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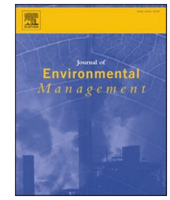

Research article

Impacts of climate change on storm event-based flow regime and channel stability of urban headwater streams

Sami Towsif Khan [a], David J. Sample [a,b,*], Theresa Wynn-Thompson [a], Jon Butcher [c]

[a] Department of Biological System Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, United States
[b] Hampton Roads Agricultural Research and Extension Center, Virginia Polytechnic and State University, Virginia Beach, VA, 23455, United States
[c] Tetra Tech, Inc., P.O. Box 14409, Research Triangle Park, NC, 27709, United States

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ABSTRACT

Due to the recent improved availability of global and regional climate change (CC) models and associated data, the projected impact of CC on urban stormwater management is well documented. However, most studies are based on simplified design storm analysis and unit-area runoff models; evaluations of the 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 input data required to develop a long-term, continuous sediment transport model. The study objective was to evaluate the impact of CC on storm event-based flow regimes and channel stability in a small, urbanized catchment (0.9 km^2) in Montgomery County, Maryland, USA. This study employed a previously developed sequential, hierarchical modeling approach, integrating a watershed-scale Storm Water Management Model (SWMM) with the Hydrologic Engineering Center River Analysis System (HEC-RAS) to achieve the study goal. Ensemble modeling results indicate that conclusions related to impacts on SCM performance drawn from simplified, unit area models are not supported by findings 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 for most 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.

1. 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 and James, 2022; Najjar et al., 2010), sedimentary, and geomorphic processes across landscapes (East and 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 and 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 and Hogue, 2022). These approaches, known under various names such as Green Infrastructure (GI), Low-Impact Development (LID), 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

* Corresponding author. Hampton Roads Agricultural Research and Extension Center, Virginia Polytechnic and State University, 1444 Diamond Springs Rd, Virginia Beach, VA, 23455, United States.

E-mail addresses: samitowsifkhan@vt.edu (S. Towsif Khan), dsample@vt.edu (D.J. Sample), tthompson@vt.edu (T. Wynn-Thompson), jon.butcher@tetratech.com (J. Butcher).

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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 requires a continuous, sequential modeling approach. 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 h 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 significant 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, 2021; Butcher et al., 2023b; 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 change in 24-hr rainfall amounts for such events (events with recurrence intervals up to 2 years) varies from decreases to minimal increases. 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 stream stability is directly related to climate-induced changes in frequent flows (Bledsoe and Watson, 2001). Consequently, their findings suggest there is no immediate need to adjust local SCM regulations (Butcher, 2021; Butcher et al., 2023b). 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 and channel shape (Bledsoe et al., 2007).

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 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 morphology 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. 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 sediment supply, 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.

2. Methodology

2.1. 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) (Fig. 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 and 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 the 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 km^2 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 (Fig. 1). Runoff generated from all impervious areas of the study site was routed through SCMs before discharging to the riparian area, 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.

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. A 425-m reach was chosen to simulate the sediment transport dynamics (Fig. 1). This reach begins downstream of a culvert and extends to the confluence with another unnamed tributary. During the construction phase (2004–2017) large-scale grading occurred and zero-order channels were replaced with SCMs. However, elevation changes in the forested riparian zone were not observed during the construction phase (Williams et al., 2022).

2.2. Input data and model setup

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

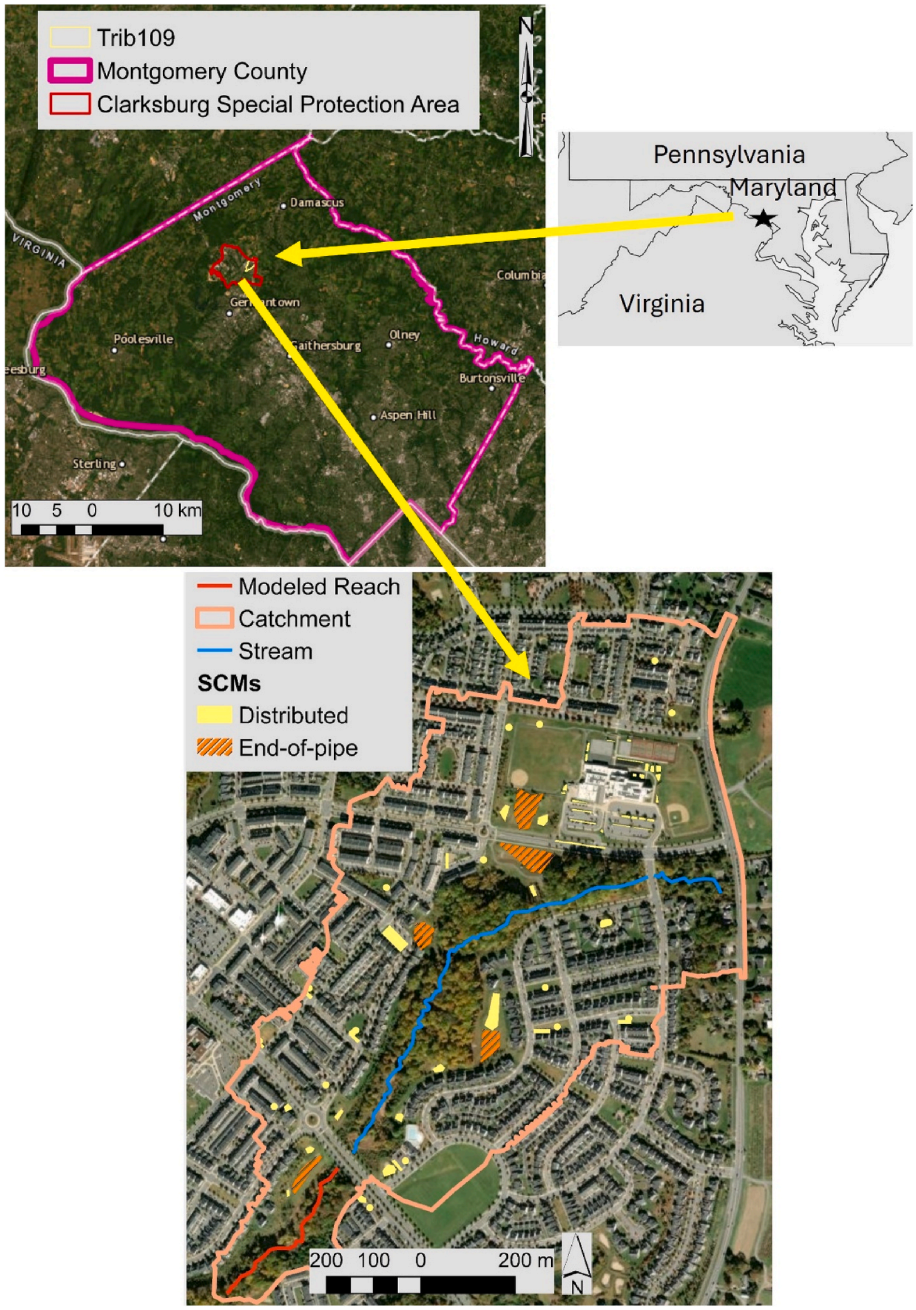

Fig. 1. Map of Tributary 109 site along with stormwater control methods (SCMs) of the study site.

a previous study (Towsif Khan et al., 2024a). Details of the model setup and calibration results are documented in Towsif Khan et al. (2024a). 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. These time series included 5-min air temperature and rainfall records from water year 2040–2099. 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) and Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou and Brown, 2012) downscaling methods. The names of these 16 GCMs are provided in Table S1 of the Supplementary Materials. 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. (2023a). 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 occurs during high flow storm events, this reduction in cumulative flow volume is unlikely to affect the outcomes of our modeling outcomes.

Because sediment transport primarily occurs during storm events, simulated stream flows less than 0.0283 cms (1 cfs) were eliminated from the SWMM flow time series 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-yr long flow time series for the current climatic condition, the measured rainfall record from water year 2004–2020 at a nearby rain station (Black Hill station, operated by Montgomery County Department of Environmental Protection) was repeated in series to develop a 59-yr long continuous rainfall time series. It should be noted that annual total rainfall depths during this period (1050–1655 mm) were as much as 37% greater than the 30-yr climate normal of 1206 mm (1991–2020) at the National Oceanographic and Atmospheric Administration (NOAA) US1MDMG0029 station, which is located 3.05 km from the catchment. 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.

2.3. Storm event and flood frequency analysis

To quantify the changes in storm event-based rainfall patterns and streamflow with changing climate, a frequency analysis was conducted for four storm event parameters: storm event peak discharge, total rainfall depth, and average and maximum rainfall intensity. Storm events were identified based on the 5-min. interval rainfall record, employing a total rainfall 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 min). 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) of 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. (2024a).

Several probability distributions were utilized to quantify the changes in the overall shape of the CC peak flow duration analysis curve (PQDC); a gamma distribution was found to be a superior fit, based on the Kolmogorov Smirnov and chi-squared goodness-of-fit tests (Chakravarti et al., 1967). To ensure the underlying assumption of temporal independence was met, a Durbin-Watson test was performed to check for serial correlation between residuals, and the autocorrelation function (ACF) was examined visually to further assess serial correlation (Helsel and Hirsch, 2002). Cheng et al. (2012) also employed 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 flow regime which has higher peak flows. The probability distribution analysis was performed using the *fitdistrplus* R package (Delignette-Muller and Dutang, 2015).

2.4. Evaluation of sediment transport dynamics

To quantify and compare the change in channel morphology under changing climate, two indices were calculated (change in cross-sectional area and change in invert elevation) employing methods adapted by Towsif Khan et al. (2024a). A Shapiro-Wilk test (Shapiro and Wilk, 1965) was performed and showed evidence of non-normality so a non-parametric paired two-sample test (Rey and Neuhäuser, 2011) was then 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 also conducted for each of the CC scenarios using methods by Towsif Khan et al. (2024a). 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 at which 50% of the total sediment load is transported over the entire simulation period, as indicated by a cumulative sediment yield curve, and was calculated using the method employed by Sholtes and Bledsoe (2016).

3. 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 et al., 2023b; Giese et al., 2019) we found that the spatiotemporally downscaled GCMs produced a broad range of aggregated rainfall and simulated runoff amounts at the study site. To effectively evaluate the results for the complete range of CC simulations in all of the graphical representations of our findings, we highlighted the results of five representative CC scenarios out of the 64 scenarios evaluated and provided the upper and lower bounds on the range of CC simulations results. These five scenarios were chosen based on the extremes of storm event peak flow distribution (scale parameter of the PQDC) and the median change in invert elevations. Additionally, we selected the CC scenario which produced the flashiest flow regime defined by the shape parameter of the PQDC. Table 1 provides key information on these five CC scenarios and their representation throughout the document.

3.1. Projected change in rainfall characteristic of storm events

Three rainfall characteristics (total rainfall depth, and 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) (Fig. 2). The projected total rainfall 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.

Table 1
Summary of five highlighted climate change scenarios, (GCM = global climate model, DM = downscaling method, RCP = representative concentration pathway, PQDC = peak flow duration analysis curve).

GCM	DM	RCP	Characteristic	Terms and acronym used represent scenario in figures
CSIRO Mk3.6.0	LOCA	8.5	Greatest channel invert change	Highest median invert elevation change (HMIC)
HadGEM2-ES365	LOCA	8.5	Highest mean peak flows (Highest scale parameter of PQDC)	Highest mean peak flows (HMPQ)
CanESM2	MACA	4.5	Least channel invert change	Lowest median invert elevation change (LMIC)
MRI-CGCM3	MACA	4.5	Lowest mean of peak flows of storm events (lowest scale parameter of PQDC)	Lowest mean peak flows (LMPQ)
BCC-CSM1.1	MACA	8.5	Most flashy	Highest flashiness (HF)

Similarly, the peak 5-min rain intensity increased by 50–200% for almost all of the storm events under CC (Fig. 3). Both results indicate that even though the total rain depth may undergo minimal change due to CC, the storm events will be more intense. The projected increase in air temperature and associated saturation vapor pressure due to CC also increased the number of cloudburst events. The American Meteorology Society (2024) defines cloudburst events as storm events with an average rainfall intensity of more than 100 mm/h. The current climate had no cloudburst events despite having rainfall totals higher than the NOAA climate normal (1991–2020). On the contrary, the median number of cloudburst events in the CC scenarios was six and each of the CC scenarios had at least four cloudburst events (Fig. 2b).

3.2. Projected change in peak flows

The PQDC frequency distributions developed employing the peak flows of the storm events for the 64 scenarios are shown as a grey band in Fig. 4, with the five selected CC scenarios and the current climate shown as lines. The CC scenarios with highest and lowest mean peak flows (based on the highest and lowest values of the gamma distribution scale parameter) follow the upper and lower bound of the PQDCs in Fig. 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 Fig. 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 CC scenarios with the lowest mean peak flows and lowest median invert elevation changes 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 Fig. 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 ($\leq$ 25%) is greater than the decrease in peak flows from high frequency storm events ($\geq$ 50%) as a result of CC. As a result, this pattern is indicative of the extent of increase in flashiness (denoted by the inverse of the shape parameter of the PQDC, Fig. 5a) predicted for almost 90% of the CC scenarios, compared to the current climate condition.

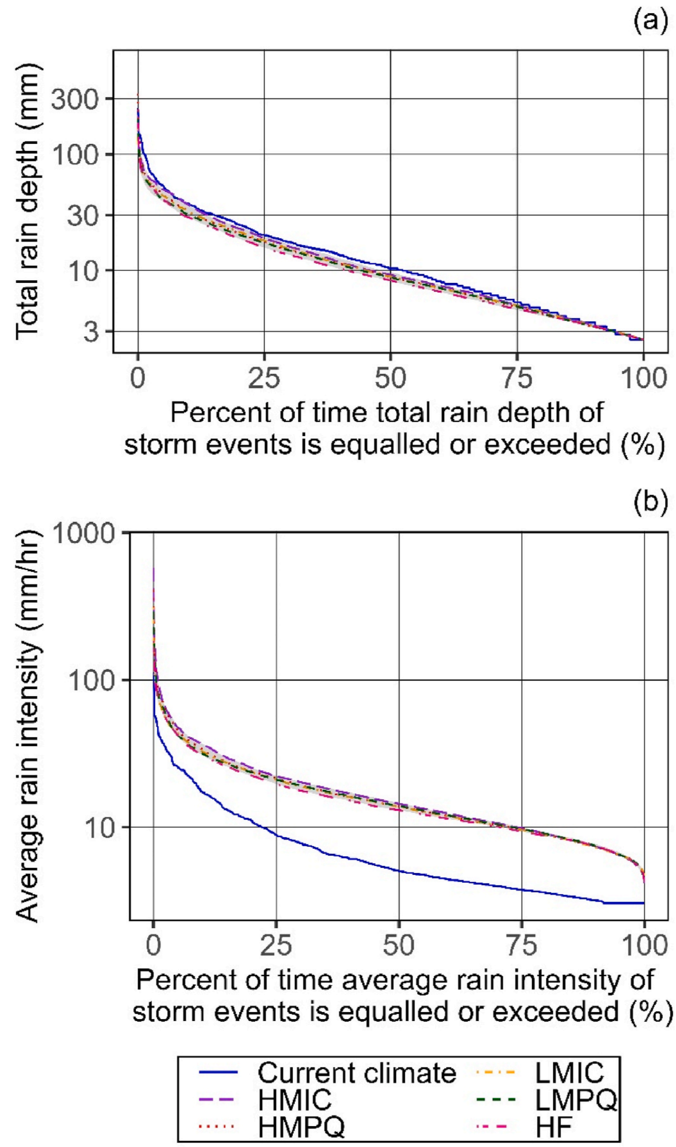

Fig. 2. Frequency distribution curve of a) total rainfall depth and b) average rainfall intensity of storm events of current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

3.3. 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 Fig. 6. Consistent with earlier studies of this region (Butcher, 2021; Butcher et al., 2023b), there is a noticeable decline in peak flows for recurrence intervals under 10 years, except in the CC scenarios with the highest mean peak flows and the highest flashiness. 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 et al., 2023b). 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. Moreover, the mean discharge of the current climate AMS was higher than the means of 84% of the CC AMS. Due to These two factors, the peak flows of higher recurrence intervals for the current climate conditions were very high as per the log Pearson type III

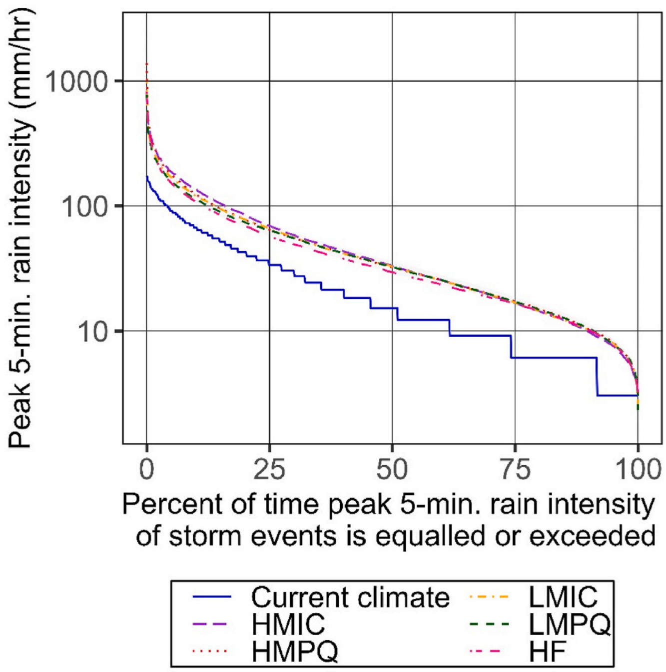

Fig. 3. Frequency of storm event peak 5-min rainfall intensity for the current climate and the climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

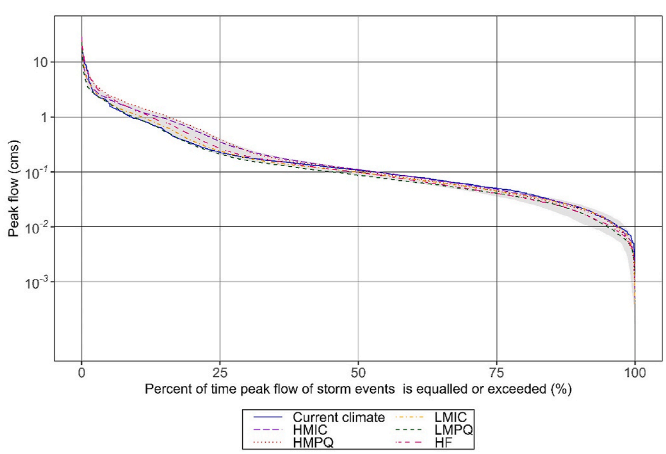

Fig. 4. Storm event peak flow distribution curve (PQDC) of current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC), and highest flashiness (HF).

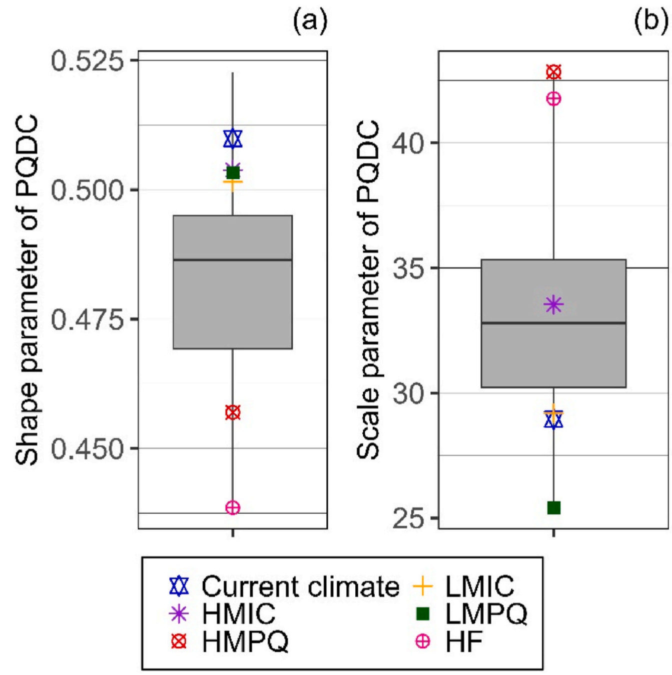

Fig. 5. Shape and scale parameters of gamma distribution fit of the peak flow distribution curves (PQDC) of current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

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 when the flow time series was relatively short (Nagy et al., 2017). However, from the simulated AMS of the current climate and CC scenarios, it was observed that many of the CC scenarios had very high annual peak flows for several years and then had periods of very dry years (Fig. 7). On the contrary, the AMS of the current climate always had high values with no low flow years (Fig. 7).

3.4. *Predicted long-term changes in the channel profile*

Under current climate conditions, even with the 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 (Fig. 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. Downstream of 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 most downstream section, the channel bed erodes to bedrock (estimated at 0.9 m below the initial channel invert elevation, Fig. 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. Fig. 8 shows the range of channel bed profiles for the 64 CC scenarios (grey-shaded region). Considering the projected CC, it is anticipated that the magnitude of the largest 25% of peak flows will increase in the future (Fig. 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. Both these riffles are situated immediately downstream of a narrowing in the channel, which induces backwater effects, reducing the sediment transport capacity and promoting deposition of coarse material mobilized from upstream. 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

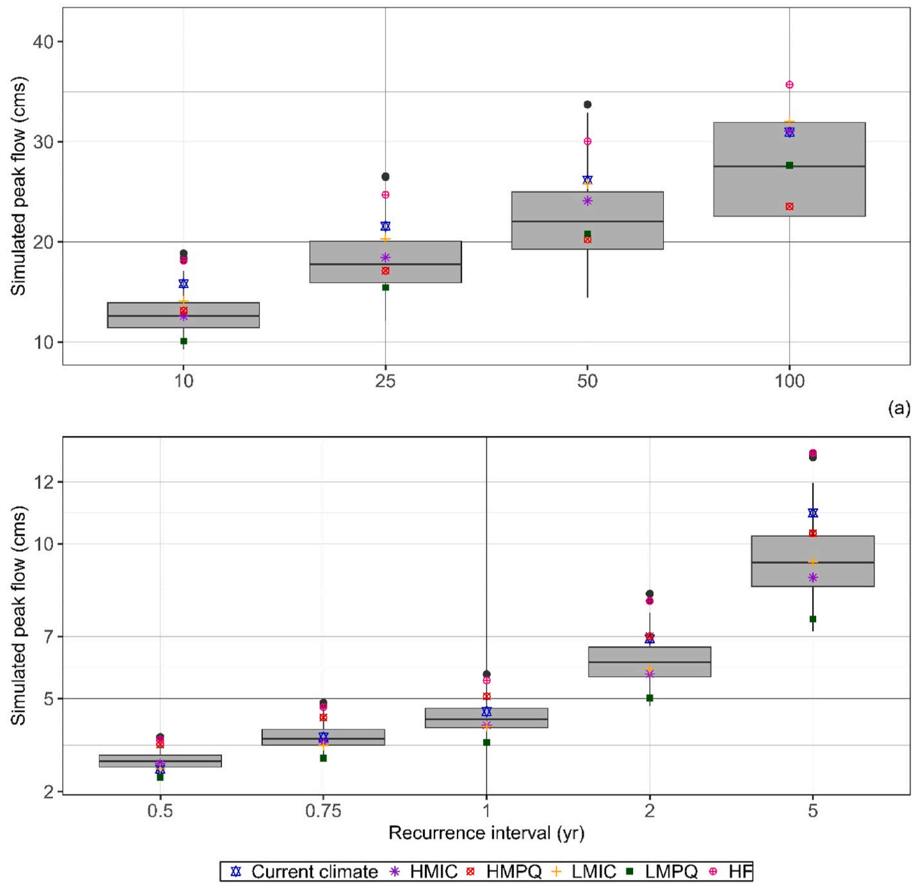

Fig. 6. Boxplots of peak flows with recurrence intervals of a) 0.5, 0.75, 1, 2, and 5 years, and b) 10, 25, 50, and 100 years for current climate and climate change scenarios with the highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

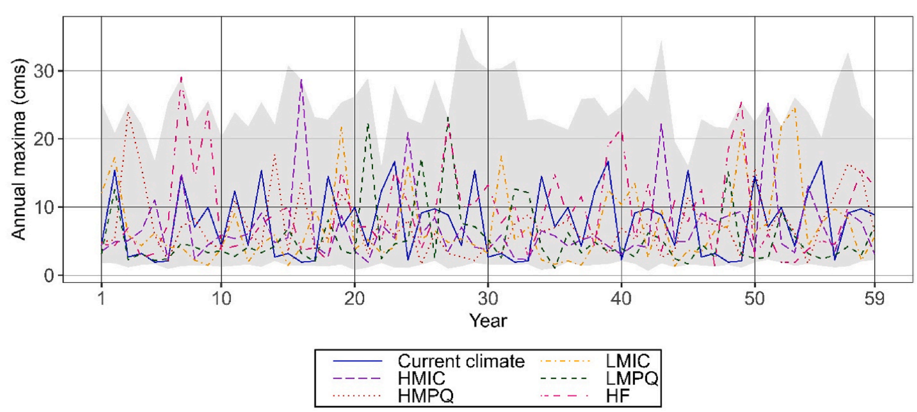

Fig. 7. Annual maxima series (AMS) of current climate and climate change (CC) scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF). The shaded region shows the range of values from all CC scenarios.

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-sectional area change) is provided in Fig. 9. The median invert elevation change and cross-sectional area change due to erosion are higher in almost 90% of the CC scenarios (Fig. 9), even the CC scenario with lowest mean peak flows experienced more erosion than the current climate condition. The standard deviation of the invert elevation also increased due to CC, indicating the extent of both erosional and depositional hotspots along the reach will increase in the future due to the increase of flashiness and shorter event duration of the catchment hydrology.

3.5. Impact of climate change on sediment transport dynamics

Channel stability occurs when the incoming sediment supply and the sediment yield through the reach are generally balanced or when the channel is resistant to erosion. The incoming sediment supply is set by the sediment load rating curve of the calibrated HEC-RAS model (Towsif Khan et al., 2024a) and is a function of the number and magnitude of

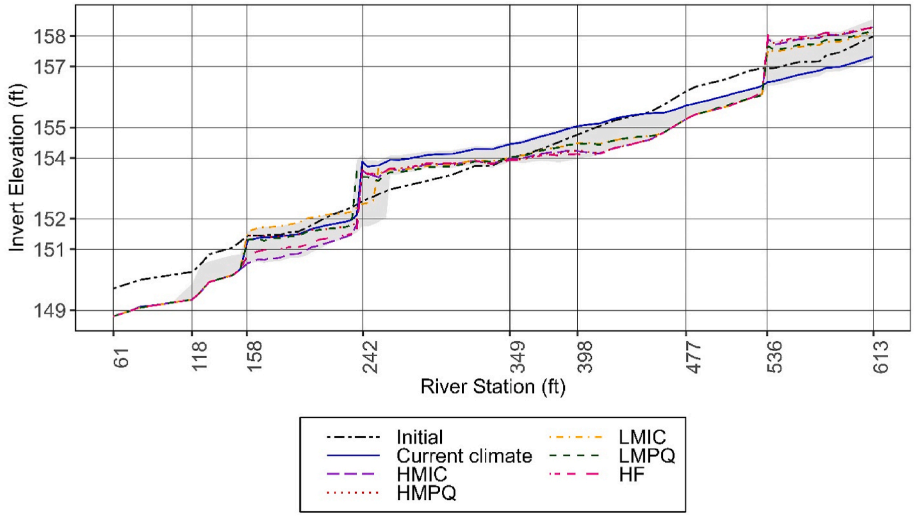

Fig. 8. Predicted channel longitudinal profile for current climate and climate change (CC) scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF). All CC scenarios (shown as a grey band).

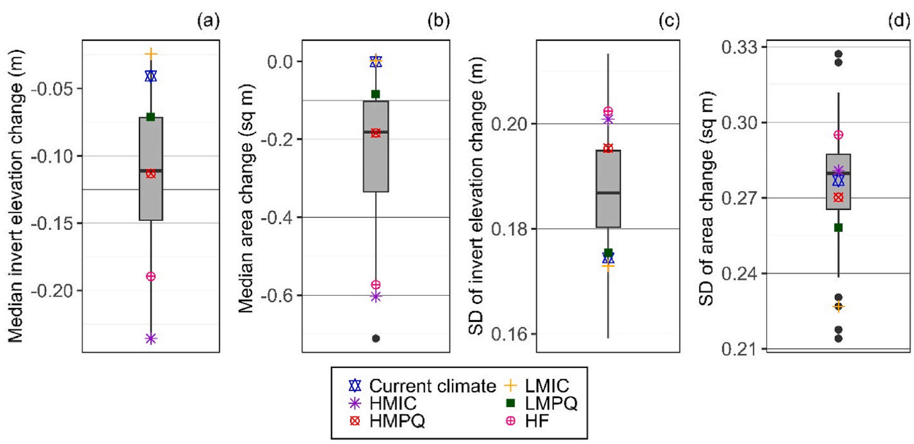

Fig. 9. Median invert elevation change (a), median cross-section area change (b), standard deviation (SD) of invert elevation change (c), and SD of cross-section area change (d) of current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

flood events. 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 (Fig. 10a). This reduced sediment supply occurs 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 Fig. 4. However, the sediment yield (median of all CC simulations) increased by 1.5 tonnes due to the predicted increase in channel erosion under CC (Fig. 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 depositional due to overbank deposition. 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 due to 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 mechanisms in the floodplain.

3.6. *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 the changing climate, with almost 90% of the CC scenarios having higher Q_{hf} than the current climate (Fig. 11a). The cumulative sediment transport curve (Fig. 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 (Fig. 4). In contrast, 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.

4. 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 prior CC studies (Butcher, 2021; Butcher et al., 2023b), which were conducted on a unit-area basis with 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 within this region projected small changes in low magnitude, and high recurrence storm events (Butcher, 2021; Butcher et al., 2023b), which typically control channel morphology. However, analysis of the expected changes in channel invert elevation shows 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. Therefore, the applicability of our results may be limited to the specific scenarios and models employed in this study.

4.1. 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 increase in the precipitation totals for less frequent storm events (Fig. 2a) (Butcher, 2021; Butcher et al., 2023b). 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 the average and peak rainfall intensities during these events potentially increasing by as much as 200% when compared to current climate conditions (Fig. 2b and c; Fig. 3). This change in storm event-based rainfall pattern is expected to drive the catchment hydrology to a flashier regime in the future (Fig. 5).

Empirical studies that have monitored rainfall-runoff dynamics in this region have demonstrated that the peak flows in urban headwater streams are 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 reveals a different result – while there is indeed an increase in the peak flow of the greatest 25% of floods, there is a decrease in the peak flow of the remaining flood events (Fig. 5). This counterintuitive finding can be attributed to the fact that the top 25% of flood events are typically caused by storms with rainfall depths exceeding 25 mm (Fig. 2a), referred to as the Water Quality Volume (WQ_v) design rainfall depth as per the Maryland stormwater regulations (MDE, 2000). Consequently, even though there is an increase in the intensity for these smaller storm events under CC, the resulting peak flows did not increase due to the stormwater storage distributed throughout the catchment, resulting in a downward shift of the lower half of the PQDC, as compared to the current climate conditions (Fig. 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 and Hogue (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 Natural Resources Conservation Service's 24-h rainfall distribution 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).

4.2. 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-h 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 the 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 (Fig. 5). In fact, in nearly 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 (Fig. 9). This trend of increasing channel degradation 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 (Fig. 4). These elevated peak flows mobilize larger, previously less mobile, bed particles within the stream reach, subsequently leading to destabilization of the channel bed and particle redeposition in areas with reduced shear stress (MacKenzie and Eaton, 2017). The shortened transport distances of these larger bed particles can also be attributed, in part, to the shorter duration and greater intensity of storm events under the changing climate (i.e. flashier hydrology). Previous research by Annable et al. (2012) and Plumb et al. (2017) demonstrated that shorter event durations and increased flow flashiness due to urbanization led to more 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, Fig. 8), in contrast to the single steep riffle observed under current climate conditions (RS 242, Fig. 8).

Although the average annual sediment supply to the reach is generally expected to decrease in the future, the median of the average annual sediment yield will likely increase when compared to the current climate (Fig. 10). This change stems from the fact that while sediment supply is influenced by the sediment rating curve and the catchment flow regime, sediment yield is also determined by channel and floodplain morphology, which impact sediment storage and transport through the reach (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 CC scenarios from the paired sediment yield and flow time series of the least disturbed river stations. Surprisingly, 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. (2024a) 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 will become more influenced by extreme events as flow flashiness increases. Considering that SCMs are typically designed to accommodate more frequent events, rather than catastrophic rare events, due to cost constraints, addressing channel stability following urbanization in the future will be complex.

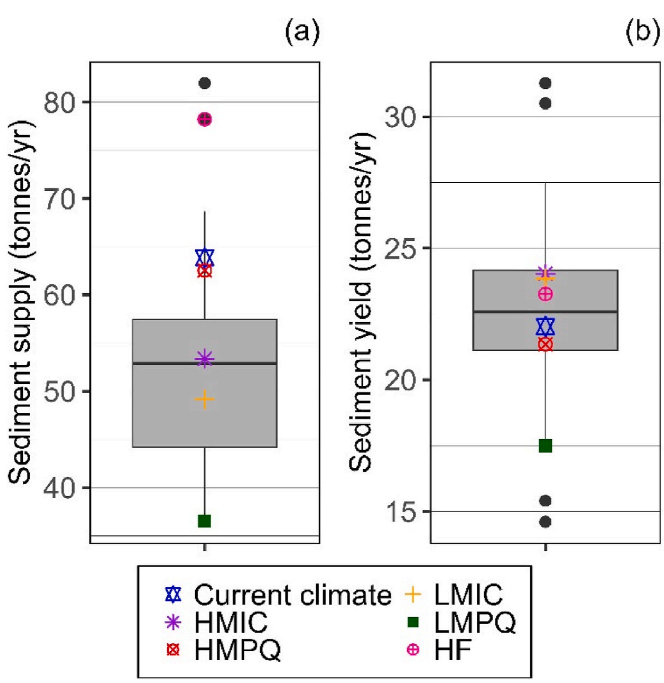

Fig. 10. Average annual a) sediment supply delivered to the reach, b) sediment yield from the reach of current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

4.3. 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 more nuanced 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 WQ_v 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 (Cp_v) criterion. The Cp_v criterion is designed to detain the runoff volume from a 1-year, 24-h storm event for 12 or 24 h, theoretically controlling bankfull and sub-bankfull discharges post-development. While our findings concur with a general decrease in rainfall amounts for most storm events, including those with a 1-year recurrence interval, we predict a significant increase in the intensity of nearly all storm events in the future due to increases in maximum 5-min rainfalls. Given the uncertainties in downscaling daily rainfall totals to subdaily intervals necessary to adequately represent urban rainfall-runoff responses, more research is needed to better predict the impact of climate change on regional rainfall distributions.

Furthermore, it is critical to recognize that individual SCMs are often designed without considering the response of other SCMs in the catchment. 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 and 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 hydrology.

In addition to predicting the cumulative change in watershed hydrology due to development with stormwater management, to protect channel stability, the effect of the altered hydrology on sediment transport must be evaluated. The design criteria can involve matching sediment transport amount to a predeveloped condition based on existing channel bed materials and cross-section conditions for CC-informed design storms. While addressing this metacriterion SCM design may pose challenges due to the complexity of sediment transport equations, spreadsheet-based tools are now available that can readily estimate sediment transport amounts without the need for data-intensive models like HEC-RAS. Although sediment transport amounts may vary significantly based on the choice of bed material estimation equations, studies such as Bledsoe (2002) have demonstrated that SCM sizing is not sensitive to equation selection, as long as the design criteria are based on a comparison between post and pre-developed conditions. Hawley et al. (2022) and Towsif-Khan et al. (2024b) showed that SCMs retrofitted to match the sediment transport capacity of the pre-development sediment regime were able to reduce the extent of erosion and instability in the channel following SCM retrofitting. Alternatively, a stormwater design criterion for the Sanitation District No. 1 in northern Kentucky, USA, targets maintenance of stormwater discharges below a regional critical discharge, which is a threshold discharge at which the bed material becomes mobile (Wooten et al., 2022). A multicriteria design approach considering the impacts of climate change on regional rainfall distributions and the interplay of multiple SCMs on watershed hydrology and local sediment transport is recommended to protect channel stability with the changing climate, given that the total volume of rainfall is less influenced by climate variations.

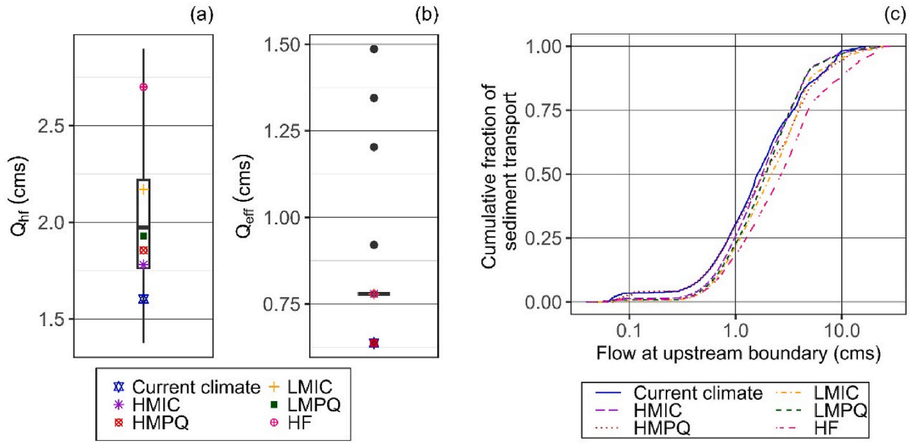

Fig. 11. Half-yield (Q_{hf}) discharge (a), effective (Q_{eff}) discharge (b), and cumulative sediment transport (c) for current climate and climate change scenarios with highest median invert elevation change (HMIC), highest mean peak flows (HMPQ), lowest median invert elevation change (LMIC) and highest flashiness (HF).

5. Conclusions

A well-calibrated, high-resolution catchment-scale hydrological model and a quasi-unsteady 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 interval storm events. However, the models indicate that the sediment supply to the reach will likely decrease and the ongoing degradation of the studied reach will be exacerbated by increasing rainfall intensity due to CC. These findings depend on the GCMs used to generate the precipitation datasets, limiting the applicability to specific scenarios and models. However, 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.

CRediT authorship contribution statement

Sami Towsif Khan: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **David J. Sample:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Theresa Wynn-Thompson:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jon Butcher:** Writing – review & editing, Data curation, Conceptualization.

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

During the preparation of this work the author(s) used ChatGPT in order to troubleshoot R code and to edit the initial draft. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123994.

Data availability

Data will be made available on request.

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