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Adaptation pathways for climate change mitigation using nature-based solutions: assessing retention ponds for flood hazard mitigation in the Tamnava Basin

Mohammed Khalafallah [a], Adam Mubeen [a,b,*], Laddaporn Ruangpan [a], Jasna Plavšić [c], Arlex Sanchez Torres [a], Zoran Vojinovic [a,d] and Mirjam Vujadinović Mandić [e]

[a] Department of Water Supply, Sanitation and Environmental Engineering, IHE Delft, Westvest 7, Delft 2611 AX, The Netherlands
[b] Department of Biotechnology, Faculty of Applied Sciences, Delft University of Technology, Van der Maasweg 9, Delft 2629 HZ, The Netherlands
[c] Faculty of Civil Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, Belgrade 11000, Republic of Serbia
[d] Centre for Water Systems, College of Engineering, University of Exeter, Harrison Building, North Park Road, Exeter EX4 4QF, UK
[e] Faculty of Agriculture, University of Belgrade, 6 Nemanjina Street, Belgrade 11080, Republic of Serbia
*Corresponding author. E-mail: a.mubeen@tudelft.nl

MK, 0009-0009-7670-2774; AM, 0000-0003-1934-6813; LR, 0000-0002-7803-0600; JP, 0000-0001-9679-8851; AST, 0000-0003-3146-2841; ZV, 0000-0002-7601-4041; MVM, 0000-0001-9583-5067

ABSTRACT

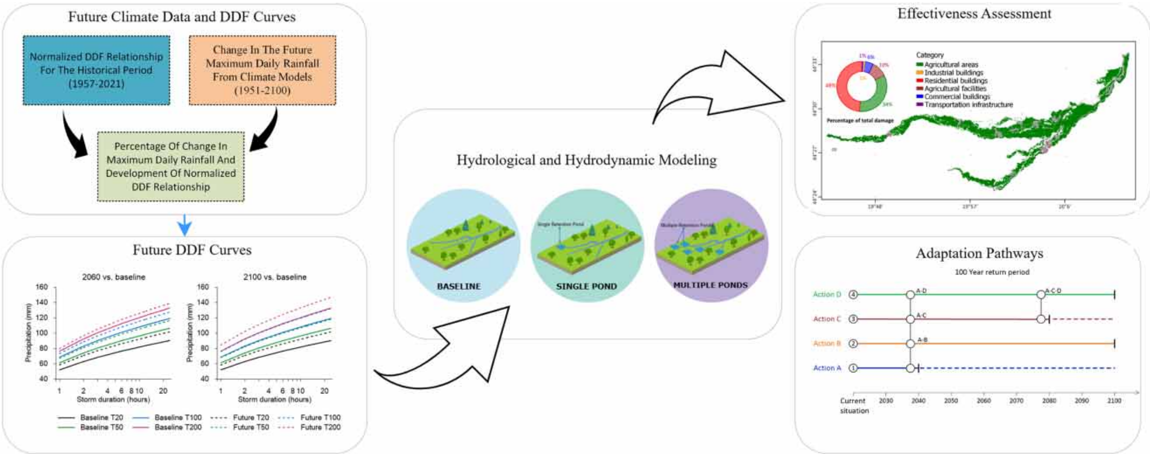
As climate change exacerbates water-related hazards in rural and urban areas, the need for robust, flexible solutions to mitigate risks and enhance resilience has become increasingly urgent. Traditional 'grey' infrastructure has long dominated flood risk management; however, nature-based solutions (NBS) are gaining traction due to their adaptability, multifunctionality, and ability to provide co-benefits. This study quantified the effectiveness of retention ponds as NBS for reducing flood hazard and risk under current and future climate conditions, employing adaptive pathways and tipping point frameworks for implementing NBS measures in response to climate change. This was applied in Tamnava Basin, Serbia, using a three-step approach: development of future sub-daily rainfall depth–duration–frequency curves (DDF), NBS performance assessment and identification of tipping points and development of adaptive pathways. Coupling HEC-HMS and HEC-RAS models with GIS tools, the study estimated reductions in flood area, volume, and damage costs by 20–27%, 28–35%, and 40–47%, respectively, over the period from the present to 2100, depending on the retention pond configurations. Different adaptive pathway maps were developed, for rainfall return periods. These maps provide decision-makers with flexible, actionable options for implementing NBS measures, bridging the gap between short-term evaluations and long-term climate uncertainties.

Key words: adaptation pathways, climate change, nature-based solution, tipping points

HIGHLIGHTS

- Development of future depth-duration-frequency (DDF) curves for future scenarios.
- Demonstrate that retention ponds as NBS can effectively reduce flood area, volume, and associated damages.
- Integrate Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Center's River Analysis System (HEC-RAS) models with GIS tools to quantify the impact of NBS on flood risk and hazard mitigation.
- Demonstrate the development of adaptive pathway maps for retention ponds, ensuring flood risk management.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Climate change has far-reaching effects on the patterns and intensities of natural processes across the globe. One of the most critical impacts is the alteration of precipitation dynamics, with substantial evidence indicating that climate change increases the intensity and duration of extreme rainfall events (Kendon *et al.* 2014; Westra *et al.* 2014). Given that rainfall-induced floods are among the most costly and hazardous natural disasters worldwide, understanding extreme rainfall's changing patterns and effects is essential. This knowledge is vital for informing both rural and urban planning policies and for guiding the design of resilient flood protection infrastructure to mitigate risks and enhance climate adaptation strategies.

Traditionally, gray infrastructure such as dikes and diversion canals has been the predominant approach for mitigating flood risks and reducing the associated damages. However, there is a growing shift towards strategies that enhance natural processes, such as increasing retention capacity and promoting infiltration, to manage flood events more sustainably. These nature-based solutions (NBS) offer a more adaptive and resilient approach to flood risk management by working with, rather than against, natural hydrological processes.

Considering the uncertainties in future conditions, the rapidly changing risk landscape, and various social challenges, adopting strategic and innovative approaches to climate change adaptation is crucial. For example, developing flexible strategies that can be adapted over time in response to evolving climatic and human-driven changes. Such an approach necessitates a fundamental rethinking of future infrastructure planning. Instead of attempting to navigate the uncertainties of likely scenarios, we should focus on proactive measures that can be implemented today to ensure resilience in the years ahead, considering the unpredictability of climate change.

The principles of creating adaptable plans have been described by Walker *et al.* (2013), who highlighted the need for exploration of a wide variety of relevant uncertainties, connecting short-term targets to long-term goals over time, committing to short-term actions while keeping options open, and continuously monitoring the world and taking further actions when necessary. This will enable more flexible plans that account for future uncertainties when we plan our strategies and prepare for changes.

In this respect, different methodologies have been applied for the planning and implementation of climate change adaptation measures such as robust decision-making (Lempert *et al.* 2006), adaptive policy making (Kwakkel *et al.* 2015), real options analysis (Swart *et al.* 2004; Woodward *et al.* 2011), and assumption-based planning (Hermans *et al.* 2012).

Adaptation pathways are defined as 'a decision strategy that entails a vision for the entity exposed to climate risks, to be met through a sequence of manageable steps over time, each of which is triggered by changing environmental or social conditions' (Barnett *et al.* 2014). They are also known as 'an analytical approach for exploring and sequencing a set of possible actions based on alternative external developments over time' (Haasnoot *et al.* 2012), while adaptation tipping points refer to critical thresholds where physical conditions exceed acceptable technical, environmental, societal, or economic limits, potentially leading to the failure of existing adaptation strategies (Haasnoot *et al.* 2011).

A key characteristic of the adaptation pathway is its capacity to outline alternative pathways that remain viable options while not immediately implemented if evolving future conditions render current strategies insufficient.

These systems exhibit anti-fragility, as they integrate flexible design elements that can enhance performance under conditions of significant uncertainty (Manocha & Babovic 2017).

In the context of managing flood risks, adaptation pathways have been applied at various spatial scales to address the diverse challenges posed by changing climatic conditions and extreme weather events. At the urban scale, studies by Deng *et al.* (2013), Hall *et al.* (2019), and Kapetas & Fenner (2020) have focused on developing adaptive strategies tailored to the unique needs of urban environments. At a broader, national level, adaptation pathways have been employed to manage flood risks in river deltas, with notable examples like the Dutch Delta Strategies (Kwadijk *et al.* 2010; Walker *et al.* 2013). These studies consider the complex interplay of environmental, societal, and economic factors within delta regions, which are particularly vulnerable to sea-level rise, and storm surges.

Despite these advancements, limited research has explored the application of adaptation pathways at the river catchment scale (Haasnoot *et al.* 2013; Lawrence *et al.* 2013; Ranger *et al.* 2013). While these studies provide valuable insights into the application of adaptation pathways and tipping point concepts into river basin plans, this study takes a step further and contributes by demonstrating a systematic approach that integrates hydrological, hydrodynamic, and GIS flood damage models in designing adaptation pathways for flood risk reduction by NBS, based on projected future rainfall intensities developed from an ensemble of climate models. Furthermore, it provides a quantified example of the effectiveness of retention ponds as NBS measures and exemplifies their potential embedded within adaptation pathways to improve flood resilience under future changing climate conditions.

Therefore, this study focuses on floods as the primary hydro-meteorological hazard and applies the adaptive pathways and tipping point approach to a case study from the RECONECT project (CORDIS 2018) in the Tamnava River Basin in Serbia. The objectives of this work are threefold: the first is to develop future sub-daily design rainfall for the study area. The second is to quantify the effectiveness of NBS under the current and future situation in terms of river catchment flood mitigation and the third is to develop adaptation pathways for NBS mitigation measures under the future climatic scenarios to aid policymakers in developing long-term adaptive plans by identifying the thresholds for each mitigation action under the future conditions.

Section 2 provides an overview of the study area. Section 3 outlines the methodological framework applied in this research, including the development of the climate data utilized for analysis. Sections 4 and 5 present the results & discussion, followed by the conclusions, respectively, underscoring the study's principal findings and their broader implications.

2. STUDY AREA

The Tamnava River Basin is one of the major sub-basins of the Kolubara River, which is a river that feeds into the larger Sava River system. It is located in western Serbia. The basin covers over 730 km^2 and is primarily made up of agricultural land which covers 79.3% of its entire area. The prominence of the basin in the agricultural economy of the area is demonstrated by the agricultural landscape, which is dominated by small-scale farms. The towns of Koceljeva and Ub comprise the majority of urban and industrial areas, which make up only 1.2% of the basin, demonstrating its predominately rural nature (Pudar *et al.* 2020; Pudar & Plavšić 2022).

The upper portions of the Tamnava Basin (Figure 1) begin at an elevation of 500 m above mean sea level (AMSL) while the elevation lowers as the watershed moves closer to its mouth, reaching 64.4 m AMSL at the Kolubara River's confluence (Milanović Pešić 2020).

Floods have a long and recorded history on the Tamnava River. Despite the Tamnava and Ub rivers' normal yearly discharges of 1.5 and 1 m^3/s, respectively, the most disastrous flood event occurred in May 2014 when their respective flows reached 178 and 146 m^3/s. Beside the flood runoff generated in the Tamnava Basin, the backwater effect from the Kolubara River at the confluence with the Tamnava River impedes the Tamnava River's ability to release water through the outlet during the floods, thus contributing to the flooding near the basin's outlet (Milanović Pešić 2020; Pudar *et al.* 2020).

3. METHODS AND DATA

The study was built on three main steps, presented in Figure 2: (1) future sub-daily climate data and DDF curves preparation, (2) baseline assessment and adaptation action simulation, and (3) tipping points calculation and adaptive pathways development.

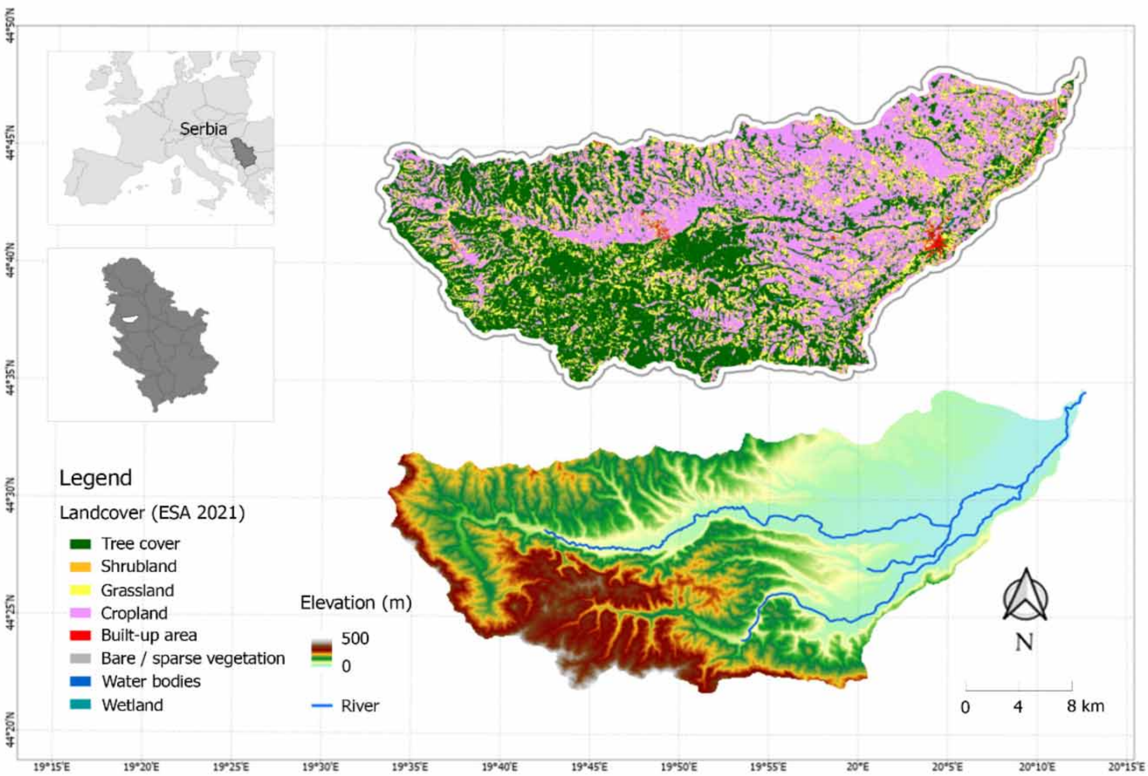


Figure 1 | Tamnava River Basin location, elevation and land cover.

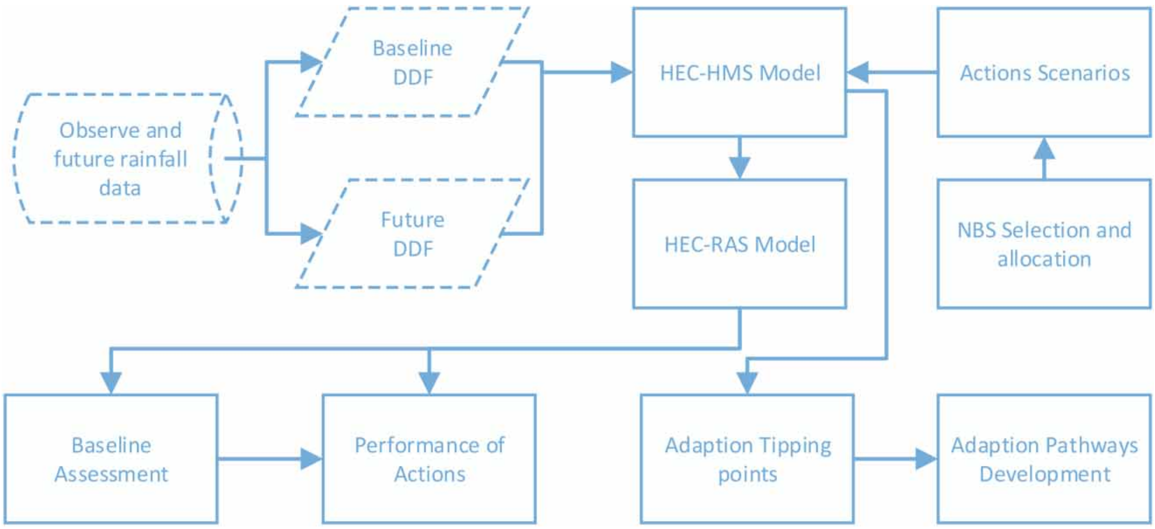


Figure 2 | Overall methodology.

3.1. Future climate data

Within the scope of this study, we worked with the assumption that the key factor responsible for driving potential floods is the increase in extreme rainfall events due to climate change. There are other critical factors such as changes in land use and the social dimensions that can also play a significant role in shaping flood dynamics. However, for the purpose of the research, the focus is exclusively on understanding the implication of changing design storms and their relationship with flooding dynamics before and after applying the mitigation measures, while excluding the consideration of changes in land use and social aspects.

To estimate the magnitude of design floods, at-site depth–duration–frequency (DDF) curves were used as the input for rainfall–runoff simulations. The lack of the observed sub-daily precipitation prevented the validation of sub-daily precipitation simulated by climate models and its use in developing future DDF curves. Therefore, changes in short-duration design storms are estimated indirectly on the basis of projected changes in at-site maximum daily precipitation using the steps outlined in Figure 3.

Firstly, a normalized DDF relationship for the historical period is computed by dividing design storm depths $P(t_d; T)$ of any duration t_d and for certain return period T with the design daily rainfall $P(1\text{d};\ T)$ of the same return period T. Normalized design storm depths are denoted by $X(t_d; T)$. In the second step, the change in the future maximum daily rainfall for each return period is devised from daily precipitation simulated by the climate models. This involves frequency analysis of annual maximum daily precipitation for the baseline and future periods and assessment of changes. Relative change in the simulated design daily precipitation, $\Delta(T)$, is computed from the T-year quantiles of the frequency distributions of simulated maximum daily precipitation $P_{\text{sim},0}(1\text{d};\ T)$ and $P_{\text{sim},1}(1\text{d};\ T)$, where subscripts 0 and 1 denote baseline and future periods, respectively. In the third step, this percentage of change in maximum daily rainfall is applied to the historical values of design daily rainfall within the baseline period, $P_0(1\text{d};\ T)$, to obtain the corresponding values in the future, $P_1(1\text{d};\ T)$. Finally, the normalized DDF relationship obtained in step 1 is assumed to be invariant in the future and is multiplied by the future maximum daily rainfall to obtain future DDF relationship, $P_1(t_d; T)$.

3.1.1. Climate data for the Tamnava Basin

Short-duration rainfall data, as the main input for design flood assessments, are not available in the Tamnava River Basin. The nearest recording rain gauge with records of sub-daily precipitation data is located outside of the southern watershed divide, at the town of Valjevo. To establish design storms needed for the assessment of design floods, we started from the rainfall DDF relationship for the Valjevo rain gauge station developed for the 1957–2006 period by Prohaska *et al.* (2014), who also provided a normalized DDF relationship (sub-daily storm depths divided by daily storm depths). The updated DDF relationship was obtained by multiplying the 1957–2006 normalized DDF curve for each return period considered with the updated daily design storm depth for the period 1957–2021. In this way, the greatest observed rainfall in 2014 that caused catastrophic floods in Serbia and West Balkans (Plavšić *et al.* 2014) was accounted for in establishing updated DDF curves. Additionally, the DDF curves were amended to produce consistent results using the principle of

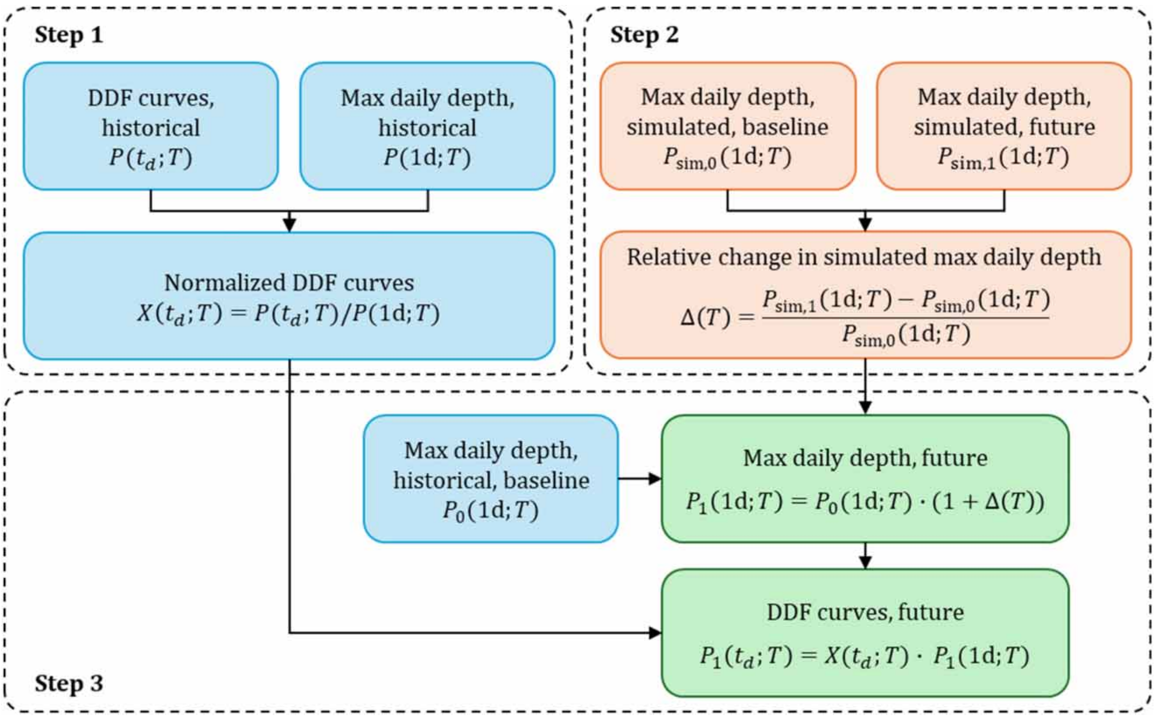


Figure 3 | Process for producing future DDF curves.

unique distribution of transformed rainfall intensities for all storm durations (Koutsoyiannis *et al.* 1998). The adjusted normalized DDF relationship for the historical 1957–2021 period, valid for all return periods, is shown in Table 1.

Valid projections of future short-duration rainfall for the Tamnava region do not exist as short-duration precipitation simulated by climate models cannot be validated nor bias-corrected for the study area due to a lack of the observed sub-daily rainfall data. Daily precipitation simulated by the climate models was therefore used for the assessment of future maximum daily precipitation in the Tamnava River Basin.

One scenario of greenhouse gas (GHG) emissions, RCP4.5, is considered in this study, belonging to the group of the relative concentration pathways (RCP) of the Intergovernmental Panel on Climate Change (IPCC 2014; RECONECT 2018). The RCP4.5 scenario predicts a global stabilisation of GHG emissions and their reduction in the second half of the century, which would limit the mean global temperature increase to approximately 3 °C compared to the pre-industrial period.

Climate model outputs are taken from the Digital Climate Atlas of Serbia (MEPRS 2022), covering the 1951–2100 period. These consist of an ensemble of eight combinations of global and regional climate models (Table 2), selected from the EURO-CORDEX project database (Jacob *et al.* 2014). This particular ensemble was previously selected as relevant for Serbia (Djurdjević *et al.* 2024) and has been used in assessing the climate change impact on different sectors within the country. The use of an ensemble of models allows for the consideration of uncertainty, which can vary across periods and variables. When analyzing future changes, it is recommended to evaluate the changes in median value for a future period in comparison to the reference period, as well as the change in the range of the 25th and 75th percentile of the ensemble results (IPCC 2013).

For each of the eight ensemble members, a series of daily precipitation at the nearby meteorological station Valjevo was extracted. To minimize the impact of systematic errors originating from simplifications and numerical methods employed by all climate models, the daily precipitation data were statistically bias-corrected using the quantile mapping method, which is used as standard for these purposes (Piani *et al.* 2010).

The series of annual maximum daily precipitation was extracted from the simulated daily precipitation over the 1951–2100 period. These series were needed to relate historical design storms with the simulated ones, above.

3.2. NBS measures in Tamnava Basin

Within the Tamnava Basin, some gray flood mitigation has been implemented to tackle the risk of flooding. These measures include the construction of levees in urban and agricultural areas with a different return period (Pudar & Plavšić 2022).

Table 1 | Normalized DDF curve (ratio between the storm depths for sub-daily and daily duration) adopted for the Tamnava River Basin

Storm duration (hours)	1	2	3	6	12	24
Normalized storm depth	0.650	0.787	0.856	0.959	1.048	1.130

Table 2 | Ensemble of eight climate models with outputs used for the Tamnava River Basin

Model	Global climate model	Regional climate model
1	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17
2	ICHEC-EC-EARTH	DMI-HIRHAM5
3	ICHEC-EC-EARTH	KNMI-RACMO22E
4	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17
5	MOHC-HadGEM2-ES	KNMI-RACMO22E
6	MPI-M-MPI-ESM-LR	CLMcom-CCLM-8-17
7	MPI-M-MPI-ESM-LR (r1i1p1)	MPI-CSC-REMO2009
8	MPI-M-MPI-ESM-LR (r2i1p1)	MPI-CSC-REMO2009

After the devastating 2014 flood, extensive studies were conducted to explore and enhance flood mitigation measures within the Kolubara River and Tamnava Basin using nature-based solution measures. UNDP Serbia (2016) proposed a combination of gray and green infrastructure to reduce the risks associated with floods. The gray measures include raising the existing levees to be able to handle floods with a 100-year return period, while the green measures include the construction of three detention basins upstream of the main tributary of the Tamnava River (Tamnava, Ub, and Gračica), as well as using anti-erosion techniques to prevent soil erosion upstream. In addition, the study conducted by Ruangpan *et al.* (2021) applied the multi-criteria decision analysis (MCDA) approach and incorporated the stakeholder perspectives to propose different NBS measures in the Tamnava Basin, the result of this study proposed and prioritized different NBS measures such as floodplain restoration, afforestation, and retention ponds.

3.3. Baseline and adaptation actions simulation

3.3.1. Baseline assessment

The baseline assessment serves as an evaluation stage aimed at analyzing the existing system to investigate and quantify the hazard in the study area. This assessment provides valuable insights into the extent and impact of the hazards in the area. Moreover, in order to accurately evaluate the efficacy of the adaptation actions, it is imperative to establish a benchmark against which their outcomes can be compared. This step works as the benchmark to quantify the performance of the adaptation actions. The simulation models were executed for different rainfall return periods under current and projected future climate conditions for the existing infrastructure for the Tamnava Basin.

3.3.2. Simulation model and adaptation measures setup

The coupled Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Center's River Analysis System (HEC-RAS) models, developed for the Tamnava Basin by Ruangpan *et al.* (2024), were used to simulate how future rainfall patterns and NBS would influence flood events within the study area. The HEC-HMS was employed to simulate the hydrological processes while the hydrodynamic processes were simulated using the 1D-2D HEC-RAS model by using the output of the hydrological model. The models were run for the current and future rainfall events with and without the measures.

Throughout this study, the focus was on simulating adaptable NBS measures, specifically the application of retention ponds in upper watersheds, in terms of size modification. The selection of the measure was guided by the results of applying the RECONECT selection and allocation tools to the case study by Ruangpan *et al.* (2021), in addition to consultations with local experts to incorporate local perspectives. The adaptation actions considered were:

- Action (A): Implementation of three small retention ponds in upstream sections of the Tamnava, Gračica, and Ub Rivers named as Ćukovina, Gračica, and Pambukovica.
- Action (B): Immediate implementation of retention ponds as in Action A, but of larger size.
- Action (C): Construction of two retention ponds in the upstream section of the Tamnava River, the main contributor to floods, and one retention pond for each of the other tributaries.
- Action (D): The use of two retention ponds in the upstream section of each tributary.

The adaptation actions are presented in Figure 4, with colors showing the storage capacity for each pond. The characteristics of the ponds are detailed in Table 3 of the appendix.

The NBS measure (retention ponds) was implemented into the HEC-HMS model using the Reservoir Creation Tool that facilitates the creation of retention ponds that can store the water based on storage elevation curve data and subsequently release the water based on outflow structure specification. The retention ponds were designed with two outflow structures. These structures consist of a bottom outflow culvert which facilitates a continuous release of water, and a broad-crested spillway designed to discharge excess water once the retention reaches its critical storage capacity.

3.3.3. Performance indicators

Different key performance indicators (KPIs) can be used to assess the effectiveness of NBS measures across various domains, depending on the specific goals to be achieved. In this study, indicators related to water quantity, specifically focusing on flood reduction metrics, were utilized. The selected actions were evaluated for their

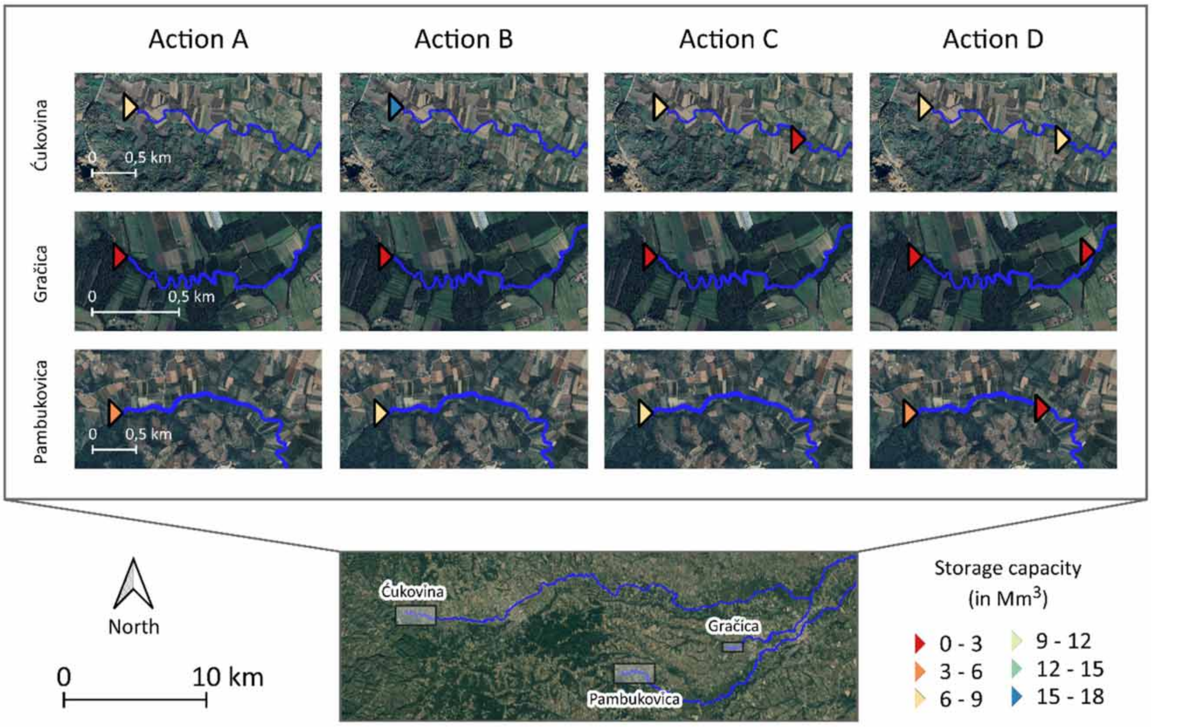


Figure 4 | Retention pond locations and sizes.

ability to reduce flood risk under both current and future conditions. The effectiveness of these actions was determined by the percentage reduction achieved relative to the baseline scenario.

To assess the effectiveness of the measures, the following KPIs were employed: (1) flood area reduction, (2) flood volume reduction, and (3) flood damage reduction.

The reduction percentages achieved by these actions were calculated using the following expression:

$$(Re \cdot P)i = \frac{((\text{Per } \times \text{Without Action}) - (\text{Per } \times \text{With Action})i)}{(\text{Per } \times \text{Without Action})} \tag{1}$$

where $(Re.P)i$ represents the reduction percentage in year i, (Per × Without Action) signifies the performance for the current situation without action, and (Per × With Action)i represents the performance of the action in year i.

The total flooded area and flood volume were calculated in GIS using the zonal statistic function. The flood damage cost values were calculated using a damage model developed in GIS in a previous study by Ruangpan *et al.* (2024) for the Tamnava River Basin. This model uses the maximum flood depth maps obtained from running the 1D-2D HEC-RAS model as an input.

3.4. Tipping points and adaptive pathways development

3.4.1. Tipping points

The tipping points are defined as the situation in which the existing approach or action fails to meet a predetermined objective and no longer yields satisfactory results. This condition signifies that the current strategy is ineffective or inadequate in achieving its intended objective. In this study, the goal was defined as the reduction of floods within the study area, and since the actions mainly consist of retention ponds the tipping points are defined as the time when these ponds can no longer store additional water from upstream areas of the basin to prevent floods in the downstream of the retention ponds.

The process of identifying tipping points is done by configuring the mitigation actions in the HEC-HMS model, which is then executed using the design storms from future DDF curves. The performance criteria for the action were defined as the storage of the water below the spillway level at the top of the ponds. If the performance of an action meets this criterion, it is considered acceptable, which indicates that the action can withhold a more intensive climate hazard and achieve satisfactory results. If not, it signifies that the action has reached its capacity and started to discharge water through the spillway structure at the top level which contributes to downstream flood. This necessitates the consideration of alternative actions. This process is repeated until all actions have been assessed for all future rainfall intensities up to 2100.

3.4.2. Development of adaptation pathway map

By using the adaptation tipping point values for each proposed action, the adaptation pathways were systematically constructed and subsequently converted into a visual representation known as the adaptation pathway map. This process has been informed by the insights gained from Haasnoot *et al.* (2012) and Manocha & Babovic (2017) which provided valuable knowledge and served as a basis for assembling the adaptation pathways by following the rules below:

- The sequence of actions within the adaptation plan must fulfill the objective throughout the entire planning time frame.
- The illogical sequences should be excluded. For example, once an adaptation measure has been upgraded from a small specification to a large specification, it is deemed illogical to revert it to the small specification in future actions.
- Ineffective upgrading should be excluded, and the adaptation tipping point should increase by at least 10 years. This criterion will ensure that any modifications or enhancements made to the adaptation actions will significantly contribute to prolonging the viability of the strategy.
- Adaptation measures that are implemented with large specifications should not be abandoned and replaced by other measures once they have been built. This is due to the substantial financial investments and potential societal consequences associated with such actions.

4. RESULTS AND DISCUSSION

4.1. Climate data

Starting from the DDF curves for the baseline period, future DDF curves under the RCP 4.5 scenario were developed as described in section 3.1. Using the annual maximum daily precipitation from each of the eight climate models, daily design storms were estimated by means of the frequency analysis. The analysis was done for the baseline period 1971–2010 and for the future 20-year periods ending at 2040, 2050, 2060, 2070, 2080, 2090, and 2100. For each 20-year period and for each climate model, future daily design storms are compared to the baseline ones to establish the relative change $\Delta(T)$. Figure 5 shows the examples of the results for the relative change in design daily precipitation.

In climate change impact assessments that involve lengthy numerical simulations, the median ensemble value of the changes is typically used instead of the whole ensemble. Alternatively, first and third quartiles (i.e., 25th and 75th percentile) of the ensemble values may be used to describe uncertainties in climate modeling. In this study, we used only the 3rd quantile of the ensemble of the changes in daily design storms for deriving the

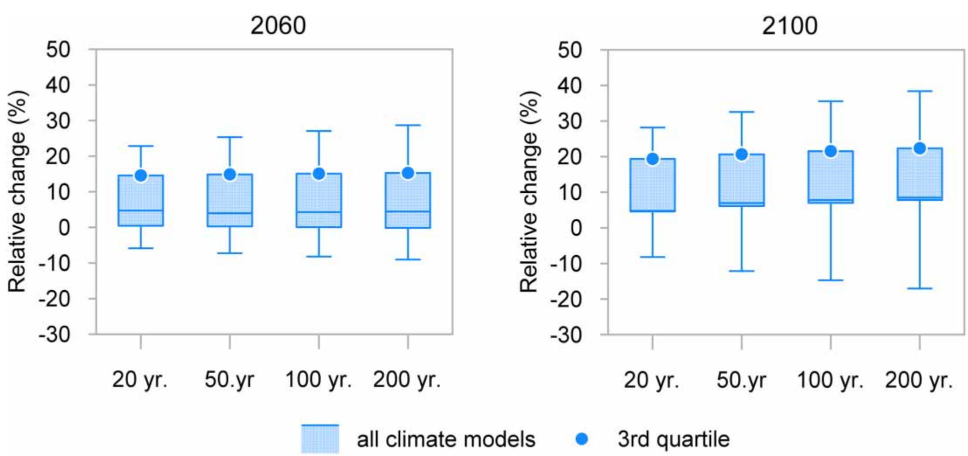


Figure 5 | Relative change in design daily storms at Valjevo for two future periods under RCP 4.5. Box plots show distributions of changes from eight climate models, and the circles indicate third quartile used in this study.

future DDF curves. This choice was made to limit extensive hydrological and hydrodynamic simulations and NBS performance assessment, while accounting for more critical conditions under which the floods in the Tamnava River Basin may occur. The selected changes are also marked in Figure 5 with circles.

With the 75th percentile values of the ensemble of the change in daily design storm depths, future DDF curves are developed by applying this change to the daily design storms for the baseline period, and finally by corresponding rescaling of the historical DDF curves. Future DDF curves are defined for the time horizons at intervals of 10 years starting from 2040 to 2100. Figure 6 shows examples of the future DDF curves in comparison to the baseline ones. All future DDF curves exhibit an increase in sub-daily design storm depths.

4.2. Baseline assessment

The baseline assessment highlights the basin's vulnerability to flooding across various return periods. Figure 7 illustrates the inundation extent, including urban areas such as Koceljeva and Ub, under rainfall intensities corresponding to 20-, 50-, 100-, and 200-year return period events.

The baseline flood analysis reveals an increasing trend in flood extent, volume, and associated damage costs in the absence of mitigation measures (see Figure 8(a)). Notably, even for lower return periods, such as the 20-year event, flooding occurs in various areas, particularly in upstream urban areas like Koceljeva and Ub (Figure 7). For higher return periods, the flood hazard extends further downstream, highlighting a spatial shift in the flood risk.

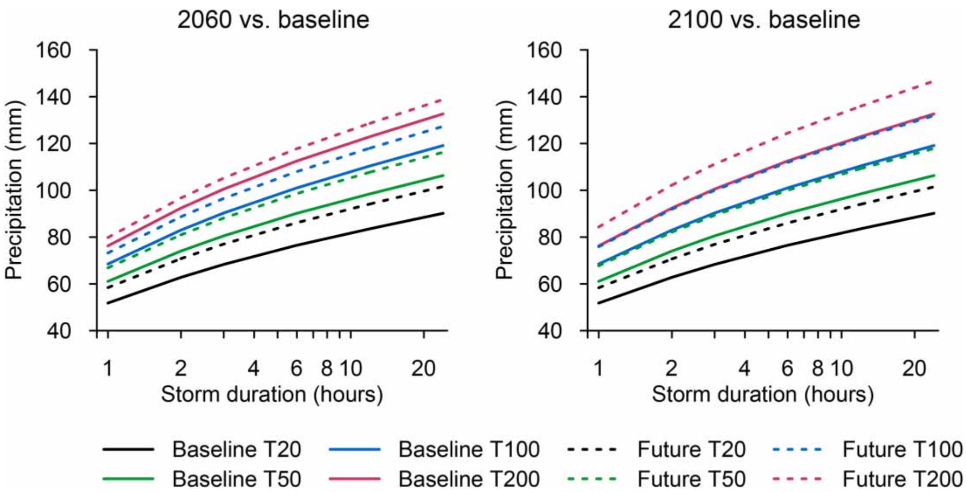


Figure 6 | Projections of DDF curves for Valjevo meteorological station for two future periods under RCP 4.5.

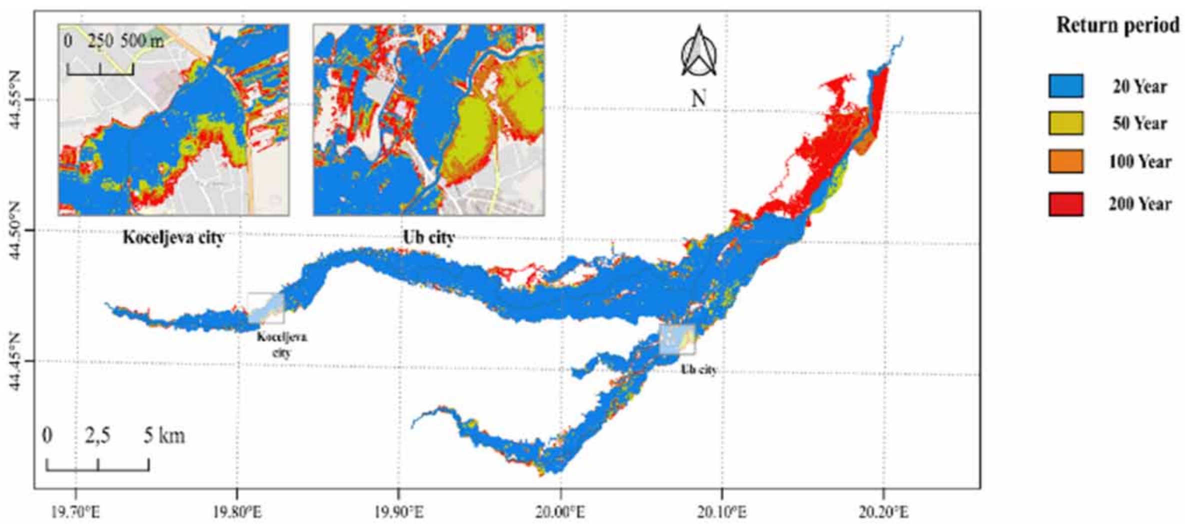


Figure 7 | Floods under different return periods.

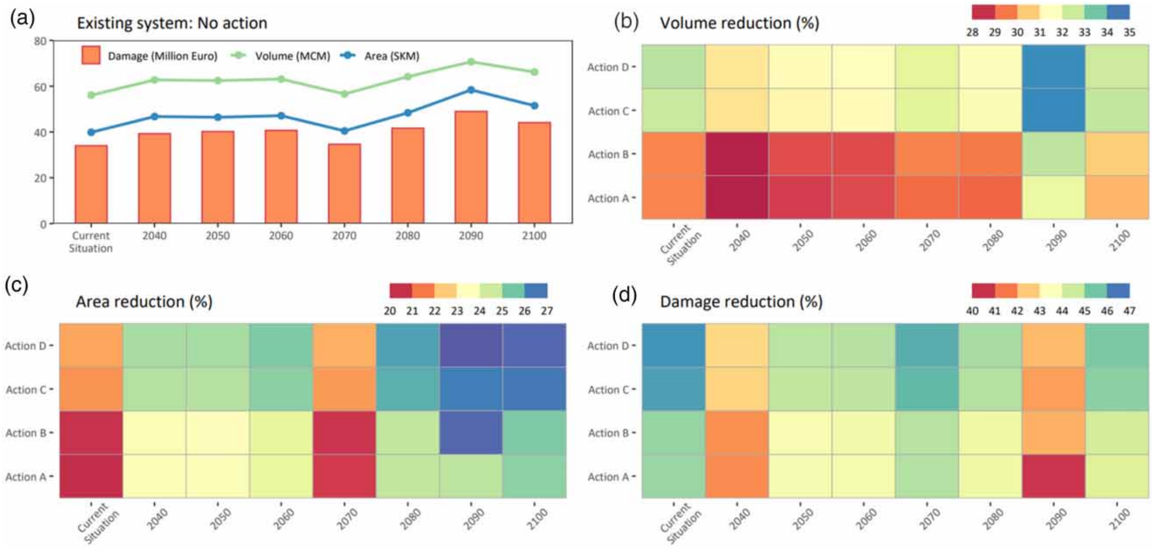


Figure 8 | Flood area, volume, and damages with and without actions. (a) Total flood area, volume, and damage without actions. (b) flood volume reduction percentages using the different actions. (c) flood area reduction percentage using the different actions. (d) Total damage reduction percentages using the different actions.

The baseline results (Figure 8(a)) for the 100-year return period show that the basin's terrain accommodates larger flood volumes by expanding the flood extent rather than increasing water depth over a fixed area. This characteristic terrain response leads to widespread inundation, amplifying the damage potential across the basin. The total values for the flood area, volume, and damage cost indicate an increased trend in the upcoming years compared to the current situation, except for 2070 where the rainfall intensity is expected to be less than the current situation and subsequently, the flood matrices are expected to be less. These findings emphasize the critical need for proactive flood mitigation strategies to address and manage the escalating flood risks under this climate scenario.

4.3. Adaptation action performance

Using the KPIs indicated in section 3.3.3, the performance of the proposed measures for the 100-year return period rainfall intensity under the current and future climate conditions is presented in Figure 8.

The heatmaps depict the percentage reduction in flood metrics across the four mitigation actions (Action A to D) under different timeframes. Overall, the different actions showed a notable reduction percentage for all the flood matrices during the timeframe from the present until 2100. As presented in Figure 8, the reduction in flood area and volume range between 20 and 27% and 28 and 35%, respectively, while the flood damage reduction percentage shows a relatively higher range between 40 and 45%.

Actions C and D demonstrate greater reduction percentages across all metrics – flood area (a), flood volume (b), and flood damage cost (c) – over Actions A and B. This indicates that these actions may be more effective in managing flood risks under projected future conditions. For flood volume reduction, these two actions achieve reductions nearing 35% by 2090, while reducing the flood-affected area, with reduction percentages close to 27% by 2090, and around 43% for the same year in terms of damage cost reduction.

The difference in the performance of the actions could be attributed to the fact that Actions C and D consist of two retention ponds in a series. This configuration increases the retention time for the stored water, allowing the peak flow downstream to pass more gradually and subsequently reducing flooding. The second pond in the series further enhances this effect by providing additional retention time through the process of its filling, enabling better regulation of peak flow rates and more effective reduction of downstream flooding.

Figure 9 presents a detailed breakdown of the damages for the different categories before and after the implementation of the actions under the current climate conditions. This includes the values for damage cost for six categories associated with the flood within the basin. The agricultural areas (represented in green) are the dominant areas flooded compared to the residential buildings (red points) or the other categories. The gray areas consist of free spaces and forest areas which are not considered in the damage assessment.

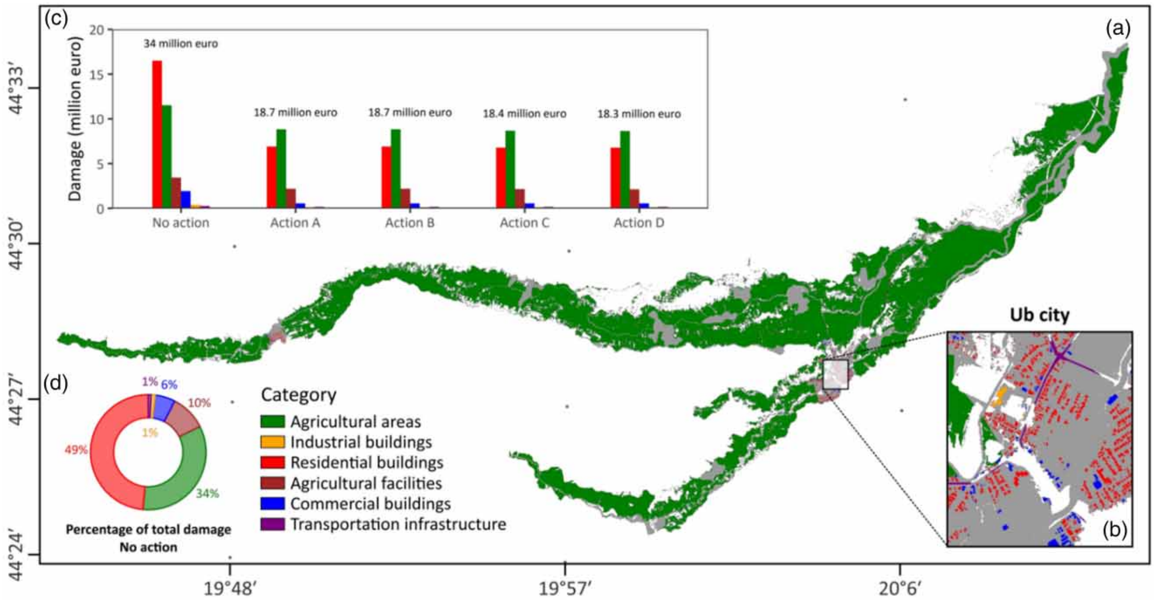


Figure 9 | Flood damage per category for the basin. (a) Areas flooded within the basin. (b) Zoom into the urban area (Ub City). (c) Values of damage cost per category with and without the actions. (d) Percentages of damage of each category to the total value.

The primary contributors to the total damage cost values within the basin, as shown in Figure 9(c) and 9(d), are the damages associated with residential buildings and their inventories, along with damages related to agriculture. This is attributed to the damage cost values for buildings and their inventories being higher compared to the other categories and being influenced by the flood depth (high depths mainly along the river areas), while the damage associated with the agricultural areas is primarily determined by the extent of the flooded area, without accounting for depth.

Moreover, from Figure 9(c), the implemented actions show more reduction in damages associated with buildings and their inventories compared to the reduction in damages related to the agricultural areas. Given that the actions are more effective at reducing flood volume (depth) rather than flood areas as presented in Figures 8(b) and 8(c), this results in more reduction in damages to buildings and their inventories.

The effectiveness results presented above for the actions offer valuable insights into their performance in mitigating floods. However, determining the best course of action requires a more comprehensive decision-making process that goes beyond effectiveness alone. A crucial aspect that needs consideration is the cost associated with implementing and maintaining these actions. While the data show how each action performs in terms of reducing the flood-related parameters, it does not account for the financial implications. In practice, the feasibility and sustainability of an action plan depends not only on its effectiveness but also on its affordability and practicality. Given this fact it is understandable that the cost analysis might not have been feasible, which is a critical factor to address in future research or decision-making processes.

4.4. Tipping points and adaptive pathways

As described in section 3.4.1, the tipping points are the situations in which the existing approaches or actions fail to meet the predetermined objective and no longer yield satisfactory results.

Using the value of the stored water of the measures, we identified when the measures reach their capacities and can no longer handle more intensive events. Figure 10 presents the volume of water stored, the storage capacity at the spillway level, and the maximum storage capacity that may be achieved for each action for the 100-year return period events.

The total storage capacity for the action is equal to the sum of individual storage capacities of the retention ponds included within the action (see Table 1 in the Appendix for storage details). The storage capacity at the spillway level in particular gains crucial significance as it functions as a crucial threshold for each action. Any extra water that is stored temporarily above this level is discharged through the spillway structure that is located

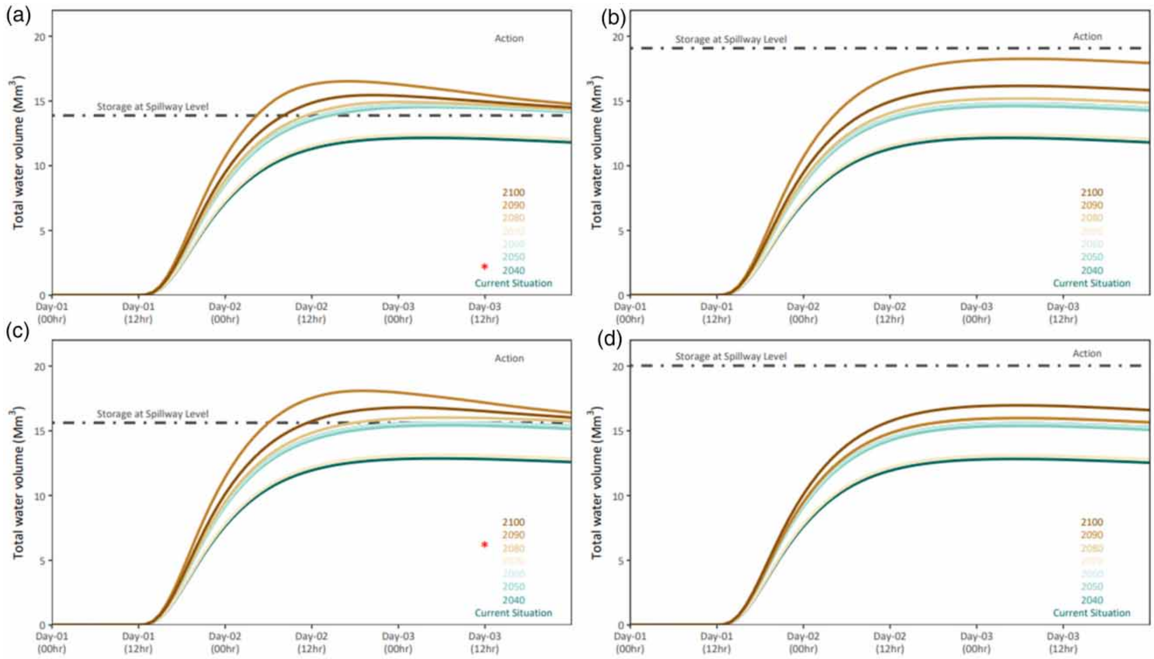


Figure 10 | Storage capacity for actions through the years.

at the top of the retentions. This is considered a threshold that signifies the tipping points of the action where they reach their allowable storage capacity.

The results in Figure 10 show that under the current situation, the storage capacities for all the actions are below the spillway level. Subsequently, all the water coming from the upstream area is controlled by the ponds and released through the bottom outlet structures. However, looking into the future conditions, the results show that under future climate conditions, some actions reach their capacities and can't handle more intensive events. For example, the total storage volume stored in Action A under the current situation was found to be 12.16 Mm^3 while the capacity of the action below the spillway is 13.88 Mm^3. This indicates that Action A still has 1.72 Mm^3 to accommodate more water from greater events. However, by 2040, Action A storage was above the spillway level, indicating Action A had reached its capacity by this time. The same process was carried out for the other actions to indicate their tipping points.

The tipping points identified in this step help to construct the adaptation pathways for the different actions using the rules stated in section 3.4.2.

The adaptation pathways diagram in Figure 11 illustrates the pathways and transitions between the four adaptation actions (A, B, C, and D) over time for different flood return periods (20, 50, 100, and 200 years). The x-axis represents the timeline from the current situation to 2100, while the colored lines indicate the duration for which each action remains effective. White circles mark the transfer station to a new action, where an action's performance is no longer sufficient, necessitating a transition to another action. Dashed lines represent periods when an action becomes ineffective.

As presented in the figure, there are four main pathways (1–4) that start with the immediate implementation of any of the actions. More pathways were developed using the roles described in section 3.2.2 and presented in the map using the transfer stations to new actions and putting the actions letters in the station. Depending on the rainfall return period selected to design the action the number of pathways increases or decreases.

Overall, the maps indicate that both Actions B and D do not reach their tipping points throughout the planning period under the different return periods 20, 50, and 100. Given that Action B applies large-size retention ponds and Action D applies two retention ponds in each tributary, pathways related to the immediate implementation of these two actions represent the approach to implementation of large-scale measures starting from the present. As long as there are no financial or resource constraints, both Action B or D can be implemented in the present and work in the future and do not require any further inventions (pathways 2 and 4). The only drawback with these two pathways is that these actions are overdesigned for the climate scenario RCP 4.5 with return periods 20, 50, and 100 years. These measures with a large specification involve substantial resources, both in terms of budget

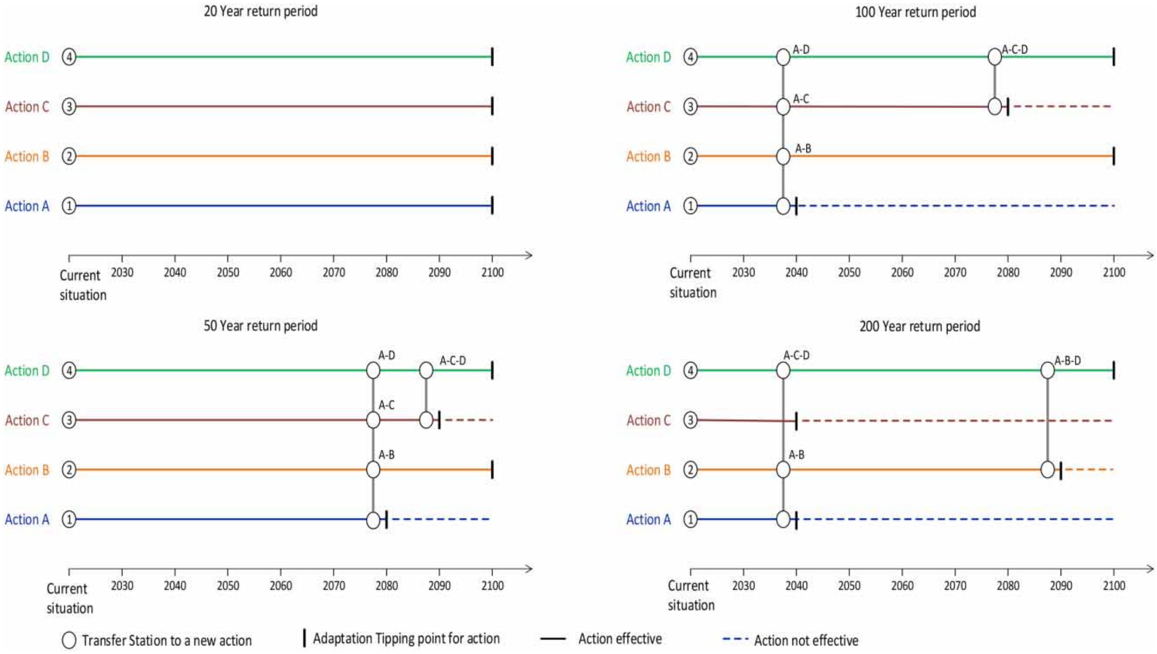


Figure 11 | Adaptive pathways map.

and effort. The rule as outlined in section 3.4.2 is that once such a measure is set in motion, it becomes challenging to reduce its scale, abandon it entirely, or eliminate it from the plan. This difficulty arises because substantial investments, both in terms of financial resources and time, have already been committed to it. Due to that, no pathways start by applying these actions and shift to other actions.

Pathway 3 starts with the implementation of Action C. This involves implementing Action C without a predefined plan for intervention once the action approaches its tipping point. However, under 50-, 100-, and 200-year return periods this pathway can be modified to Pathway 3 → A-C-D to incorporate a forward-thinking strategy by accounting for the possibility of transition to Action D. This contingency plan entails the addition of two extra retention ponds in the Ub and Gračica tributaries without implementing them at present.

Moreover, pathways can adopt a staged approach, initially implementing small-sized retention ponds in Action A, then adapting other actions based on climate conditions. For example, pathway 1 represents the implementation of Action A without consideration for transitioning to other actions in the future. In contrast, pathway 1 → A-B plans for a potential shift toward a larger retention pond if climate change hazards escalate. This pathway begins with the implementation of small-size ponds while keeping the possibility of future expansion in mind. In other words, it involves designing for larger ponds but implementing smaller ones in the present. Moreover, pathway 1 → A-C suggests an alternative approach by proposing the implementation of an additional pond downstream of the pond in Tamnava River instead of increasing the size of existing ponds. This pathway allows for preparation and planning for the additional ponds from the present, with implementation only occurring if the need arises. Moreover, pathway 1 → A-D starts with Action A and anticipates a transition to Action D, achieved by implementing additional ponds downstream of the one established in Action A. Lastly, Pathway 1→ A-C → A-C-D is a two-stage pathway that begins with Action A and moves to Action C by adding a retention pond downstream of the one in the Tamnava tributary if the hazard continues to rise; in addition, it considered the possible shift to Action D by adding two retention ponds in the other tributaries if Action C reaches its capacity.

The adaptation pathways illustrated in Figure 11 along with the effectiveness results in Figure 8 provide an overview of potential decision-making trajectories tailored to varying return periods and projected rainfall intensities. While these pathways serve as a valuable framework for visualizing adaptive options, they currently do not incorporate a systematic approach to selecting or ranking the pathways based on the performance and effectiveness of specific actions. The selection and prioritization process could benefit from the application of robust decision-support methodologies such as multi-criteria analysis, cost-benefit analysis, or scenario analysis. These approaches can evaluate pathways against diverse criteria, including economic feasibility, environmental impact, and long-term resilience, thereby enabling more informed and strategic decision-making. Addressing this gap in pathway prioritization represents a critical area for future research, with the potential to enhance the practical applicability and impact of adaptation planning frameworks in dynamic and uncertain contexts.

4.5. Benefits and limitations

The proposed adaptation pathways facilitate a fundamental assessment of the system's adaptive capacity in the case study by identifying the extent to which the application of the retention ponds strategy remains effective under varying climate conditions. As highlighted by Kwadijk *et al.* (2010), conveying uncertainty through the estimated timeframe in which a flood risk management strategy remains viable – i.e., the point in time at which the tipping point is reached – is more intuitive for decision-makers than expressing it through probabilistic forecasts of specific climate outcomes within a given period. A number of previous studies (Haasnoot *et al.* 2013; Lawrence *et al.* 2013; Kapetas & Fenner 2020) have effectively demonstrated the application of adaptation pathways for flood risk management. Our study is the first to demonstrate an integration of hydrological and hydrodynamic modeling with GIS flood damage modeling. Kapetas & Fenner (2020) applied an adaptive pathways approach over a borough in London, an area of 0.97 km^2, using Storm Water Management Model (SWMM) for 1D drainage modeling for a heavily urbanized setting where pipe flow could be utilized to assess flooding. Whereas Tamnava Basin is somewhat larger (730 km^2) and consists of 79.3% agricultural landuse. We utilized 2D overland flow simulation by using the HEC-RAS 1D-2D, generating flood depth maps that are used for flood damage calculation. Furthermore, rather than extrapolating historical rainfall trends to the future based on a uniform percentage increase or decrease as done by Manocha & Babovic (2017), our study developed dynamic future design rainfall based on high-resolution climate model outputs to guide the development of adaptation pathways, ensuring a more physically consistent representation of future precipitation extremes.

The work presented here acknowledges certain fundamental assumptions that act as limitations: (1) it allocates the system's entire overcapacity (retention ponds capacities) to a single influencing factor (rainfall intensities). However, this overcapacity is generally designed to accommodate a variety of uncertain drivers and pressures, including model uncertainties, rather than being exclusively reserved for rainfall intensities. This is also described by Haasnoot *et al.* (2012), who highlighted the way to incorporate a range of uncertainties in the adaptation pathways of flood management strategies. (2) The study exclusively focuses on large-scale NBS utilizing a storage approach (retention ponds) to address flood hazards, neglecting alternative NBS measures like floodplain restoration, afforestation, and reforestation. (3) The emphasis is placed solely on the flood reduction benefit, disregarding the broader range of advantages and co-benefits of NBS measures, such as water quality improvement, groundwater recharge, and increased biodiversity. Consideration of the co-benefits of NBS measures requires a multi-objective tipping point calculation. (4) The evaluation of proposed measures concentrates on their effectiveness in reducing flood hazards but overlooks the associated costs of implementation and maintenance. (5) The calculation of future damage costs assumes a static value, and the assessment of measures' ability to store and release water does not consider the change in the vulnerability of the area. These limitations highlight the need for a more comprehensive approach in future research.

5. CONCLUSIONS

Climate change uncertainties and changes in precipitation patterns are characterized by high variability, unpredictability, and constant change. Therefore, the current practice of planning scenarios offers minimal guidance for future needs and conditions when it comes to planning the implementation of NBS for flood mitigation in both urban and rural settings. In this paper, an approach to assess adaptive pathways to implement NBS measures under climate change conditions by using the concept of tipping points is presented. The approach provides valuable insights into the effectiveness of NBS measures to reduce flood hazards under future conditions in a sustainable way. The approach also represents an endeavor to mitigate uncertainty associated with climate change by formulating adaptive pathways that decision-makers can adopt during the initial phases of the planning process. In this work, the case study area of the Tamnava River Basin in the Republic of Serbia is used to evaluate the approach. The NBS adaptation actions include retention ponds of different scales and different application methods (i.e., small size of retention, large size of retention, two retentions in series). The tipping points and the effectiveness of the adaptation action were simulated in a coupled model in the HEC-HMS and HEC-RAS models.

The effectiveness of the proposed actions in the case study was assessed in terms of flood area and volume reduction, and flood damage reduction under the current and future climate conditions, up until 2100. The effectiveness of the actions was presented as reduction percentages compared to the current conditions without NBS measure.

The results support the decision-makers in their initial planning phase through three main points: (1) estimation of hazards and risks associated with floods within the case study area in the present and under future climate change conditions, (2) evaluation of the effectiveness of the adaptive NBS actions to reduce the flood hazards and damages under the current and future conditions, (3) establishment of flexible, long-term plans for the construction of large-scale NBS measures and flood prevention infrastructure that will help to reduce flooding in the Tamnava River Basin until the year 2100.

The outlined approach described in the manuscript can be applied generally to other areas and different hazard contexts. The adaption tipping points used were established based on the NBS measures used to mitigate the hazards, but they could be easily adjusted to other circumstances, regardless of the scenarios that were shown. Nonetheless, defining tipping points in terms of additional indicators, i.e., biodiversity enhancement capacity, water quality and groundwater recharge may become necessary.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.K., A.M., Z.V., A.S.T., and L.R.; methodology, M.K., A.M., L.R., A.S.T. and M.V.M.; formal analysis, M.K., M.V.M., A.S.T.; resources, J.P.; data curation, M.K., and M.V.M.; writing – original draft preparation, M.K., A.M., and M.V.M.; writing – review and editing, M.K., A.M., L.R., J.P., A.S.T., Z.V., M.V.M.; visualization, M.K., and A.M., supervision, A.M, L.R., Z.V., A.S.T., and J.P.; project administration, Z.V., and J.P. All authors have read and agreed to the published version of the manuscript.

ETHICS STATEMENT

The authors declare that this research does not involve human participants or animal testing.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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