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ORIGINAL PAPER

The Nature-Based Solutions and climate change scenarios toward flood risk management in the greater Athens area—Greece

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Abstract

This research paper focuses on implementing two Nature-Based Solutions (NBS) in the Sarantapotamos river basin upstream of Magoula settlement, evaluating their effectiveness through flood hydrograph calculations before and after NBS, and under future climate scenarios, encompassing lower, mean, and upper conditions representing ± 95%. The study area covers an area of 226 km^2 in Attica, Greece, susceptible to extreme flood events. The research contributes to NBS knowledge, emphasizing flood resilience and protecting settlements downstream. Land cover change and retention ponds, applied individually and combined, serve as NBS approaches. Flood hydrographs are calculated using the time–area (TA) diagram method in a geographic information system (GIS) with the Hydrological Engineering Center's Hydrological Modeling System (HEC-HMS). Results demonstrate NBS effectiveness in current climate conditions, reducing peak discharge by 9.3% and 28% for land cover change and retention ponds, respectively. The combined NBS achieves a 40.5% peak discharge reduction and a significant 15.7% total flood volume decrease. Under climate change scenarios, impacts on design precipitation and flood hydrographs vary. The upper climate change scenario exhibits a 3348% increase in peak discharge and a 600% rise in total flood volume, while the lower scenario sees a 44.6% reduction in total flood volume. In the mean climate change scenario, land cover change and retention ponds reduce peak discharge by 9.73% and 23.11% and total flood volume by 9.25% and 2.17%, respectively. In conclusion, retention ponds show substantial peak discharge reduction, while land cover changes extend the time to peak, emphasizing their potential in flood risk management.

Keywords Greater Athens area · Nature-Based Solutions (NBS) · Land cover changes · Retention ponds · Climate change · Flood risk

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1 Introduction

Climate change is becoming more severe over time, causing more extreme weather events like floods, which are natural hazards. Additionally, the climate change is increasing the strength and occurrence of severe storms, raising the risk of flooding, causing extensive damage to property and the environment on a global scale (Edamo et al. 2023). Floods stand out as one of the most perilous natural hazards that impact the development of a region in terms of communities and the economy (Youssef et al. 2021). Similarly, the flash floods represent a highly impactful category of natural disasters, causing substantial human and economic losses. These rapid inundations have resulted in significant damage to transportation networks, residential areas, agricultural landscapes, and overall livelihoods in diverse countries around the world (Youssef et al. 2015). Globally, occurrences of flooding result in the highest number of fatalities and substantial property damage (Bathrellos et al. 2016). Natural hazards encompass physical events capable of significantly influencing both the natural and human environments. Within this framework, the morphological alterations of landforms resulting from natural disasters have the potential to limit human interaction with the ecosystem (Skilodimou et al. 2021). Natural disasters related to flooding are inevitable, yet a thorough examination of these occurrences is pivotal for discerning effective strategies in mitigating and adapting to manage such disasters (Mishra and Nagaraju 2021). In this context, in order to efficiently prevent, mitigate, and finally tackle flood events, a range of measures is employed. More specifically, the implementation of conventional "gray" solutions, including the building of a dam, a concrete dam, and embankment dam, as well as innovative "green" solutions, like river diversions, constitutes some effective measures. However, it is essential to acknowledge that these measures can have substantial impacts on both the economic and environmental domains. Therefore, the search for more natural treatment approaches is considered worthwhile; thus, NBS play a significant role in offering a multitude of benefits. NBS derive inspiration and support from the natural world (European Commission 2022). They are considered a promising approach to address social challenges by harnessing the nature’s fundamental principles, providing a cost-effective way to deliver societal, economic, and environmental benefits while simultaneously enhancing resilience against natural disasters (Unguendoli et al. 2023). The European Water Association has recognized the significance of NBS in tackling climate change as one of the prominent challenges in water management throughout Europe (Beceiro et al. 2022).

The increasing threats of flooding in natural basins require efficient measures to protect downstream settlements from inundation. In this context, the European Commission has initiated to pay special attention to NBS, which have gained prominence as a method to protect vulnerable areas by utilizing natural processes and harnessing the benefits of natural system services. NBS encompass a range of measures such as riparian buffer zones, land cover changes, altering river roughness, construction of retention ponds that possible enhance infiltration, decrease peak discharge, while increase time to peak, reducing the vulnerability of downstream settlements to flooding. In the literature, numerous global studies have been conducted to examine how NBS can be implemented to reduce flood risk (Potočki et al. 2021; Staccione et al. 2021; Vojinovic et al. 2021; Spyrou et al. 2022; Mashiyi et al. 2023; Inácio et al. 2023; Penny et al. 2023; Unguendoli et al. 2023). In this paper, two NBS are implemented, specifically land cover change and construction of retention ponds, as well as a combination of the two, within Sarantapotamos river basin upstream of the Magoula settlement, located in Greece. Additionally, this study investigates the effectiveness of NBS by calculating the flood hydrographs at the outlet of the basin through hydrological analysis. It examines the conditions both before and after the implementation of NBS for current climate scenarios, as well as future climate change scenarios. The scenario prior to the application of NBS serves as the baseline for comparison, considering both current and future climate conditions. The equations of the future intensity–duration–frequency (IDF) curve used for future climate scenarios, specifically for estimating future design precipitations, are adopted from Kourtis et al. (2023). The implementation of NBS in future climate scenarios encompasses the mean, as well as the worst-case climate scenarios. The hydrological analysis is based on the User-Specified (US) Unit Hydrograph (UH) method as a rainfall to runoff transform method, using the HEC-HMS software to compare various scenarios. This analysis assumes a critical role in assessing the performance, effectiveness, resilience, and adaptability of NBS under diverse climate conditions. The study area is selected due to its vulnerability to floods and its significant flood history. The region has faced repeated flooding events that have posed significant hazards to both the local population and the surrounding environment.

The innovation of this paper is that makes a valuable contribution to the increasing amount of knowledge on NBS, with a specific focus on how they improve flood resilience and protect settlements located downstream of a basin outlet. In this context, this paper presents a practical methodology for the implementation of NBS and conducts a detailed assessment of the resulting flood hydrographs under both current and future climate conditions. This allows for the evaluation of the effectiveness of these NBS in flood risk management, providing valuable insights for environmental agencies, policymakers, and local communities, in terms of flood mitigation strategies.

2 Study area and data used

This paper presents a case study focusing on a river basin within the Sarantapotamos watershed, located upstream of the Magoula settlement in the western part of Attica, in the greater area of Athens, located in Central Greece (Fig. 1). The basin covers an area of 226 km^2, where the elevation ranges from 93 to 1271 m, bordered by Mount Pateras to the west, Mount Parnitha to the east, and Mount Kitheronas to the northwest. Saint Vlassis, Ksirorema, and Grant Katerini streams are the major streams that flow into the main watercourse of the Sarantapotamos River (Theochari et al. 2019). The primary land cover types in the area are coniferous forest and transitional woodland/shrub. The study area experiences a typical Mediterranean climate characterized by hot summers and cold winters. The mean annual rainfall ranges from 300 to 400 mm, while the average annual temperature varies between 17 and 19 °C (Theochari et al. 2019). The region is also prone to experiencing extreme rainfall events characterized by high intensities, leading to significant and severe historic floods.

To conduct the analysis, a digital elevation model (DEM) provided by the National Cadastre and Mapping Agency of Greece is used. This DEM has a pixel size of 5 m×5 m and meets certain accuracy standards. Additionally, IDF curve about Mandra meteorological station is sourced from the Ministry of Environment and Energy. Another important data that play a crucial role in all stages of the methodology are land cover, which is a vector layer provided by CORINE Land Cover (CLC 2018). Finally, the vector file of geology

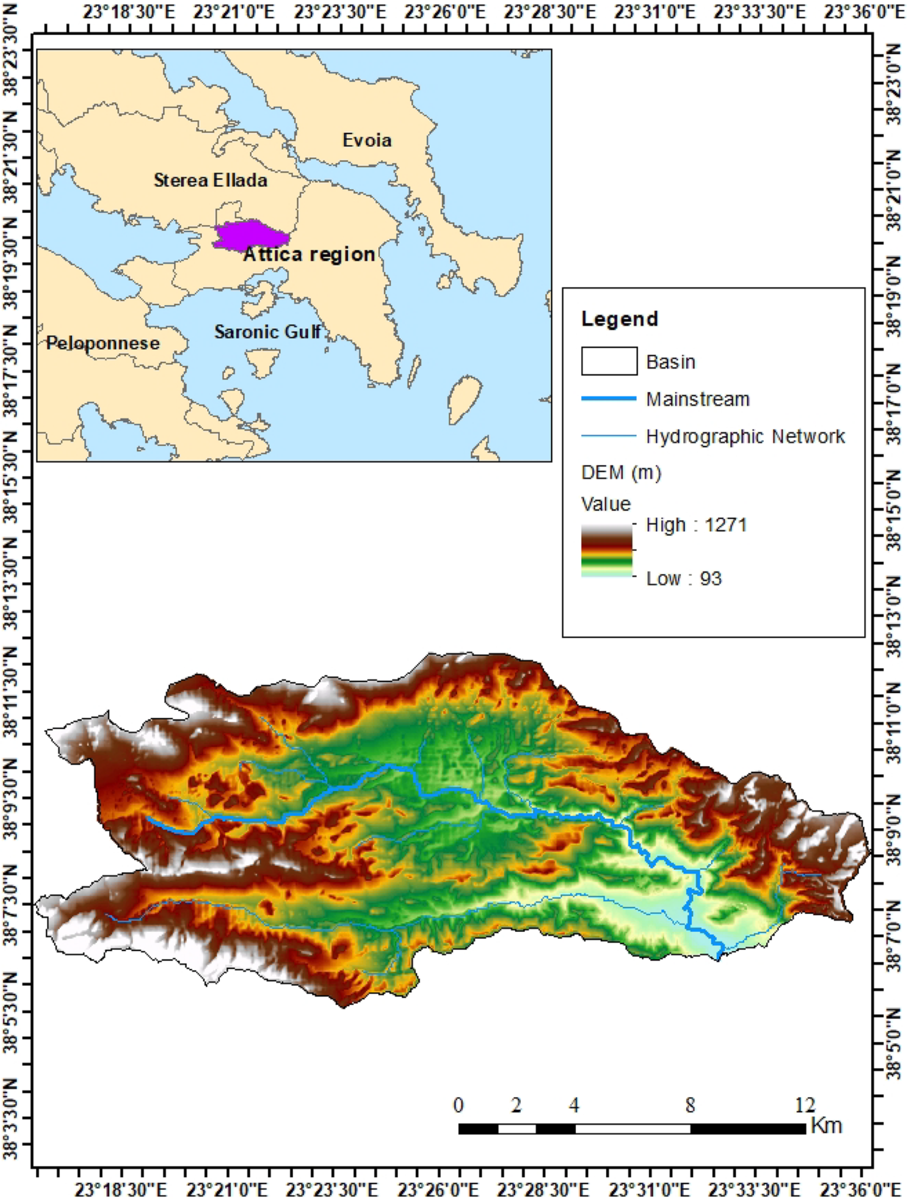

Fig. 1 The study area

is highly significant for conducting the hydrological analysis and implementing land cover changes, as it contributes in combination with land cover to the calculation of the Soil Conservation Service (SCS) curve number (CN) value.

3 Methods

3.1 Hydrological analysis

3.1.1 Flood hydrograph computation before and after NBS

In order to calculate the flood hydrographs at the outlet of the basin and compare them before and after the implementation of NBS, a hydrological analysis is conducted through the HEC-HMS software. This requires multiple components to conduct the simulation, comprising of a basin model, a meteorological model, control specifications, and a time-series data manager (USACE 2018). Each of these components is denoted by distinct methods responsible for computing runoff volume, direct runoff, channel flow, and base-flow. For the transformation of rainfall into runoff, the US UH method is utilized, which requires a UH as input in HEC-HMS. The TA diagram method is conducted within a GIS environment executing a series of commands to calculate this UH, taking into account the basin's physical characteristics such as the DEM and the vector CLC file. The fundamental concept of the approach is represented by the TA histogram, which illustrates how the partial watershed areas, contributing to runoff at the outlet of the watershed, are distributed based on travel time (Theochari and Baltas 2022).

One of the essential input data for HEC-HMS is also the rainfall, for which a precipitation design is calculated to correspond to a specific return period (T) of 100 years. To determine the rainfall intensity for the desired T, a rainfall duration of 24 h is considered. The distribution of rainfall depths (P) and the computation of the design precipitation hyetograph are performed using the Alternating Block Method with the aid of the IDF curve for the Mandra hydrometeorological station. This method makes the rainfall temporal distribution using the IDF, locating the rainfall peak at the center, the next largest rainfall intensity is located alternately to the right and left of the rainfall peak in turn, following a similar pattern as Mononobe model (Na and Yoo 2018). Additionally, the SCS CN method for estimating losses is selected. For this particular method, the CN values are assigned based on the land cover and geology types present in the basin and thus the spatially distributed vector file of the CN is computed according to Wanielista et al. (1996) into GIS environment. The CN value, ranging from 0 to 100, represents the runoff potential of a specific land cover and soil type (Viji et al. 2015). Lower CN values indicate higher infiltration capacity. The average CN value is found to be 67 and is input as parameter into HEC-HMS. Consequently, the flood hydrograph is calculated by combining the aforementioned components. Once the NBS for implementation are selected, the hydrological analysis is repeated to evaluate the effectiveness of the interventions. More specifically, to calculate the new after land cover change flood hydrograph, a new CN value is computed as the land cover is altered within the polygons, resulting in different CN values as shown in Fig. 2. A new average CN value of 62 is calculated due to the polygons with altered land cover and input into HEC-HMS, while keeping the remaining data the same. The new flood hydrographs are compared with the pre-NBS scenarios, assessing the reduction in peak flows and providing valuable insights into the potential flood risks and the effectiveness of the implemented measures in mitigating those risks toward a more resilient and sustainable future.

Regarding the application of NBS with construction of retention ponds, based on the hydrological analysis prior to their implementation, it is determined that the volume of the initial flood hydrograph should be reduced by approximately 75% of the ascending limb

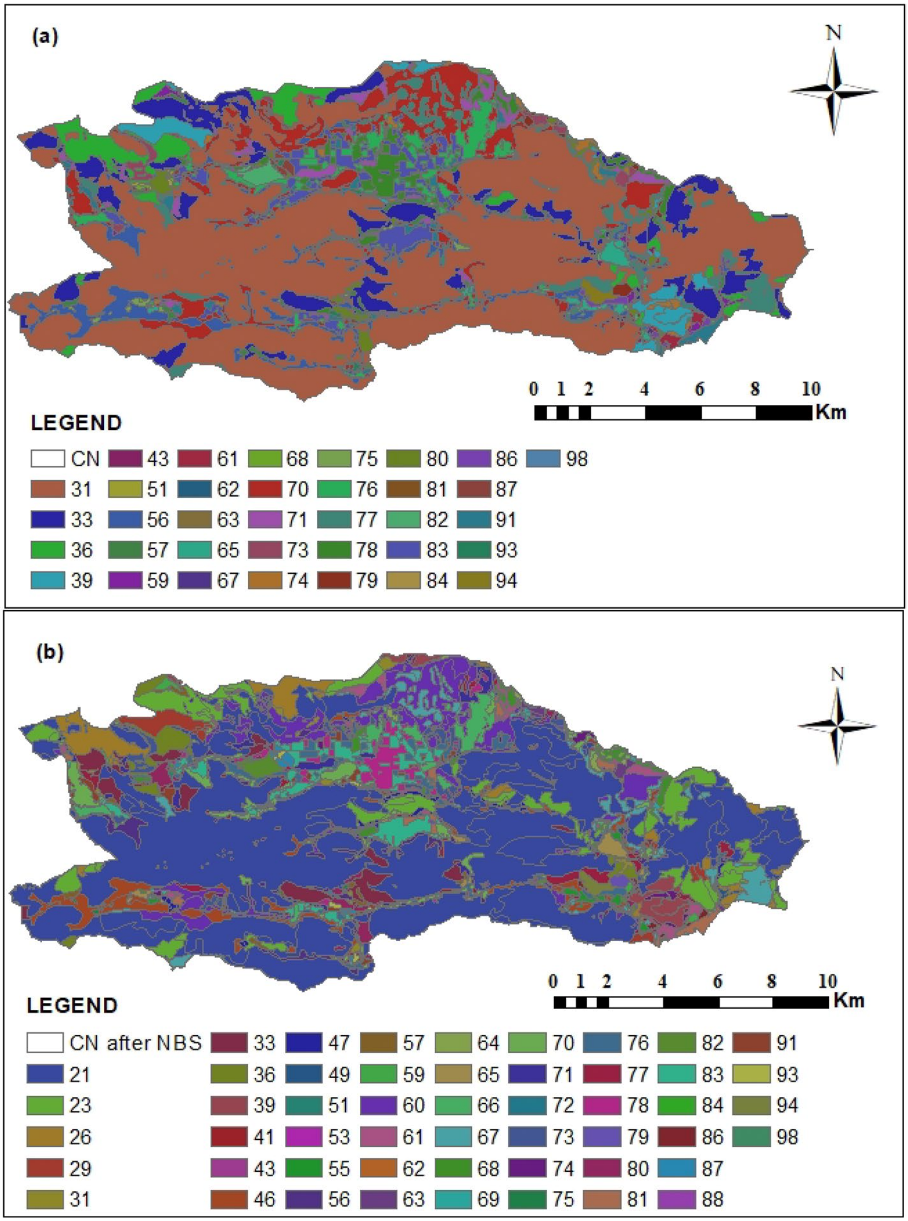

Fig. 2 Distributed curve number (CN) values before (**a**) and after (**b**) land cover changes

of the flood hydrograph. The design of the retention ponds is based on the excess volume calculated above the desired peak discharge, as determined from the hydrological analysis. The 75% reduction in the ascending limb of the flood hydrograph, achieved through the implementation of NBS, ensures that the peak of the flood remains manageable and within safe limits.

3.1.2 Flood hydrograph computation under climate changes

Following the previous hydrological analysis as described, an additional analysis is performed under climate change conditions. This analysis aims to estimate the flood hydrograph for various future scenarios, while simultaneously evaluating the effectiveness of NBS, when implemented under the mean and the most adverse climate scenario. Consequently, there are changes in the design precipitation, as well as the IDF curves used. The new IDF are derived from Kourtis et al. (2023), who developed future IDF curves obtained rainfall data from the Thissio station, based on bias-corrected and temporally disaggregated climate projections, using the empirical model proposed by Sherman (1931), specifically the Future IDF curves using GEV distribution without Scaling by analyzing the 1-h annual maxima series. Future IDF curves are developed to account for climate changes from the hydrological years 2021–2022 to 2099–2100. These curves have a spatial resolution of 0.11° and a daily temporal resolution. The climate changes are represented by three scenarios, corresponding to the production of three future IDF curves. These scenarios encompassed the overall uncertainty by considering bootstraps for all climate models (GCMs and RCMs), climate scenarios (RCPs 4.5 and 8.5), as well as the various bias correction methods employed for spatial downscaling and bias correction. Kourtis et al. (2023) examined the climatic aspects by considering two general circulation models, four regional climate models, two representative concentration pathways, five bias correction techniques, two temporal disaggregation approaches, and two probability distributions for the development of future IDF curves. Assessing climate change impacts and updating IDF curves heavily relies on projections from General Circulation Models (GCMs). Recognizing the limitations of GCMs, especially their coarse spatiotemporal scale, enhancement is necessary through dynamic and/or statistical approaches (Kourtis and Tsihrintzis 2021). According to Kourtis et al. (2023) dynamic downscaling involves utilizing Regional Climate Models (RCMs) driven by GCMs under diverse climate scenarios, such as Representative Concentration Pathway-RCPs or Special Report on Emissions Scenarios-SRES. Regarding the three scenarios, they included both a ± 95% range and the mean, where the future mean intensity is calculated as the ensemble mean generated using the empirical bootstrapping method. Upper and lower intensities are estimated as ± 95% confidence intervals using the same bootstrapping approach. By incorporating these future IDF curves, the hydrological analysis accounted for potential changes in rainfall patterns and intensities due to climate change. This enables a more comprehensive understanding of the future hydrological response within the study area. Using Thissio station's IDF data, instead of the closer Mandras station, for the study area can be justified due to several reasons. Firstly, Thissio station possesses a comprehensive dataset spanning multiple years, making it more suitable for historical data analysis and rainfall model development within the Attica region. In contrast, Mandras station has limited recent data available. Additionally, the elevations and climate conditions between Thissio and the study area are relatively similar, ensuring the applicability of Thissio station's data. The proximity in elevations guarantees that rainfall patterns observed at Thissio station accurately represent the study area's conditions. Lastly, the Thissio station's rainfall data with a spatial resolution of 12 km adequately cover the region of interest, providing a reasonable representation of rainfall patterns and variations in the study area. After the hydrological analysis, three flood hydrographs are calculated for future upper, mean, and lower intensity. Using design precipitations from mean and worst-case climate scenarios, a new hydrological analysis evaluates NBS effectiveness. NBS measures aim to reduce peak discharge and mitigate flood impacts. The analysis applies NBS to the hydrological model, comparing resulting flood hydrographs with the baseline scenario. Evaluating hydrological responses of these scenarios, including NBS and combined approach, offers valuable insights on flood risk mitigation. This analysis informs decision-makers on selecting and implementing suitable NBS measures to reduce future flood impacts.

3.2 Implementation of NBS

3.2.1 Land cover changes

After the hydrological analysis, the appropriate NBS are selected and incorporated into the basin. For the implementation of the NBS involving land cover change, a systematic methodology is employed. Initially, a meticulous analysis of the land cover patterns is conducted within the basin, utilizing the CLC (2018). By harnessing the advanced spatial analysis capabilities of the ArcGIS (ESRI 2010) environment, a comprehensive assessment of the distribution and characteristics of various land cover types is performed. To identify areas suitable for land cover modification, an extensive examination is carried out focusing on regions with low human utilization or considered non-essential for human survival, as well as areas with limited capacity to effectively absorb runoff water, such as transitional woodland/shrub, sparsely vegetated areas, and burnt areas. Subsequently, a strategic decision is made to replace these land cover types with broad-leaved forest, which offered numerous advantages for flood protection and ecosystem enhancement. Broad-leaved forest not only provides exceptional water retention capabilities but also promotes biodiversity. In consideration of potential uncertainty parameters affecting the selection of areas suitable for land cover modification, it is crucial to recognize that uncertainties may arise in data accuracy and dynamic environmental conditions. Furthermore, a multicriteria approach could indeed be a valuable future step. This approach would involve incorporating multiple criteria, such as ecological, hydrological, and socioeconomic factors into the decision-making process.

Once the appropriate areas are identified, careful consideration is given to the selection of proper broad-leaved forest species and the sourcing of suitable plant material. This included evaluating the ability of the chosen species to adjust to the weather, soil conditions, and water patterns in the area. In the study area, the recommended broad-leaved forest species are oak forests and plane tree forests. In total 61 km^2 of land has been transformed into a broad-leaved forest resulting in a significant transformation of the landscape. This transformation represents a step, in the efforts to create a more resilient and sustainable basin. Specifically, the replacement of 59.4 km^2 of transitional woodland/shrub with broad-leaved forest, along with 1.5 km^2 of sparsely vegetated areas and 0.25 km^2 of burnt areas with broad-leaved forest, is carried out. Figure 3 illustrates the land cover before and after the change, where the intervention polygons are depicted in fuchsia pink color.

3.2.2 Retention ponds construction

Retention ponds enhance the resilience of residential areas by mitigating the impact of extreme weather events induced by climate change, including heavy rainfall and increased flood risks. These ponds serve as natural buffers, absorbing and retaining excess water, which helps decrease the susceptibility of communities to flooding. Retention ponds are

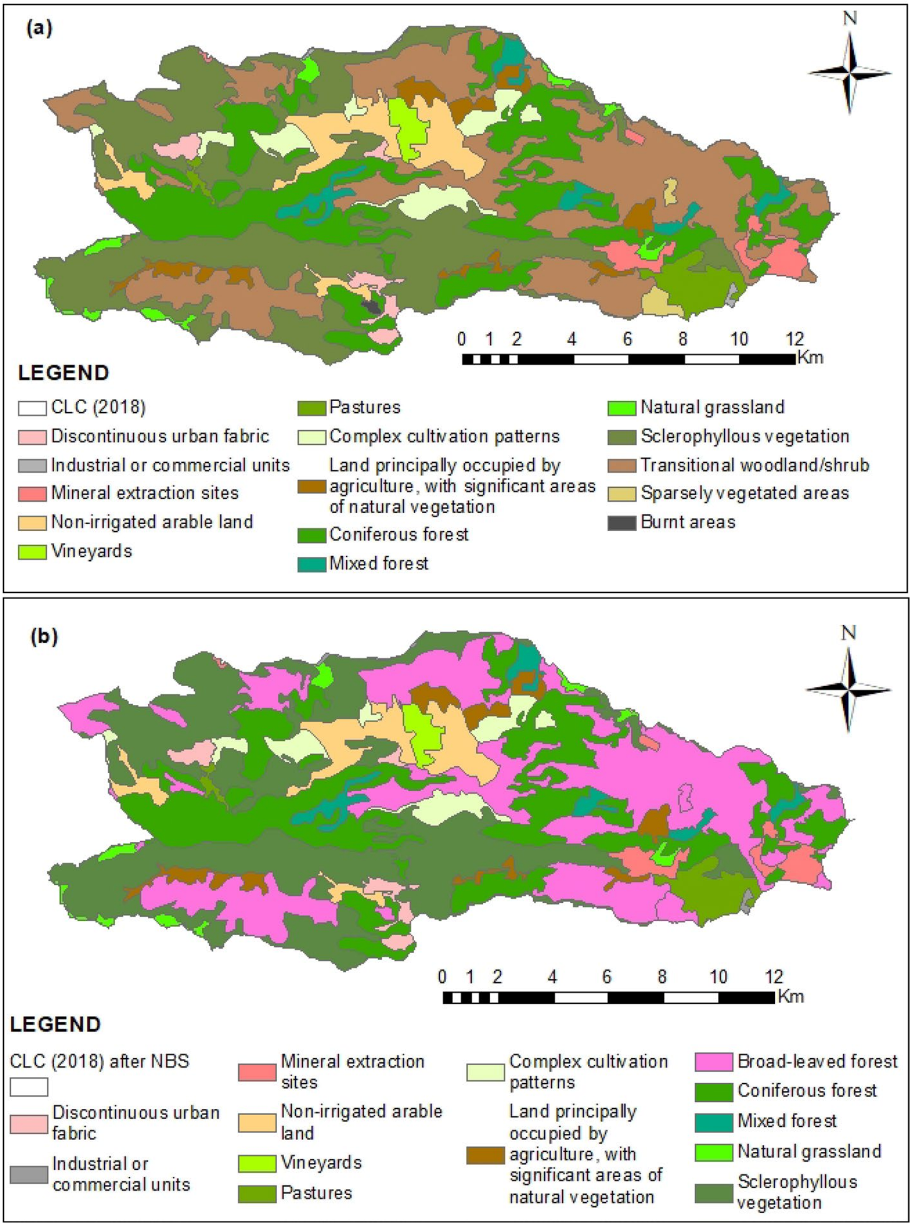

Fig. 3 Corine Land Cover before (**a**) and after (**b**) Nature-Based Solutions (NBS)

commonly constructed alongside flood-prone rivers to redirect and retain excess river discharge during high flows, utilizing the low-lying areas along the rivers as effective storage areas (Chan et al. 2020). Retention ponds are established through various methods, including utilizing pre-existing natural depressions, excavating new depressions, or constructing embankments to create the desired storage space for excess water (European Commission

2013). In this research work, an extensive review of existing literature (Mardjono et al. 2022; Munfarida and Rizal 2022; Ferk et al. 2020; Staccione et al. 2021; Collentine and Futter 2018) is undertaken, but finally the design criteria for retention ponds have been considered by the authors based on the topography of the region, the slopes and the density of the river network, and the study of the cross section. However, the number of ponds affects the cost of the integrated design, but in the framework of this research, it is taken into consideration only the effectiveness of the number of the retention ponds. In order to design the retention ponds, the central concept is to create a system of ponds along the mainstream on both sides, utilizing non-exploitable land areas. Due to their shallow depth and placement on relatively flat surfaces, these ponds primarily involve small-scale earthworks, deviating from the category of "gray" constructions. The soil volume resulting from excavation is used for perimeter reinforcement, possibly creating earthen embankments. Based on hydrological analysis prior to the implementation of NBS, and after the assumption for the volume of the initial flood hydrograph reduction by approximately 75%, the peak discharge of the flood hydrograph after the implementation of NBS will decrease to approximately 75% of the ascending limb, corresponding to a value of 383 m^3, and will follow a horizontal line. The 75% value is an indicative maximum flow rate to reduce the flow dictated by the required technical work, based on the shape of the hydrograph, who it is derived from small catchment. Consequently, the volume encompassed by the initial flood hydrograph above the horizontal line representing the desired new peak discharge will correspond to the total volume of the retention ponds targeted to design, which is calculated to be 3.3 hm^3 according to the diagram. This volume corresponds to the excess water above the desired peak discharge, which will be effectively managed by the constructed ponds. The shape of the retention ponds is chosen to be elliptical, with a major axis of 80 m, a minor axis of 20 m, and a depth of 2 m, based on good engineering principles in terms of avoiding excessive earthworks that would have ecological and economic costs. The distance between the ponds is considered suitable and designed to be 10 m. Additionally, it is assumed that each retention pond will have an area of 5024 m^2, resulting in a volume of 13,397 m^3. Taking all these factors into consideration, it is concluded that the total number of ponds to be designed is 245. These ponds will be constructed on both sides of the river in sections corresponding to land cover such as sclerophyllous vegetation, coniferous forest, and mixed forest, which are not exploitable by humans. The design of the ponds is created using AutoCAD Civil 3d (2023) (Fig. 4). However, this NBS also present certain challenges, with the main one being the maintenance cost. As the ponds receive surface water runoff, it is natural for sediments to accumulate at the bottom. Therefore, regular investments are required to ensure their proper functioning by removing accumulated materials. Moreover, measures can be implemented to prevent the accumulation of sediments upstream of the ponds, serving as sediment retention works.

4 Results

This paper presents a comparative analysis of flood hydrographs resulting from a hydrological analysis conducted in the Sarantapotamos river basin upstream of Magoula settlement, Greece. The primary objective is to evaluate the effectiveness of different NBS applications in mitigating floods indicating their respective contribution to reducing peak discharge. The comparison is conducted between the initial flood hydrograph under current climate conditions and the flood hydrographs following the implementation of the two

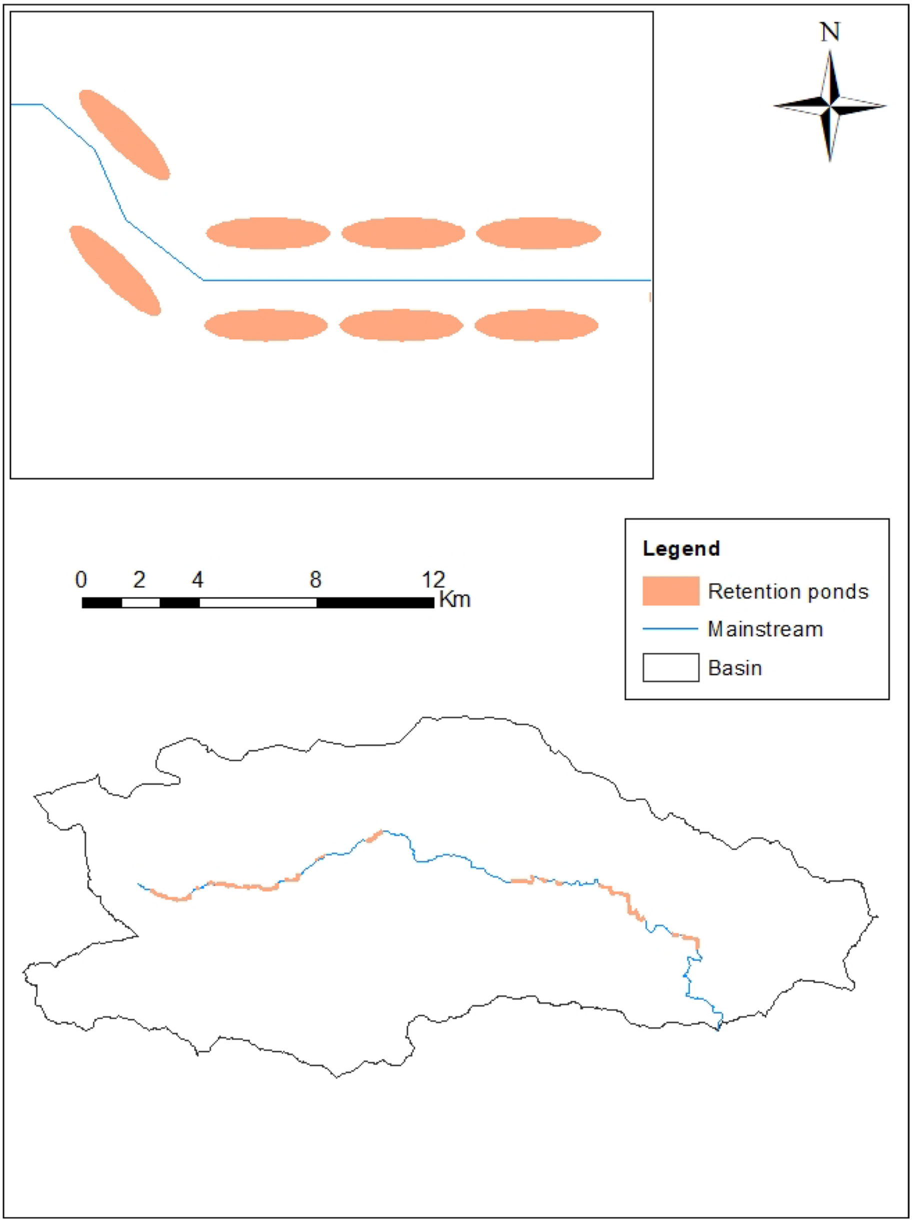

Fig. 4 The retention ponds across the mainstream

proposed NBS. Furthermore, the comparison is made between the baseline scenario and the hydrographs resulting from three future climate scenarios, including also the mean and the worst-case climate scenarios, after applying the two NBS measures. By examining the baseline scenario, the peak discharge is found to be 535.7 m^3/s and occurred at 19 h, while the land cover change NBS results in a reduced peak discharge of 465.8 m^3/s and a delayed time to peak at 20 h, while the total flood volume is decreased to 103 hm^3 compared to the baseline scenario that it is calculated at 118 hm^3. This reduction in peak discharge can be attributed to the alteration of land cover patterns, which helps facilitate better stormwater infiltration, leading to decreased surface runoff and reduced flood volumes. Similarly, the construction of retention ponds leads to a significant decrease in the peak discharge, reaching 383.3 m^3/s, and the time to peak is accelerated to 15 h as it is assumed that the peak occurs at approximately 75% of the ascending limb after the implementation of this NBS. The calculated number of retention ponds to be constructed is found to be 245, with a total flood volume capacity of 3.3 hm^3. Consequently, the flood hydrograph after this NBS implementation results in a total flood volume of 115 hm^3. Furthermore, a combination of both NBS is applied, resulting in an even lower peak discharge of 318.5 m^3/s, representing a reduction of approximately 41% compared to the pre-NBS scenario and the time to peak remains constant at 15 h, suggesting that the combined NBS does not affect significantly the timing of the flood peak compared to the retention ponds scenario. It is noteworthy that the flood volume has significantly decreased to 99.7, which is attributed to the retention ponds capacity to withhold 3.4 hm^3 of flood water. In relation to the total flood volume that it is emerged in the baseline scenario, this reduction corresponds to a significant decrease of approximately 15.3%. Moreover, it is important to mention that to achieve these results, a total of 250 lakes will need to be constructed. The comparison of the flood hydrographs discussed earlier is presented in Fig. 5.

Additionally, the study assesses the impact of climate change scenarios on the design precipitation used to calculate the rainfall depths and consequently on flood hydrographs. Prior to considering climate change, the rainfall peak of the design storm is 61.6 mm, with a cumulative rainfall depth of 219.5 mm and an intensity of 9.1 mm/h. Under the upper climate change scenario, the cumulative rainfall depth and the rainfall intensity are increased significantly to 962.3 mm and to 40 mm/h, respectively. Similarly, the rainfall

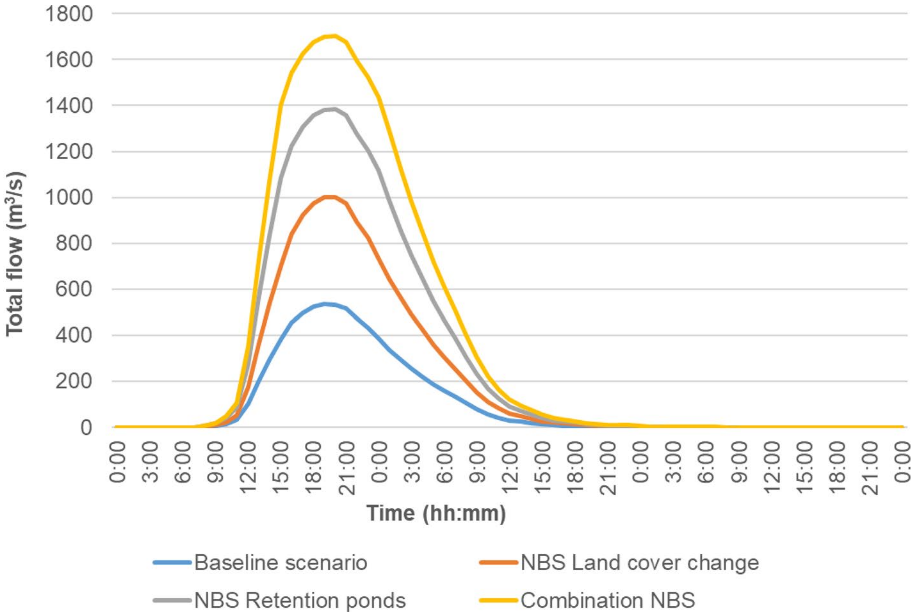

Fig. 5 Flood hydrographs before and after Nature-Based Solutions (NBS) for current climate conditions

peak intensified to 312.8 mm. Such intensified design precipitation poses additional challenges for flood management, highlighting the urgency of implementing effective NBS to mitigate the potential impacts of climate change. In contrast, the lower climate change scenario results in a reduction in both cumulative rainfall depth and rainfall peak. The cumulative rainfall depth is decreased to 154.2 mm, representing a decrease of approximately 30% compared to the baseline scenario. The rainfall peak is reduced to 63 mm, indicating a lower intensity of the design precipitation, which is decreased to 6.4 mm/h. This scenario offers a more favorable outlook in terms of flood risk. In the mean climate change scenario, the cumulative rainfall depth reaches 325 mm, while the rainfall peak is measured at 130.6 mm, and the rainfall intensity is increased to 13.5 mm/h. To assess the impact of the latter on flood hydrographs, hydrological simulations are also conducted, demonstrating the importance of combining NBS with climate change adaptation strategies. More specifically, in the upper climate change scenario, the peak discharge increased to 4075 m^3/s, occurring at 19 h. Additionally, it is important to note that the flood volume is calculated to be 826.8 hm^3, indicating an increase compared to the initial volume of 118. This represents a significant percentage increase of approximately 600%. The observed increase in flood volume and peak discharge highlights the need for taking measures and implementing plans to enhance resilience from the potential risks and impacts caused by extreme weather events resulting from climate change. The mean climate change scenario results in a peak discharge of 1107.4 m^3/s, occurring one hour earlier at 18 h. Furthermore, the flood volume is increased to 211.7 hm^3, indicating a percentage increase of approximately 79.2% compared to the initial volume of 118. The observed increase in flood volume and peak discharge in the mean climate change scenario highlights also the need for effective adaptation measures to address the flood risk. Conversely, the lower scenario results in a peak discharge of 337.9 m^3/s, with no change in the time to peak at 19 h, while the total flood volume is decreased to 65.6 hm^3. Figure 6 illustrates the flood hydrographs for all

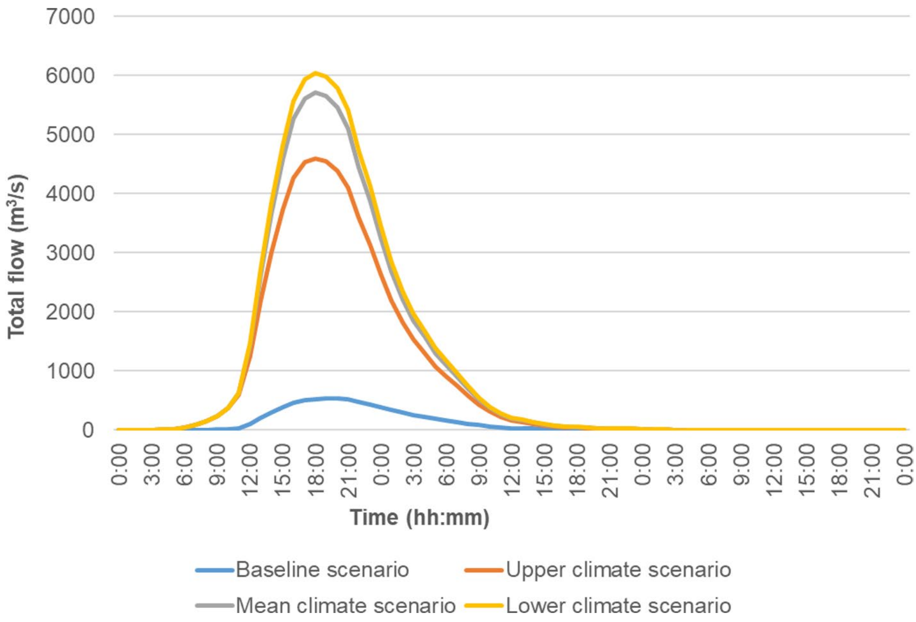

Fig. 6 Flood hydrographs before and after Nature-Based Solutions (NBS) for future climate conditions

climate change scenarios, providing a comprehensive visual representation of the different flood dynamics.

Based on hydrological analyses conducted to calculate flood hydrographs under three climate change scenarios, the upper and the mean scenarios are selected. These scenarios are chosen to assess the effectiveness of implementing NBS under these specific climate conditions. Considering the upper scenario, the two NBS, land cover change, and construction of retention ponds are applied individually, as well as in combination. After land cover change, the peak discharge is decreased to 3945.5 m^3/s, representing a reduction of approximately 3.7% from the initial value of 4075 m^3/s. Additionally, the time to peak remains constant at 18 h. Moreover, the total flood volume is reduced to 797.7 hm^3, signifying a decrease of approximately 3.5% from the initial volume of 826.8 hm^3. These results highlight the effectiveness of land cover change in mitigating flood risks by reducing the peak discharge and the total flood volume. Furthermore, the implementation of retention ponds leads to an additional reduction in peak discharge, resulting in a value of 2702.9 m^3/s, while the time to peak decreased to 14 h taking into account the assumption for 75% decrease of the initial peak discharge. The presence of retention ponds provides valuable storage capacity during flood events and effectively mitigates the downstream impacts of flooding. Additionally, the calculated volume of the retention ponds is determined to be 29.4 hm^3. Consequently, the final total flood volume amounts to 797.4 hm^3. These results highlight the substantial effectiveness of retention ponds in mitigating flood impacts. Additionally, it is determined that a total of 2198 retention ponds are required to achieve the desired flood mitigation goals. Finally, through the combined implementation of both NBS, the peak discharge is reduced to 2567.4 m^3/s, while maintaining a constant time to peak of 14 h. This combined approach shows how different NBS can work together to enhance the stakeholders' alert level for floods and reduce the effects of climate change. Moreover, the calculated water storage capacity of the retention ponds is estimated to be 30.2 hm^3. Consequently, the total flood volume at the basin outlet is calculated to be 767.55 hm^3. When compared to the initial volume of 826.8 hm^3, this represents a reduction of approximately 7.2%. Furthermore, it is estimated that a total of 2258 retention ponds will need to be constructed to achieve the desired flood mitigation objectives. Figure 7 presents the flood hydrographs for the upper climate scenario before and after implementing NBS.

In the context of the mean climate change scenario, notable transformations are observed following modifications in land cover. The peak discharge is decreased to 999.8 m^3/s, indicating a reduction of approximately 9.73% compared to the initial value of 1107.4 m^3/s. Interestingly, the time to peak remains unchanged at 18 h, while the total flood volume is decreased to 192.1 hm^3, representing a reduction of approximately 9.25% from the initial volume of 211.7 hm^3. Moreover, the implementation of retention ponds leads to further reductions in peak discharge. The recorded value decreased to 851.7 m^3/s, accompanied by a shortened time to peak of 15 h. The calculated volume of the retention ponds is determined to be 4.6 hm^3. Consequently, accounting for the reduced volume due to the implementation of these ponds, the final total flood volume amounts to 207.1 hm^3. This underscores the significant impact of these ponds in minimizing the intensity of flood events. It is determined that a total of 340 retention ponds will be necessary to achieve the desired flood mitigation goals. By adopting a combined approach, the peak discharge is further reduced to 755.9 m^3/s, while maintaining a consistent time to peak of 15 h. Additionally, the estimated water storage capacity of the retention ponds is 4.4 hm^3. Thus, considering the reduced volume, the total flood volume at the basin outlet is found to be 207.3 m^3. It is estimated that a total of 327 retention ponds will need to be constructed to achieve the desired flood mitigation objectives. These findings emphasize the

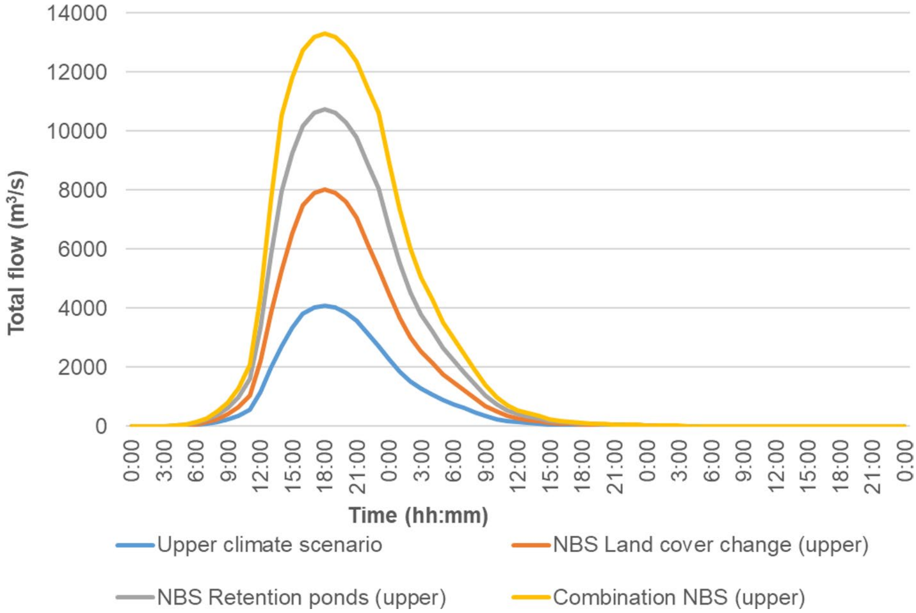

Fig. 7 Flood hydrographs before and after Nature-Based Solutions (NBS) for the upper climate scenario

comprehensive efforts required to effectively address flood risks and enhance the overall resilience of the basin. Accompanying Fig. 8 illustrates the flood hydrographs for the mean climate scenario, both before and after implementing NBS.

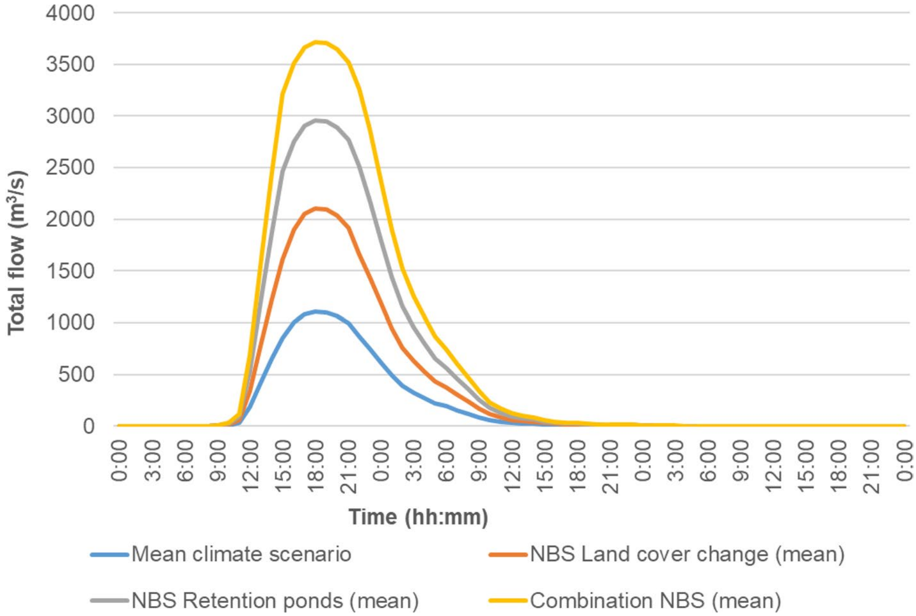

Fig. 8 Flood hydrographs before and after Nature-Based Solutions (NBS) for the mean climate scenario

Overall, based on the aforementioned findings, the combination of NBS demonstrates the greatest reduction in peak discharge and flood volume across all scenarios. Therefore, it can be considered the ideal solution for effectively addressing flood risks. The results highlight the importance of combining multiple NBS techniques to achieve improved flood resilience. Among the NBS, the construction of retention ponds achieves the highest decrease in peak discharge, while land cover change generally leads to an increase in the time to peak, demonstrating its potential for regulating the timing of flood events. However, it is important to note that the choice of the most suitable NBS approach depends on various factors such as the basin characteristics, relief, density of the hydrographic network, and topographic features. Moreover, according to Reaney (2022), the efficiency of an NBS depends on its placement within the catchment, influenced by four key factors: local flood water generation, hydrological connectivity to the river, travel times to the impact point, and the spatial pattern of the rainfall event. In this particular study, a preliminary investigation suggests that the combined use of NBS, considering the gentle relief and accessible areas in the study area, results in the lowest peak discharge across all climate scenarios. Additionally, among the NBS evaluated, it is believed that retention ponds offer a superior solution. Unlike land cover changes, which are dependent on the uncertain factor of soil permeability, retention ponds allow us to have direct control over the volume of water they can retain and are considered a more immediate solution in terms of construction time compared to the other solution. Due to their relatively simple design and construction requirements, retention ponds can be implemented in a shorter timeframe. This attribute makes them a favorable option for quickly addressing flood risks and providing immediate benefits to communities at risk. Regarding the cost of implementing the two proposed Nature-Based Solutions (NBS), it is important to consider different approaches and prerequisites. Land cover change may involve expenses related to land acquisition, infrastructure adjustments, and personnel training. Conversely, constructing retention ponds may include costs for materials, labor, and maintenance. In the current study, given the high cost of land cover change and the associated projects, a more economically feasible solution is the construction of retention ponds. Nevertheless, it is crucial to conduct a comprehensive and detailed study of the specific area to fully understand its unique characteristics and determine the optimal NBS measures to be implemented.

5 Conclusions

This paper emphasizes the importance of incorporating NBS in flood risk management strategies in Sarantapotamos river basin upstream of the Magoula settlement, located in Greece. It is presented a methodology for effectively implementing NBS, such as land cover change and construction of retention ponds. More specifically, it is conducted a comprehensive evaluation of the resulting flood hydrographs, taking into account the current as well as future climate conditions, which correspond to three climate change scenarios: lower, mean, and upper, representing ± 95% confidence intervals, and applying both NBS for the mean and upper climate scenario. This analysis provides a detailed understanding of the impacts and effectiveness of each NBS and their respective contribution to reducing peak discharge in mitigating floods. Regarding the findings that concern the implementation of NBS in current climate conditions, it is observed that the land cover change NBS is resulted in a significant reduction in peak discharge, with a decrease of approximately 9.3% compared to the baseline scenario. Moreover, the construction of retention ponds is proved to be an effective NBS, leading to a substantial decrease in peak discharge by approximately 28%. The combined implementation of NBS presents the most significant reduction in peak discharge, with a decrease of approximately 40.5% compared to the pre-NBS scenario. The analysis of the total flood volumes revealed notable reductions across all NBS scenarios. The land cover change NBS leads to a decrease by approximately 12.3%, while the retention ponds scenario achieved a reduction of approximately 15.3%. The combined NBS resulted in the most substantial decrease in flood volume, with a reduction of approximately 15.7%. Furthermore, the incorporation of climate change scenarios in this study reveals significant impacts on design precipitation, which subsequently affected flood hydrographs. The upper climate change scenario exhibits intensified design precipitation, with a notable increase in cumulative rainfall depth, rainfall intensity, and rainfall peak, leading to the peak discharge increase of approximately 3348% compared to the initial peak discharge. The observed total flood volume presents an increase of approximately 600% compared to the initial volume. Conversely, the lower climate change scenario demonstrated a reduction in both cumulative rainfall depth and rainfall peak. The total flood volume decreased to 65.6 hm^3, indicating a reduction of approximately 44.6% compared to the initial volume. In the mean climate change scenario, the rainfall intensity observed at 13.5 mm/h indicates an intermediate level of flood risk compared to the other climate change scenarios examined. The peak discharge is increased of approximately 838% compared to the initial value, while the calculated total flood volume is increased of approximately 79.2% compared to the initial volume. Under the upper climate change scenario, the implementation of land cover change and retention ponds resulted in substantial reductions in peak discharge. Land cover change alone reduced the peak discharge by approximately 3.7%, while retention ponds further decreased it by approximately 33.6%. These NBS measures also contributed to a reduction in the total flood volume by approximately 3.5% and 3.6%, respectively. Similarly, in the mean climate change scenario, land cover change and retention ponds prove effective in reducing the peak discharge by approximately 9.73% and 23.11%, respectively. The total flood volume is also reduced by approximately 9.25% and 2.17%, respectively. In conclusion, among the evaluated NBS approaches, the construction of retention ponds has shown the highest decrease in peak discharge. On the other hand, land cover changes have demonstrated potential in regulating the timing of flood events by increasing the time to peak. In this paper, a preliminary investigation suggests that the combined use of NBS results in the lowest peak discharge across all climate scenarios. In the framework of future research, it is suggested the investigation of the soil erosion influence on the retention ponds effectiveness. It would be also great of interest the performance of hydraulic simulation in the position downstream of the basin before and after NBS application.

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Declarations

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