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Research paper

PERFORMANCE AND ECONOMIC VALUE OF NATURE-BASED SOLUTIONS FOR FLOOD RISK REDUCTION IN THE TAMNAVA RIVER BASIN

Jasna Plavšić[1], Ranko Pudar[2], Nikola Rosić[3], Andrijana Todorović[4], Filip Stanić[5], Laddaporn Ruangpan[6], Adam Mubeen[7], Jelena Kovačević Majkić[8], Vujica Šarenac[9]

Abstract

Flood risk management is evolving from sole reliance on traditional grey infrastructure towards nature-based solutions (NBS), which work with natural processes to reduce flood impacts while providing additional environmental and socio-economic benefits. However, we still lack evidence on their effectiveness and economic viability at the catchment scale. This paper presents an ex-ante assessment framework that integrates hydrological and hydrodynamic modelling with economic evaluation of flood damage reduction and selected co-benefits. The framework is applied to the Tamnava River basin using a coupled modelling chain (3DNet-Catch and HEC-RAS) to assess flood hazard, vulnerability and risk under three scenarios: a baseline or "do nothing" scenario, a grey scenario with retention ponds only, and a hybrid green-grey scenario combining retention ponds with afforestation, floodplain restoration, riparian buffer strips and removal of flow obstacles. Flood risk reduction is evaluated for design floods with return periods from 5 to 1000 years using high-resolution, micro-scale hazard and risk mapping. Economic performance is assessed through expected avoided annual damage and a life-cycle cost-benefit analysis including monetised co-benefits. The results show that retention ponds dominate in peak attenuation for extreme floods, while NBS enhance risk reduction for low- and medium-magnitude events. The hybrid scenario proves to be cost-effective when co-benefits are included, highlighting the importance of multi-benefit evaluation of flood mitigation measures.

Key words: *flood risk assessment, hybrid infrastructure, cost-benefit analysis, co-benefits*

[1] PhD, Full Professor, Faculty of Civil Engineering, University of Belgrade, Serbia, jplavsic@grf.bg.ac.rs, ORCid 0000-0001-9679-8851
[2] PhD, Pudar Mitigation Consulting, Inc., USA, ranko_pudar@pudarconsulting.com, ORCid 0000-0001-6781-1762
[3] Associate Professor, Faculty of Civil Engineering, University of Belgrade, Serbia, nrosic@grf.bg.ac.rs, ORCid 0000-0002-1001-9739
[4] Associate Professor,Faculty of Civil Engineering, University of Belgrade, Serbia, atodorovic@grf.bg.ac.rs, ORCid 0000-0003-0271-5993
[5] Associate Professor, Faculty of Civil Engineering, University of Belgrade, Serbia, fstanic@grf.bg.ac.rs, ORCid 0000-0002-7803-0600
[6] PhD, Deltares, The Netherlands, milk.ruangpan@deltares.nl, ORCid 0000-0003-1934-6813
[7] PhD Student, Delft University of Technology and IHE Delft Institute for Water Education, The Netherlands, a.mubeen@tudelft.nl, ORCid 0000-0003-2411-6166
[8] PhD, Research Associate, Serbian Academy of Sciences and Arts, Geographical Institute "Jovan Cvijić", Serbia, j.kovacevic@gi.sanu.ac.rs, ORCid 0000-0003-2411-6166
[9] MSc, Lead Engineer, IWA Consult d.o.o., Serbia, vujica.sarenac@iwa-cons.com, ORCid -

1. INTRODUCTION

In response to the increasing frequency and intensity of extreme weather events caused by climate change, nature-based solutions (NBS) are introduced as a paradigm shift away from sole reliance on traditional grey infrastructure [1]. NBS are defined as actions to protect, sustainably manage, and restore natural or modified ecosystems to address societal challenges effectively and adaptively [2] [3]. The main advantage of NBS is their multi-functionality. Unlike grey infrastructure, NBS provide a range of co-benefits such as carbon sequestration, biodiversity enhancement, improved water quality, and socio-economic opportunities like recreation, public health improvements, and green job creation.

In flood- prone rural catchments, large-scale NBS offer a promising complementary or alternative strategy. The effectiveness of large-scale NBS in mitigating floods is increasingly supported by scientific evidence, which shows that NBS performance is highly sensitive to watershed scale, flood intensity and type of intervention [4]. On the other hand, widespread implementation of NBS is often hindered by a lack of evidence regarding their long-term economic viability, which would aid the decision-makers in comparing investment alternatives [3][5]. Traditional assessments often focus narrowly on expected annual damage (EAD) reduction, which can lead to the conclusion that NBS are economically inefficient, and neglect the co-benefits of NBS [6]. Recent reviews indicate that NBS can be as effective as grey solutions, with many studies finding them consistently more cost-effective when the full suite of co-benefits is considered [3] [7]. When co-benefits are integrated into a life-cycle cost-benefit analysis (CBA), interventions such as afforestation and retention ponds frequently demonstrate positive net economic impacts [6]. Furthermore, a social CBA perspective is essential to capture the value of these investments for the broader community, including environmental and social impacts that extend beyond direct economic effects [8][9][3].

Building a compelling business case for investors and policymakers in new NBS projects requires a rigorous ex-ante assessment. However, ex-ante planning typically faces problems such as a lack of baseline data for evaluating benefits and a lack of standardised methods for monetary valuation, particularly for integrating intangible social and ecological outcomes. The methods applied therefore range from rapid assessments using the value transfer approach to high-resolution probabilistic risk modelling.

This paper presents a methodological framework for the ex-ante assessment of NBS, focusing on combining performance modelling with monetary evaluation of both primary risk reduction benefits and a set of co-benefits. Using the Tamnava River basin as a case study, the paper investigates whether the existing grey measures can be effectively complemented by NBS to reduce flood risk, improve ecosystem services and achieve economic viability. Specifically, the paper aims to (i) assess flood risk under current conditions and alternative intervention scenarios and quantify the effectiveness of these intervention strategies, (ii) evaluate primary benefits and selected environmental and social co-benefits, and (iii) assess economic feasibility through cost-benefit analysis. Overall, the paper aims to provide a systematic roadmap for practitioners to identify, predict, and value the multiple benefits of NBS for flood risk

reduction in similar projects. Such a holistic approach is expected to support broader integration of NBS into climate resilience and sustainable development strategies.

2. DATA AND METHODS

2.1. Study area

The Tamnava River is a 78.5 km long left tributary of the Kolubara River (Figure 1), draining a catchment area of 726 km². Elevations range from about 470 m above sea level in the upper basin to 64 m at the confluence with the Kolubara. Agricultural land dominates the basin (around 79%), primarily located in wide alluvial floodplains along the Tamnava and its major tributaries, the Ub and Gračica rivers. Urban land cover is limited (around 1.2%) and concentrated in the towns of Ub and Koceljeva.

The hydroclimatic regime in the catchment is characterised by strong seasonality. High flows typically occur in early spring due to combined rainfall and snowmelt, and in early summer as a result of intense convective storms. Streamflow measurements from three gauging stations show modest mean annual discharges but very high peak flows during extreme events, underscoring the basin's flash- flood character and its sensitivity to short- duration rainfall.

Frequent flooding is therefore the primary hazard affecting the Tamnava River basin. The most catastrophic event occurred in May 2014, while other significant floods were recorded in 1999, 2006, 2009, 2021, and 2023. Since Tamnava is one of the downstreammost tributaries of the Kolubara River, attenuation of flood peaks within its basin is crucial for reducing flood risk further downstream, particularly at the town of Obrenovac at the confluence with the Sava River.

Existing flood protection in the basin relies mainly on embankments near populated areas and the Gračica-Ub bypass channel. Following the May 2014 floods, three large retention ponds were planned by Serbian water authorities [10].

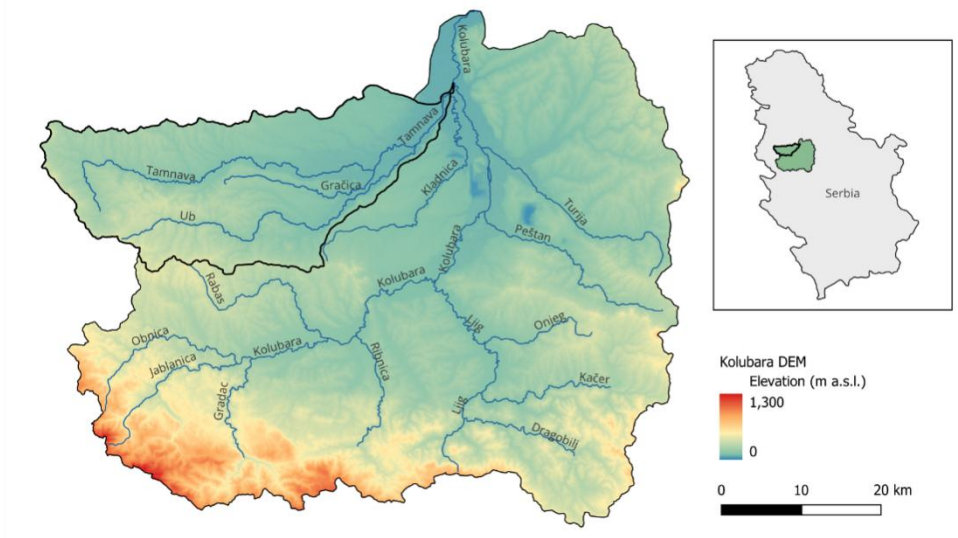


Figure 1. The Tamnava River basin delineated within the Kolubara River basin

2.2. Mitigation scenarios

Suitable flood mitigation interventions were selected using the Measure Selector Tool and the GIS-based NBS spatial suitability tool developed within the RECONECT project [11][12][13][14], previous studies [15][16], field inspections and stakeholder consultations [17]. The final set of measures includes (Figure 2):

- Retention ponds, already planned in spatial planning documents;
- Afforestation and reforestation, primarily in upper catchment areas;
- Floodplain restoration, focused on reconnecting abandoned or disconnected floodplain areas;
- Buffer strips along selected river reaches to increase hydraulic roughness and enhance retention;
- Removal of flow obstacles, especially road embankments and bridge constrictions, identified during field surveys.

Three mitigation scenarios were analysed for design floods with return periods ranging from 5 to 1000 years:

- S0 – Baseline or "do nothing" scenario: current setup of flood defences with no additional measures implemented;
- S1 – Hybrid green-grey scenario: retention ponds combined with all selected NBS;
- S2 – Grey scenario: retention ponds implemented as a stand-alone measure.

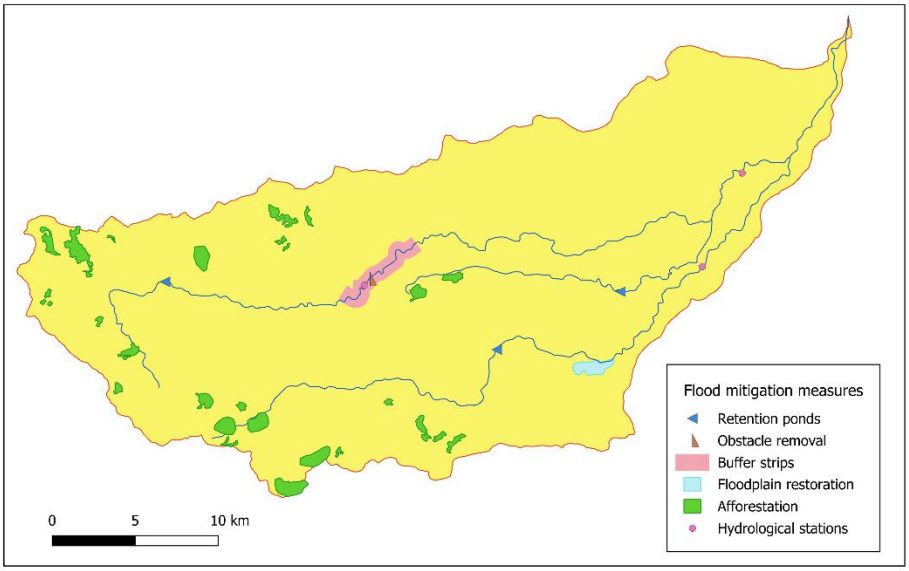


Figure 2. Planned flood mitigation measures in the Tamnava River basin

2.3. Hydrological and hydrodynamic modelling

Flood hazard was assessed using a modelling chain combining a semi-distributed hydrological model (3DNet-Catch [18]) and a coupled 1D-2D hydrodynamic model (HEC-RAS [19]). The hydrological model simulates runoff generation in 21 sub-basins in hourly time steps, while the hydrodynamic model computes flood wave propagation

and inundation across river channels and floodplains. Figure 3 shows the computational domain of the hydrodynamic model.

Both models were calibrated and validated against the observed flood events, including the extreme flood of May 2014 and more recent events, showing good reproduction of observed discharges, water levels, and inundation extents (see Figure 4). In calibration, the hydrological model achieved Nash–Sutcliffe efficiency (NSE) ranging from 0.64 to 0.85 and relative runoff volume bias from −0.9% to 17.6% across the gauging stations. In validation, NSE ranged from 0.50 to 0.89, and the volume bias from −21.2% to 24.3%.

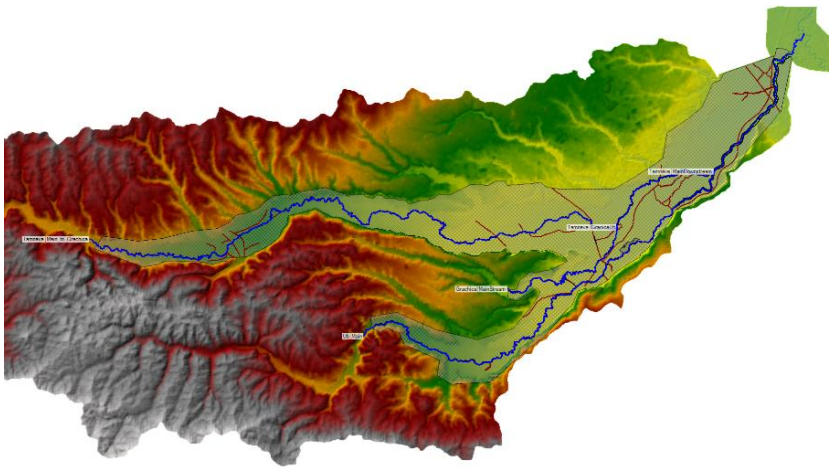


Figure 3. Computational domain of the HEC-RAS hydrodynamical model of the Tamnava River basin

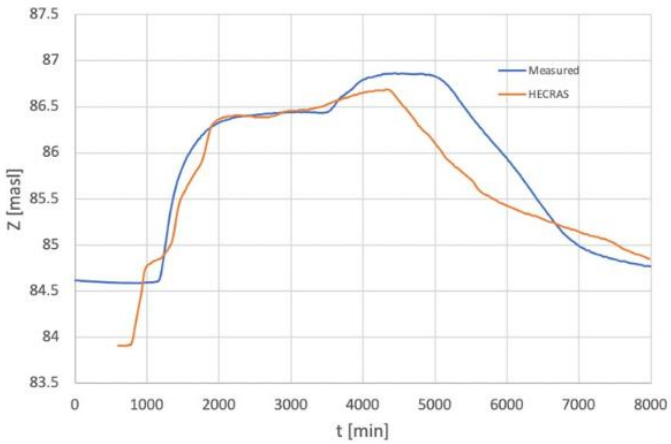


Figure 4. Simulated vs. observed stage hydrograph at Ćemanov most during the June 2020 flood

2.4. Hazard, vulnerability and risk assessment

Flood hazard maps were generated as raster layers of maximum water depth for each scenario and return period. Flood hazard was classified by water depth into four hazard classes following the national regulation [20], ranging from low hazard when water depth is less than 0.5 m, moderate between 0.5 m and 1.5 m, high between 1.5 m and 4 m, and very high (extreme) when it exceeds 4 m.

Vulnerability was assessed using an index-based approach that combines physical, economic, environmental, social, and institutional indicators. Flood risk was then calculated as the product of normalised hazard and vulnerability, resulting in spatially explicit risk maps. The effectiveness of alternative mitigation scenarios in reducing flood risk relative to the baseline was measured by the Flood Risk Reduction Index (FRRI), an index computed by comparing risk classes in each pixel of the flooded area [21].

2.5. Benefit and cost assessment

Primary benefits were quantified as expected avoided annual damage (EAAD), computed using a micro-scale GIS-based damage model [15] (Figure 5). Damages were estimated for buildings, crops, transport infrastructure, and the temporarily displaced population. Selected co-benefits of NBS were monetised using value transfer methods, including carbon sequestration, habitat creation, air quality improvement, and educational value [6]. The cost-benefit analysis was carried out over a 30-year time horizon using a 5% discount rate.

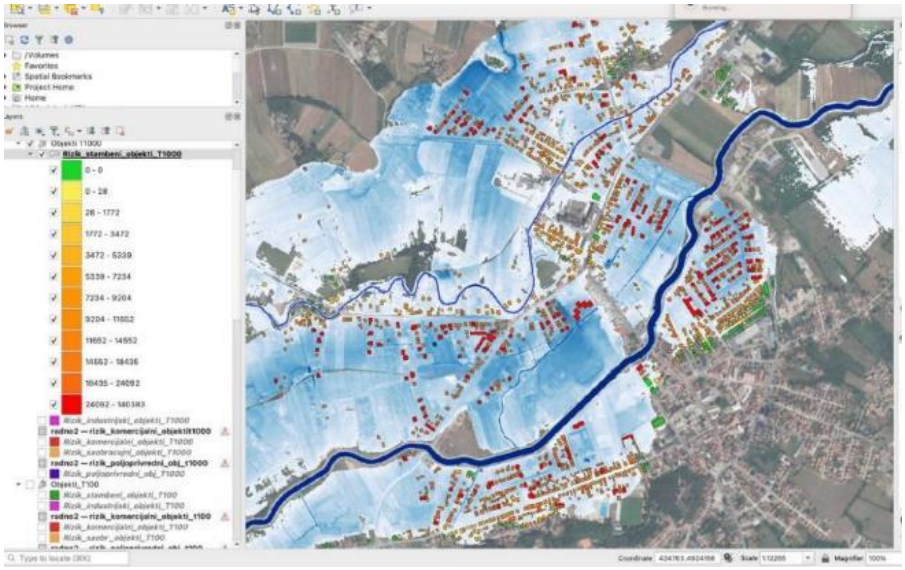


Figure 5. GIS-based micro-scale assessment of damages.

3. RESULTS

3.1. Flood hazard and risk reduction

Both intervention scenarios reduce flood peaks and flood extents relative to the baseline for all considered flood probabilities. This is illustrated in Figure 6, which shows flood hazard maps for the area near the town of Ub during the 1000-year design flood. The scenarios perform similarly because retention ponds play a dominant role in attenuating high-magnitude floods, reducing peak flows by up to 25% during extreme events. NBS included in S1 further enhance flood risk reduction for lower-magnitude floods by increasing catchment retention and floodplain storage.



Figure 6. Flood hazard near the town of Ub for the 1000-year flood for scenarios S0, S1, and S2.

Figure 7 shows the composite risk maps for the whole Tamnava basin from the 100-year design flood, shown in four classes from low to very high risk. Reduction of the flood risk is especially visible in the populated areas of Koceljeva and Ub for both mitigation scenarios. Computation of FRRI provides a more precise evaluation of flood risk reduction (Table 1). FRRI results show that both S1 and S2 reduce overall flood risk across all return periods. The hybrid scenario S1 performs better for low- to- moderate floods and for environmental and physical vulnerability components, while differences between S1 and S2 diminish for the most extreme floods.

Table 1. Flood risk reduction index for three characteristic return periods.

Mitigation scenario	Return period		
	20 yr	100 yr	500 yr
Scenario S1 (hybrid grey-green – all measures)	0.054	0.065	0.081
Scenario S2 (grey – retention ponds only)	0.051	0.068	0.079

3.2. Economic performance

Expected annual damage (EAD) under the baseline scenario S0 is estimated at approximately €1.9 million. Both S1 and S2 lead to substantial reductions, with EAD decreasing to 62% and 66% of the baseline EAD under S1 and S2, respectively. However, avoided damages alone are insufficient to justify investments in large retention ponds.

Table 2 shows the costs and benefits broken down into the primary benefit of avoided damage and co-benefits. When co- benefits are included, the economic performance changes markedly for both scenarios. Scenario S1 achieves a benefit-cost ratio (BCR) greater than one, indicating overall cost- effectiveness over the project lifetime. In contrast, BCR for retention ponds alone (S2) remains lower than 1 even when co- benefits are considered.

Table 2. Results of the cost-benefit analysis over a 30-year time horizon.

Present values (million EUR)	Benefit from avoided damage only		With co-benefits	
	Scenario S1	Scenario S2	Scenario S1	Scenario S2
Costs	48.1	35.5	48.1	35.5
Benefit from avoided damage	12.3	11.0	12.3	11.0
Co-benefits			58.3	15.1
Total benefits	12.3	11.0	70.7	26.0
Benefit-cost ratio	0.26	0.31	1.47	0.73

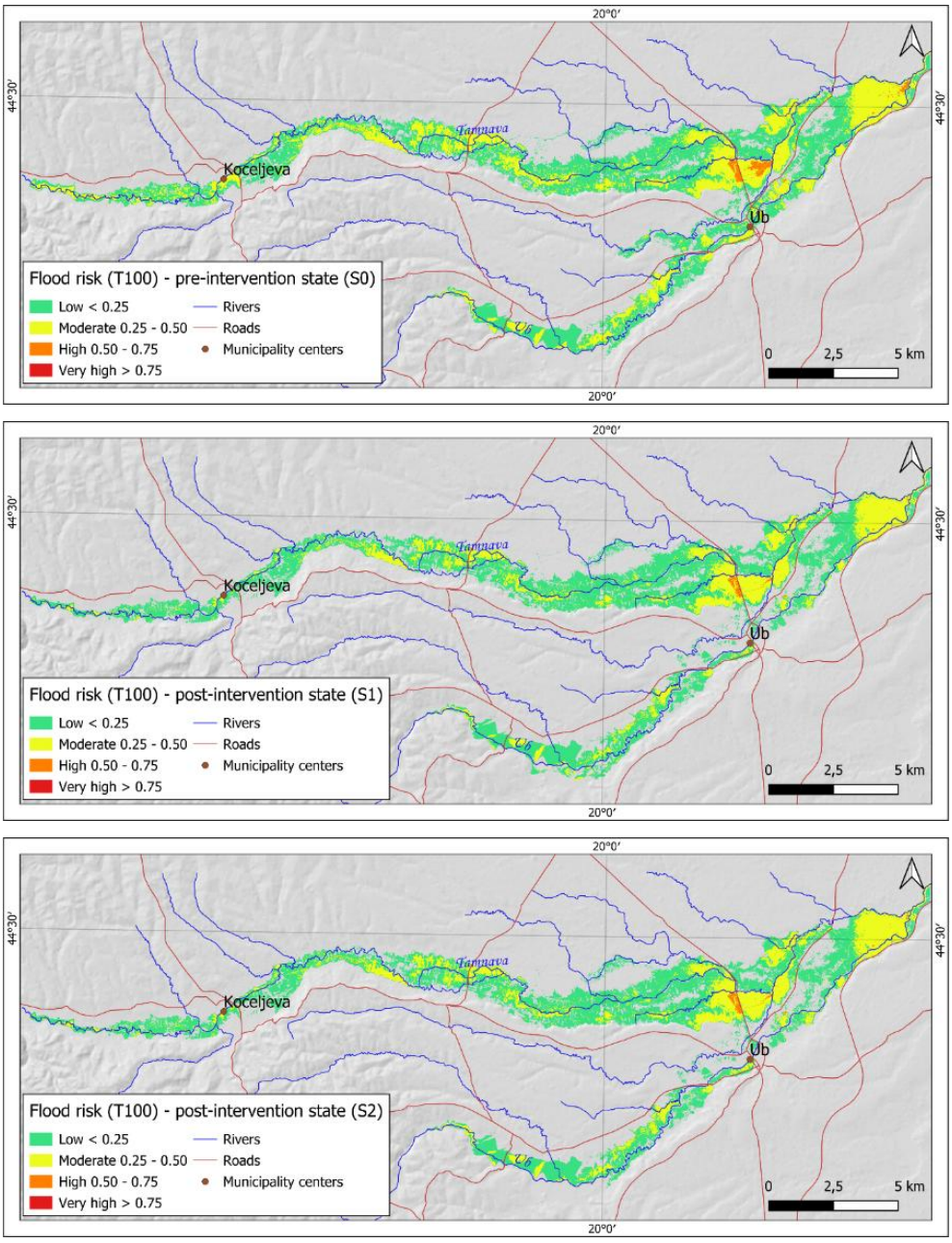


Figure 7. Risk maps of the Tamnava River basin for the 100-year flood under scenarios S0, S1, and S2.

4. CONCLUSIONS

This study highlights the importance of adopting a holistic, multi-benefit perspective in flood risk management. While large grey measures are necessary for controlling extreme floods, NBS provide additional benefits that improve economic efficiency and provide significant environmental advantages. The Tamnava case study

demonstrates that hybrid green-grey solutions can outperform purely grey approaches, especially when evaluated over broader benefit categories, and can therefore enhance project feasibility. Key conclusions include:

- Retention ponds are effective in reducing flood peaks, especially for extreme events, but are not cost-effective as stand-alone measures;
- NBS such as afforestation, floodplain restoration, and buffer strips provide additional risk reduction and substantial environmental co-benefits;
- Accounting for co-benefits is crucial for demonstrating the economic viability of hybrid flood management strategies;
- A multidisciplinary, stakeholder-engaged approach is essential for successful NBS implementation.

These findings provide quantitative evidence supporting the mainstreaming of nature-based solutions as integral components of flood risk management under both engineering and socio-economic criteria. The results may encourage wider adoption of such strategies in similar rural catchments across Southeast Europe and beyond. The integrated modelling framework and evaluation approach presented in this paper provide a sound basis for decision-making under current planning assumptions. However, uncertainties about future land-use changes and climate variability remain and highlight the need to integrate them into future feasibility assessments for long-term resilience planning.

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