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Research article

Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits

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ABSTRACT

Flooding is expected to increase due to climate change, urbanisation, and land use change. To address this issue, Nature-Based Solutions (NBSs) are often adopted as innovative and sustainable flood risk management methods. Besides the flood risk reduction benefits, NBSs offer co-benefits for the environment and society. However, these co-benefits are rarely considered in flood risk management due to the inherent complexities of incorporating them into economic assessments. This research addresses this gap by developing a comprehensive methodology that integrates the monetary analysis of co-benefits with flood risk reduction in economic assessments. In doing so, it aspires to provide a more holistic view of the impact of NBS in flood risk management. The assessment employs a framework based on life-cycle cost-benefit analysis, offering a systematic and transparent assessment of both costs and benefits over time supported by key indicators like net present value and benefit cost ratio. The methodology has been applied to the Tamnava basin in Serbia, where significant flooding occurred in 2014 and 2020. The methodology offers valuable insights for practitioners, researchers, and planners seeking to assess the co-benefits of NBS and integrate them into economic assessments. The results show that when considering flood risk reduction alone, all considered measures have higher costs than the benefits derived from avoiding flood damage. However, when incorporating co-benefits, several NBS have a net positive economic impact, including afforestation/reforestation and retention ponds with cost-benefit ratios of 3.5 and 5.6 respectively. This suggests that incorporating co-benefits into economic assessments can significantly increase the overall economic efficiency and viability of NBS.

1. Introduction

Continued global temperature rise is expected to change the global water cycle, including precipitation patterns and the intensity of wet and dry events, as highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2021). Simultaneously, the combined changes of climate change, urban development, population growth and land use are increasing flood risk in watersheds globally (Alfieri et al., 2017; Jongman et al., 2012; Najibi and Devineni, 2018; Tellman et al., 2021). In response to these challenges, there is a need for investing adaptation strategies that protect people, properties, infrastructure and the environment from flooding (Jongman et al., 2015). In recent years, Nature-Based Solutions (NBSs) have gained attention and have been adopted by policymakers as innovative and sustainable approaches to flood risk management (FRM) and climate change adaptation (Cohen-Shacham et al., 2016; Ruangpan et al., 2020a; Schindler et al., 2014; Seddon, 2022; Su et al., 2023; Vojinovic et al., 2021). NBSs are actions inspired by, supported by or copied from nature. They can also generate co-benefits, i.e. additional positive outcomes such as social, economic and environmental enhancements alongside a primary benefit (European Commission, 2015). Co-benefits of NBS may include carbon sequestration, enhancing biodiversity, recreational activities,

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controlling sediment erosion, and reducing air pollution, among others.

To identify the most effective and efficient flood risk management strategies, quantitative evaluation is essential. While several studies have been carried out to assess the performance of small-scale (i.e. urban) NBS, limited attention has been given to large-scale (i.e. catchment) NBS (Kumar et al., 2021; Ruangpan et al., 2020a). For example, Wang et al. (2023) assess the hydrological performance under Shared Socio-economic Pathways (SSPs) based on long-term rainfall time series, However, previous studies on the catchment scale have only focused on the benefits of risk reduction and have not considered NBSs co-benefits (Hu et al., 2017; Klijn et al., 2018; Wagenaar et al., 2019). For example, Te Linde et al. (2010) evaluated the effectiveness of flood management measures focusing on reducing flood-peak discharges and water levels for different locations along the Rhine, while Jonkman et al. (2013) primarily focused on estimating the cost of adapting measures. Research suggests that the assessment of both costs and benefits should be considered, as economic assessment is a key step in the decision/planning process to select and evaluate NBS (Alves et al., 2019; Ghafourian et al., 2021; Le Coent et al., 2023; Quagliolo et al., 2022; Vojinovic et al., 2016; Wild et al., 2017).

Cost-benefit analysis (CBA) is a common method used for economic evaluation in flood risk management. However, traditional CBA studies often narrow their focus to expected annual damage (EAD) reduction and overlook the potential co-benefits of the measures (e.g., improving water quality, enhancing biodiversity, or increasing habitat structure). For instance, Wagenaar et al. (2019) evaluate adaptation measures for reducing flood risk by using CBA to compare the costs of measures with the expected flood damage reduction. Therefore, a methodology for incorporating co-benefits into CBA is still needed as it is essential for maximising the potential of NBS. Furthermore, assessing co-benefits is crucial for anticipating trade-offs and capturing economic, social, and ecological outcomes of implementing NBSs (Alves et al., 2020; Calliari et al., 2019). By quantifying the diverse co-benefits, decision-makers, policymakers, and stakeholders can make well-informed choices and investments, ensuring the most effective and efficient use of resources.

From the studies referenced above, it can be seen that there are still some knowledge gaps in economic assessment for flood risk management. Specifically, these are: (i) estimating only the cost of adapting measures but not the benefits; (ii) focusing on expected flood damage reduction as the only benefit of implementing measures; (iii) including co-benefits at the urban scale rather than on river catchment.

To address the knowledge gaps mentioned above, this research aims to develop a methodology for the economic assessment of NBSs at a river basin scale. The methodology expands beyond the traditional flood risk management evaluation by incorporating co-benefits, thus considering environmental and socio-economic values of NBSs. This economic assessment is based on a cost-benefit analysis (CBA) using Net Present Value (NPV) and Benefit Cost Ratio (BCR). To achieve this, the proposed methodology has been applied to the process of planning NBS measures for a case study within the Tamnava River basin in Serbia, as part of the EC-funded RECONECT project (RECONECT, 2018). As part of the case study application, five co-benefits have been included into the analysis of various NBS measures. These co-benefits consist of carbon sequestration, biological control, habitat creation, air pollution reduction and education, while the considered measures are afforestation/reforestation, retention ponds, floodplain restoration, and removing obstructions (e.g. bridge).

2. Methodology

2.1. Overall methodology

This study focuses on conducting an economic assessment of NBSs by expanding on traditional economic flood risk assessment to include the co-benefits of NBSs. In order to assess the performance of NBS, it is necessary to select applicable measures and determine their associated benefits. However, not all benefits can be easily quantified in monetary terms, thus priority should be given to the most significant co-benefits or co-benefits that can be readily quantified.

The economic assessment process comprises four main components: cost estimation, benefit estimation, value adjustment and cost-benefit analysis – all of which are explained in detail in the following sections. Fig. 1 shows the complete process for NBS assessment, with the economic assessment process highlighted in blue. The cost estimation includes capital expenditures and maintenance and operational expenditures. The benefits are identified and divided into two categories; main benefits (i.e., risk reduction benefits) and co-benefits. Risk reduction benefits are based on expected annual avoided damage (EAAD), while the co-benefits are assessed by determining the value of change in biophysical indicators. This study employs the value transfer method for assessing monetary value by adjusting value to the local contexts (e.g. year of implementation, currency). Finally, both the benefits and costs of NBS are evaluated and compared using life-cycle CBA (LCCBA).

CBA is a theoretical analysis technique that evaluates whether it is economically beneficial to enact a project, as it provides important information for the identification, option analysis and appraisal of investments. Two metrics commonly used in LCCBA are NPV and BCR. The reason that NPV and BCR are selected is that they account for the time value of money by discounting future cash flows back to their present values using a discount rate. This is crucial because it recognises that a euro today is worth more than a euro received in the future. Moreover, NPV provides an absolute monetary value, making it easier to interpret. A positive NPV indicates that a project is expected to generate a surplus, while a negative NPV suggests a deficit. BCR, although a relative value, clearly indicates whether benefits outweigh costs (BCR >1) or not (BCR <1). This allows for a comprehensive evaluation of the economic viability of NBS, considering both the primary risk reduction benefits and the additional co-benefits they provide.

2.2. Cost estimation

The life-cycle cost (LCC) of proposed NBS measures includes the capital expenditure as well as the maintenance and operation. LCC analysis provides valuable information for ensuring the continued functionality of the NBS throughout its lifespan.

Capital expenditure or CAPEX entails various costs, including research costs, land acquisition and construction costs. These capital costs are assumed to be incurred at the beginning of the project (year zero) and therefore do not need to be discounted in time. Maintenance and operation expenditures, also known as Operational Expenditure or OPEX, are the day-to-day management, maintenance and operation expenditures required to keep a measure performing as expected.

In line with the Flood and Coastal Erosion Risk Management Appraisal Guidance (Environment Agency, 2010), an optimism bias should be included during project assessment to ensure adequate budgeting, allowing for unknown factors and the uncertain nature of cost estimates. An optimism bias of 60% is commonly used for projects at an early stage of consideration, while a value of 30% is utilised at a more detailed project stage. This percentage is added to the original estimate and used in the cost-benefit calculations.

2.3. Primary benefit estimation

The primary benefit is flood risk reduction, which is assessed based on flood hazard and vulnerability assessment (Klijn et al., 2015; Sahani et al., 2019; Vojinovic, 2015). EAD is a common indicator and has increasingly been applied to quantify flood risk (Alves et al., 2019; Klijn et al., 2015; Wagenaar et al., 2019). EAD can be used to quantify the economic impact of potential hazards or risks, providing decision-makers with a clear and measurable understanding of the expected monetary losses on an annual basis.

To quantify EAD, flood damage should be calculated, ideally using a

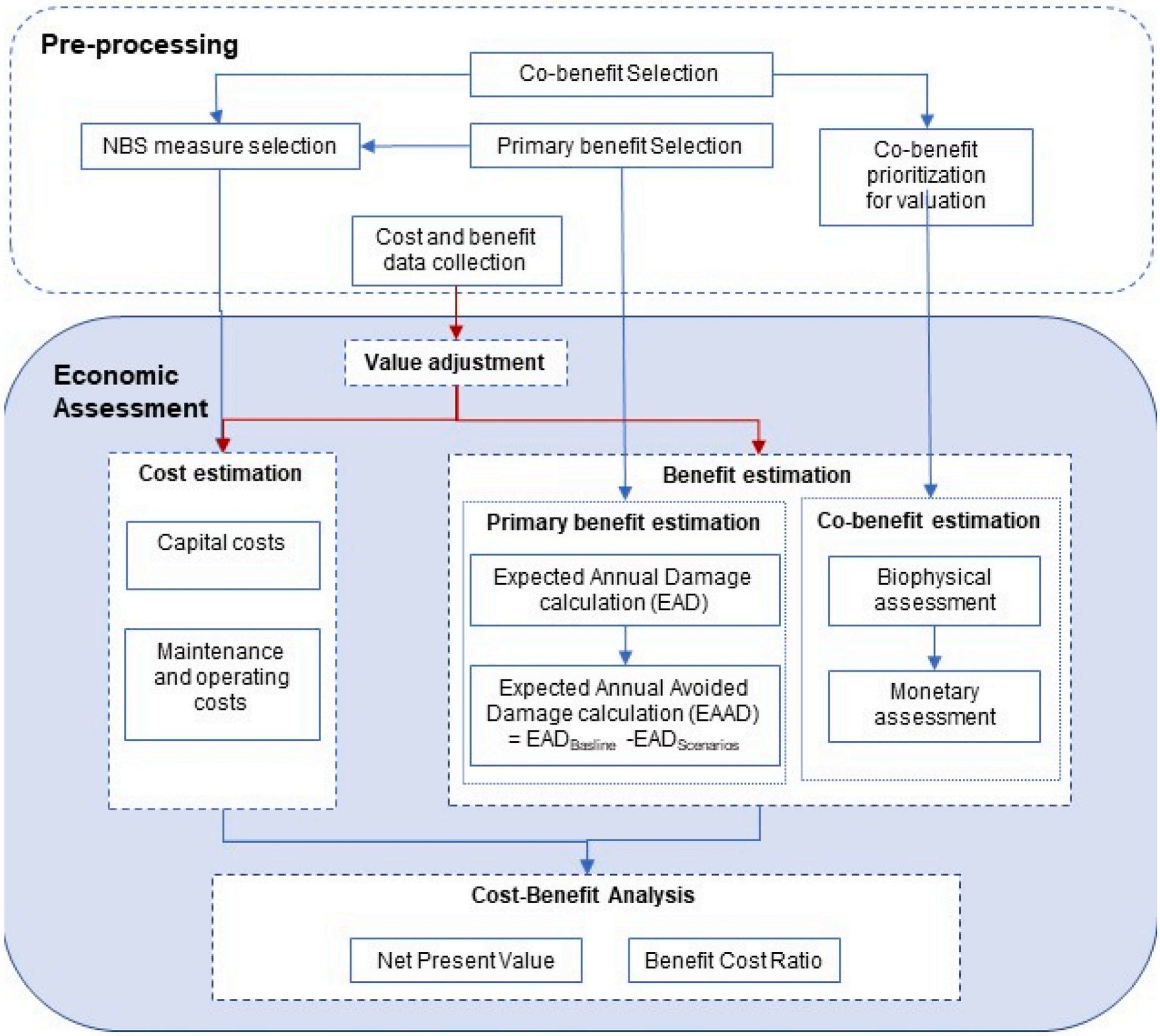

Fig. 1. Overall methodology for economic assessment of Nature-Based Solutions for flood risk reduction and co-benefits.

hydrodynamic model and damage curve. Hydrodynamic models such as HEC-RAS, MIKE, LISFLOOD and others provide flood characteristics such as the extent of the affected area, velocities, and depths. For an in-depth exploration of hydrodynamic models, a comprehensive review is available in Jodhani et al. (2023).

Furthermore, the damage data caused by these floods can be derived from functions that establish the relationship between flood depth and damage for different types of assets, i.e. depth-damage curves. One well-established source for such depth-damage data is the publication titled "Global Flood Depth-Damage Functions: Methodology and the Database with Guidelines" by Huizinga et al. (2017) whereas issues concerning 1D and 2D models for estimation of hazards and damages can be found in Vojinovic and Tutulic (2009). Also, issues concerning terrain data collection and processing (e.g., filtering) for the purpose of mapping hazards can be found in Abdullah et al. (2011a, 2011b).

The EAD for a specific year is calculated by integrating the exceedance probability of expected flood damage cost per year for all possible flooding events (Delelegn et al., 2011). This calculation considers the likelihood of different flood scenarios and their associated costs, providing valuable insights into the expected annual impact of flooding (Equation (1)):

$$\text{EAD} = \int_{f=0}^{\infty} \text{Damage}(z_f)\,df \qquad \text{Equation 1}$$

where f is frequency of occurrence (inverse of return period), and Damage is the flood damage due to the flood level z_f corresponding to the event frequency f.

Under the assumption that it is a continuous function of the return period, Equation (2) can be used to calculate EAD (Delelegn et al., 2011):

$$\text{EAD} = \sum_{i=1}^{n}\left(\frac{\text{Damage}_{i+1} + \text{Damage}_i}{2} \times \left(\frac{1}{R_i} - \frac{1}{R_{i+1}}\right)\right) \qquad \text{Equation 2}$$

where Damage_i is the flood damage corresponding to return period event R_i (Euro), and n is the number of return periods considered.

After calculating EAD, the Expected Annual Avoided Damage (EAAD) can be calculated by comparing the EAD values before and after implementing these measures. EAAD serves as a meaningful indicator to assess the effectiveness of measures implemented for risk reduction.

2.4. Co-benefits estimation

In addition to flood risk reduction estimation, co-benefits of NBS are also estimated in this research to provide additional benefits beyond flood risk reduction. Incorporating co-benefits into NBS planning and implementation provides a holistic approach to addressing flood risk and broader socio-environmental challenges.

Estimating the co-benefits of NBS involves a systematic assessment of the potential positive outcomes that arise from their implementation. Fig. 2 shows the conceptual framework to estimate the value of co-benefits used in this research, adapted from Hérivaux et al. (2019). The first step is to identify the relevant co-benefits specific to the case study. In this research, a multi-criteria analysis framework developed by Ruangpan et al. (2020b) was employed to select the preferable co-benefits. In this framework, various co-benefits are included such as improved water quality, change in habitat area, increase in green space, carbon sequestration and biological control. Since not all the co-benefits can be quantified in monetary terms, it is necessary to prioritise them for valuation purposes.

The next step involves characterising the relationships between NBS measures and co-benefits (i.e., changes in the environmental condition and benefits). This can be achieved by assessing biophysical indicators, such as water storage expressed in m^3/year or habitat creation expressed in m^2.

Once the change in biophysical indicators is identified, various valuation methods can be applied. Several methods are available for valuating co-benefits of NBSs, such as market value, avoided damages, travel cost method, replacement cost method, contingent valuation and contingent choice benefits (value), and transfer methods. A comprehensive overview of these valuation methods can be found in Brander (2014) and Dominati et al. (2014). The selection of suitable economic valuation methods for the co-benefits associated with NBS should align with the specific characteristics and objectives of the assessment. Practical considerations include:

- When co-benefits possess clear market value or can be traded in existing markets, the market value method can be used. This approach is apt for valuing co-benefits such as increased agricultural productivity, carbon sequestration prices, and the creation of green jobs.
- When co-benefit values are contingent on resources not traded in traditional markets, revealed preference methods like the travel cost method, hedonic pricing, and averting behavior can be employed. These methods are particularly valuable for assessing co-benefits associated with activities like educational trips, recreational visits, and increase in property values.
- When co-benefits are contingent on individuals' willingness to pay, contingent valuation methods can be applied. This approach allows for the valuation of co-benefits where individuals express their willingness to pay for non-market benefits, such as change in erosion, or visiting the NBS site.
- When co-benefits involve the replacement cost of resources, methods like replacement costs can be utilised. This method is particularly valuable for assessing co-benefits associated with activities like habitat creation
- When assessing co-benefits related to risk reduction and damage prevention, the avoided damage cost method can be used.

The monetary value of co-benefits can be calculated based upon the availability of specific input data and the unique attributes of each co-benefits associated with each NBS measures. Equations (3)–(5) have been established to facilitate the calculation. Equation (3) can be applied when both biophysical assessments per area and corresponding price per unit per year are available. Equation (4) can be applied when biophysical assessments per area per year are available, alongside the corresponding prices per area. Equation (5) can be applied in scenarios where the monetary value of the co-benefits is only received at the moment of implementation. These equations collectively provide a flexible and context-sensitive means of assessing co-benefit monetary values.

$$CB_{monetary/year} = Biophysical_{assessment/unit} Unit \times Biophysical_{adjusted_{price}/unit/year} \quad \text{Equation 3}$$

$$CB_{monetary/year} = Biophysical_{assessment/unit/year} \times Unit \times Biophysical_{adjusted_{price}/unit} \quad \text{Equation 4}$$

$$CB_{monetary} = Biophysical_{assessment/unit} \times Unit \times Biophysical_{adjusted_{price}/unit} \quad \text{Equation 5}$$

where: CB is co-benefits, Unit is the potential benefits, which could be area, number of trees, number of NBS trips, etc.

2.5. *Adjusting value to different contexts*

Accounting for differences in characteristics between the study site and the policy site is challenging when conducting accurate and credible value transfers (Brander, 2014). The study site refers to a site elsewhere mentioned in the existing literature (i.e., reports, research articles), while the policy site refers to a current case study of interest. Considering the rarity of finding values that perfectly align with the specific context, it becomes necessary to adjust transferred values to reflect the unique characteristics of the policy site accurately. This research adapted two steps from Brander (2014) to address this challenge and enhance the accuracy of the transferred values.

Firstly, year of value and general price levels should be standardised. In most cases, values obtained from study sites differ from those applicable to policy sites due to variations in the years when the assessments were conducted. Therefore, when transferring values from a study site that were estimated for previous years, it is necessary to adjust historical values to the same base. The adjustment can be accomplished by using the available consumer price index (CPI), which measures an economy's annual rate of price change. CPI data is available from the World Bank World Development Indicators (World Bank, 2022). Equation (6) can be employed to standardise the general price levels and ensure

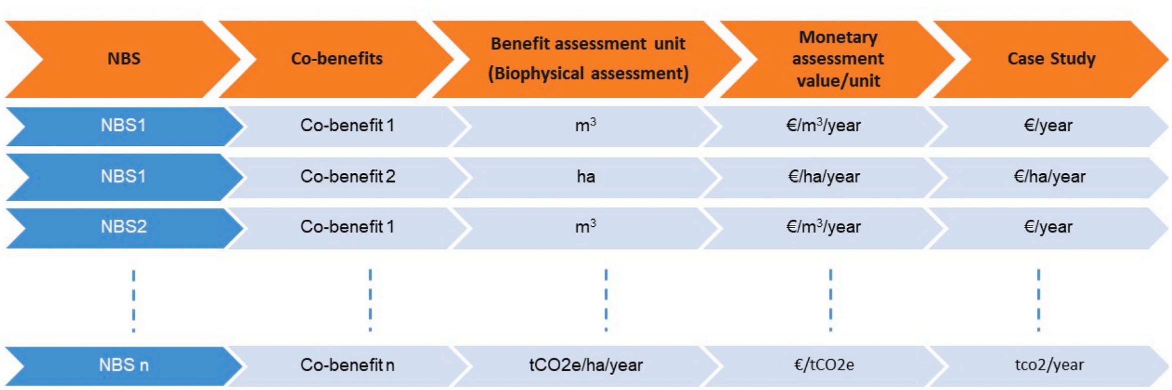

Fig. 2. The conceptual framework for estimating the value of co-benefits (adapted from Hérivaux et al. (2019)).

comparability.

$$\text{Value}_p = \text{Value}_s \text{ x } \frac{\text{CPI}_p}{\text{CPI}_s} \quad \text{Equation 6}$$

where: Value_p is value at the policy site, Value_s is value at the study site, CPIP = consumer price index for the year of the policy site assessment, CPIS is consumer price index for the year of the study site valuation.

Secondly, currency should be standardised when transferring values from a study site conducted in one country to a policy site in another country that used different currencies. This standardisation ensures that all the values are expressed in the same monetary unit to compare the cost and benefits. In this research, the currency is standardised into the EURO. The transfer of values between countries can be achieved by using exchange rates, as shown in Equation (7).

$$\text{Value}_p = \text{Value}_s \text{ x PPP} \quad \text{Equation 7}$$

where: value_p is value in currency of the policy site, value_s = value in currency of the study site, PPP is purchasing power parity adjusted exchange rate between policy and study site currencies.

2.6. Cost-benefit analysis

NBS measures are economically assessed through life-cycle cost-benefit analysis (LCCBA). LCCBA is the most widely applied approach as it involves evaluating values of benefits and costs over the project's lifespan, considering that the annual benefits and costs of NBS will continue into the future. LCCBA is well-suited for assessing NBSs because it acknowledges the multifaceted nature of these solutions and their long-term impacts. Moreover, NBS often has operating and maintenance costs, thus it is important to consider their life cycle in the analysis.

By thinking about how much future benefits are worth today, decision makers can compare benefits that are produced at various points in time. This process of converting the value of all future benefits into present terms is called discounting. Discounting requires carefully selecting a discount rate, which determines to what extent the value of future benefits will be reduced when translating them into present terms.

This study proposes the NPV and BCR as economic efficiency indicators to perform a cost-benefit analysis. In the context of co-benefits associated with NBSs, NPV and BCR help decision-makers weigh the economic advantages of projects that extend beyond their primary objectives. They provide a quantitative basis for assessing whether the inclusion of co-benefits enhances the overall economic efficiency and viability of NBS initiatives.

NPV represents the difference between the present value of all expected costs and benefits of the project over its lifetime. This can provide insight into the total net economic benefits that a measure generates in the long term. A positive NPV indicates that the project is expected to generate more benefits than costs and is considered financially favourable. Conversely, a negative NPV suggests that the project is likely to result in more costs than benefits. The NPV can be estimated by using Equation (8).

$$\text{NPV} = \sum_{t=0}^{T} \frac{(\text{EAD}_{t,ref} - \text{EAD}_{t,measures}) + \text{CB}_t}{(1+\text{dr})^t} - \left(\text{Cost}_{exp} + \sum_{t=0}^{T} \frac{\text{OM}_t}{(1+\text{dr})^t} \right) \text{ x optimal bias} \quad \text{Equation 8}$$

where $EAD_{t,ref}$ is the expected annual damage of baseline scenario in year t, $EAD_{t,\ measures}$ is the expected annual damage of implementing measures in year t, CB is the total co-benefits from implementing measures per year in year t, dr is the discount rate of future value, and the investment horizon is T year, $Cost_{cap}$ is the capital costs, and OM_t is the operation and management cost in year t.

Conversely, the BCR indicates the relative benefits generated per unit of investment. It is calculated by dividing the total present value of benefits by the total present value of costs, as in Equation (9):

$$\text{BCR} = \frac{\sum_{t=0}^{T} \frac{(\text{EAD}_{t,ref} - \text{EAD}_{t,measures}) + \text{CB}_t}{(1+\text{dr})^t}}{\left(\text{Cost}_{exp} + \sum_{t=0}^{T} \frac{\text{OM}_t}{(1+\text{dr})^t} \right) \text{ x optimal bias}} \quad \text{Equation 9}$$

where notation is the same as for Equation (8).

A BCR greater than 1 indicates that the project is expected to deliver more benefits than costs and is considered economically favourable. Conversely, a BCR of less than 1 suggests that the project's costs are expected to outweigh its benefits.

3. Case study

3.1. Description of the study area

The methodology used in this research builds upon work carried out by the EC-funded RECONECT project in the Tamnava River basin of Serbia. The Tamnava River basin is a tributary of the Kolubara River in the western part of Serbia, eventually flowing into the Danube. The three main rivers in the Tamnava River basin are Tamnava, Ub, and Gračica. The basin covers a total area of 726 km^2. With 79.3% of the total area, the predominant land-use in the river basin is agriculture, while urban and industrial land use is limited to small population centres, such as towns of Ub and Koceljeva, comprising only 1.2% of the area.

The Tamnava river basin is prone to torrential rainfall, particularly during May and July, and has experienced significant recent flooding in 1999, 2006, 2009 and 2014. The flooding that occurred between April and May 2014 was the worst experienced in the West Balkans region this century (Plavšić et al., 2014). This caused significant damage to people, housing and the environment, with losses estimated at over €1.5 billion. Consequently, many studies were initiated to improve the basin's resilience to flood hazards. The most important of these is by UNDP Serbia (2016), which attempts to comprehensively evaluate various proposed flood mitigation measures in the Kolubara watershed. Another study by, Pudar et al. (2020) investigated the benefits of implementing green and grey flood mitigation measures for the Tamnava river basin.

The present research uses part of the results from UNDP Serbia (2016) and Pudar et al. (2020), focusing on the Tamnava river basin as the starting point. The hydrodynamic model developed in the UNDP study is also incorporated into this research with improvements as described in Section 4.2.

3.2. Nature-based solutions measures and co-benefits selection

NBS measures and their benefits have been selected based on incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale NBS as proposed by Ruangpan et al. (2020a,b). This analysis involved considering local characteristics and incorporating stakeholders' preferences. The results of applying the method provide a ranking of applicable measures and the most preferable benefits. From this ranking, the top three measures were selected. Additionally, an extra measure, proposed by stakeholders, was included in the assessment process.

The location of measures has been analysed by using the planning and suitability assessment method developed by Mubeen et al. (2021). This method considers various factors to assess the suitability of different areas. By utilising this approach, the study identified locations for implementing the NBS measures.

The NBSs selected to reduce flood risk and enhance co-benefits analysed in this study include afforestation/reforestation, retention ponds, floodplain restoration, and removing obstructions (e.g. bridge). Removing obstructions is considered as a NBS because it allows the water to flow naturally without obstacles in the flow path. The descriptions of NBS measures are given in Table 1, and the locations of the measures are shown in Fig. 3.

Since not all co-benefits can easily be expressed in monetary terms, in this research priority is given to those that could be quantitatively assessed. These included carbon sequestration, biological control, habitat creation, air pollution reduction and education (through school nature trips). By assigning value to these co-benefits, it was possible to incorporate them into the economic assessment of the NBS measures.

4. Application to the case study

4.1. Cost estimation

The cost associated with the NBS strategies in this research is based on the concept of the LCC. It considers various cost components, including capital expenditures, and maintenance and operation expenditures. To estimate these costs, a literature review on unit costs was conducted, and values were transferred from other relevant studies. The unit cost information was sourced from studies such as Aerts (2018); Altamirano and de Rijke (2017); Ayres et al. (2014); NWRM (2015); World Bank (2021).

After reviewing the costs, they were adjusted for the Serbian context to the year 2022 as the base year to ensure consistency. Subsequently, each cost was transformed into unit costs in euro (€), such as €/m^3 for retention pond and €/m^2 for floodplain restoration, to standardise the cost assessment. Whenever several unit cost values are available, the average value is used. Finally, an optimal bias of 30% is used to account for unknown factors and uncertainties to ensure adequate project budgeting.

The values were verified with the stakeholders during the co-creation process. The summary of results, including the implementation cost and maintenance and operation costs per year, is presented in Table 2.

From Tables 2 and it can be seen that afforestation/reforestation has a relatively lower implementation costs compared to retention ponds and floodplain restoration, but the floodplain restoration has very low maintenance and operation costs. Removing obstructions has the lowest implementation cost, and no maintenance/operation costs.

4.2. Primary benefit estimation - expected annual avoided damage

The flood risk assessment was conducted by integrating water level results from a hydrodynamic model, exposure (land use) and vulnerability data (damage curves), and historical maximum damage data. The hydrological (HEC-HMS) and hydrodynamic (HEC-RAS) models used in this research are based on the model initially developed and calibrated by UNDP Serbia (2016) for studying an extreme flood event in May 2014. The original hydrodynamic model was one dimensional (1D), and used to simulate levee breaches, overtopping, and backwater effects during flood events in May 2014 (Pudar et al., 2020). The model was further developed and calibrated in this research to include 2D effects (1D-2D), thus enabling enhanced hydrodynamic simulations and flood inundation estimation for different scenarios.

Table 1
The description and size of selected NBS measures.

Measures	Description	Size of the measures
Afforestation/ reforestation	They are mostly located in the upper basin	• 1409.41 ha
Retention ponds	Large retention pond is located at the upstream part of Tamnava river and smaller retention pond is located at the upstream part of Gračica river.	• Total volume of 14,190,000 m^3 • Total area of 239 ha
Floodplain restoration – dike relocation	Dikes at section 7 are moved back for 30 m on each side of the river	• 4.074 km on the left bank • 3.927 km on the right bank • Total area of 24 ha
Removing obstructions	Reconstructing the bridge at 10 km around upstream from the downstream of Tamnava river	

The flood inundation outputs from the hydrodynamic simulation were converted into high-resolution water depth grids. These grids are based on the Light Detection and Ranging (LiDAR) sensing data with a 1-m resolution, to calculate the flood damage in the area.

After estimating flood inundation, the direct flood damage cost was calculated. The direct flood damage assessment used in this study relied on depth-damage functions (DDF) developed by Pudar et al. (2020). The direct flood damage included; physical damage to buildings (residential/public), physical damage to building contents and equipment, damage to crops, physical damage to roadway infrastructure, and losses related to temporary displacement of the affected population.

While direct losses capture the immediate physical damage caused by flooding, many researchers have recognised the importance of considering indirect losses to account for broader impacts and consequences. For example, Koks et al. (2015) showed that the expected annual damage of indirect losses is 65 percent of direct losses, Tanoue et al. (2020) estimated that the indirect economic loss of flooding in 2011 in Thailand is 70 percent of economic direct losses, Carrera et al. (2013) approximated indirect losses amount to around a fifth (19–22 percent) of the direct losses for the Po river and (Sieg et al., 2019) showed that the indirect economic impacts of a flood event in 2013 was 70%–90% of the direct economic impacts. These studies indicate that indirect impacts are highly variable and can almost be as large as direct. However, due to the lack of indirect damage data for the case study, this research estimated indirect economic losses based on the percentage of direct losses reported in those studies, which is 70%.

The calculation of total damage for different return periods under five scenarios is presented in Fig. 4. The results indicate that retention ponds provide the greatest damage reduction (about 20%) for all return periods except the 1000-year return, where the afforestation leads to lower damage. On the other hand, removing obstructions shows minimal difference in damage costs compared to baseline scenarios. A similar pattern can be observed for the floodplain restoration. However, floodplain restoration has a higher impact in reducing damage especially during larger flood events.

In Table 3 the calculated EAD and EAAD are provided for all of the above scenarios. As previously stated, the EAD represents the total cost of damage incurred due to flooding and is a crucial measure for assessing the potential impacts of flooding in the area. It is clear from both the damage calculation (Fig. 4) and the EAD values that the greatest benefits achieved in terms of reducing losses compared to the baseline scenario are obtained by the retention ponds, followed by afforestation/reforestation. The retention ponds have a value almost three times higher than afforestation/reforestation (Table 3).

4.3. Co-benefits estimation

Five co-benefits have been selected for the purpose of the co-benefit valuation in relation to NBS: carbon sequestration, biological control, habitat creation, air pollution reduction and education (NBS school trips).

Carbon sequestration refers to the process of capturing and storing carbon dioxide, leading to a reduction in social costs associated with carbon emissions. By implementing NBS, the need for costly carbon emission mitigation measures can be avoided, thereby providing a financial benefit. Biological control involves reducing the needs for interventions to restore and maintain the natural balance within ecosystems. This helps enhance the resilience and functionality of ecosystems, leading to potential cost savings in restoration efforts. The value of

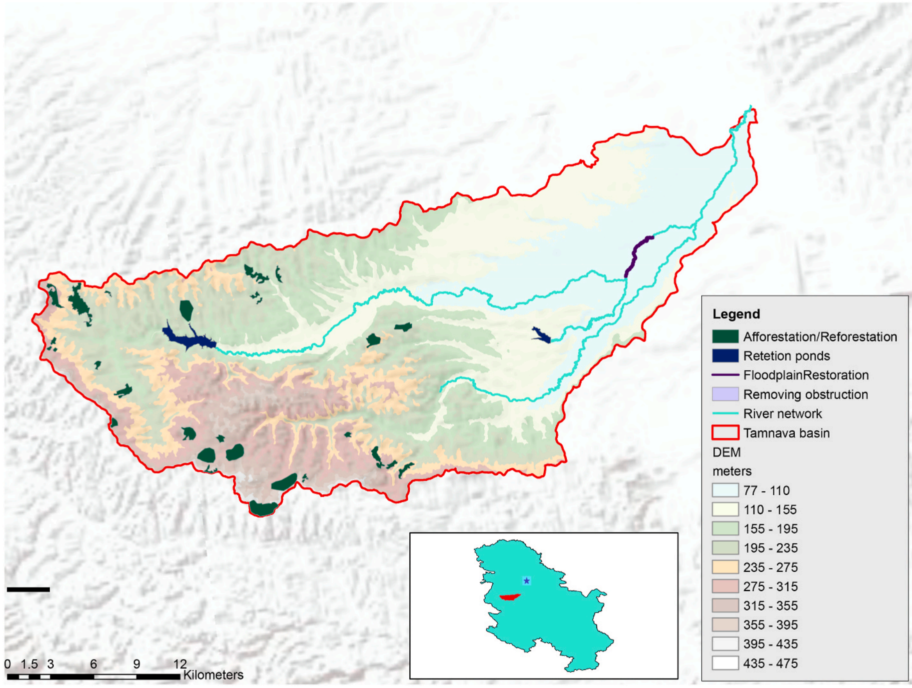

Fig. 3. Case study map with the locations of selected NBS.

Table 2
The implementation cost, maintenance and operation costs per year.

NBS measures	Implementation cost (million euro)	Maintenance and operation cost (million euro/year)
Afforestation/ reforestation	8.841	0. 242
Retention ponds	15.475	0. 471
Floodplain restoration	14.464	0.043
Removing obstruction	0. 217	–

habitat creation is derived from the avoided costs of establishing habitats for various forms of wildlife, including birds, mammals, fish, reptiles, and insects. By implementing NBS, which inherently creates or restores habitats, the expenses that would otherwise be incurred to establish these habitats can be avoided. Air pollution reduction is another co-benefit provided by NBS. A reduction in air pollution leads to potential health benefits and cost savings associated with healthcare and air pollution mitigation. Education, specifically through NBS school trips, is estimated from the cost that educational organisations pay to visit NBS sites, which becomes an economic benefit in society. These trips provide valuable educational experiences for students, fostering knowledge and awareness of NBS and their associated benefits.

To assess the economic value of the co-benefits associated with NBS, a

Table 3
Expected Annual Damage (EAD) and Expected Annual Avoided Damage (EAAD) for each scenario.

	EAD (million euro/year)	EAAD (million euro/year)
Baseline	4.325	–
Afforestation/ reforestation	3.838	0.488
Retention ponds	2.931	1.394
Floodplain restoration	4.228	0.097
Removing obstruction	4.320	0.005

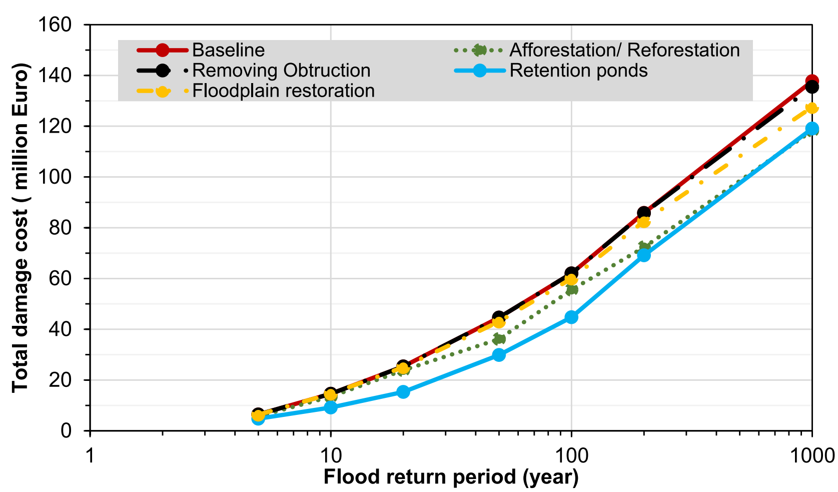

Fig. 4. An overview of total damage cost of various flood return period for baseline and four NBS measures.

comprehensive approach involving scientific research, modelling techniques, and data analysis is required. This process entails collecting diverse data and various methods to quantify both the biophysical indicators and the monetary value of the co-benefits. The relevant information and methodologies for this purpose were obtained through an extensive literature review, for which the details can be found in Table A1.

There are various valuation methods were used in this study to assess the economic impacts of NBS.; Firstly, the market value method was applied to quantify the economic value of carbon sequestration by using EU carbon permit prices as shown in Table A1. Secondly, the avoided damage method was employed for air pollution reduction and biological control. This damage value is based on the literature review to estimate the potential avoided damage to human health resulting from reduced air pollution and to biological from the biological control facilitated by NBS implementation. Thirdly, travel cost method was applied for Education (NBS trip) which involved estimating the monetary value based on the costs incurred for travel to NBS sites, enriching the understanding of the educational benefits associated with these visits. Lastly, replacement cost method was used for habitat creation, focusing on the costs associated with replacing or restoring damaged habitat area.

By employing a range of techniques and data sources, the evaluation allows for a comprehensive understanding of the potential impacts and economic value associated with implementing NBS. The valuation results of co-benefits for each scenario have been calculated using Equations (3)–(5), and are shown in Table 4.

These results show the contribution of each NBS measure to each co-benefit. In term of the benefits per year among these measures, afforestation/reforestation has the highest annual value (€2.62 million) in terms of overall benefits apart from habitat creation. However, when considering the first year alone, retention ponds provide a higher benefit amounting to €11 million, due to the immediate habitat creation and the subsequent cost avoidance. While floodplain restoration shows a lower value compared to afforestation/reforestation and retention ponds, it still plays a significant role in providing co-benefits.

4.4. Cost-benefit analysis

The cost-benefit analysis provides the calculation of NPV and BCR for all measures, in terms of both the flood damage reduction benefit alone and the total benefit. The results of the CBA for a 30-year life cycle with 3% discount rate are presented in Fig. 5. The life-cycle and discount rate values are selected as they are recommended by the European Commission, (2021) for infrastructural projects with co-financing from different funds.

The NPV of the primary benefit (flood risk reduction) and the total cost is plotted for each measure with orange bars in Fig. 5a. The results show that all measures have negative NPV, meaning that the project is likely to result in more costs than benefits in terms of flood risk reduction alone. However, when the flood reduction is combined with co-benefits, the NPV becomes positive for afforestation/reforestation, retention basins as well as floodplain restoration (indicated by green hatched bars in Fig. 5a). This indicates that these measures can generate a positive financial impact when considering additional benefits to flood risk reduction. In contrast, the NPV remains negative for the measure of removing obstructions, indicating that it may result in financial losses even when considering all benefits.

Similarly, a BCR calculated based on flood damage reduction alone is less than one calculated for all types of measures. This suggests that when evaluating the project solely based on flood reduction, the costs are expected to outweigh the benefits. However, when the flood reduction is combined with co-benefits, the BCR is higher than 1 for all measures except removing obstruction as shown in the green hatched bars in Fig. 5b. This implies that when considering the additional benefits, these measures become more cost-effective. It is interesting to note that while the BCR of retention basin for flood risk reduction is almost double that of afforestation, the NPV between these two measures are relatively close because the capital costs for afforestation are higher. Such information is crucial for decision makers in implementing decisions that are both robust economically viable.

From the results, it can be seen that while retention basins may have a better economic impact when considering flood reduction alone, afforestation and reforestation has the highest economic impact when both flood risk reduction and co-benefits are considered.

The total value of benefits was analysed by breaking it down into individual benefits (Fig. 6). This breakdown shows how each benefit contributes to the total NPV value, facilitating a comparison with the associated costs. Although the primary benefits of implementing afforestation/reforestation and floodplain restoration is flood risk reduction, the air pollution reduction co-benefit provides more value. However, in the case the retention ponds, flood risk reduction remains the most relevant benefit. Other benefits, such as education and biological controls have relatively minor impact for all the measures.

4.5. Sensitivity analysis

A sensitivity analysis was performed to assess the impact of various parameters on NPV and BCR. This analysis involves changing discount rate and length of the life cycle to observe the corresponding changes to NPV and BCR. The results are shown in Fig. 7A for NPV and Fig. 7B for BCR, where the lines cover the ranges in which the results move when the parameters are changed. The sensitivity analysis was carried out separately for each parameter, examining the impact of discount rates of 0, 3, 5, and 7 percent (blue boxplot in Fig. 7) as well as life cycle durations of 30, 50, 100, and 200 years (grey boxplot in Fig. 7). The findings indicate that the discount rate has a more significant impact on NPV compared to life cycle years. The NPV demonstrates lower sensitivity than the BCR, except in the case of retention ponds. These results highlight the importance of the parameters in evaluating the economic viability of projects, especially the discount rate.

5. Discussion

The main objective of this research is to develop a comprehensive

Table 4
Monetary values of co-benefits for each scenario.

Co-benefits	Measures				Unit
	Afforestation/Reforestation	Retention ponds	floodplain restoration	Removing obstruction	
Carbon sequestration	83,461	75,073	11,680	–	euro/year
Biological control	46,228	50,649	–	–	euro/year
Habitat creation	8,126,566	11,404,997	41,053	–	euro
Air pollution reduction	1,510,324	–	1,153,288	–	euro/year
NO_2	726,271	–	90,081	–	euro/year
SO_2	298,627	–	31,113	–	euro/year
O_3	230,562	–	875,592	–	euro/year
PM-10	254,862	–	–	–	euro/year
PM-2.5	–	–	156,500	–	euro/year
Education (NBS trips)	62	62	62.47	–	euro/year

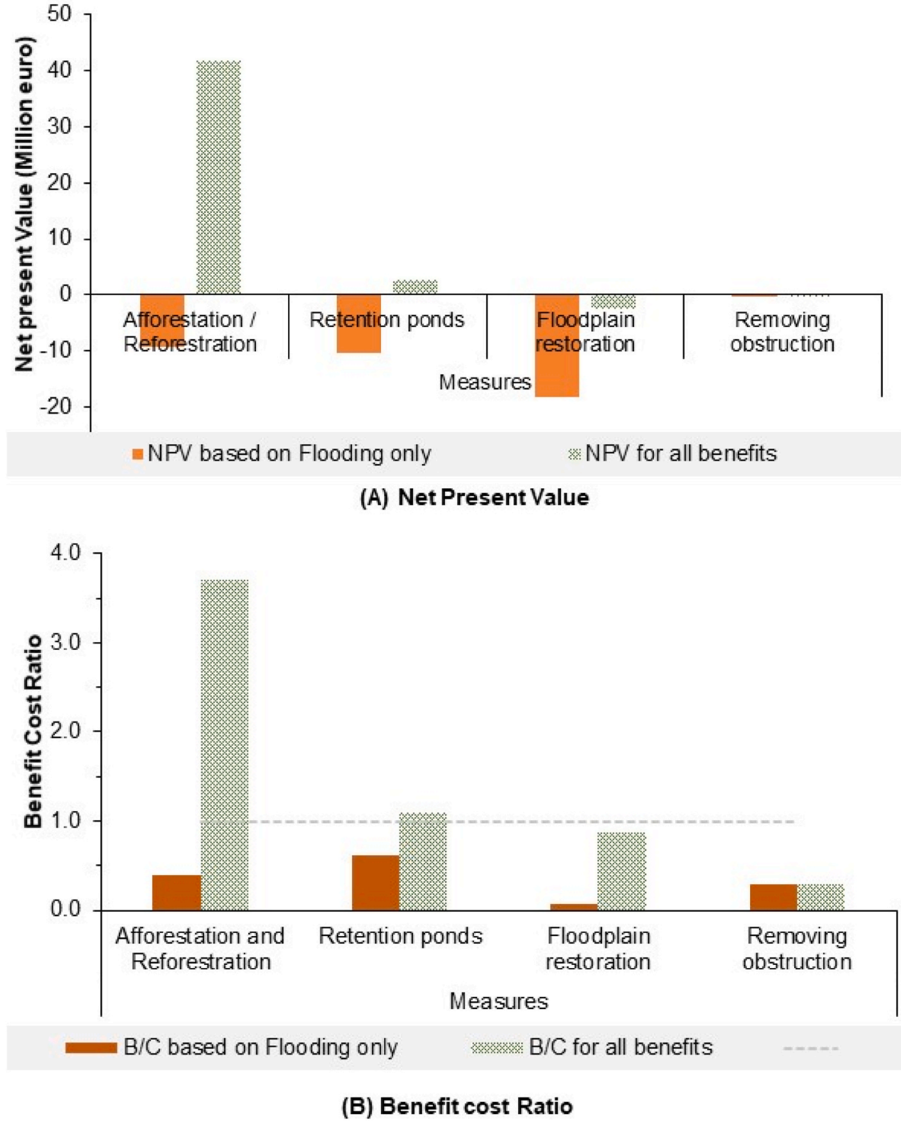

Fig. 5. Cost-Benefits analysis results of Net Present Value (A) and Benefit Cost Ratio (B) for 30-years life cycle with 3% discount rate.

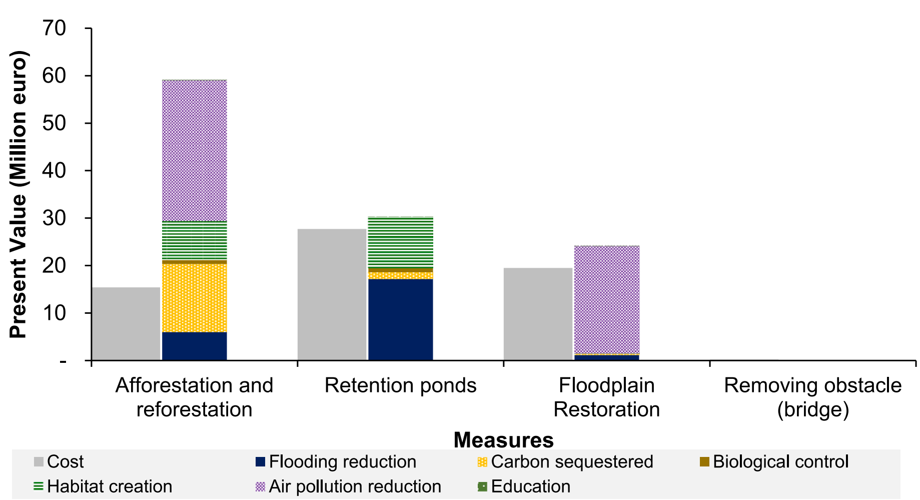

Fig. 6. Present value of costs and relevance of individual benefits for 30-years life cycle with 3% discount rate.

methodology for assessing the economic value of NBSs at the river basin scale. The methodology is based on a CBA incorporating NPV and BCR. To achieve this, the monetary analysis of flood risk reduction, co-benefits and the costs of NBS were estimated. CBA plays an important role in the decision-making process as it provides a formal structure and significantly enhances transparency (Kumar et al., 2021).

It is important to note that the cost and co-benefits values in this study are based on literature review and local data, while the flood risk reduction benefit was calculated using a hydraulic model and vulnerability data. Given limited local information, the study employs the value transfer method to estimate the cost and co-benefits by adjusting value to the local contexts. It is also important to note that the study does not attempt to provide precise costs and benefit values but rather presents a methodology that provides a systematic approach to enable a broader assessment of the economic value of NBS. As a result, it may not fully represent the potential costs, benefits, or uncertainties related to the specific NBS project and may introduce inaccuracies or biases in the economic evaluation. However, by adopting this approach, practitioners, researchers, and planners can have a more comprehensive understanding of the costs associated with implementing NBS and the potential benefits derived from their implementation.

Since not all benefits for all measures can be monetised for CBA (Van Zanten et al., 2023), this research focuses on four measures (afforestation/reforestation, retention basins, floodplain restoration, and removing obstruction) and five co-benefits (carbon sequestration, biological control, habitat creation, air pollution, and education). One of the limitations of economic assessment of NBS including co-benefits is the substantial effort required for quantifying the biophysical characteristics. Furthermore, the quantification of their monetary value necessitates advanced skills in environmental and societal economics.

In terms of flood risk reduction, the results show that measures implemented at the upstream part of the catchment, such as afforestation and reforestation, and retention basins, have a higher potential for avoiding flood damage. On the other hand, local measures like floodplain restoration and removing obstructions show minor differences in damage costs compared to the baseline scenario. One reason for this could be that damage calculation in this research encompasses the whole catchment, while rebuilding bridge or floodplain restoration are localised measures implemented at only one section of the river. Therefore, looking at the impact at a local scale or at the implementing locations may have more significant results for rebuilding bridge or many of these measures should be implement across the catchment.

Regarding co-benefit evaluation, several valuation techniques have been employed in conducting co-benefits estimation. For example, market value is used for carbon sequestration, avoided damages cost is used for air pollution reduction and biological control, travel cost

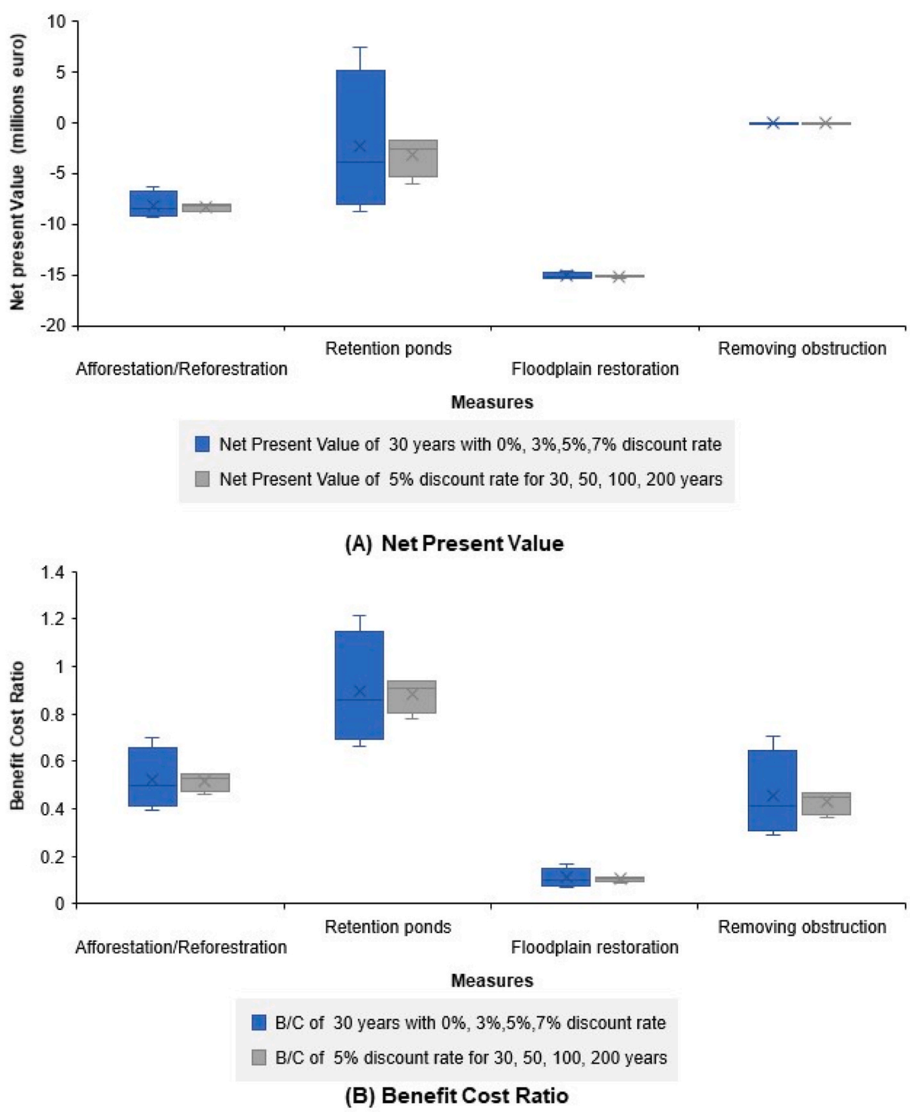

Fig. 7. Sensitivity analysis of cost-benefit analysis including Net present value (A) and Benefit Cost Ratio (B).

method is used for Education (NBS trip), and replacement method is used for habitat creation. Using these methods, floodplain restoration shows significantly lower co-benefits compared to afforestation and reforestation and retention basins. This disparity can be attributed to the smaller area involved in floodplain restoration projects. As floodplain restoration focuses on restoring specific areas of floodplains, the coverage is limited compared to the broader scale of afforestation and reforestation initiatives. Consequently, the smaller area impacted by floodplain restoration results in a reduced contribution to the overall co-benefits. In relation to co-benefits assessment, it is evident that various valuation techniques are required, due to the differences in the nature of each measure and the availability of data. Another reason is that some approaches like contingent valuation or choice experiments, necessitate the execution of surveys involving resident samples (Le Coent et al., 2023). While the valuation methods employed in this study offer valuable insights into the economic impacts of NBS, it is important to acknowledge their limitations. The market value method for carbon sequestration, relying on EU carbon permit prices, may oversimplify the dynamic nature of carbon markets, potentially neglecting regional variations and non-market values associated with carbon sequestration. The avoided damage method, while informative, relies heavily on literature reviews, introducing uncertainties and subjectivity in estimating avoided damages from air pollution and biological control. The travel cost method for NBS trip valuation may encounter challenges in accurately capturing the diverse and often intangible educational benefits associated with nature-based educational experiences. Finally, the replacement cost method for habitat creation might potentially overlook the intrinsic value and uniqueness of the process of habitat creation.

The CBA results indicate that when considering flood risk reduction alone, all the measures have a higher cost than benefit from flood damage reduction. However, when incorporating the co-benefits into the analysis, afforestation/reforestation, and retention ponds have positive NPV values and BCR, indicating potential financial gains and cost-effectiveness. Therefore, it is important to include co-benefits as it enhances the economic efficiency of NBS, as seen in results obtained by Alves et al. (2019) and Ossa-Moreno et al. (2017). The evaluation of NBS when co-benefits are included can help to improve the confidence and acceptance of NBS, potentially leading to policy changes in flood risk management. Similar conclusions were also found by Kumar et al. (2020).

The breakdown of the total value of benefits and the costs in Fig. 4 helps in understanding the contribution of NBS benefits, which can be used to inform decision-making processes and help prioritise NBS measures based on their potential benefits and costs. Moreover, the sensitivity analysis performed in the study highlights the importance of discount rates in evaluating the economic viability of projects. The findings indicate that the higher discount rate led to a lower economic impact.

In this study, only individual measures were considered for cost-benefit analysis as the aim of the research is to develop a methodology to include both flood risk reduction and co-benefits into the cost-benefits analysis. It is important to first have a methodology to assess the economic value for each measure. Future work should aim to compare NBS measures with traditional flood management measures and also optimise the combination of NBS measures or combination of NBS measures with traditional flood managements measures, in order to identify the most cost-effective scenarios. By analysing the potential synergies and interactions between different NBS measures, it is possible to identify optimal combinations that provide the greatest overall benefits and cost-effectiveness. Such an approach would enhance the practicality and applicability of NBS in real-world river basin management and decision-making processes.

6. Conclusion

This work provides a methodology to enhance traditional flood risk management by incorporating the monetary analysis of co-benefits into economic assessment of NBSs. The methodology employs life-cycle Cost-Benefits Analysis with key indicators like the Net Present Value (NPV) and Benefit Cost Ratio (BCR). In addition, this research introduces a conceptual framework for monetarily assessing NBS co-benefits and a methodology to enhance the accuracy of the economic assessment by adjusting site-specific. Standardisation techniques are employed to ensure comparability, including adjusting general price levels and currency exchange rates.

The methodology is applied to a case study, the Tamnava river basin in Serbia, where the costs and benefits are analysed with and without co-benefits. The findings show that when considering only the primary benefit (flood risk reduction), the project is expected to result in more costs than flood damage reduction, becoming economically inefficient. However, when the flood reduction is combined with co-benefits, certain measures can generate a positive financial impact.

These results emphasise the importance of incorporating co-benefits into the economic assessment to achieve economically viable implementations of NBS. Although the numerical results are context-specific to this case study, it is proposed that that the insights derived from the integration of co-benefits into economic assessments have broader and more generalisable implications. In essence, our research suggests that the integration of co-benefits into economic assessments has the capacity to significantly enhance the overall economic efficiency and viability of NBSs. The most important strength of the developed methodology is its potential for replication in other regions. It offers a systematic approach to evaluate NBS and therefore serves as a valuable tool for practitioners, researchers, and planners, enabling them to effectively integrate co-benefits into the economic assessment of flood risk reduction measures during the decision-making process. By utilising this methodology, decision-makers can make informed choices that maximise economic efficiency while addressing the multifaceted challenges of flood risk.

CRediT authorship contribution statement

Laddaporn Ruangpan: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Zoran Vojinovic:** Supervision, Visualization, Writing - review & editing. **Jasna Plavšić:** Conceptualization, Resources, Writing - review & editing. **Alex Curran:** Software, Writing - review & editing. **Nikola Rosic:** Software, Writing - review & editing. **Ranko Pudar:** Resources, Writing - review & editing. **Dragan Savic:** Writing - review & editing. **Damir Brdjanovic:** Writing - review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Co-benefits assessment matrix

No	Assessment matrix		Biophysical assessment Method			Estimate monetary value/unit			Case study metrics			
	Measures	Co-benefits	Calculation Source	Unit	Assessment method/value	Estimate source	Unit	Estimate price	Price for the case study	Unit	Biophysical assessment	unit
1	Afforestation and Reforestation	Carbon sequestration	WCC_carbonCalculation	tCO2e/ha/ year	Dynamic	Tradingeconomics (2023)	€/tCO2e	90.21	90.21	€/tCO2e	9251.8*	tco2/ year
2	Afforestation and Reforestation	Biological control	Pudar (2021)	ha	GIS approach	Pudar (2021)	€/ha/ year	32.8	32.8	€/ha/ year	1409.41	ha/year
3	Afforestation and Reforestation	Habitat creation	Environment Agency (2015)	ha	GIS approach	Environment Agency (2015)	£/ha/ year	245	465	€/ha/ year	1409.41	ha
4	Afforestation and Reforestation	Reduce air pollution										tonnes/ year
4.1	Afforestation and Reforestation	NO_2	CNT (2008)	lbs/tree/ year	1.1	(McPherson et al., 2006)	$/lb	3.34	2.28	€/kg	906	tonnes/ year
4.2	Afforestation and Reforestation	SO_2	CNT (2008)	lbs/tree/ year	0.69	(McPherson et al., 2006)	$/lb	2.06	1.41	€/kg	529	tonnes/ year
4.3	Afforestation and Reforestation	O_3	CNT (2008)	lbs/tree/ year	0.28	(McPherson et al., 2006)	$/lb	3.34	2.28	€/kg	214	tonnes/ year
4.4	Afforestation and Reforestation	PM-10	CNT (2008)		0.35	(McPherson et al., 2006)	$/lb	2.84	1.94	€/kg	268	tonnes/ year
5	Afforestation and Reforestation	Education	(Mourato et al., 2010)	No. NBS trips/year	2	(Mourato et al., 2010)	£/trip	18.71	18	€/trip	2	trips/ year
6	Retention ponds	Carbon sequestration	(Badiou et al., 2011)	tCO2e/ha/ year	3.21	Tradingeconomics (2023)	€/tCO2e	90.21	90.21	€/tCO2e	832.2	tco2 /year
7	Retention ponds	Biological control	Pudar (2021)	ha	GIS approach	Pudar (2021)	€/ha/ year	197.8	197.8	€/ha/ year	256.06	Ha/year
8	Retention ponds	Habitat creation	Environment Agency (2015)	ha	GIS approach	Environment Agency (2015)	£/har	1900	3610	€/ha	256.06	Ha
9	Retention ponds	Education	(Mourato et al., 2010)	No. NBS trips/year	2	(Mourato et al., 2010)	£/trip	18.71	18	€/trip	2	trips/ year
10	Floodplain restoration	Carbon sequestration	(Badiou et al., 2011)	tCO2e/ha/ year	8.3	Tradingeconomics (2023)	€/tCO2e	90.21	90.21	€/tCO2e	199.2	tco2/ year
11	Floodplain restoration	Biological control	Pudar (2021)	ha	GIS approach	Pudar (2021)	€/ha/ year	97.8	97.8	€/ha/ year	24	Ha
12	Floodplain restoration	Habitat creation	Environment Agency (2015)	ha	GIS approach	Environment Agency (2015)	£/ha/ year	70	140	€/ha/ year	24	Ha
13	Floodplain restoration	Reduce air pollution										tonnes/ year
13.1	Floodplain restoration	NO_2	(Gopalakrishnan et al., 2018)	g/m2/year	0.25	(McPherson et al., 2006)	€/tonne	7000	2.28	€/kg	60	tonnes/ year
13.2	Floodplain restoration	SO_2			0.14	(McPherson et al., 2006)		4000	1.41	€/kg	33.6	tonnes/ year
13.3	Floodplain restoration	O_3			2.43	(McPherson et al., 2006)		2400	2.28	€/kg	583	tonnes/ year
13.4	Floodplain restoration	PM-2.5			0.03	BeTa Version E1.02a in Netherlands year 2000		1800	3344.03	€/tonne	7.2	tonnes/ year
14	Floodplain restoration	Education	(Mourato et al., 2010)	No. NBS trips/year	2	(Mourato et al., 2010)	£/trip	18.71	18	€/trip	2	trips/ year

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