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Enhancing climate-resilient urban river restoration: predictive modeling of geomorphic changes

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ABSTRACT

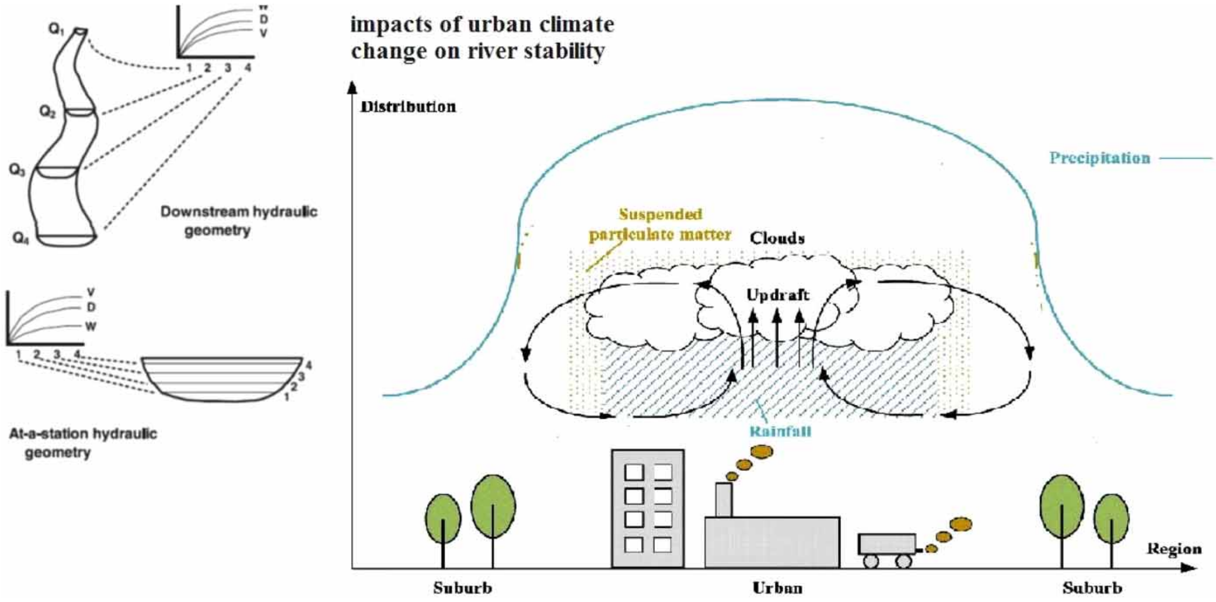
Urbanization and climate change are two potent forces shaping the contemporary environment. Urban rivers, integral to city life, are profoundly affected by these dynamics. While restoration efforts have yielded promising results, a persistent challenge lies in the inadequate consideration of geomorphic processes and climate change impacts in restoration planning. This study addresses this critical gap by proposing a novel approach for designing stable urban river geometries in ungauged basins. Leveraging the Soil Conservation Service (SCS) method in conjunction with General Circulation Model (GCM) data, our research focuses on determining design discharge and channel stability. Our principal finding, based on the incorporation of parameters related to precipitation, runoff, and effective discharge, indicates a projected 35% increase in the width of stable urban rivers in the future. These results underscore the urgency of integrating climate change considerations into urban river restoration initiatives. Neglecting this imperative aspect risks the failure of restoration projects, particularly in addressing geomorphic challenges intensified by climate change. This research offers a valuable framework for future restoration efforts, ultimately contributing to the resilience and sustainability of urban river ecosystems.

Key words: bankfull discharge, climate change, effective discharge, hydraulic geometry, natural channel design

HIGHLIGHTS

- The manuscript advocates for a resilience-centric approach to urban river management. It underscores the importance of recalibrating historical reference conditions to adapt to climate-induced alterations.
- The findings have immediate and far-reaching implications for urban river restoration projects. By recognizing the profound imprint of climate change on river stability parameters, stakeholders can recalibrate their restoration strategies to align with evolving environmental conditions. This adaptability is pivotal for preserving and enhancing urban river ecosystems.
- Determine the design discharge according to the effective and bankfull discharge in the future.
- This paper proposed a method to use the initial abstraction ratio to determine the discharge with a return period in ungauged basins.

GRAPHICAL ABSTRACT



INTRODUCTION

Predicting the stable cross-section of natural rivers has been the point of interest of many researchers for a long time (Francalanci *et al.* 2020). Rivers change their hydraulic geometry to remain stable against flow rates and sediments of the inlet and outlet. Thus, understanding hydraulic geometry is a primary engineering task for managing and organizing rivers. The hydraulic geometry of the river expresses the relationships between the channel geometry of width, average depth, velocity, longitudinal slope of the bed, and flow rate in a transverse section (local hydraulic geometry) or over an interval (intermittent hydraulic geometry) (Singh 2003; Eaton & Davidson 2013). Although river cross-sections are subjected to a wide range of flows, the shape and their geometry are generally regulated by a dominant discharge at a specified return period (Sharifi *et al.* 2021). The dominant discharge is used to describe the flow which itself has the main responsibility for governing the channel shape and form and is usually approximated by the discharge at bankfull or the effective discharge. Q_e is the flow that transports the maximum amount of sediment over time. Knowing the frequency of design discharges in rivers is crucial for river restoration. Changes in the river flow regime caused by climate change will alter the frequency of floods and bankfull discharge, and consequently affect the morphological and ecological functions of the river system (Eslamian 2014). Discharge indicators such as effective discharge and bankfull discharge enable hydrologists to better understand the geomorphology of rivers and the relationship between flow and sediment transport. Therefore, the most important thing for river restoration is determining the design discharge and consequently hydraulic geometry of the river (Gupta & Mesa 2014). The regime theory is used to estimate the stable geometry of river channels (Lacey 1930, 1934, 1946; Blench 1952, 1969, 1970; Lacey *et al.* 1958; Simons & Albertson 1960), as well as hydraulic geometry for stable river channels (Leopold & Maddock 1953; Parker 1979; Huang & Warner 1995; Huang & Nanson 1998).

In particular, Leopold & Maddock (1953) declared that the channel width, the average flow depth, and the average flow velocity are functions of the annually averaged flow discharge.

The process of widening straight channels in order to attain a stable cross-section has been simulated numerically by Pizzuto (1990), to derive the cross-sectional distribution of bed shear stresses. The channel bed topography was then derived according to the sediment flux balance equation and a heuristic bank failure law, based on exceeding the sediment repose angle. Kovacs & Parker (1994) continuously simulated the widening of a channel up to the equilibrium, without introducing any empirical bank collapse law.

Hydraulic modeling and the understanding of river processes stand as fundamental aspects of river management and restoration studies. Researchers have made significant strides in exploring various facets of river dynamics, including the pivotal impact of climate change on river systems.

Notably, Mann & Gupta (2022) conducted an insightful study titled 'Temporal Trends of Rainfall and Temperature over Two Sub-Divisions of Western Ghats'. This research delved into the temporal trends of rainfall and temperature, providing invaluable insights into evolving climate patterns within specific regions. While their primary focus was not exclusively on rivers, such investigations contribute essential climate data that can illuminate and inform river management strategies in the face of changing environmental conditions.

In a distinct yet relevant context, Chomba *et al.* (2022) made significant contributions through their work on 'Integrated Hydrologic-Hydrodynamic Inundation Modeling in a Groundwater Dependent Tropical Floodplain'. Their research underscored the intricate interplay between hydrological and hydraulic processes, emphasizing the complexity of floodplain dynamics. Such studies broaden our understanding of how rivers interact with their surrounding landscapes, particularly in flood-prone areas, and can have profound implications for effective river management and restoration practices.

Furthermore, Faye (2022) enriched the body of literature with the study titled 'Comparative Analysis of Meteorological Drought based on the SPI and SPEI Indices'. While meteorological drought and river flow represent distinct phenomena, the comparative analysis of drought indices offers valuable perspectives on how shifting precipitation patterns might reverberate through river ecosystems and influence water availability. This holistic view is instrumental in comprehending the multifaceted impacts of climate change on river systems.

These aforementioned articles, in conjunction with existing research, underscore the multidisciplinary nature of river management and restoration. They emphasize the critical significance of considering climatic factors, hydrological processes, and hydraulic dynamics in comprehensive river restoration endeavors. These contributions collectively contribute to our broader understanding of the intricate and evolving relationship between climate change and river systems, which is of paramount importance in contemporary river management practices.

Many approaches have been proposed in the literature but still, a framework capable of explaining the stable width of urban rivers under climate change is rare. In this paper, we try to fill this gap by developing a method that predicts the stable bankfull width of urban rivers with cohesive erodible banks. In fact, one way of reducing the cost of river maintenance (dredging) and optimal use of floodplains in cities is to identify the river morphologically. This could only be achieved by understanding the river's adjustment to climate changes (Sharifi *et al.* 2021). Global climate change leads to alterations in rainfall patterns, especially the intensity and frequency of heavy rainfall (Steensen *et al.* 2022), and urban areas are now considered a vital part of the global response to climate change (World-Bank 2010; UN-Habitat 2011). Farahzad River, in Iran, is one of the urban rivers that could be used to test the theory. This article tries to find the river forming discharge and the stable design by studying the bankfull and effective discharge under climate change.

In addition, the findings of the current study indicate that the rainfall intensity under climate change is drastically increasing. Using intensity–duration–frequency (IDF) curves based on historic rainfall data may lead us to an underestimation of the stable channel geometry. Especially in cities, the highly modified environment and the lack of open spaces make it harder to apply the concept of river stable channel geometry, and it is even more difficult to apply, especially in cities that have highly modified environments with almost no open spaces. It raises doubts about the feasibility of adopting restoration approaches for urban rivers.

According to the research conducted by the authors, the need to consider climate changes in urban rivers for design purposes has been emphasized, but no practical solution to consider changes in cross-section due to climate change has been presented in the past articles, in which this research, the issue has been presented. The structure of the article is in such a way that in order to implement the presented method, a case sample of Tehran's urban river in Iran, which is located in the unmeasured basin, has been selected. Then, the runoff due to current and future rainfall is calculated and, after modeling in HEC-RAS and using geometric hydraulic methods, the average changes of cross-section in depth, and width are predicted in the future.

MATERIALS AND METHODS

This section details the methodology applied in the study (Figure 1), which includes the use of historical and future rainfall data to estimate the discharge with a return period, the use of geometric data to estimate bankfull discharge, the use of sediment data to effectively discharge calculation, and finally the use of hydraulic geometry to estimate the stable channel.

Study area

The case study is a part of the Farahzad River Basin (Figure 2) which is located in the west of Tehran, bound by the Darake River from the east and the main branch of the Hesarak River from the west. Its coordinates are east longitude 22′–51° to 20′–51° and north latitude 45′–35° to 53′–35°.

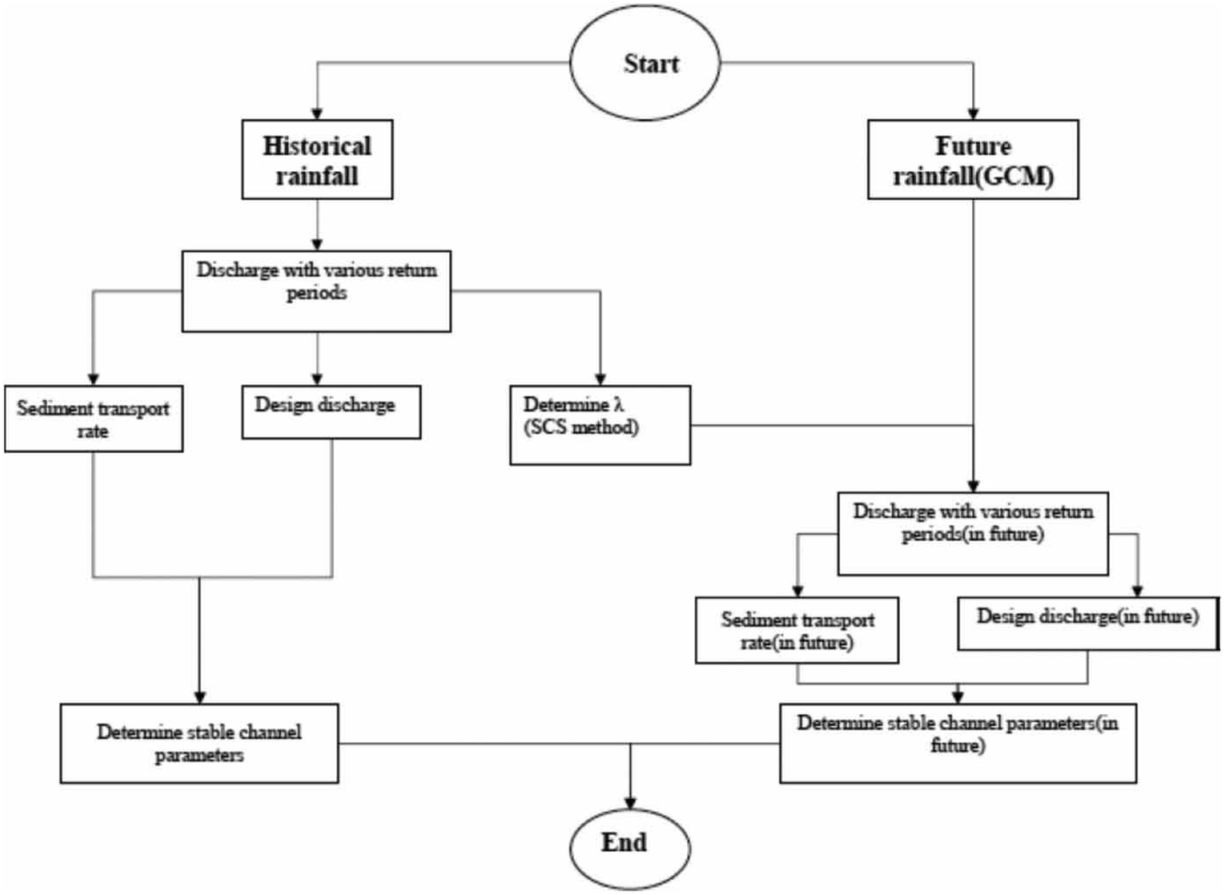


Figure 1 | Flowchart of the proposed methodology.

Determination of the discharge with a return period

Estimation of design peak discharge, which has always been of paramount importance in hydrology, has been used as an indicator for water-related plans. Due to the lack of sufficient statistical data about flow type and its quantity, researchers proposed various empirical methods to determine the maximum discharge. A Fuller empirical formula, developed in the east USA, is one of them. It was developed by analyzing hundreds of flood peaks and has been used all around the world. Their coefficients are calibrated for many regions (Fuller 1914), and another method was developed for smaller basins by the US Soil Conservation Service (SCS) in 1957 which uses the daily precipitation values to calculate the peak flow rate (Gulbahar 2016).

In this study, Fullers' method is used to calculate peak flows with a return period, using historical data for the base period Equation (1), and the SCS method for future peak flows with a return period (Equations (2)–(4)), using future rainfall data under climate change from previous studies by many authors (Binish *et al.* 2018; Binesh *et al.* 2019) (Figure 4):

$$Q_{\max} = C.A^{0.8} \cdot [1 + 0.8log(T_r)] \cdot (1 + 2.66)^{-0.3} \tag{1}$$

where $Q_{\max}$ is the maximum instantaneous discharges in T years of return periods (m^3/s), A is the basin area (km^2), C is a regional coefficient that depends on climatic and geographical situations and characteristics of the basin:

$$S = \frac{25,400}{\mathrm{CN}} - 254 \tag{2}$$

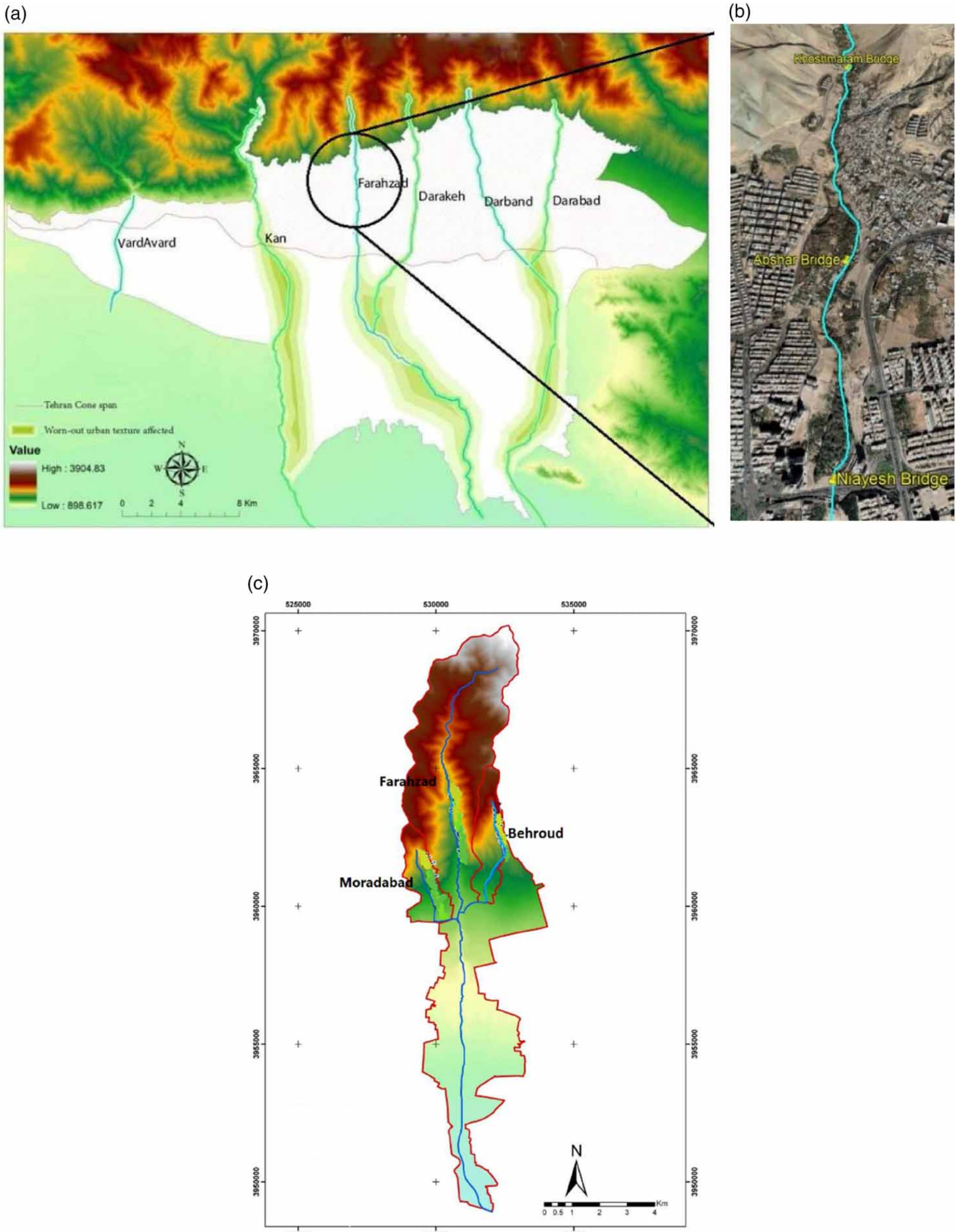


Figure 2 | Location of Farahzad River in Tehran.

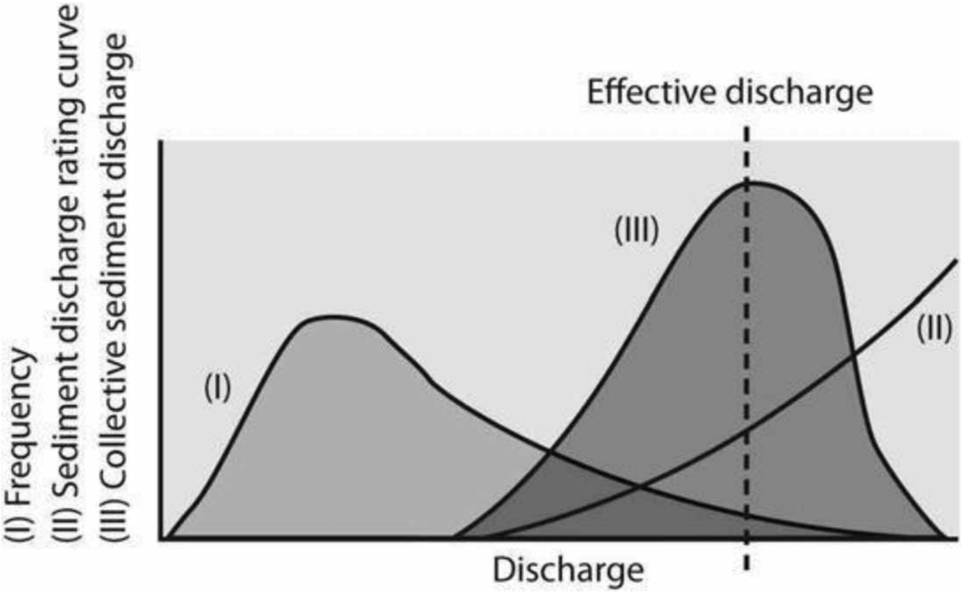


Figure 3 | Wolman & Miller (1960) model for magnitude and frequency of sediment transport events. Curve (I) is the flow frequency, curve (II) is the sediment transport rate as a function of discharge, and curve (III) is the distribution of sediment transport during the period of record (product of curves II and I). Effective discharge is the flow rate that transports most sediment over time, defined by the maximum value of curve (III). Curve (I) is partitioned into arithmetic discharge bins (Barry *et al.* 2008; Klasz *et al.* 2012). Figure from Skidmore *et al.* (2011).

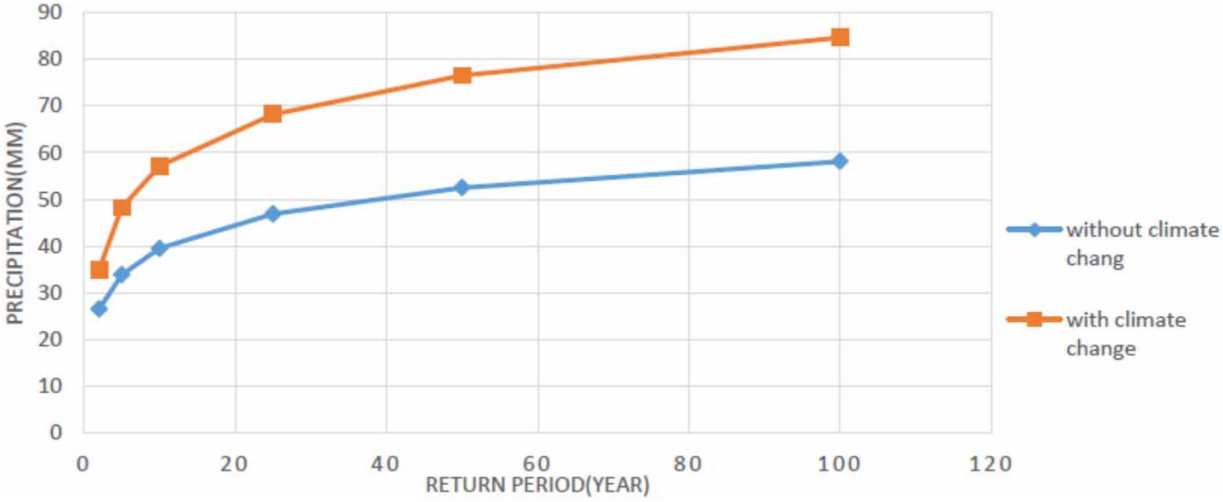


Figure 4 | Future rainfall with and without climate change (GCM model).

$$R = \frac{(P - \lambda S)^2}{(P + 0.8S)} \tag{3}$$

$$Q_p = \frac{2.083A \cdot R}{0.6T_c + \sqrt{T_c}} \tag{4}$$

where S is the maximum holding capacity and penetration in soil (in millimeters), CN is the number of curves related to the amount of water infiltration in the soil of the basin, which is calculated based on the area's hydrologic soil group and land use, R is the runoff height (in millimeters), P is the 6-h rainfall with a return period of 50 and 100 years (in millimeters), λ is a coefficient set to 0.2 for the maximum 24-h of rainfall; in Iran, according to Alizadeh (2013) and Petroselli *et al.* (2020), it is equal to 0.2 for the return period of more than 10 years (Figure 5). Moreover, A is the basin area (in square kilometers), and Q_p is the peak runoff flow rate (in m^3 per second), and T_c is the focus time (in hours).

To approach the aim of the current study, bankfull and effective discharge, with a maximum return of 10 years, λ is determined using Equations (5)–(7):

$$P = I_a + F + Q \tag{5}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{6}$$

$$I_a = \lambda S \tag{7}$$

where Q is the runoff (in millimeters), I_a is the initial abstraction (in millimeters) that has to be exceeded so that the direct runoff can start to form, F is the cumulative infiltration (in millimeters) not including I_a.

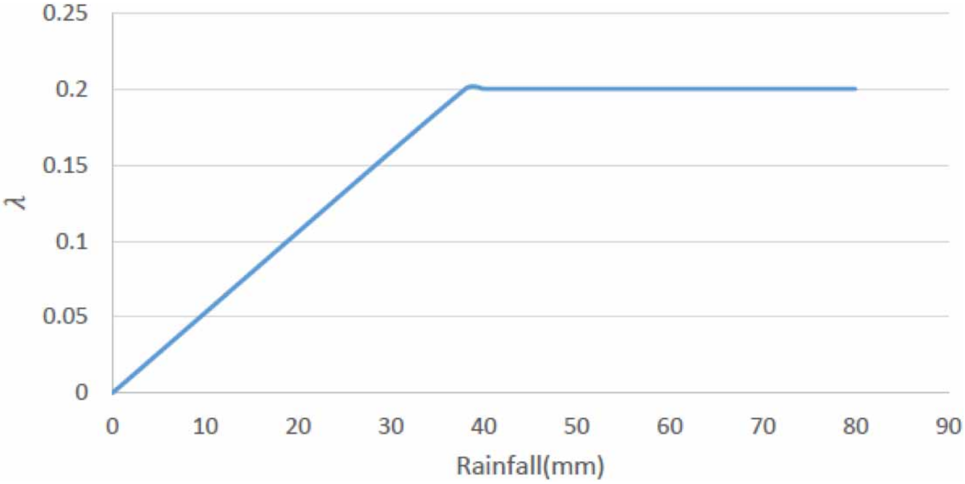


Figure 5 | λ changes due to precipitation.

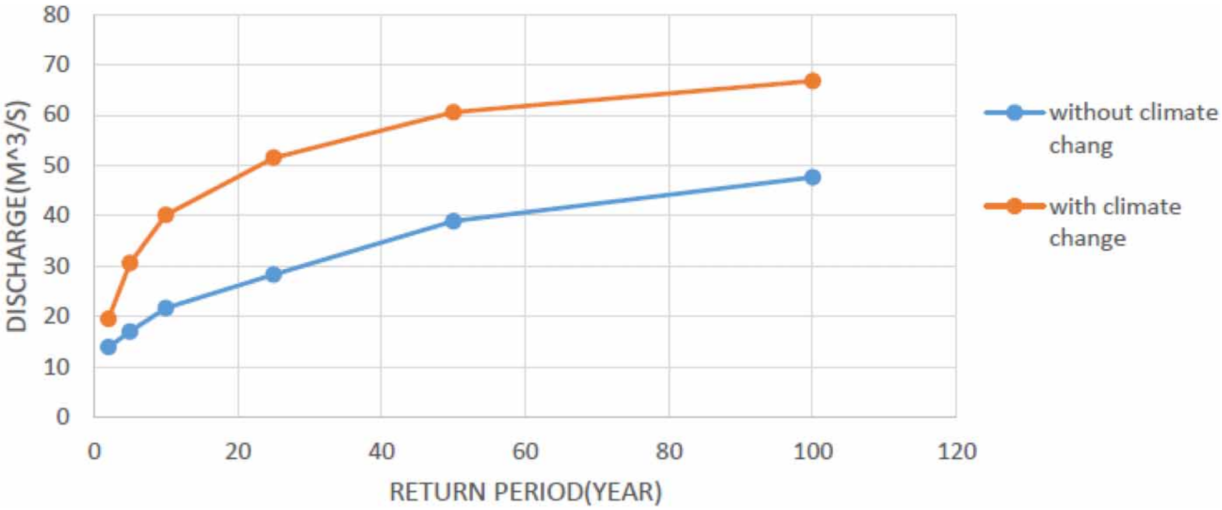


Figure 6 | Discharge return period with and without climate change.

Bankfull discharge

In this section, we employ the hydraulic modeling package HEC-RAS, developed by the U.S. Army Corps of Engineer's Hydrologic Engineering Centre River Analysis System, to investigate how changes in the flow discharge and depth impact the shear stress on the riverbed. We then plot the shear stress against increasing discharge. The results reveal a clear pattern: as the flow discharge increases, the bed shear stress also rises, reaching its peak around the bankfull level (Török *et al.* 2020). This underscores that the maximum shear stress occurs in proximity to the bankfull level within the channel (see Figure 7).

Effective discharge

Effective discharge plays a significant role in sediment and nutrient transport, landscape modification, and river restoration (Pradhan *et al.* 2021). It is the amount of flow that carries the highest sediment load over a period of 1 year (Figure 3). Therefore, by plotting a flow discharge–sediment discharge curve and frequency histogram of daily discharges with a specified class and multiplying the widths of the two curves, we get another curve representing the amount of sediment transported by each discharge. Here, the discharge matching to the maximum sediment is defined as the effective discharge (Sharifi *et al.* 2021).

Sediment rating curve

The sediment rating curve plots the daily discharge data against measured suspended sediments. In other words, a sedimentation curve was plotted between Q and Q_s using data from the Water Organization, and then, a line was fitted to the data (Figure 9). The method that has been used in this study has been widely utilized by other researchers (Sharifi *et al.* 2021). Regarding the definition of effective discharge, this method finds the most amount of sediment transported from the sediment rating curve and frequent histogram, with the most possible accuracy:

$$Q_s = aQ^b \tag{8}$$

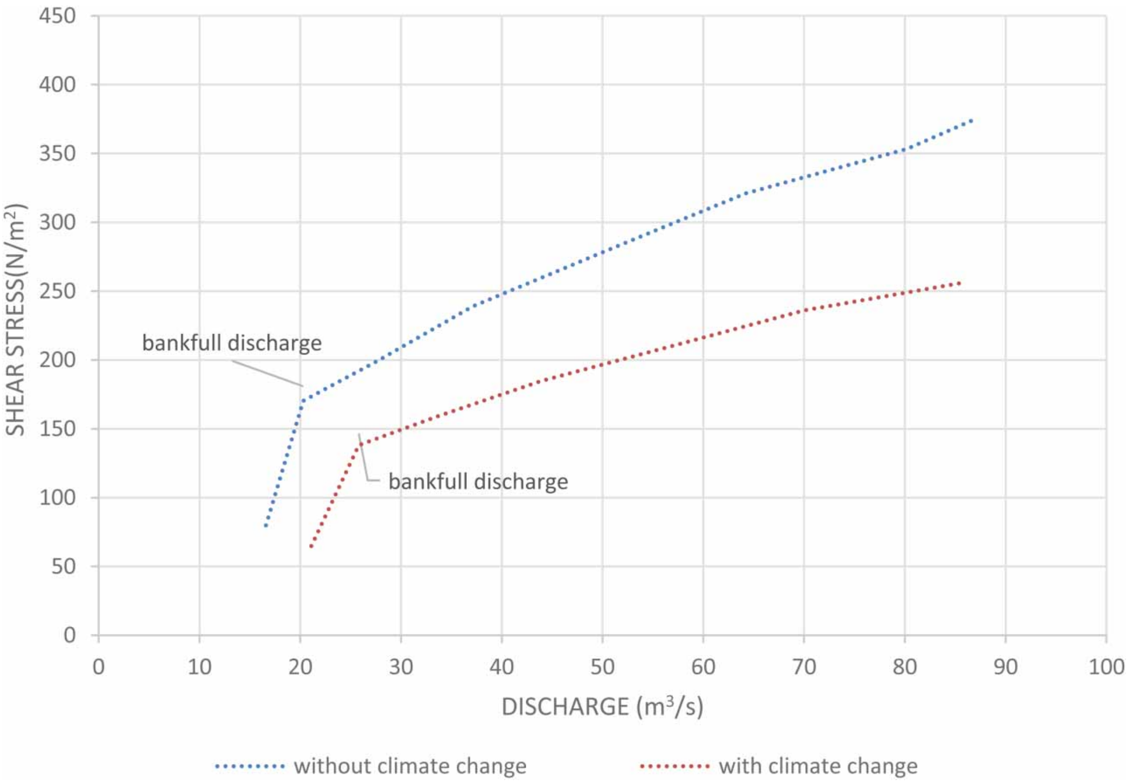


Figure 7 | Relationship between bed shear stress and flow discharge. *Note*: reduction in the rate of increase in shear stress as discharge rises, with critical point that corresponds to the bankfull discharge at which the floodplain begins to become inundated.

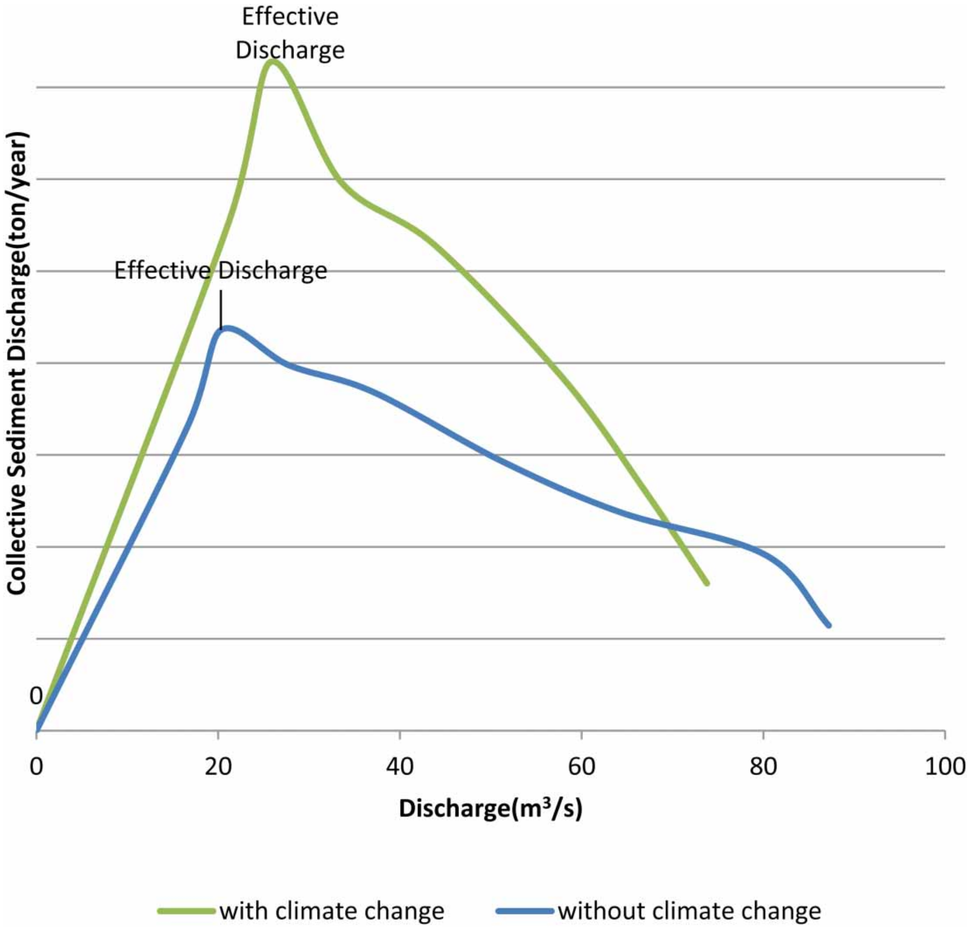


Figure 8 | Derivation of total sediment load–discharge from flow frequency and sediment load rating curves.

Q_s represents the sediment transport in ton/day and Q represents the river discharge in m^3/s. The coefficients a and b are constants.

Hydraulic geometry

Following conventional methods (e.g., Leopold & Maddock 1953), predictive relations for channel geometry in terms of variables are used where width, depth, and velocity decrease exponentially as discharge increases. Although 'hydraulic geometry' normally has a complicated form, it can be approximated simply by the following form of regime theory:

$$W = aQ^b \tag{9}$$

$$V = kQ^m \tag{10}$$

$$D = cQ^f \tag{11}$$

where W is the width of the water level (m), d is the medium depth (m), V is the average (mean) velocity (m/s), and Q is the discharge (m^3/s).

The coefficients and exponents are specified for a given cross-section of a river. While these regime relationships are a response to a set of interacting factors associated with the amount of water and sediment in transport and many other factors like local vegetation, sediment texture, and regional gradient, they can simply be approximated in the form of river channels (Leopold & Maddock 1953; Parker 1979; Huang & Warner 1995; Huang & Nanson 1998). They can be demonstrated experimentally and they can be represented as $b = 0.5$, $m = 0.2$, and $f = 0.3$ (Schumm 1960; Ferguson 1986; Huang & Nanson 2000).

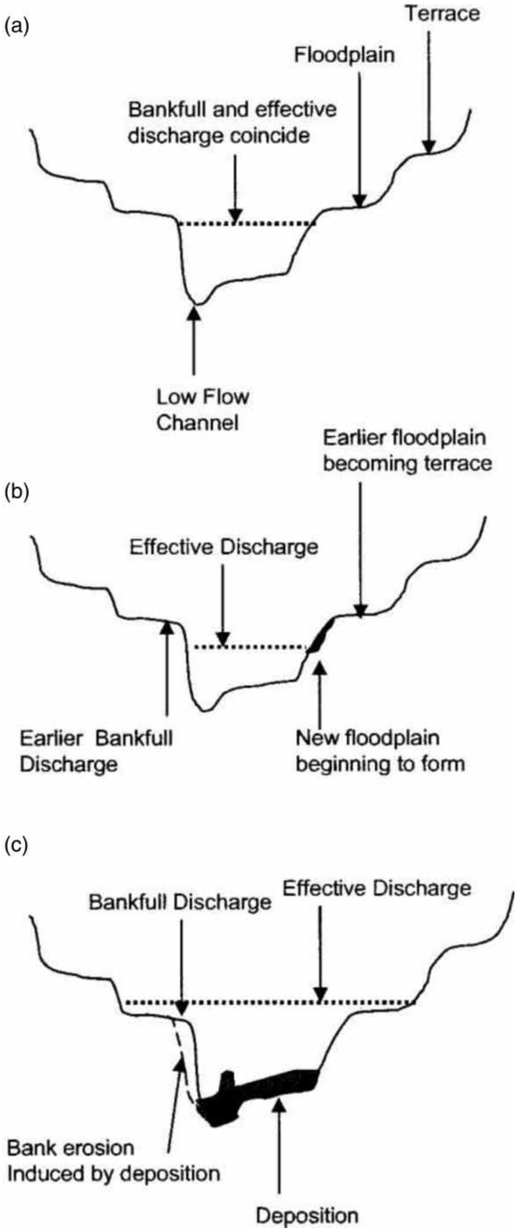


Figure 9 | Theoretical relation between the effective and bankfull discharges for (a) channel in dynamic equilibrium, (b) incising channel, and (c) aggrading channel (Goodwin 2004).

Width (W), velocity (V), and depth (D) were estimated through HEC-RAS simulations for different design discharges in the base period, then using Equations (9)–(11); b, m, f were evaluated, by comparing these values with the corresponding values of the stable channel, changes in the width and depth of the channel to reach stability were predicted (Figure 10). Repeating previous steps with the future dominant discharges under climate change, we can predict the width and depth of the channel in the future under climate change (Figure 10).

RESULTS AND DISCUSSION

The hydrologic result of the study is the effect of climate change on peak floods for the return period. It applied to the rainfall data series under climate change conditions (Figures 4–6). Extreme events happen when we have high-intensity rainfall caused by climate change which leads to a growth in precipitation and consequently in the peak discharge.

Bankfull discharge analysis

The assessment of bankfull discharge is pivotal for understanding the river morphology and stability. The study entails cross-sectional bed shear stress plotted against increasing discharge for various reaches of the Farahzad River (Figure 7). Within this graphical representation, the maximum shear stress value signifies the reach-averaged bankfull discharge (Q^{bf}).

Effective discharge and comparison

Effectively managing river ecosystems demands a thorough examination of the concept of effective discharge. To achieve this, daily discharges and sediments were meticulously aligned in an Excel dataset, with sediments on the y-axis and discharges on the x-axis. Employing regression analysis, a line was fitted to the data, yielding the equation $Q_s = a{\cdot}Q^b$, accompanied by the calculation of the coefficients 'a' and 'b'. The derived equation, $Q_s = 32.613\mathrm{Q}^{2.33}$, offers critical insights into the relationship between sediment transport and discharge dynamics within the river (Figure 8).

A noteworthy revelation in this study is the discernible disparity between bankfull and effective discharge. In comparison to the effective discharge, bankfull discharge is found to be 28% higher in the upstream section and 22% lower in the downstream section (Figure 9). This discrepancy has been corroborated by previous research, including Goodwin (2004), who posits that such variations can provide valuable indicators of the river channel's dynamics. When the effective discharge can be comfortably contained within the active banks, it suggests the potential for river incision. Conversely, when the effective discharge surpasses the capacity of the active channel, it signifies a propensity for general deposition, marking a transformative phase in river morphology.

Hydraulic geometry

In line with the dynamic nature of rivers, particularly in urban settings, this study illuminates a critical facet of river behavior hydraulic geometry. Rivers, as observed, adapt by widening and increasing in velocity downstream while simultaneously reducing their depth in their quest for a stable configuration. What sets this study apart is its innovative approach, where hydraulic modeling is seamlessly integrated with climate change projections and hydrological analysis.

This integration allows us to predict the stable bankfull width of urban rivers with cohesive erodible banks under climate change scenarios as pioneering methodological innovation. The results unequivocally show a 35% increase in the width of the urban river as a consequence of the annual peak discharge (Figure 10). This finding revolutionizes our understanding of how climate change influences urban river morphology and, in turn, offers practical tools for sustainable river management.

In summary, this study not only advances our comprehension of climate change impacts on urban river systems but also introduces a groundbreaking methodological innovation for predicting river behavior under changing environmental

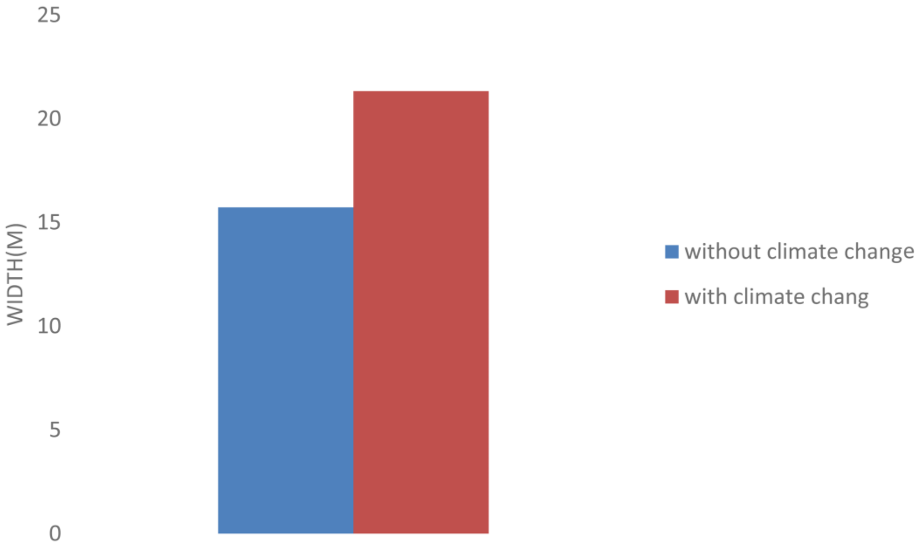


Figure 10 | Sustainable river width with and without climate change.

conditions. These results are essential for river managers, urban planners, and policymakers seeking effective strategies to protect and manage urban rivers in an era of climate uncertainty.

CONCLUSIONS

This research has undertaken a comprehensive exploration to unravel the profound impact of climate change on the stable dimensions of urban rivers. Through meticulous analysis, including the comparison of effective and bankfull discharges and an exhaustive examination of hydraulic channel geometry, a multitude of significant findings and implications has surfaced.

Scientific value added

Revealing climate-channel synergy: This study makes a substantial contribution by uncovering the intricate dynamics at the intersection of climate change and urban river morphology. By quantifying the effects of climate-induced perturbations, notably the intensification of high-intensity rainfall events, it introduces a groundbreaking perspective that bridges the realms of climate science and river geomorphology.

Innovative predictive methodology: A pivotal innovation presented in this research is the development of a predictive methodology to discern stable channel dimensions under climate change scenarios. This innovative approach not only enriches the scientific discourse but also equips river managers, researchers, and policymakers with a practical tool to assess and manage urban rivers in an era of climate variability and change.

Applicability and practical implications

Enhancing urban river restoration: The findings of this research hold immediate and far-reaching implications for urban river restoration projects. By recognizing the profound imprint of climate change on river stability parameters, such as width and depth, stakeholders can recalibrate their restoration strategies to align with evolving environmental conditions. This adaptability is pivotal for preserving and enhancing urban river ecosystems.

Ensuring resilience in a changing climate: In an era where climate change is reshaping the landscapes of natural resource management, this research underscores the importance of recalibrating historical reference conditions. By acknowledging climate-induced alterations, practitioners can design more resilient and adaptive restoration strategies, ensuring the long-term sustainability of urban rivers.

Limitations

It is imperative to acknowledge certain inherent limitations within this research. The reliance on climate change projections introduces inherent uncertainties, necessitating ongoing refinement and validation of these projections against empirical data. Furthermore, the study's focus on a specific urban river, the Farahzad River, while insightful, may not capture the full spectrum of urban river dynamics. Expanding the study's scope to encompass a broader range of urban river systems could offer a more comprehensive perspective.

Future research directions

The journey of comprehending urban river response to climate change is an ever-evolving quest. To further enrich this field, future research endeavors may explore:

Ecological impacts: Delving into the ecological ramifications of changing river morphology and discharge dynamics under climate change scenarios can provide a deeper understanding of how urban river ecosystems adapt to evolving conditions.

Scenario-based analyses: Expanding the analysis to encompass various climate change scenarios and assessing their impacts on different urban river typologies can yield nuanced insights into the intricate interplay between climate, hydrology, and river morphology.

Interdisciplinary investigations: Collaborative research efforts that span climate science, hydrology, geomorphology, and ecology can provide a holistic perspective on urban river systems and their response to the multifaceted challenges posed by climate change.

Innovation highlight

This research stands as a pioneering endeavor by introducing an innovative predictive methodology that integrates climate change projections, hydrology, and river morphology. This methodological innovation not only advances scientific understanding but also empowers stakeholders with a practical instrument for informed urban river management in an era of climate uncertainty.

In conclusion, this research offers substantial contributions to climate change impact assessment, urban river management, and restoration practices. By quantifying the influence of climate change on river stability and providing a predictive tool, it empowers stakeholders to make informed decisions amid the complex and dynamic landscape of urban river management. Acknowledging its limitations and charting the course for future research, we anticipate that these findings will serve as a cornerstone for enhancing the sustainable management of urban rivers on a global scale.

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The authors received no funding for this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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