 m (0.7 m) Ø .1 m (1.5 m)	Ø 0.1 m (0)	Ø 0.07 m (0)
Pond N	8.5 m × 0.6 m (2.7 m)	8.5 m × 0.6 m (3.2 m)	8.5 m × 0.6 m (2.7 m)	-	Ø .1 m (2.7 ,)	Ø 0.1 m (0)	Ø 0.07 m (0)

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