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VALUATION OF FLUVIAL ECOSYSTEMS RESTORATION IN FUNCTION OF FLOOD RISK MITIGATION

Doctoral Dissertation

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ABSTRACT

Floods cause considerable damages worldwide, and mitigation of their adverse effects through increased flood resiliency is needed. This need is expressed in two ways: a need for a quantitative escalation, related to the challenging climate conditions; and a qualitative change, related to the transformation from passive flood defense to a concept of active, integrated flood risk management, including nature-based solutions (NBS).

This thesis develops a framework for an evaluation of different flood mitigation scenarios for small rural watersheds, through a comprehensive flood risk assessment of each option and their subsequent comparison. The flood mitigation scenarios generically include grey, green, and combined grey-green flood mitigation measures. The proposed framework also enables a quantification of the effects of nature-based flood mitigation measures on the natural capital. The methodology for evaluation comprises: (1) A spatial damage (risk) model based on combination of flood hazard and vulnerability assessments. The model can be characterized as a micro-scale flood damage model, because it uses high-resolution hazard map outputs from hydrodynamic modelling and fine-detail, multi-category assets data. The flood mitigation options are compared by calculating benefits as avoided damages and losses in comparison to the baseline conditions; (2) An improved estimate of the value of ecosystem services in the watershed by implementing NBS in site-specific settings. The proposed approach is based on the assessment of secondary benefits (or co-benefits) from implementing a flood mitigation measure and relating it to specific ecosystem service in the watershed. This approach allows an estimation of updated site-specific value of ecosystem services under a given flood mitigation scenario.

The proposed methodology is illustrated using a case study of the Tamnava River watershed in Serbia. Four scenarios are considered: (1) existing flood protection system; (2) grey infrastructure enhancement by raising the existing levees and diverting flood discharges; (3) green scenario involving new detention basins and limited counter-erosion measures; and (4) grey-green scenario that combines scenarios (2) and (3). The benefits (loss reduction) are the greatest with the combined grey-green scenario and marginally lower with the green scenario. The results suggest that for small rural watersheds, a holistic, integrative approach that includes both types of infrastructure can provide the most effective flood risk mitigation.

Implementation of mitigation scenarios comprising NBS provides additional long-term benefits, by increasing an overall watershed ecosystem value and bringing savings through reduced cost of repairs and maintenance of the alternative grey infrastructure. The high-resolution valuation of these benefits is made possible by annualized damage estimates from micro-scale modelling, whose framework fits seamlessly with the concept of ecosystem service annual valuations. For valuations of ecosystem services (ESS) in rural watersheds, the research focuses on a relatively small example (forestation of the Tamnava watershed headwaters). The derived result is a reliable, localized ESS value, related specifically to the control of erosion and overall restoration of the considered watershed. A higher-resolution analysis would be achievable with an addition of more asset categories and more quantifiable benefits, thus producing localized valuations for more eco-system functions.

The methodology presented in this thesis is a framework that can be applied to other rural, agricultural watersheds. The vulnerability functions for man-made and natural assets may be modified to better suite local conditions. The ESS value(s) derived and refined by this methodology are site- and region-specific and can be utilized for an improved initial valuation of the watersheds within the same geographic realm.

The analysis presented in this research indicates that inclusion of NBS through green mitigation scenarios in rural watersheds clearly demonstrates a high level of engineering and economic efficiency in reducing their flood hazards, and flood-related losses. In addition to inherently increasing flood resiliency of the rural watersheds, the application of NBS restores their fluvial eco-systems and increases their ecological valuation in long-term time horizons.

Keywords: flood risk; flood damage; flood mitigation measures; green infrastructure; nature-based solutions; micro-scale flood damage assessment; depth-damage functions; ecosystem services, rural watersheds

Research area: Civil engineering

Specific research area: Hydrology

Наслов докторске дисертације: ВРЕДНОВАЊЕ ОБНОВЕ РЕЧНИХ ЕКОЛОШКИХ СИСТЕМА У ФУНКЦИЈИ СМАЊЕЊА РИЗИКА ОД ПОПЛАВА

РЕЗИМЕ

Поплаве изазивају значајне штете у целом свету и стога је неопходно да се мере заштите од поплава усмере на повећање отпорности на њихова штетна дејства. Потребе за повећаним степеном заштите од поплава су двојаке: са једне стране, због изазова везаних за климатске варијације, неопходна је квантитативна ескалација у заштити од поплава; са друге стране, потребна је квалитативна промена кроз трансформацију од пасивне одбране од поплава до концепта активног и интегралног управљања ризиком од поплава, укључујући природи блиска решења.

У овој дисертацији је развијен методолошки оквир за вредновање различитих сценарија заштите од поплава на малим руралним сливовима кроз поступак процене ризика од поплава и компаративне анализе свих појединачних варијанти.. У предложеној методологији, генерички сценарији заштите од поплава обухватају сиве, зелене и сиво-зелене мере заштите. Овај методолошки оквир омогућава и квантификацију доприноса који мере засноване на природи блиским решењима имају за природни капитал. Методологија за вредновање обухвата: (1) Просторни модел штета (ризика) од поплава који се заснива на проценама угрожености и рањивости. Модел се може окарактерисати као микро-модел штета јер користи карте угрожености високе резолуције добијене хидрауличким моделима и детаљне податке о рецепторима ризика. Сценарији заштите од поплава се вреднују према користи (добити), које се одређују као штете и губици избегнути са мерама у разматраном сценарију у односу на штете у постојећем стању заштите. (2) Унапређену оцену локалне вредности екосистемских функција за разматрани слив услед примене природи блиских решења. Предложени приступ се заснива на процени секундарне користи од примењених мера заштите и повезивањем те користи са одређеним екосистемским функцијама на сливу. Овакав приступ омогућава да се добије ажурна локална вредност екосистемских функција за разматрани сценарио заштите.

Предложена методологија је илустрована на примеру слива реке Тамнаве. Разматрана су четири сценарија: (1) постојећи систем заштите, (2) сиве мере које се састоје од надвишења постојећих насипа и преусмеравања вишка великих вода у растеретни канал; (3) зелени сценарио који подразумева изградњу ретензија и пошумљавање узводних области, и (4) сиво-зелени сценарио који обухвата сценарије (2) и (3).

Сценарији заштите од поплава који укључују природи блиска решења доносе додатне дугорочне користи кроз повећање свеукупне вредности екосистема (тј.

природног капитала) на сливу, као и уштеде кроз смањене трошкове одржавања сиве инфраструктуре. Детаљна анализа и вредновање ових користи је могућа јер се процењене годишње штета добијене помоћу микро-модела могу директно поредити са годишњим вредностима екосистемских функција. У погледу вредновања екосистемских функција, у овој дисертацији приказан је пример пошумљавања горњих делова слива Тамнаве. Добијени резултати представљају поуздану локалну вредност екосистемских функција шумских површина на сливу у погледу смањења ерозије. Шира анализа локалних екосистемских функција би била могућа разматрањем више врста рецептора ризика и више различитих користи.

Приказана методологија у овој дисертацији се може применити на друге руралне сливове са пољопривредним површинама, уз модификацију функција штета од дубине плављења према локалним условима. Вредности екосистемских функција које се могу добити овом методологијом, како почетне тако и ажуриране за планиране сценарије заштите од поплава, представљају специфичне локалне и/или регионалне вредности које се могу даље користити за побољшане почетне процене природног капитала на сливовима у сличним подручјима.

Анализе спроведене у дисертацији показују да се укључивањем природи блиских решења у зелене сценарије заштите од поплава на руралним сливовима постиже значајна техничка и економска ефективност у смањењу угрожености и штета од поплава. Поред подизања отпорности на поплаве у руралним сливовима, примена природи блиских решења доприноси обнови речних екосистема и дугорочно повећава њихову вредност.

Кључне речи: ризик од поплава, мере заштите од поплава, зелена инфраструктура, природи блиска решења, микро-модел штета од поплава, зависности дубина и штета, екосистемске функције, рурални сливови

Научна област: Грађевинарство

Ужа научна област: Хидрологија

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1 INTRODUCTION

1.1 Description of the research topic with literature review

Today's needs for an increase in flood resiliency come in two forms: a need for a quantitative escalation related to the challenging climate conditions; and a qualitative change ("the paradigm shift") related to the way this resiliency is achieved.

Floods are considered the most frequent natural disaster (43% of all disasters between 1995-2015; CRED & UNISDR, 2015) and one of the three most devastating disasters in terms of damages induced (along with extreme weather and earthquakes; EM-DAT, 2017). Floods and extreme rainfall events are becoming more frequent as a consequence of global warming (EASAC, 2018), and the frequency and severity of floods are expected to increase in the future (IPCC, 2018).

Paradigm shift in flood risk management is a well-documented process (Butler & Pidgeon, 2011; Thomas & Knüppe, 2016; Karrasch et al., 2021), which demonstrates a change of perception and a gradual transformation "from safety-based, to risk-based approaches" in flood management. The management process is turning away from the passive flood defense (e.g., flood protection structures) to a concept of active, integrated flood risk management (including NBS).

Flood risk reduction involves a complex decision-making process, related to the selection of appropriate mitigation measures. The complexity of this process arises from multiple objectives and multiple stakeholders (Akter & Simonovic, 2005). Reducing flood risk in the past has been typically based on structural flood mitigation measures, the most of which could be qualified as the "grey infrastructure" (e.g., culverts, concrete-lined river channels, levees, flood barriers, etc.). In an era when state and municipal governments are facing depleting natural and financial resources, adverse climate change impacts, and many socio-economic challenges, continuation of industrial, transportation and utility services is critically dependent on sustained construction and maintenance of flood protection infrastructure. This infrastructure requires significant investments, but is also demanding in terms of annual maintenance costs (Jonkman, 2004). Large drainage and structural flood protection systems are being exposed to natural decay and require constant investment. They are characterized by a limited life span and declining benefits, and are under additional stress by the changing climate (Collentine & Futter, 2018). Additionally, the human and material assets protected by grey infrastructure are becoming more valuable over time, so their exposure to flood hazard grows even faster. Grey infrastructure rarely provides benefits other than flood risk reduction, and largely ignores or supplants ecosystem functions (Depietri & McPhearson, 2017).

Currently, attention is shifting towards NBS or "green infrastructure", for the purpose of mitigation of flood risks (Ruangpan et al., 2020). Green infrastructure is defined as "strategically planned network of natural and semi-natural areas that …

deliver a wide range of ecosystem services" (EEA, 2015). Nature-based solutions are defined by European Commission (EC, 2015) as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more and more diverse nature, and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions." This definition was recently adjusted by the following (Kopsieker et al., 2021): "Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services." Riverine floodplains, natural detentions, reclaimed wetlands etc. are examples of green infrastructure applicable for flood risk mitigation. NBS are increasingly becoming a part of various strategies and policies related to sustainable adaptation and resilience, in Europe and beyond (e.g., EU Biodiversity strategy[1]).

It has been shown in many cases that NBS for flood risk reduction can be less expensive than grey infrastructure (Cohen et al., 2012; EEA, 2015). Equally important, NBS can additionally provide a wide array of environmental and socio-economic co-benefits (Vojinovic et al., 2016). Green solutions rely on healthy, functioning ecosystems and their regulating services that can contribute to the reduction of risk, but also to human well-being and pollution control (Depietri & McPhearson, 2017). Identifying these co-benefits (or secondary benefits) and quantifying them in monetary terms can assist decision-makers in investing in flood-risk reduction projects (Vorhies et al., 2016). An effective application of NBS needs to be preceded by a comprehensive options assessment and a robust selection strategy (World Bank, 2017). However, the standards and guidelines for this process are still lacking.

Due to the growing challenges related to urban areas, such as population growth, rapid urbanization and climate change effects, there has been an abundant emergence of research and projects on coping with flood risk in urban areas, using small-scale green infrastructure and NBS (e.g., Ristić et al., 2013; Rozos et al., 2013; Schubert et al., 2017; Alves et al., 2020).

In contrast to relative space constrictions in urban settings, flood mitigation solutions in rural areas may address watershed-wide or regional scale issues; they may include larger scale NBS, or some combination of green and grey infrastructure. Concurrently, there has been very little research on the quantitative and monetary effectiveness of green infrastructure for flood mitigation in rural settings, such as flat valleys of large rivers or small hilly watersheds prone to flash floods. One of the reasons for this is that the present level of understanding of the trade-offs between flood risk reduction and economic consequences in rural settings needs improvement (Collentine & Futter, 2018). As of recently, the term "large-scale nature-based solutions" has been commonly used for flood risk mitigation measures in rural settings, on either a watershed or a regional scale (Ruangpan et al., 2020). In small- to medium-size watersheds, flood risk reduction

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[1] https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en

measures can vary from conventional grey infrastructure to various scales and levels of green infrastructure. In some cases, depending on the size of the watershed, solutions gravitate towards larger scale NBS, or some combination of the green and grey infrastructure approach.

Both green and grey infrastructure as flood mitigation measures have their specific advantages and drawbacks; neither one alone may be a universal solution, to be applied indiscriminately to all types of watersheds and local conditions. The two types of flood mitigation measures should not be a substitute for each other, but should rather be considered as complementary measures (Cohen et al., 2021; Dong et al., 2017; Alves et al., 2019). For rural watersheds with some flood mitigation measures already present, the combination of green and grey infrastructure may be the most suitable solution.

Quantitative evaluation of different flood mitigation measures is necessary to select the most effective strategy for flood risk management, or for an adaptation to climate change. The flood risk assessment framework is generally aimed at evaluating potential consequences of floods (Merz et al., 2010; Olesen et al., 2017) and is conventionally used as a basis for evaluating different mitigation options. Comparing the risks (i.e., losses) from floods under different flood mitigation scenarios provides information on benefits from the options considered, and supports making optimal decisions on flood mitigation measures. The flood risk assessment can serve additional purposes, such as identifying vulnerability of communities to floods, developing flood risk maps or financial appraisals for the insurance sector (Merz et al., 2010).

The risk assessment framework, as applied in conventional engineering applications, may not be sufficient for a comprehensive evaluation of flood mitigation options involving green infrastructure. Addressing flood risk mitigation with NBS requires a more complex approach, incorporating additional environmental and socio-economic aspects (World Bank, 2017). Consequently, evaluating primary (or main) benefits related to flood risk reduction by nature-based flood mitigation measures should be complemented by evaluating secondary (or co-) benefits, as the non-disaster related benefits of socio-economic or environmental nature.

New evaluation frameworks for quantifying the benefits from NBS are currently being developed. For example, Watkin et al. (2019) developed a framework for non-monetary evaluation of the benefits from NBS, based on numerical grades obtained from selected indicators. Giordano et al. (2020) developed a methodology for NBS assessment that is based perception and valuation of co-benefits by stakeholders, resulting in non-monetary evaluation of expected NBS impacts on several sectors such as agricultural production, river transportation, tourism, community well-being etc. Wong et al. (2020) use an agent-based model to compare the primary and secondary benefits from proposed green solutions for urban runoff reduction in New York City; the model simulates the benefits in terms of physical consequences (e.g., runoff volume captured, carbon sequestered, number of positively affected people, etc.), while economic evaluation of the proposed scenarios is obtained by applying annual economic values from the New York City Green Infrastructure Co-Benefits Calculator. Recently, Perosa et al. (2021) evaluated benefits from NBS in three river watersheds in the Danube River Basin, using the TESSA toolkit (Peh et al., 2013) for site-specific ecosystem services assessment, with an aim to develop a systematic method for evaluation of ecosystem services of restored floodplains.

Based on the literature survey, monetary estimation of a full range of benefits and co-benefits from flood mitigation scenarios that combine green and grey measures is still a major challenge, especially for large-scale solutions in rural or semi-urban areas. The few existing studies are focused on limited types of green infrastructure (from small-scale urban measures such as green roofs, to large-scale solutions such as floodplain restoration), so there is little conclusive evidence about various additional benefits offered by green infrastructure, that could systematically explain the relationship between flood mitigation measures and natural capital. This thesis is aimed at addressing this challenge for smaller rural watersheds, by evaluating the benefits from different flood mitigation scenarios (grey, green, and combined grey-green), and using them to assess the effects of flood mitigation measures on the value of ecosystem services of a watershed.

1.2 Research objectives and hypothesis

The goal of the research in this thesis is to identify methodology for comprehensive evaluation of various flood mitigation strategies and their contribution to restoration of fluvial ecosystems. The methodology is focused on smaller, predominantly rural watersheds, where it comprises a complex appraisal of the range of flood mitigation scenarios. These flood mitigation scenarios may exhibit various degree of inclusion of NBS, as an alternative, or a complement to conventional grey infrastructure. The methodology monetizes the co-benefits of proposed NBS, in addition to the commonly analyzed (primary) benefits from hazard reduction. This methodology demonstrates engineering feasibility and financial effectiveness of NBS, through a range of benefits that these measures provide in terms of flood risk reduction and restoration of natural ecosystems. The proposed methodology is, therefore, aimed at assessing the benefits, and as such, it provides necessary information and sets up a framework for any future, comprehensive benefit-cost analysis. Furthermore, the methodology provides a basis for incorporating secondary benefits from NBS in site-specific monetary evaluation of ecosystem services in the watershed.

The main hypothesis in this dissertation is that the active protection from floods, through application of NBS, exhibits considerable economic advantages over passively defending the assets via conventional flood protection measures (grey infrastructure). Mitigation configurations that consider NBS inherently improve natural capital of the existing watersheds, and their fluvial ecological systems. Such configurations reduce the flood risk for man-made and human capital, by lowering losses to infrastructure, agriculture, building stock and its inhabitants, but they also contribute to restoration of the environment, increase natural capital, and improve human well-being.

The methodology proposed in the dissertation is used to test the above main research hypothesis on a case study that involves a small rural watershed. The analysis conducted within the thesis quantifies the advantages of active green flood mitigation measures from both engineering and economic point of view. The research is also aimed at confirming that the restoration of fluvial ecosystems by such mitigation measures leads to an increase in natural capital, quantified by the site-specific value of ecosystem services.

Finally, by addressing small, rural watersheds and their natural ecosystem restoration, the analysis is aimed at providing a better understanding of interaction of pertinent ecosystem functions, and at illustrating possibilities of combined application of active and passive measures in optimal function of flood risk reduction.

1.3 Outline of the thesis

This thesis develops a framework for an evaluation of different flood mitigation scenarios for small rural watersheds, through a comprehensive flood risk assessment of each option and their subsequent comparison. The flood mitigation scenarios generically include grey, green, and combined grey-green flood mitigation measures. The proposed framework also enables quantification of the effects of nature-based flood mitigation measures on increasing the natural capital. The methodology for evaluation comprises:

- A spatial damage (risk) model, based on a combination of the flood hazard and vulnerability assessments. The model can be characterized as a micro-scale flood damage model, because it uses high-resolution hazard map outputs from the hydrodynamic modelling and fine-detail, multi-category assets data. Flood mitigation options are compared by calculating benefits as avoided damages and losses, in comparison to baseline conditions.
- An improved estimate of the value of ecosystem services in a watershed by implementing NBS in site-specific settings. The proposed approach is based on the assessment of secondary benefits (or co-benefits), from implementing a flood mitigation measure and relating it to specific ecosystem service in a watershed. This approach allows estimating updated site-specific value of ecosystem services under a given flood mitigation scenario.

The proposed methodology is illustrated using a case study of the Tamnava River watershed in Serbia.

Chapter 2 presents the methodology for the proposed evaluation framework. Section 2.1 describes general outline of the methodology. Section 2.2 presents the case study area of the Tamnava River watershed. Main steps of the evaluation framework are then given in sections 2.3 (flood hazard assessment), 2.4 (asset identification), 2.5 (flood-related damage assessment), and 2.6 (valuation of ecosystem services). Section 2.7 presents the final step in the methodology: a definition of flood mitigation scenarios and evaluation of their benefits.

Chapter 3 describes and discusses results of the methodology application on a case study of the Tamnava River watershed.

Chapter 4 presents the conclusions of this thesis and recommendations for further research.

2 METHODOLOGY

2.1 General outline of the methodology

The proposed methodology for evaluating flood mitigation scenarios with NBS extends the traditional flood risk assessment methods with an assessment of associated ecosystem benefits, related to various configurations of flood resiliency measures. The process of evaluation includes application of NBS and their applicability in conjunction with the functions of the ecological systems of rural watersheds.

The process follows the basic steps, namely the definition of the problem, the diagnostic analysis, the potential solution assessment, and evaluation of mitigation scenarios (Figure 1).

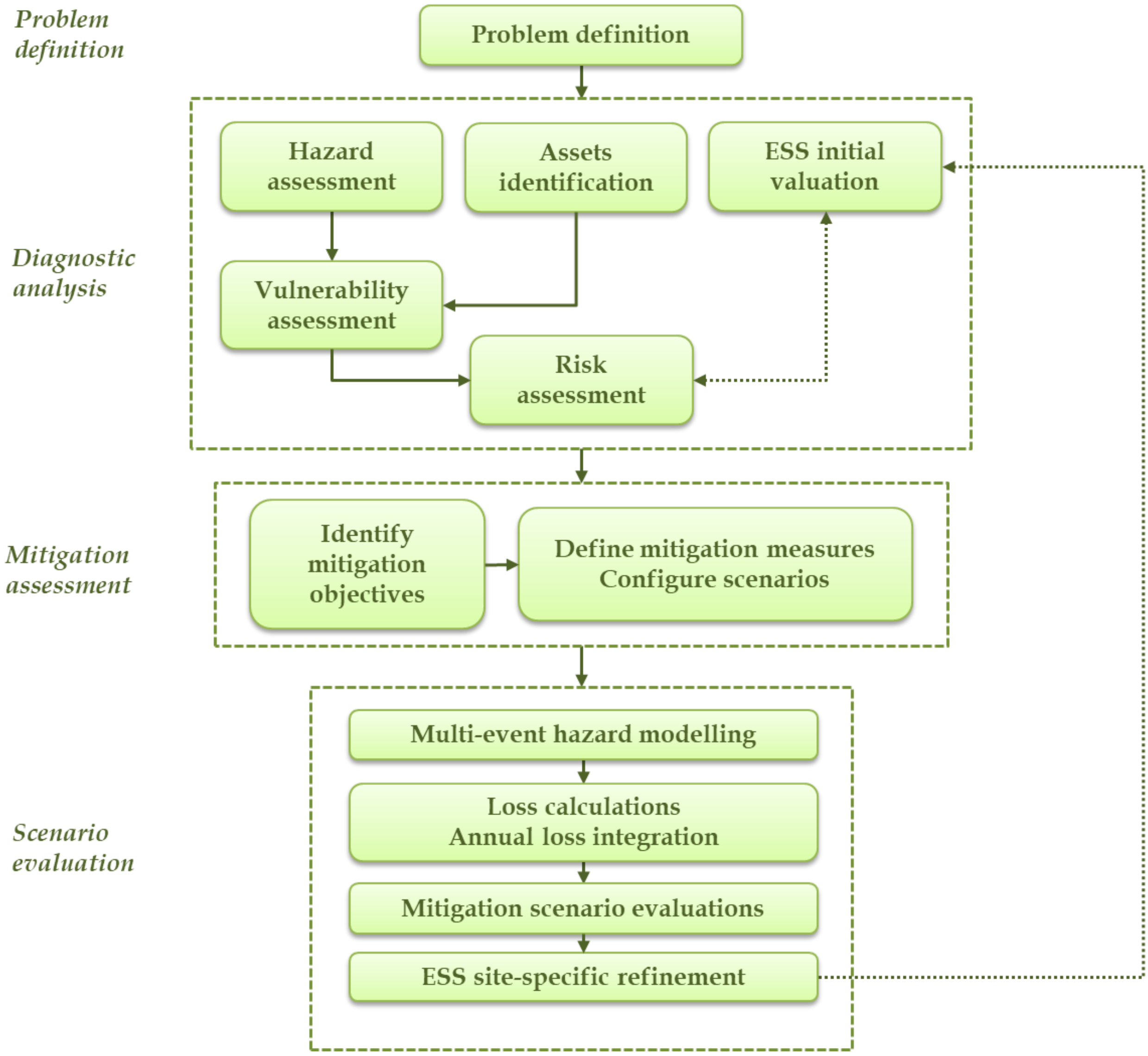

Figure 1. General approach to flood risk assessment for multiple mitigation scenarios.

Problem definition is generally related to identifying key problems, prevalent hazards, stakeholders, project scope and objectives.

Diagnostic analysis is related to the assessment of current (or some other baseline) conditions in the watershed or focus area, aimed at evaluating the flood hazard magnitudes and effects on population and assets, but also at making an initial evaluation of the ecosystem and its services in the focus area. Consequently, this part of the methodology comprises flood risk assessment and the initial estimation of ecosystem services (Figure 1).

Flood risk assessment in the proposed methodology follows a process well elaborated in literature, with risk being quantified as a function of hazard and vulnerability (Kron, 2005; Messner et al., 2007; Jovanović et al., 2012). The hazard assessment results in flood hazard maps for different recurrence periods (probabilities of exceedance). The flood hazard maps are produced through hydrodynamic modelling, and they provide information on floodplain boundaries, water depths and velocities (if relevant). Flood hazard assessment is further discussed in section 2.3.

Asset identification is related to all vulnerable elements in the watershed, such as population, infrastructure, buildings, agricultural production, etc. This step essentially includes collection of all relevant data for estimating exposure and vulnerability of these elements to floods (e.g., population density, building typology, location of infrastructure etc.). Categories of assets, identified in the diagnostic analysis stage as the most important ones in the case study used in this thesis, are presented in section 2.4.

Vulnerability is usually defined as the expected loss from a hazardous phenomenon (i.e., floods) of a given magnitude and frequency (Fuchs et al., 2012). There is an extensive literature on quantifying vulnerability for different asset categories (Messner et al., 2007; Wagenaar et al., 2018). Typically, the vulnerabilities are quantified through direct and indirect losses from floods (e.g., Merz et al., 2010). A common approach to estimating the direct losses is by applying depth-damage relationships, i.e., by calculating the damage in function of the flood depth (Pistrika er al., 2014; Lehman & Hasanzadeh, 2016). This approach is particularly useful for physical assets and is also used in this thesis. Estimating indirect losses is highly dependent on the category of assets. For example, the indirect losses of population displacement during the flood are estimated here on the basis of daily unit costs per person displaced. Details on the vulnerability and damage assessment approaches suitable for the case study used in this thesis are further discussed in section 2.5.

Risk assessment encompasses all methods for hazard assessment, asset identification, and vulnerability assessment. The entirety of these methods is referred to as the flood damage model or flood risk model (e.g., Olesen et al., 2017). One of the outputs of the *Diagnostic analysis* step is the flood damage model. In this dissertation, a micro-scale flood damage model is developed for the case study of the Tamnava River watershed, meaning that the model uses high resolution flood hazard maps and fine-detail, multi-category asset data. Once the flood damage model is established, it can be validated against the observed data, i.e., against post-disaster loss estimates if these are available. For the selected case study in this thesis, this was possible and is discussed in section 0.

Overall understanding of the watershed's ecological system is an important step in application of NBS as potential flood mitigation measures. The ecosystems can play a role in reducing flood hazard and vulnerability (e.g., by attenuating flood waves and reducing flood peaks). Understanding the risk reduction value of the current ecosystem is important (World Bank, 2017) and the proposed methodology is, therefore, additionally supported through initial valuation of ecosystem services (ESS) in the watershed (as described in section 2.6).

As part of the *Mitigation assessment* phase, the overall objectives of flood mitigation in the watershed are identified. In this thesis, specific concerns related to rural agricultural watersheds, small population centers, and existing flood protection measures are addressed. In this step, NBS can be introduced either as an alternative or as a complement to the traditional flood mitigation measures. The measures taken into consideration may then be assessed as configurations of an existing and upgraded conventional infrastructure (grey scenario), NBS (green scenario) or their combination (grey-green scenario). These three configurations are subsequently evaluated by the proposed methodology, with a restoration of ecosystem services constituting an important component of both green and grey-green scenarios. The existing flood protection configuration (baseline conditions) serves as a comparative benchmark, to quantify effectiveness of each of the proposed scenarios. The scenarios defined in this step should assist in identifying the optimal solution for the watershed.

The final stage in the proposed methodology is the *Scenario evaluation.* In the first step of this stage, the measures proposed under each mitigation scenario are integrated into the flood damage model to perform post-mitigation risk assessment. This step encompasses flood hazard simulations and monetary valuation of losses under the proposed mitigation scenarios. The flood damage model is applied to a series of synthetic (probabilistic) flood events under each mitigation scenario.

The effectiveness of a particular mitigation strategy under each specific scenario is measured as the damage avoided by implementing that particular option, i.e., as the difference between the losses of the baseline scenario and the considered mitigation scenario. The scenarios are typically valuated by calculating expected annual benefits, or the net present value of benefits over a planning time horizon, as outlined in section 2.7.3.

The final step in the damage modelling phase is a refinement of the ecosystem services related to flood risk reduction. The valuation of the watershed becomes more refined by implementing a set of site-specific ESS values. These refinements can be achieved by identifying the concrete change in land use categories that contributed to flood risk reduction, and subsequently updating the initial ESS values by formulating the benefits through the modified land area on an annual basis. The updated ESS values can greatly enhance the overall ecological value of the considered watershed and can be applied to other regional studies for an improved initial eco-system valuation. This step is elaborated in sections 2.6.2 and 2.7.3.

The next section provides a description of the case study used to demonstrate the proposed methodology in this thesis. The remaining subsections of section 2 describe main steps in the methodology: flood hazard assessment, asset identification, vulnerability assessment through evaluation of flood-related damages, valuation of ecosystem services in context of flood mitigation measures and, finally, assessment of benefits for a particular flood mitigation scenario.

2.2 Case study area – the Tamnava River watershed

2.2.1 Description of the watershed

The study area comprises the watershed of river Tamnava and its tributaries Gračica and Ub. This area is part of the larger Kolubara watershed, depicted in Figure 2. The Tamnava watershed covers 726 km^2 and is primarily rural, with 79.3% of the area being cultivated (UNDP Serbia, 2016). Figure 3 shows a land cover map of the area, according to the CORINE Land Cover 2012. Urbanized and industrial land constitutes only 1.2% of the area and is concentrated in two small population centers, the towns of Ub and Koceljeva. The terrain elevation ranges from 470 m a.s.l. in upper reaches of the watershed to 64.4 m a.s.l. at its mouth (Figure 4), with arable land located in wide floodplains of the three rivers. The agricultural landscape consists primarily of small farms, with emphasis on several main crops. The rest of the economy is based on service industry located in towns of Ub and Koceljeva. The watershed area is situated within boundaries of the municipalities (counties) of Ub and Koceljeva.

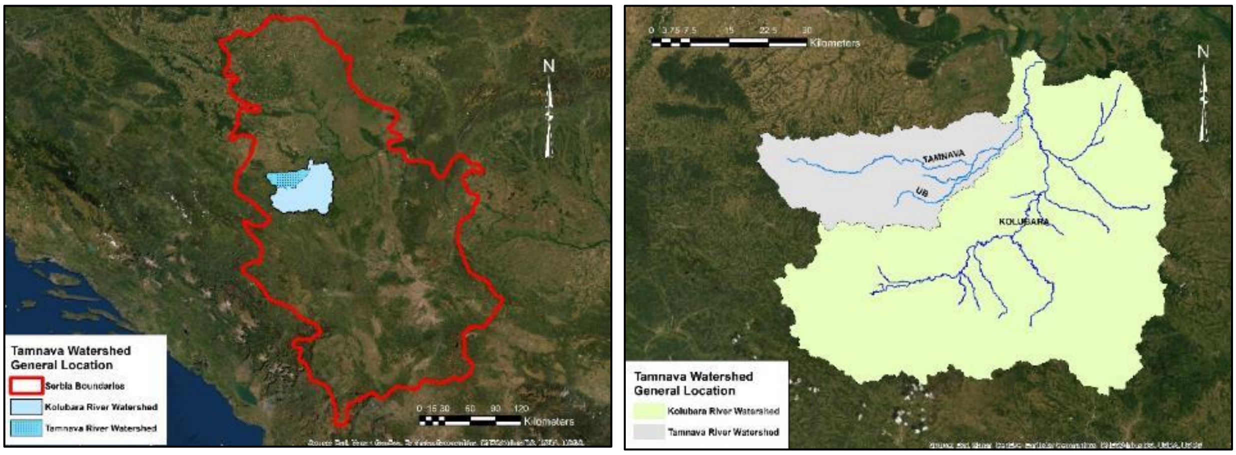

Figure 2. The study area: location of the Kolubara River watershed in Serbia (left) and the subbasin of the Tamnava River (right).

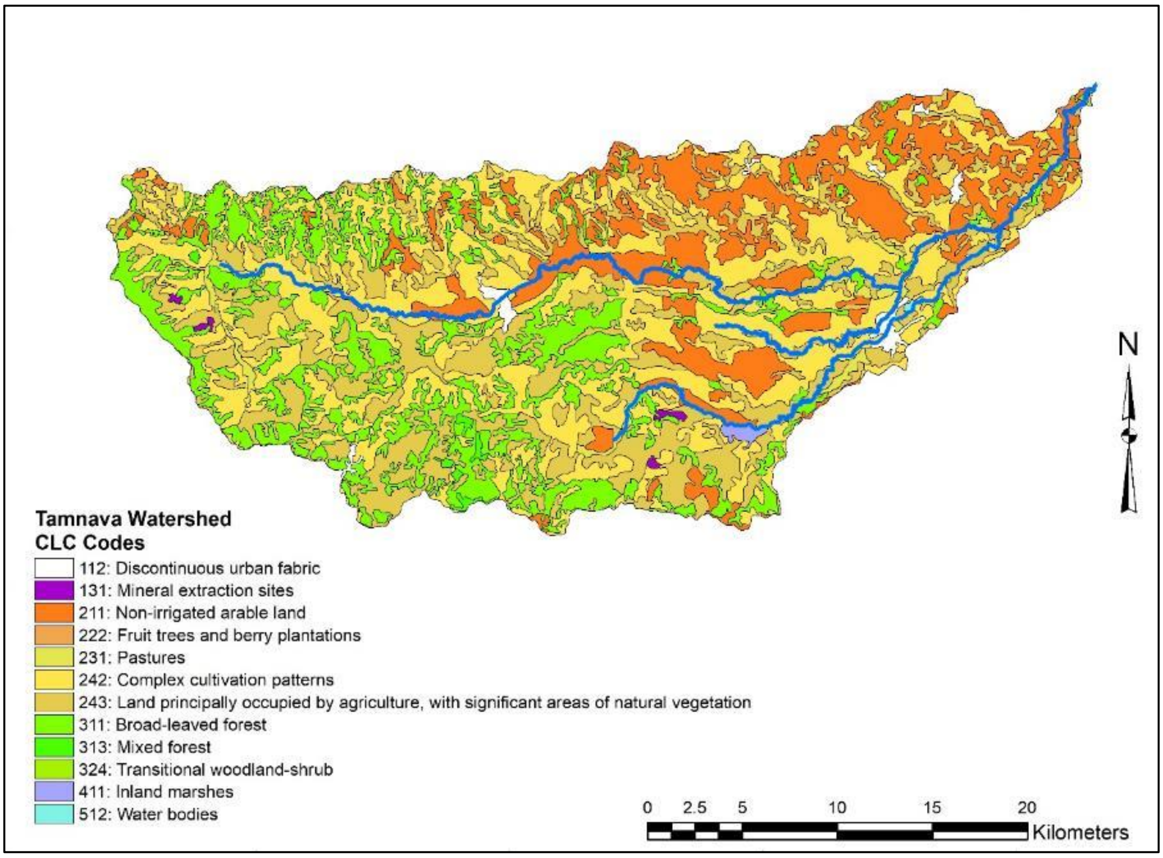

Figure 3. Map of land cover categories of the Tamnava River watershed.

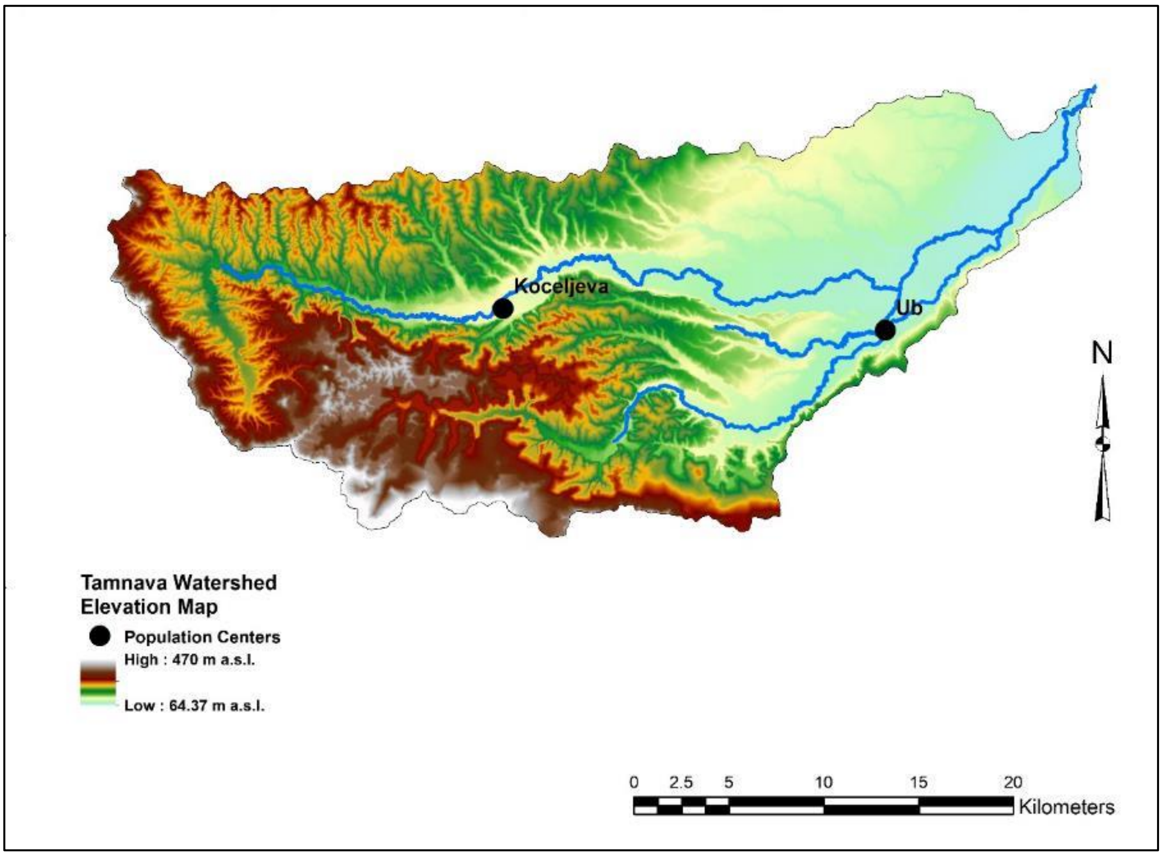

Figure 4. Map of terrain elevations of the Tamnava River watershed.

Hydroclimatic regime of the Tamnava watershed is characterized by pronounced seasonal patterns, with the highest flows in early spring due to combined rainfall and snowmelt, and in early summer due to high-intensity convective rainfall events. The latter mainly occur in June, which is the month with the greatest precipitation amount. Mean annual precipitation amounts to 787.7 mm, while mean annual temperature is 11.4 °C for 1981-2010. Mean annual flow of the Tamnava River at Koceljeva is 0.99 m^3/s, and of the Ub River at the Ub gauge is 1.01 m^3/s. The greatest flows at these gauges are 178 m^3/s and 146 m^3/s, respectively, and were observed during a great flood in May 2014.

The study area has been affected by a number of historic flood events (1999, 2006, 2009, 2020 and earlier), including a catastrophic flood in May 2014. Flooding in the Tamnava watershed has often been caused by flooding of the river Kolubara, whose high-water levels would prevent efficient drainage from the Tamnava watershed and result in excessive backflow flooding in its interior. Historically, floods along the Tamnava River have caused considerable damages, particularly in the vicinity of its confluence with the Kolubara River.

The May 2014 flood was an unprecedented flood in the hydrological record of the whole West Balkans region (Plavšić et al., 2014). It was triggered by heavy rain falling during several days over near-saturated soils after several similar antecedent events. The extent of flooding exceeded historical records, with the Kolubara basin being among the most affected ones. High water levels remained in the river valleys for weeks; the damages were substantial, and casualties were reported.

2.2.2 Flood mitigation system in the Tamnava watershed

To reduce flood hazard and consequent damages, the flood mitigation system in the Tamnava watershed has been set up since the 1950s. A flood protection system in 2014, which is the existing system used as reference in this study, is primarily based on the levees along several sections of the Tamnava and Ub rivers. Figure 5 shows the division of the valleys of the Tamnava, Ub and Gračica rivers into sectors (see also Table 1) and locations of the existing levees. The levees that protect the populated areas along the Tamnava River are designed for 50-year or 100-year floods, while the remaining levees provide protection of agricultural land from 25-year floods. Specifically:

- levees along the Tamnava River designed for 50-year floods in sectors 7′ and 9;
- levees along the Ub River designed for 100-year floods in the urban areas of sectors 11′ and 11′′, and levees designed for 25-year floods in the agricultural areas of sector 12.

It should be noted that there is no protection from floods along the Gračica River.

A special study on the effects of the 2014 catastrophic flood and proposal for improved flood mitigation in the whole Kolubara watershed was undertaken (UNDP

Serbia, 2016; herein referred to as the "Kolubara study"). The goal of the Kolubara study was to reconstruct the 2014 flood event, and to perform an evaluation of the proposed flood mitigation measures.

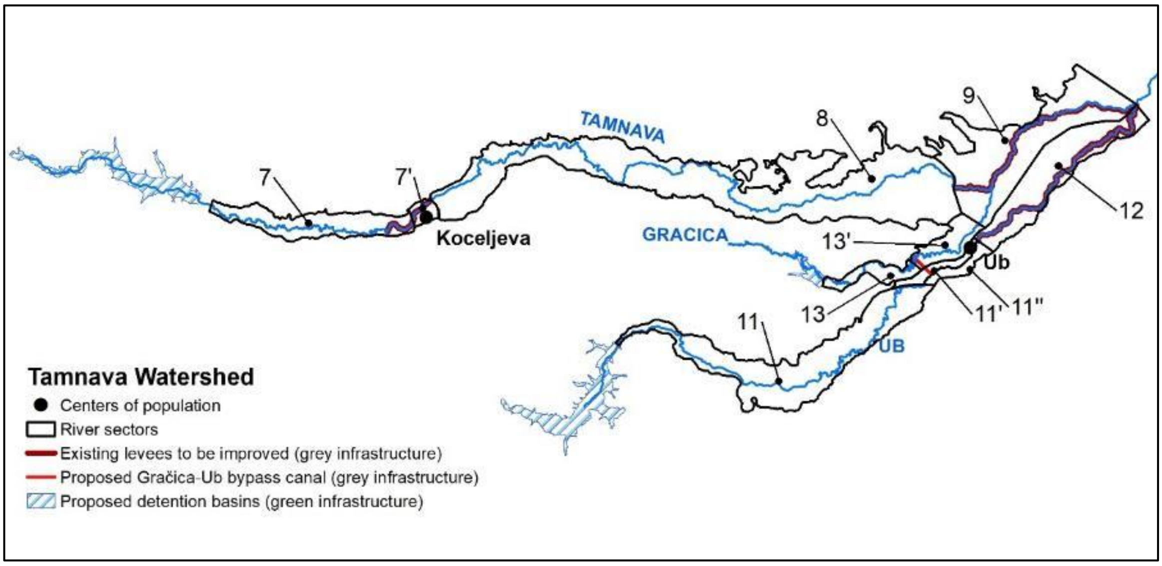

Figure 5. Division of the Tamnava, Ub and Gračica river valleys into sectors. Figure also shows locations of levees and planned detention basins.

One of the outputs of the Kolubara study were hydrologic and hydrodynamic models that were used for reconstruction of flood event in May 2014 and for long-term flood risk-reduction projections. The hydrodynamic model is used in this research with necessary adjustments needed to perform flood hazard simulations in existing conditions and under the proposed mitigation scenarios.

The notation for river sectors along the Tamnava, Gračica and Ub rivers shown in Figure 5 is adopted from the Kolubara study report. The sector boundaries correspond to the areas of maximum potential flooding extent. The sectors are distinct in their prevalent land use in the river valleys and in proposed flood mitigation measures. Basic information on the sectors (area and percentage of agricultural land) is shown in Table 1.

Table 1. River sectors in the study area.

Sector	Stream	Area [ha]	General description	Agricultural land use [%]
7	Tamnava	573.20	Rural	99.86%
7'	Tamnava	75.28	Urban	35.18%
8	Tamnava	3,184.30	Rural	91.22%
9	Tamnava	1,429.02	Rural	92.72%
11	Ub	1,384.33	Rural	85.25%
11'	Ub	103.75	Urban	82.07%
11''	Ub	101.16	Urban	43.99%
12	Ub	859.49	Rural	94.28%
13	Gračica	173.23	Rural	100.00%
13'	Gračica	244.58	Semi-urban	71.09%

The Kolubara Study proposed the following measures for improved flood mitigation in the Tamnava watershed:

- three detention basins with earthen dams at the upper reaches of Tamnava, Ub and Gračica rivers (namely Kamenica, Pambukovica and Gračica detention basins, respectively) that should serve as flow regulating and erosion prevention structures during floods and would otherwise retain minimal amount of water;
- reinforcement and crown elevation of the existing levees along rivers Tamnava and Ub, in sectors 7′, 9 and 12, respectively;
- construction of a bypass canal connecting Gračica and Ub rivers (sector 13′);
- counter-erosion measures in upper watershed area.

The existing levees that already provide certain level of flood protection are planned to be elevated as follows:

- Sector 7′, bank protection and levee protecting downtown Koceljeva: increasing flood protection level from recurrence interval of 50 years to 100 years;
- Sector 9, agricultural levee on both banks of river Tamnava: increasing flood protection level from recurrence interval of 50 years to 100 years;
- Sector 12, agricultural levee on both banks of River Ub: increasing flood protection level from recurrence interval of 25 years to 100 years.

Different combinations of the proposed measures for the Tamnava watershed from the Kolubara study are considered in this thesis as different flood mitigation scenarios, described in section 2.7.1.

2.3 Flood hazard assessment

The goal of flood hazard assessment is to indicate the level of assets exposure and its probability of occurrence. The riverine flood hazard and resulting flood risks are articulated through flood mapping, where areal maps with associated assets are overlayed with the flood boundaries, indicating the extend of flooding for a specific recurrence interval. The flood boundaries are calculated from interaction of the water surface (produced through hydrodynamic stream modelling) and available digital terrain data. The quality of the terrain information can vary greatly, from conventional aerial photogrammetric digital terrain models to the high-resolution LiDAR (Light Detection and Ranging) sensing data. Various hydrologic scenarios are introduced through input hydrographs, calculated for synthetic storms, and for various recurrence intervals. Depending on the quality of input data, resulting flood hazard information can additionally be presented through depth grids, indicating an actual projected depth of water for various scenarios at any point within the flood hazard boundaries. The models are calibrated for flows or high-water marks with the recorded historical data.

The outputs of the flood hazard assessment for the Tamnava watershed performed in the Kolubara study (UNDP Serbia, 2016) are used in this thesis. These include the outputs from the hydrodynamic model that was originally developed for reconstruction of the extreme flood event in May 2014. It is a one-dimensional HEC-RAS model, specifically developed to simulate all levee breaches and overtopping, and backwater effects that occurred during the flood event in May 2014. This model version was calibrated against the observed water stages and surveyed flooding extents. Hydrological reconstruction of this flood event is described in detail by Stanić et al. (2018).

The hydrodynamic models of the Tamnava, Ub and Gračica rivers developed within the Kolubara study use the flood runoff hydrographs as the upstream boundary conditions, and stages of the Kolubara River at the confluence with Tamnava as the downstream boundary condition. The flood runoff hydrographs were produced for a range of flood probabilities using HEC-HMS hydrologic model, previously calibrated on several major flood events in the framework of the Kolubara study. More details on how the model was deployed for this thesis is given in Pudar et al. (2020).

The water surface outputs from the hydrodynamic simulations are converted into high-resolution water depth grids. Combining these grids with the digital terrain model (DTM), adopted from the Kolubara study and further refined to the 1-meter square resolution, enables detailed damage assessment and subsequent micro-scale damage modelling, as described in sections 2.5, 2.6, and 2.7.

2.4 Asset identification

Flooding events frequently cause damages that can be very large in magnitude, long lasting, and very complex, affecting economies, infrastructure, and populace in many direct and indirect ways. Floods may affect very large geographic areas, damaging the building stock, disrupting whole sectors of the economy, and displacing large populations. Floods are considered the most frequent natural disaster (43% of all disasters between 1995-2015; CRED & UNISDR, 2015), and there are many metrics developed to quantify their economic impact. Flood-related losses can be direct and easily quantifiable, or indirect and assessable through various computational methods. The major subcategories of losses are economic, environmental and social.

Assessment of the economic impact of floods starts with identification of vulnerable assets in the area affected by flood hazard. The most commonly used vulnerability categories are presented in Table 2.

Selection of the vulnerability categories for this study was based on availability of data, prevalence of assets in the area, and compatibility with categories used in the Kolubara study for the purpose of verification and comparison of flood damage estimates.

Four principal assets and five corresponding vulnerability categories are identified:

- Building stock and its inventory (contents);
- Agricultural production;
- Transportation infrastructure;
- Population affected by flooding and cost associated to its temporary displacement.

These categories are discussed below in the context of the case study used in this thesis.

Table 2. Typical categories used in estimating losses due to flooding.

Losses category	Subcategory	Vulnerability categories
Direct losses	Economic	• Physical damage to buildings (residential/public)* • Physical damage to building contents and equipment* • Damage to agricultural crops and/or livestock* • Physical damage to infrastructure* • Debris removal and cleanup cost
	Environmental	• Environmental cleanup cost
Indirect losses	Economic	• Business displacement • Lost productivity • Loss of infrastructure services • Increased cost of providing critical services
	Social	• Population displacement* • Loss of employment/income • Mental stress and anxiety • Death and injuries

Notes: Categories with (*) denote the ones used in the research.

2.4.1 Building stock and its contents

In this study, an approach of the micro-scale flood damage assessment is adopted, meaning that evaluation of vulnerabilities is performed on a level of individual buildings for a series of hazard events. This approach is more detailed in comparison to the aggregated approach applied in the Kolubara study.

Individual buildings in this study are identified from the aerial photogrammetric imagery, and their outlines are digitized to enable overlaying with the flood hazard map. Field investigations were conducted to identify types of buildings in terms of structure types and occupational classes. For flood vulnerability assessment, an important feature of the buildings is the first finished floor elevation, and its relative distance from the surrounding grade. For structures without basements, this distance is the height of the entrance step, and it can be determined from field observations and assumed for the particular type of structure.

Basements are difficult to identify, they may or may not be finished, and their characteristics (size, height) have to be determined individually. Albeit the buildings with basements incur more flood damages, large-scale flood studies usually don't take them into account. This study assumes no basements in its calculations.

The buildings contents vary depending on the occupational class, and include all household items, equipment, machines, or stored agricultural products. Their value is usually expressed as a percentage of the building structure value.

2.4.2 Agricultural production

Agricultural production and its vulnerability can be analyzed in different ways, depending on the type of production present in the area. In the case of the Tamnava watershed, prevailing agricultural activity is crop production. The Kolubara study (UNDP Serbia, 2016) identified three principal crops (corn, potatoes, apples) and unbaled hay as the predominant agricultural products.

The seasonality of the flood event and resulting various levels of vulnerability of each crop can have an impact on the vulnerability assessment. However, when planning the long-term flood mitigation measures (instead of analyzing a specific event), a conservative approach of assuming total damage of crops after flood in all seasons can be adopted. For these reasons, and partly because of lack of more detailed data on agricultural production, this conservative approach was chosen in this work for the Tamnava watershed.

2.4.3 Transportation infrastructure

Transportation infrastructure may be affected by floodwaters in several different ways, including direct physical damages, and indirect functional losses. In this thesis, transportation infrastructure is limited to roadway infrastructure. Direct damages to the roadways are usually caused by hydrodynamic forces of flash floods and high flood waters, most frequently at the bridge crossings and culvert locations (Figure 6). Roadways can be damaged by the flood-related landslides or rockslides or by logjams and other types of water-borne debris, especially in the case of small, torrential streams. Long duration of submergence under floodwater may cause softening of the roadway subbase and embankment and compromise the structural stability of the road. As a result, floods can also frequently cause substantial indirect losses, through lengthy detours and delay times.

All of the above effects become more pronounced for rural roadways, which usually suffer from heavy seasonal use, low traffic conveyance and irregular maintenance.

Figure 6. Damaged road near town of Koceljeva in the Tamnava River valley during the May 2014 flood (source: Koceljeva municipality web site[2])

2.4.4 Population affected by flooding and temporarily displaced

Population may be affected by flooding in various ways, from having their habitats directly damaged to being directly exposed to or having to be evacuated due to impeding environmental, structural, infrastructural, or health-related hazards. In this study, only the inhabitants whose residences can be directly affected by flooding are considered.

For the planning purposes, the number of inhabitants is usually determined from the census data (or similar municipal information) and verified against the number of residential structures determined to be affected by the flooding.

2.5 Calculation of flood-related damages

2.5.1 Direct losses to building stock and contents

Flood-related damages to structures can be estimated using the depth-damage function (DDF), which generally shows the damage in monetary units as a function of water depth in the structure. DDFs can be developed in different ways, but most often they are developed based on data from previous flood events at particular study area or on expert judgment (Huizinga et al., 2017). However, DDFs are seldom readily available for a region of interest. In Serbia, DDFs have been developed only for a small number of studies (e.g., Jovanovic et al., 2014).

Huizinga et al. (2017) developed a global data base of DDFs under the European Commission Joint Research Centre (herein referred to as JRC). The DDFs in the JRC data base are developed from extensive literature survey for each continent in a non-dimensional form, with damages expressed not in absolute monetary values, but as

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[2] www.koceljeva.gov.rs/index_files/htm/Poplave%20galerija.htm

percentage of the "maximum damage value", which is the value of replacing the completely destroyed structure with a new one. The maximum damage values are provided in JRC data base for different countries, based on the construction costs level in these countries.

On the other hand, conventional high-level damage estimates, including the one utilized in the Kolubara study, consider only severely flooded buildings and utilize a fixed cost of repair per unit of flooded building area (€/m^2).

In this study, the DDFs for residential, commercial, industrial, and transportation occupancy classes of buildings are adopted from the JRC global data base, with modifications applied for Serbia and for inflation. It is conservatively assumed that buildings have no basements. All the modifications applied to DDFs from the JRC data base are made in accordance with field investigations.

The damages to the building contents are here estimated using the shape of DDF for corresponding building type. It is adopted that the maximum damage value for the building content ranges between 50% and 150% of the maximum damage value for the corresponding building structure, as shown in Table 3. An example of the DDF for residential buildings used in the study is presented in Figure 7.

Table 3. Maximum building damage values used in the study, based on JRC global database (Huizinga et al., 2017).

Building type	Maximum damage[3] [€/m^2]	
	Structure	**Content**
Residential[4]	203 – 271	101-136
Commercial	298	298
Industrial	207	310
Transportation	107	n/a
Agricultural[5]	149 – 298	75 – 298

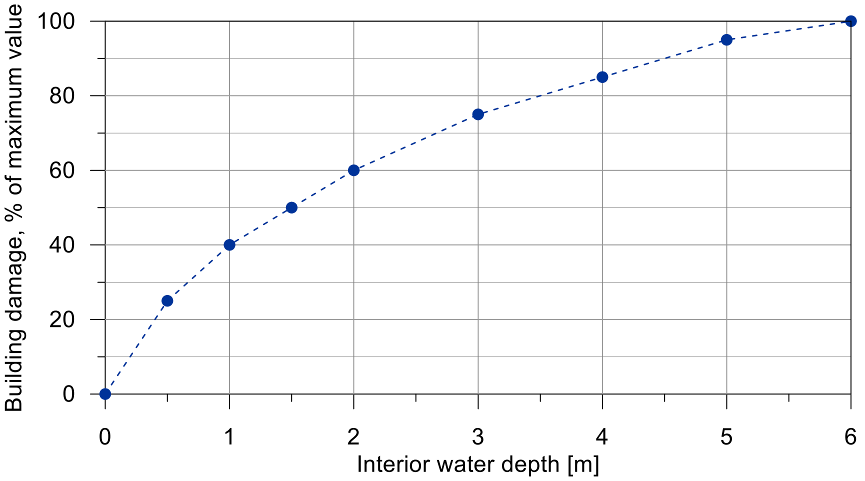

Figure 7. An example of depth-damage function for residential buildings.

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[3] Inflation corrections are made to reflect costs for 2020.

[4] For very old buildings, maximum damage for the structure is reduced by 50%.

[5] Adopted commercial DDFs with reductions for content and structural damage.

2.5.2 Agricultural losses

Vulnerability of agricultural resources and crop producing areas is assessed as their direct exposure to flooding. There are several factors that influence this vulnerability: water depth, time spent under water, and seasonality of crops. The amount of time that crops spent under water is generally disregarded because the damage is already done even for a short-time of flood exposure. As mentioned in 2.4.2, the seasonality of crops is not taken into account when deriving long-term vulnerability estimates.

When exposed to flood waters, root vegetables (e.g., potatoes) or cultures sensitive to moisture (e.g., unbaled hay) are considered a total loss, regardless of the amount of flooding. For the taller-growing cultures, such as apples and corn, damages are adjusted with respect to the flooding depth and field investigations.

The economic valuation of agricultural losses can be very comprehensive. A simple and conservative approach is to assume that the crops have a constant buyout cost, and that the production yield would remain unchanged over time. In this thesis, the values are adopted from the Kolubara study and modified for inflation, as presented in Table 4.

Table 4. Agricultural production and potential losses due to flooding.

Culture	Yield [tonnes/ha]	Revenue [€/ha]
Corn	5.90	770
Potatoes	18.40	3,851
Apples	16.90	7,318
Unbaled hay	1.60	208

2.5.3 Transportation infrastructure losses

As mentioned previously, transportation infrastructure is limited to roadway infrastructure in this thesis. The losses considered specifically focus on direct roadway damages caused by the static water. For this purpose, an appropriate depth-damage function (DDF) is adopted from JRC global data base (Huizinga et al., 2017), similarly to the ones for buildings and their content (section 2.5.1). This approach considers only depth of water, and not the duration of road flooding. Damages to the roadway are calculated in relative terms, i.e., as a percentage of maximum replacement cost of the roadway. Figure 8 depicts normalized DDF for roadway infrastructure. Any roadway flooding over five meters in depth is assumed to cause 100% (total) roadway damage.

Calculation of roadway damages can be simplified using GIS-based inundation and depth-grid models. For every recurrence interval and mitigation scenario, GIS model is used to calculate length of road segments and average depth of flooding. For a specific road classification, a prescribed width and the replacement (max. damage) cost are incorporated into calculations to provide direct roadway damage for a specific flood scenario (Figure 9).

In this thesis, the maximum roadway damage for the Tamnava case study is based on initial JRC estimates and subsequently modified to reflect inflation and actual roadway construction costs in Serbia[6,7]. While the local roadway construction costs in Serbia vary greatly, a conservative cost of 25 €/m^2 (equivalent of 200,000 €/km of corresponding state roads in the Tamnava watershed) is adopted in this thesis.

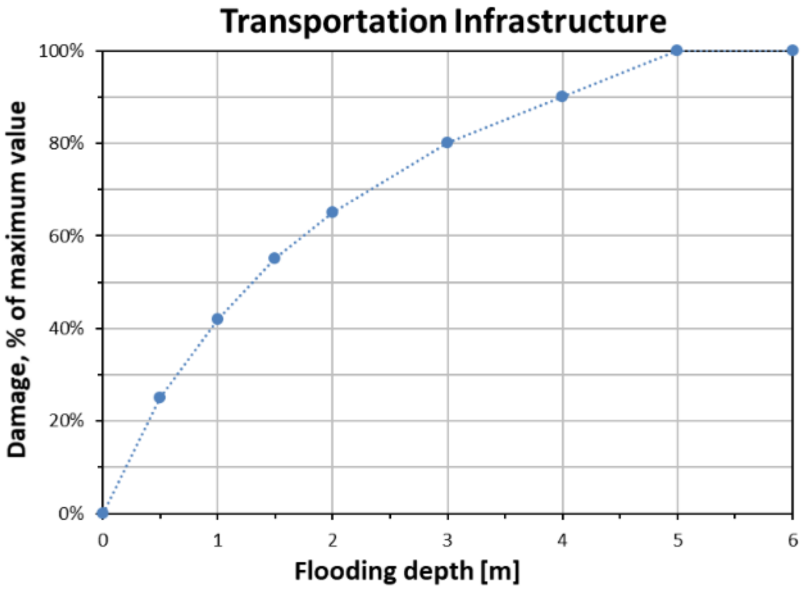

Figure 8. Depth-damage function for roadway infrastructure in the Tamnava watershed.

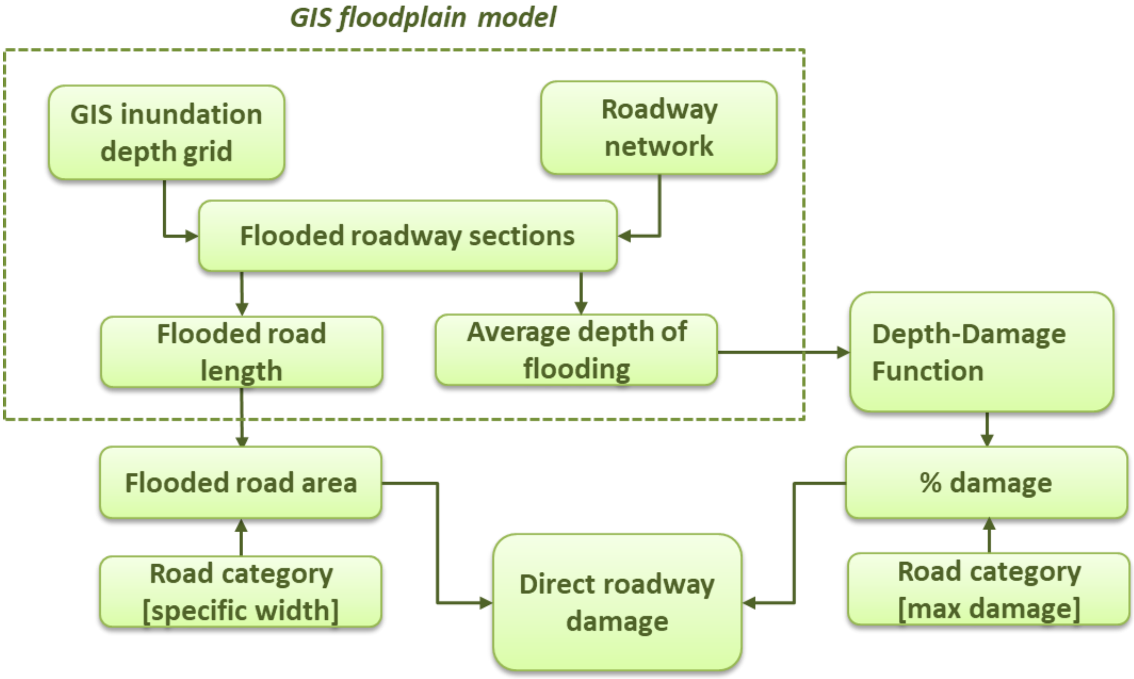

Figure 9. Flowchart of GIS -applied floodplain/inundation models in calculating roadway damage losses for individual recurrence intervals.

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[6] https://www.daibau.rs/cene/gradnja_puteva
[7] https://www.daibau.rs/cene/asfaltiranje

2.5.4 Losses related to temporary displacement of affected population

The vulnerability of population can be defined through several quantifiable metrics, including evacuation, displacement, and loss of employment/income. Some other loss categories (injuries, fatalities, mental stress and anxiety) are less tangible and harder to quantify, albeit they can be used when the information is available (FEMA, 2011).

The displacement time is the time for residents to be relocated until imminent danger is gone, or until the necessary repairs are completed. The displacement duration varies with the depth of interior flooding (FEMA, 2011) and is presented in Figure 10. For the case study in this thesis, a minimal displacement time of seven days is assumed for houses with no interior flooding but within the flooded area. The operating assumption is that, despite not being flooded internally due to an elevated first floor, the residents were evacuated because of the life-threatening conditions in its immediate surroundings.

The cost of relocation usually includes both the one-time evacuation costs and the expenses related to temporary housing. This study considers only the temporary housing expenses estimated at approximately 10 € per person per day (UNHCR Serbia, personal communication).

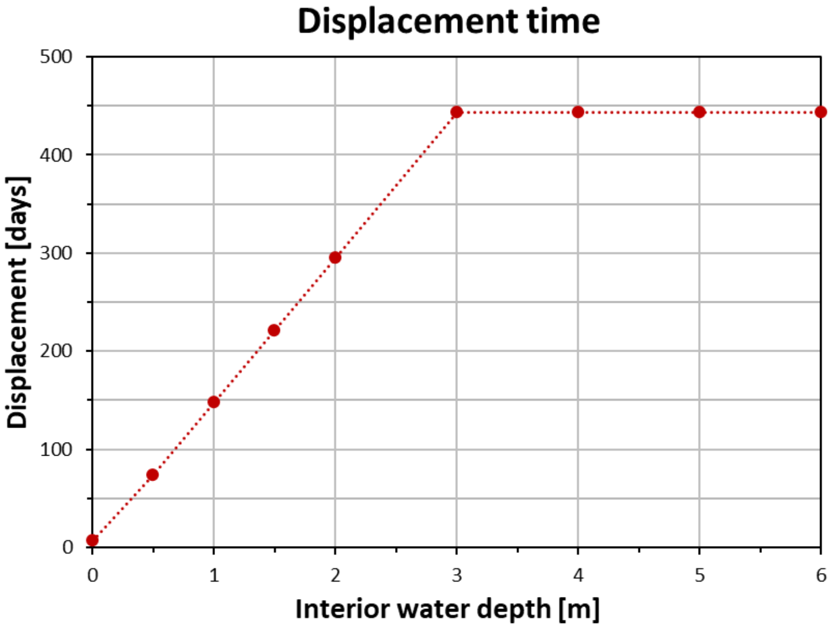

Figure 10. Displacement time for flooding in residential structures within the flood boundaries, based on FEMA (2011).

2.6 Valuation of ecosystem services

2.6.1 General concept

Although the term “natural capital” was first coined in the early 1970s (Schumacher, 1973), the concept of ecosystem services (ESS) in today’s format was developed in the late 1990s (Daily, 1997). Ecosystem services were internationally formulated within the regulatory framework through Millennium Ecosystem Assessment in 2001 and 2005 (MEA, 2005), and in Europe (EU) through biodiversity strategy for 2030 (EC, 2020).

Ecosystem services are defined as “the benefits that people obtain from ecosystems” (MEA, 2005), where ecosystems can be part of the urban, rural, or undisturbed natural setting. The benefits can be very diverse, ranging over environmental, socio-economic, or conservation objectives, but they can broadly be grouped into four distinct categories (Daly & Farley, 2004; Kocian et al., 2012):

- **Provisioning services**; securing 1) drinking water, 2) food (biomass), 3) raw materials, and 4) medicinal resources;
- **Regulating services;** providing 1**)** gas and climate regulation, 2) protection from disturbances (storms, flooding, and drought), 3) soil erosion control (by vegetation roots and tree canopies), 4) water regulation (water absorption, and release, temperature and flow regulation), 5) biological control, 6) water quality and waste processing, and 7) soil formation;
- **Supporting services;** ensuring and supporting 1) nutrient cycling, 2) biodiversity and stable habitat, 3) primary productivity (of plant growth for sustenance of food chains), and 4) pollination (by fertilization of plants and crops);
- **Cultural services;** providing 1) aesthetic value, 2) recreation and tourism, 3) values for scientific and educational research, and 4) spiritual, religious or historic purposes.

The ecosystems, through providing goods and services, should be valued as natural assets, and applied the same treatments as other, non-natural assets (Kocian et al., 2012). Contribution of ecosystems to biodiversity, natural environment, and human well-being can be expressed as the monetary value of the ecosystem services.”

Figure 11 below (from Schrier et al., 2013) illustrates the significance of the ecosystem services (ESS) in increasing the value of the natural capital over time. The ecosystems, which constitute the natural capital, while self-maintained, grow and flourish, by drawing energy and living resources from environment. The built capital (man-made objects, such as roads, concrete structures and drainage systems), if not maintained well over time, depreciates in value and diminishes in its operational functionality. We can, within the framework of this research, identify the grey infrastructure as a component of built capital, which also includes all the structures and all the roadways considered with the case study of the Tamnava River watershed.

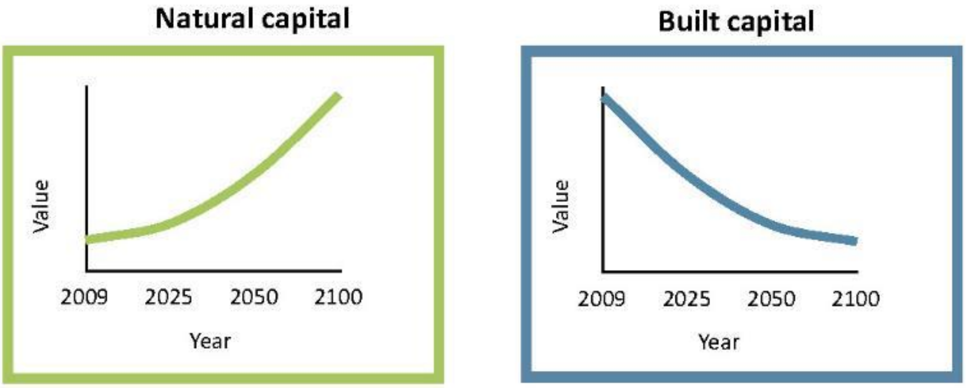

Figure 11. Temporal change of value of natural and built capital; while the natural capital value grows, self-maintained, over time (left), the value of the built capital (right) diminishes over time, even with applied maintenance (from Schrier et al., 2013).

Valuation of ecosystems and their services is a complex process, assigning them (usually) an economic value. Value assessment can be performed using several approaches (de Groot et al., 2012), grouped principally into direct-use value, and indirect use-value methods. The results of numerous economic and academic valuation analysis are synthesized in several international data compendiums, of which The Economics of Ecosystems and Biodiversity (TEEB, 2010a, 2010b) and later Ecosystem Service Value Database (ESVD; de Groot et al., 2012; ESVD, 2020) are the most widely used and researched. The most common set of units of valuating ecosystem services is international $/ha/year, i.e., per unit area on the annual basis. Each of the biomes (subsystems) within a particular ecosystem is represented by the corresponding land cover; the specific set of ecosystem services, provided by the biome, is assessed and assigned a range of economic values.

The concept of ecosystem services embraces the approach that the natural ecological systems (including watersheds) should be viewed not as natural resources, but as assets, with the aim to increase their inherent value through mitigation measures, protecting both the natural and man-made (built) capital. This value enhancement process can be extremely diverse, depending on the type and nature of the observed ecosystems, but it can be broken into several basic steps:

- Identification of objectives;
- Identification of ecosystem services pertinent to the natural system;
- Initial valuation of the natural capital;
- Identification of mitigation strategies;
- Evaluation of the scenarios;
- Verification of the selected strategy and re-evaluation of the natural capital.

Nowadays, there is a growing attention toward a holistic planning in flood risk management that emphasizes the ecosystems and human values along with the primary goal of reducing the risk (e.g., Vojinović et al., 2017; Ruangpan et al., 2020). This trend has brought into focus the green infrastructure or so-called nature-based solutions for flood risk mitigation. These measures provide the main benefit of reducing flood risks, but can also provide an array of environmental, social and economic co-benefits. The ultimate aim of this holistic approach, while applying NBS to reduce flood hazards, is to consequently increase the intrinsic value of the natural capital in river watersheds. To quantify this process, the value of a watershed is initially estimated through the valuation of its existing ecosystem services, monitored through the application of NBS, and subsequently reevaluated following the mitigation contributions in reducing local flood hazards.

2.6.2 Application to rural watersheds

In this research, the valuation process is customized to fit the environmental conditions in rural watersheds. Reduction of flood hazards is identified as a principal objective. The ecosystem services pertinent to rural watersheds are identified from within the overall four categories of services listed in section 2.6.1, first, by the type of the system (continental watershed), and then, by its predominantly rural characteristics. The five principal biomes (land cover categories) identified in the study area are: agricultural, pasture, forest, wetlands, and lakes and streams. Table 5 depicts a matrix of interdependency of the considered ecosystem services and biomes identified within the Tamnava River watershed. Some services are contributed to by several biomes; similarly, each of the land use categories provides numerous ecosystem services. Not all of the services are considered in this study; either due to the lack of information, insignificant contributions, or low relevancy in reduction of natural (flood) hazard.

For the Tamnava River watershed, the values of ESS are adopted from the literature, except for the value of the Soil Erosion and Control ESS for forest land cover. This ESS is specifically evaluated for the Tamnava watershed having in mind that the planned detention basins and their flood mitigation effectiveness would be affected by excessive sediment deposition if there were no erosion control in upper reaches of the watershed (Ristić & Macan, 1997). Specifically, this value is obtained by calculating the benefit from implementing the counter-erosion measures in the watershed, and then dividing this benefit with the land area where the measures are applied (see also section 2.7.3.2). The benefits from the counter-erosion measures are estimated as a reduction in sediment dredging expenses after the measures are implemented. The sediment loads before and after implementation of the measures are estimated at the locations of the three planned detention basins considering runoff volume and maximum concentration of suspended sediment in flood hydrograph.

Having estimated the values of ESS per unit area on the annual basis for different land cover categories, the overall value of ESS in a watershed are obtained by multiplying the unit value by corresponding areas and summing over all land cover categories. This process is also known as an initial ESS valuation. The benefits from implementing specific mitigation scenarios are then re-evaluated per land cover category, and the updated ESS values are compared to those for baseline conditions.

Table 5. Ecosystem services identified in the Tamnava River watershed

Type of ecosystem services	**Principal land covers**				
	Agricultural	**Pasture**	**Forest**	**Wetlands**	**Rivers and lakes**
Provisional					
Food production	X	-	-	-	X
Water supply	X	-	X	X	X
Regulatory					
Climate regulation	X	X	X	X	X
Flood risk mitigation	X	-	X	X	X
Soil erosion control	X	-	X	X	-
Water regulation	-	-	X	X	X
Biological control	X	X	X	X	-
Water quality	-	X	-	-	X
Soil formation	X	X	-	-	-
Nutrient cycling	X	-	-	-	-
Supporting					
Habitat refugium	-	-	X	X	X

Note: (X) Ecosystem service produced by land cover class and valued in this research (-) Ecosystem service either not produced by the land cover class, or not valued in this research.

2.7 Evaluation of benefits from flood mitigation strategies

2.7.1 Development of mitigation scenarios

To enable comparison of benefits from implementing green and grey measures, and, consequently, identification of the optimal flood protection setup, four general alternative flood mitigation scenarios can be considered:

- baseline scenario;
- grey scenario;
- green scenario;
- grey-green scenario.

The baseline or "no action" scenario is necessary in any kind of analysis that should evaluate the effects of the planned measures. The grey scenario consists only of man-made (grey) measures. Similarly, the green scenario comprises only the green infrastructure or nature-based solutions. Finally, the mixed grey-green scenario represents a realistic assumption that an area or watershed of interest already has some mitigation measures implemented, which are most probably grey measures.

It should be noted that the distinction between green and grey measures is not a clear, straightforward one. In terms of the building material, grey measures are usually imagined as the concrete structures, while the green measures are thought to be built from natural material.

In this thesis, the distinction between the two groups of measures is not made upon the building material, but rather according to the ecosystem services that the measures can provide. This categorization is in line with the definition provided by European Commission, stating that green infrastructure "provides great benefits for both citizens and biodiversity" and is "designed and managed to deliver a wide range of ecosystem services."[8] For example, the dams of the detention basins, which are generally considered green infrastructure, may be made of (reinforced) concrete or steel; however, the detention basins may provide habitat for wildlife and keep a fish stock, and their application is deemed to "contribute to meeting the objectives of the 2020 Biodiversity strategy" (NWRM, 2015). In addition, detention basins may offer recreational opportunities. On the other hand, the levees are generally made of local earthen material, but they cannot be considered a habitat (moreover, they require constant maintenance to prevent presence of rodents and vegetation that may affect their stability). Consequently, the levees are considered grey measures.

The four alternative scenarios described above are applied in this thesis for the Tamnava River watershed. The mitigation measures for this area proposed in the Kolubara study and described in section 2.2.2, are grouped as grey and green infrastructure measures. The scenarios are compared in Table 6 and can briefly be described as follows:

- **Baseline scenario** (existing conditions, "no action" scenario). This scenario includes only existing grey measures (levees) and assumes that flood protection level in the watershed would remain the same in the future;
- **Grey scenario** expands the baseline scenario with raising the existing levees and construction of the Gračica-Ub bypass canal;
- **Green scenario** builds on the baseline scenario with addition of three proposed detention basins and natural counter-erosion measures as green measures;
- **Grey-green scenario** adds to the baseline scenario both grey (heightened levees and the Gračica-Ub bypass canal) and green measures (detention basins and counter-erosion measures).

Table 6. Comparative scenario and mitigation measures used in the study.

	Existing	**Grey measures**		**Green measures**	
Mitigation scenario	**Urban and agricultural levees**	**Existing levee raising**	**Gračica-Ub bypass**	**Detention basins**	**Natural counter-erosion measures**
Baseline	X				
Grey	X	X	X		
Green	X			X	X
Grey-green	X	X	X	X	X

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[8] https://ec.europa.eu/environment/nature/ecosystems/benefits/index_en.htm

2.7.2 Validation of the baseline scenario model using historical data

Estimating potential losses from floods is a complex process, generally associated with high uncertainties. These uncertainties accompany all phases of the process, starting from flood hazard modelling (e.g., uncertainties related to hydrologic or hydrodynamic model parameters) to damage assessments (e.g., uncertainties in depth-damage functions). It is therefore desirable to validate the damage assessment methodology (i.e., the damage model) against the observed (historical) data, to appraise the capability of the methodology for realistic damage estimates under hypothetical (unobserved) flood events (Merz et al., 2010). However, historical damage data are seldom available for a range of flood magnitudes to perform full model validation. Yet, limited observed damage data is still beneficial in developing and validating the damage model. In absence of any historical data, Merz et al. (2010) recommend validating the damage assessments by comparing alternative damage models or by using expert knowledge.

The available historic data can be used to validate micro-scale damage modelling in two different ways:

- **Quantitatively**; to calibrate hydrodynamic models, which constitute the base of the flood hazard simulations. Historically recorded high water marks, and the observed boundaries of flooded areas are used to confirm hydrologic, morphologic, and hydraulic assumptions used in building and refining the overall watershed model;
- **Qualitatively**; the losses from the historic flood events can be estimated using the developed damage model and compared to the (official) post-event assessments in all corresponding damage categories.

In this thesis, the flood hazard in the Tamnava River watershed is assessed based on the outputs of hydrological and hydrodynamic models, calibrated against the historical flood events and validated on the major 2014 flood.

The micro-scale damage model for the baseline scenario is validated against the 2014 flood post-disaster damage assessments in the Kolubara study for four asset categories: combined damages for building structures and content, agricultural losses, and damages to transportation infrastructure. Population displacement was not considered in the Kolubara study, but the number of flood-affected individuals in the model was estimated as described in 2.4.4, and compared to the reported data.

2.7.3 Evaluating benefits from flood mitigation strategies

Two types of benefits resulting from implementation of flood mitigation measures are considered in this thesis. Primary benefits are the losses avoided, due to application of mitigation measures designed to protect major asset categories. The losses are estimated as described in sections 2.4 and 2.5, and the mitigation benefits are consequently calculated through the reduction of these losses.

Secondary benefits are generally considered the non-disaster related benefits, of socio-economic or environmental nature. They may arise under limited number of scenarios and may be restricted to a smaller geographic area.

An example of secondary benefits considered in this thesis is related to the natural counter-erosion measures in upper reaches of the Tamnava River watershed, included in green and grey-green scenarios. These measures mainly consist of reforestation, and their principal purpose is to reduce soil erosion and sediment inflow to the detention basins, while they can also contribute to reducing flood runoff from the upstream areas. By reducing soil erosion and flood runoff, the reforestation measures provide primary benefit for the flood mitigation in the watershed. However, additional forested area provides additional ESS, such as habitat refugium, water supply and control, etc. and therefore provides secondary benefits in an increased value of the watershed.

2.7.3.1 Primary benefits

The effectiveness of a particular flood mitigation scenario S is measured by the reduction of losses in comparison to the baseline scenario. In other words, the benefit gained by implementing specific scenario S is quantified in terms of avoided damages, i.e., as the difference between flood damage D_0 estimated without these measures (baseline scenario) and the damages D_S with these measures (scenario S).

For the natural (historic) events, the magnitude of the flood is a random variable with a probability distribution. Consequently, the damage induced by the flood is also a random variable with generally unknown probability distribution. For the simulated events, the damages are evaluated for a range of selected flood probabilities, i.e., for a range of selected recurrence intervals.

The expected annual damage EAD is the common quantifier of the flood risk and can be obtained from the probability distribution of the damages (Olsen et al., 2015). In practice, EAD is calculated as a sum-product of damages and their annual probabilities of exceedance:

$$\mathrm{EAD} = \sum_{i=1}^{M} D_i p_i \tag{1}$$

where M is the number of probabilities of flood hazard for which the damages are evaluated. The expected annual benefit from the mitigation scenario S can then be computed based on all M considered recurrence intervals $T_i = 1/p_i$, and taking into account L loss categories:

$$\mathrm{EAB}_S = \sum_{i=1}^{M} \sum_{j=1}^{L} \left(D_{0,ij} - D_{S,ij}\right) p_i \tag{2}$$

where EAB_S denotes expected annual benefit for flood mitigation scenario S, $D_{0,ij}$ are damages estimated for the baseline scenario (existing flood protection level in the watershed), and $D_{S,ij}$ are damages under flood mitigation scenario S. Subscript i indicates loss category, whereas subscript j is related to flood recurrence interval. Five different loss categories are considered in this study ($L = 5$).

For the long-term monetary analysis, it is useful to compute the total benefit as the net present value NPV_S from implementing specific flood mitigation scenario S by taking into account discount rate d and planning horizon N, as follows:

$$\text{NPV}_S = \sum_{t=1}^{N} \frac{\text{EAB}_S}{(1+d)^t} \tag{3}$$

Flood mitigation scenarios for the case study of the Tamnava River are evaluated in this thesis for a total of seven recurrence intervals: 2-year, 10-year, 20-year, 50-year, 100-year, 200-year, and 1,000-year recurrence interval. The long-term benefits are calculated for the planning horizon of 50 years, assuming the standard discount rate of 7%.

2.7.3.2 Secondary benefits: site-specific value of ESS

To estimate a site-specific value of ESS, the above EAB needs to be isolated for measures that include a change in land cover (forestation, vegetation filling, creation of wetlands) that will actively result in flood mitigation. Calculations are performed for a specific land cover category and for a specific regulatory function of ESS (flood reduction and erosion control being the most common ones for flood mitigation projects). As discussed in section 2.6.2, not all land cover categories contribute to flood mitigation. Equally, not all flood mitigation benefits can be attributed to improvement of ESSs. A part of the benefits for mitigation scenario S that does result from ESS can be defined as:

$$\text{EAB}_{ESS,S} = \sum_{i=1}^{O} \sum_{j=1}^{P} \text{EAB}_{i,j} \tag{4}$$

where O is the number of land cover categories in the watershed, and P is the number of ESSs germane to the flood loss reduction. $\text{EAB}_{i,j}$ are the EABs resulting from change in land cover i and ESS j. The site-specific value $\text{ESS}_{i,j}$ pertaining to a specific land cover category $\boldsymbol{i}$ and specific regulatory service j is calculated by dividing the annual benefits with the area A_i under land cover i:

$$\text{ESS}_{i,j} = \frac{EAB_{i,j}}{A_i} \tag{5}$$

The site-specific value of ESS [in $/ha/year] will then replace the initial assumed value, used in initial valuation of the considered watershed ecosystem.

3 CASE STUDY: THE TAMNAVA RIVER

3.1 Results of evaluating the flood mitigation scenarios

3.1.1 Flood hazard assessment

The flood hazard maps under the baseline and three alternative flood mitigation scenarios in the Tamnava watershed result from hydrodynamic modelling, as described in section 2.3, for each considered recurrence interval (2, 10, 20, 50, 100, 200 and 1,000 years) and each flood mitigation scenario. All 28 flood hazard maps (seven recurrence intervals for four mitigation scenarios) are shown in Appendix A.

The hazard map of the 100-year flood under existing flood protection system is shown in Figure 12. As described in section 2.1, the existing levees already provide some flood protection level to certain parts of the Tamnava watershed, primarily within the population centers (e.g., sectors 7′, 11′ and 11′′). These parts of the watershed have a lower flood hazard level under current conditions than the other sectors in the watershed. Flood hazard is particularly pronounced in the most downstream parts of the watershed (e.g., sectors 9 and 12, some parts of sectors 8 and 13′; see Figure 12).

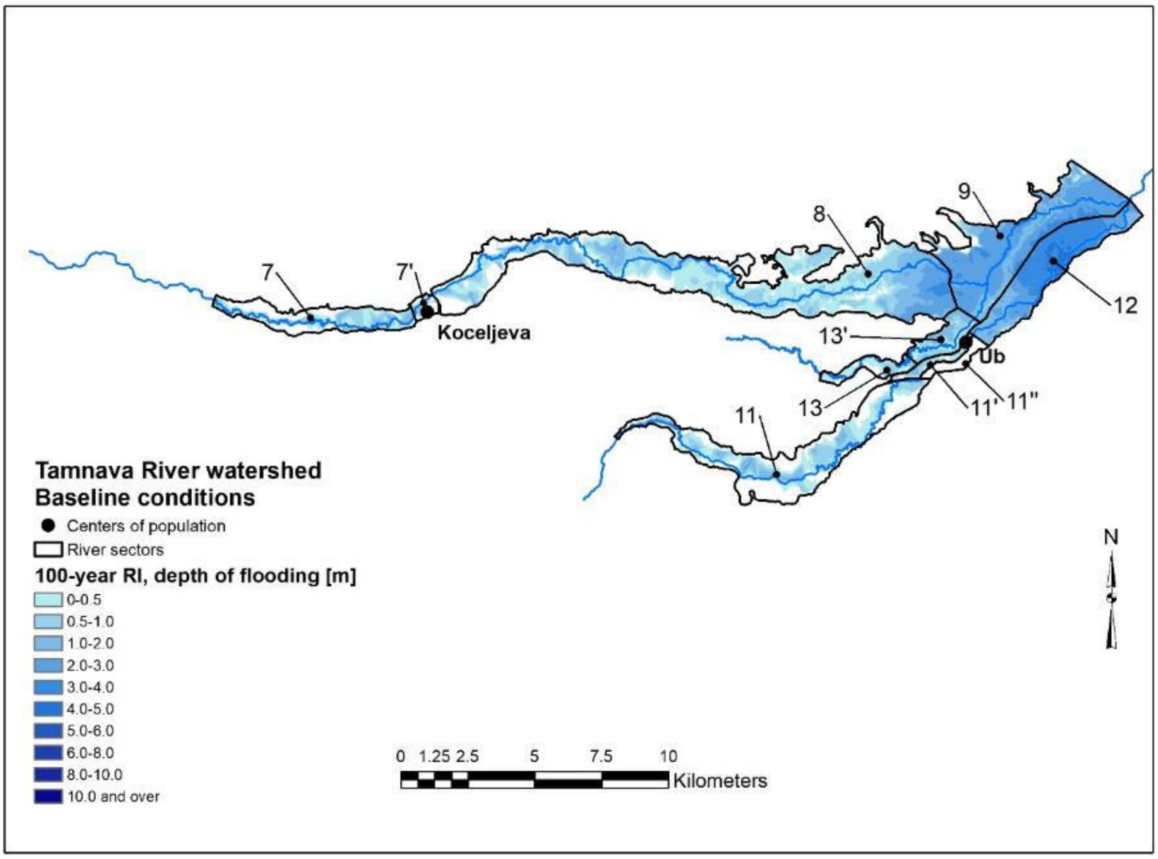


Figure 12. Flood hazard due to 100-year flood in the Tamnava watershed under the baseline scenario (existing flood protection system).

Figures 13, 14 and 15 present the 100-year flood inundation maps in the Tamnava watershed under the three considered scenarios of flood mitigation measures. The effects of the three scenarios can be inferred by comparing these hazard maps to the map in Figure 12. The greatest hazard reduction is obtained under the grey-green scenario. An interesting example are the most downstream sectors 9 and 12, which are not flooded by the 100-year event under any of the three mitigation scenarios. Although the protection level of the existing levees does not exceed 50 and 25 years, respectively, the detention basins proposed within the green and grey-green scenarios provide sufficient reduction of the 100-year flood peaks, so that they can be conveyed without overtopping in these sectors. Similar results are also observed for the 200-year flood, while the 1,000-year flood (not illustrated here) causes the levees to overtop in sectors 9 and 12. A reduction of flood hazard is also noticed in sector 13′, where construction of the bypass canal is planned (see Figure 5, Section 2.2.1)). Similar comparison of flood hazard maps for other recurrence intervals shows that the grey measures have effect in their immediate proximity, while the green measures (i.e., detention basins) reduce peak flows and pertinent flood levels along the downstream river sections, thus having farther-reaching effects.

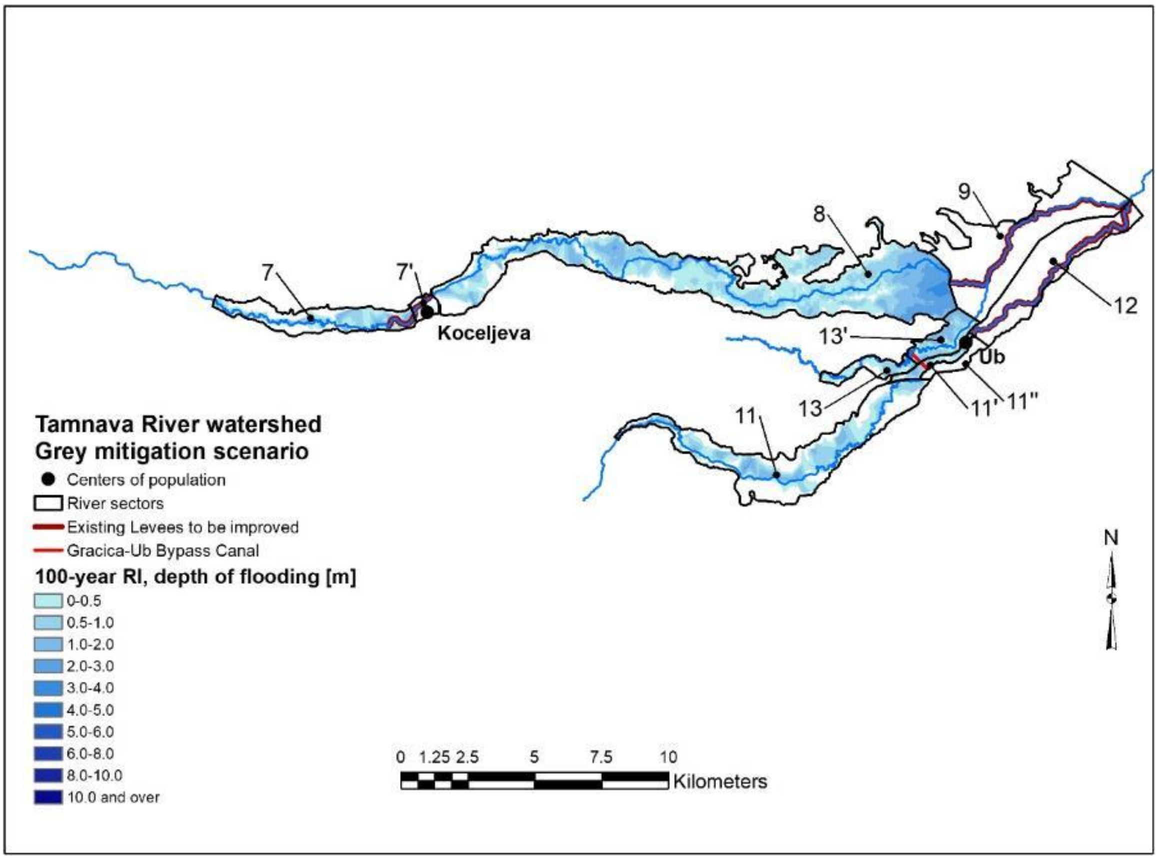


Figure 13. Flood hazard due to 100-year flood in the Tamnava watershed under the grey mitigation scenario (improvement of the existing flood protection system and construction of Gračica-Ub bypass canal).

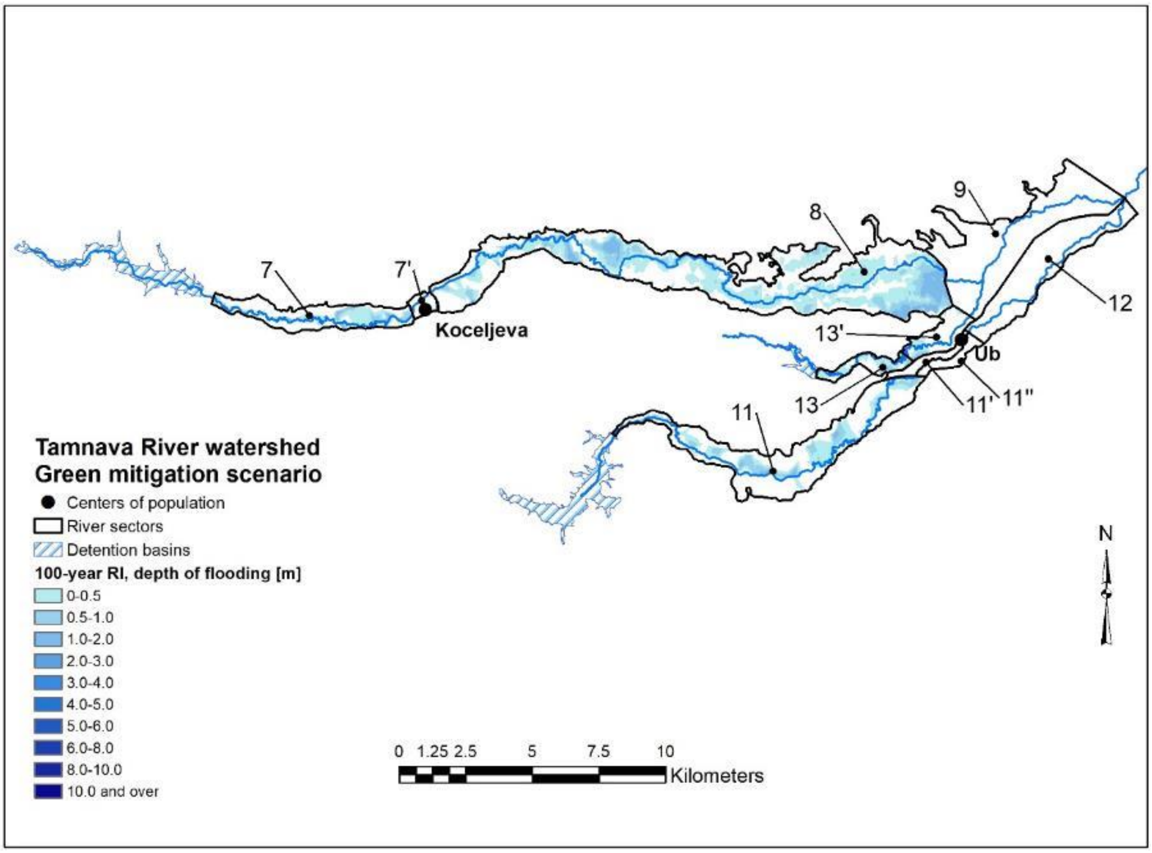


Figure 14. Flood hazard due to 100-year flood in the Tamnava watershed under the green mitigation scenario (construction of detention basins Kamenica, Gračica, and Pambukovica).

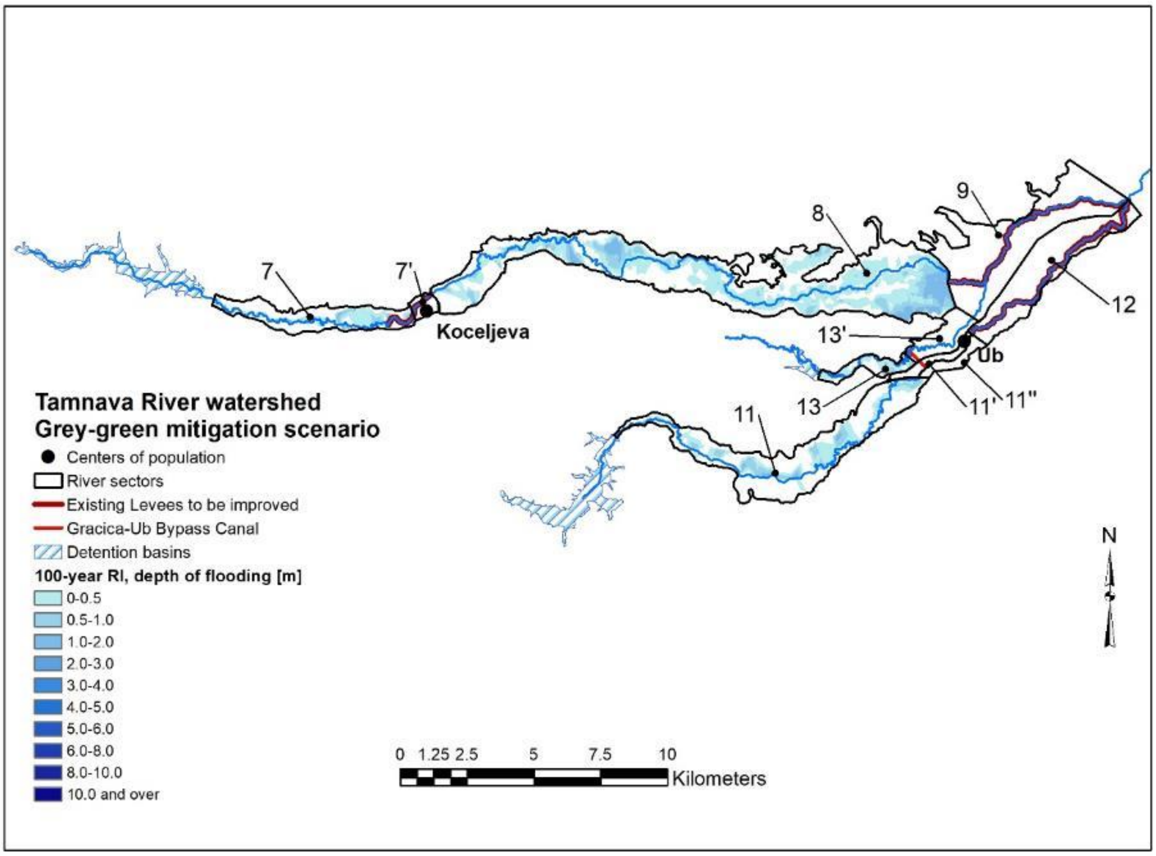


Figure 15. Flood hazard due to 100-year flood in the Tamnava watershed under the scenario combining grey and green mitigation measures.

The flood hazard/depth inundation maps for all scenarios and all recurrence intervals are produced with a one meter-square resolution, thus enabling a relatively precise identification of the affected assets and the depth of flooding water. Figure 16 shows water depth in each building in downtown Ub due to 200-year flood event under baseline and green scenarios and illustrates how the fine-scale asset data and a high-resolution hazard map (depth grid) facilitate the micro-scale assessment of damages.

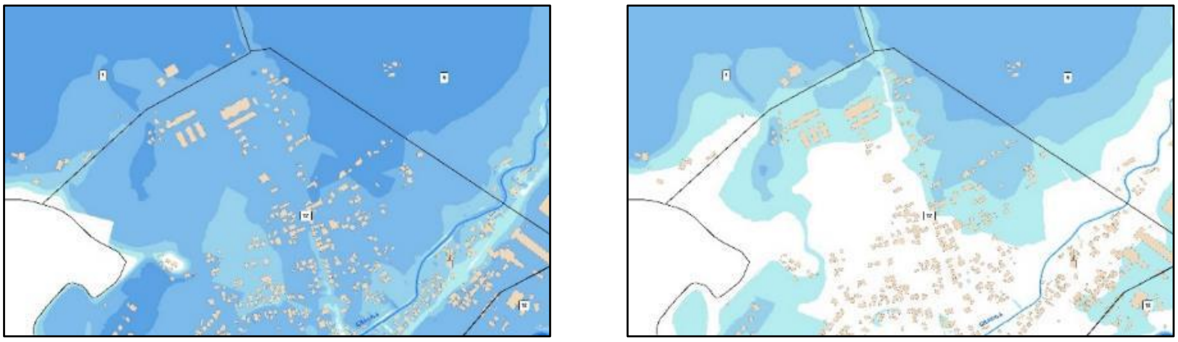


Figure 16. Water depths caused by 200-year flood event in downtown Ub, including part of sectors 8, 9, 12 and 13', under the baseline conditions (left panel) and under green scenario (right panel).

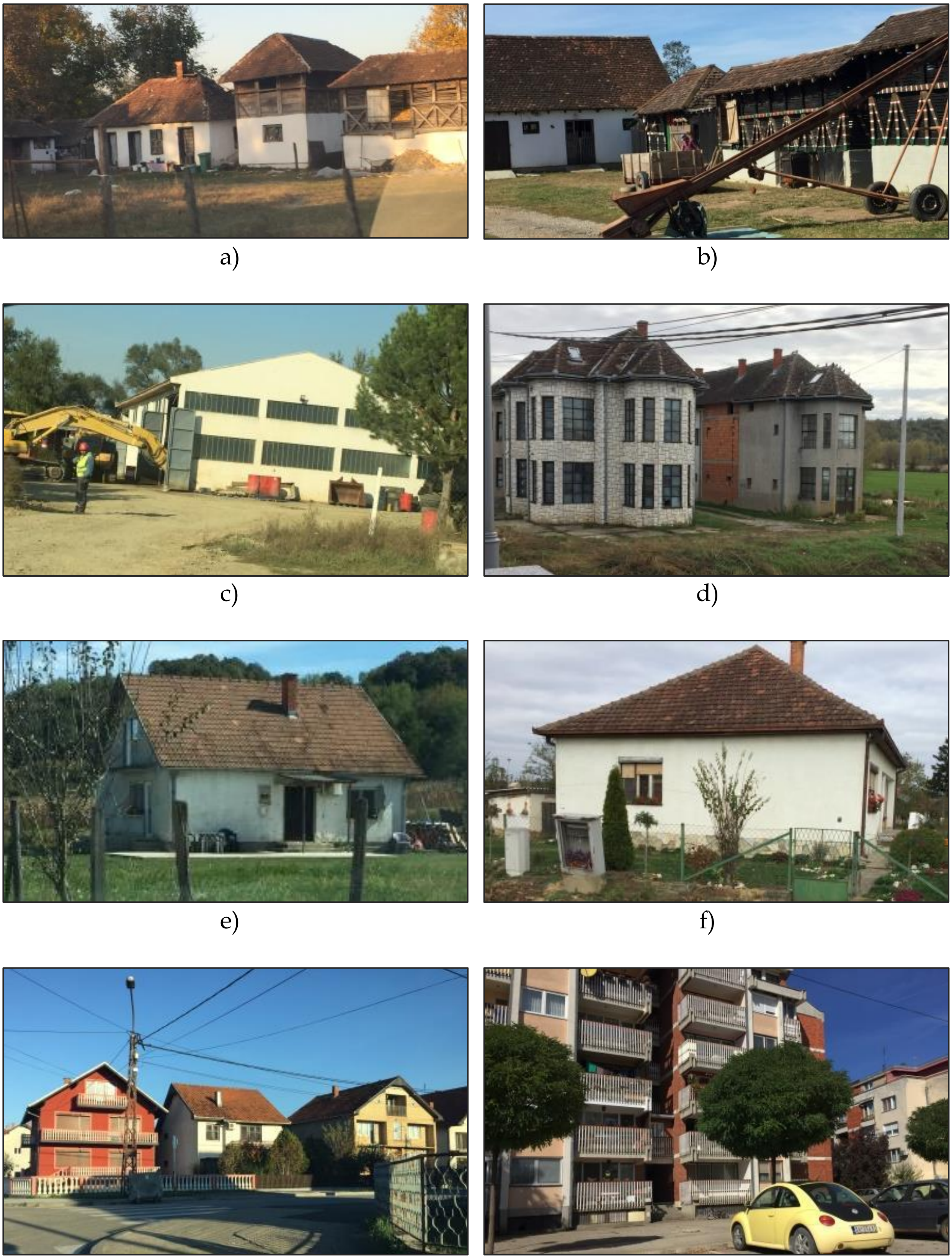
3.1.2 Asset identification and vulnerability assessment

3.1.2.1 Building stock

Using the aerial photogrammetric imagery, a total of 5,984 permanent structures were identified within the watershed's 1,000-year flood boundaries (adopted as the maximum potential extent of flooding). The breakdown of structures by type is presented in Table 7. The number of structures and their occupational classes were verified in the field. Of these, 63.5% are residential buildings (primarily single family, low-density and farm houses, with some multifamily residential housing), 27.8% are agricultural facilities, 6.4% are commercial, educational, and government structures, with the remaining 2.3% being light industrial buildings. The characteristics of the above types of structures (i.e., occupancy classes) are typical for this region and this part of the country (Jovanović Popović et al., 2012), as depicted in Figure 17.

Table 7. Breakdown of structures by type within the maximum potential extent of flooding.

Building occupational class	Building count	Percentage of total
• Residential (all types)	3,800	63.5%
• Commercial, educational, governmental, institutional	380	6.4%
• Manufacturing and light industrial	140	2.3%
• Transportation facilities	3	0.1%
• Agricultural facilities	1,661	27.8%
TOTAL	5,984	100%



a) b) c) d) e) f) g) h)

Figure 17. Typical structure types within the Tamnava watershed: a) and b) agricultural buildings; c) light industrial; d) commercial; e) and f) single family rural residential; g) and h) transitional and multifamily urban residential (source: author)

3.1.2.2 Agricultural production

As stated in section 2.4.2, the agricultural production losses in the Tamnava watershed are considered for the three principal crops (corn, potatoes, apples) and unbaled hay. These crops are selected so that the damage assessment can be compared to reported 2014 losses for the same categories from the Kolubara study. Using the 2012 CORINE land cover information (CLC, 2012), the principal agricultural subcategories are correlated with the corresponding land use categories within the study area: 211 (non-irrigated arable land), 231 (pastures), 242 (complex cultivation patterns), and 243 (agricultural land with natural vegetation). As stated in 2.4.2, the agricultural losses are only sustained in the areas exposed to direct flooding, and the extents of flooding vary for different recurrence intervals and different mitigation scenarios (Figure 18).

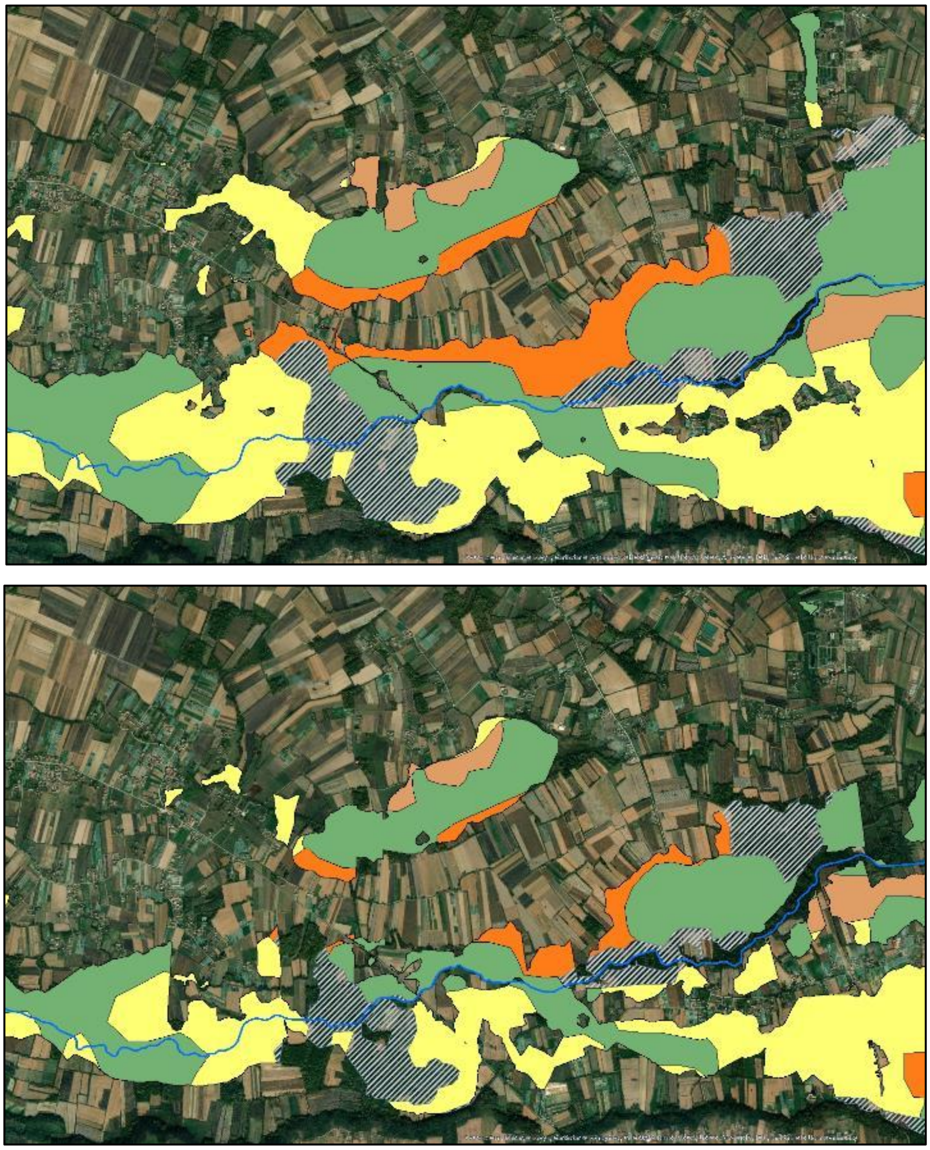


Figure 18. Illustration of reduction of the agricultural area exposed to flooding for a 100-year recurrence interval event along River Tamnava for baseline conditions (top) and after application of nature-based measures (bottom). Reduction of the agricultural area is monitored separately for each of the four agricultural land covers: 211 (orange), 231 (brown), 242 (yellow), and 243 (green).

The crop producing area exposed to agricultural losses reaches its maximum of 6,120 hectares during the 1,000-year recurrence interval flood event in baseline conditions. The breakdown of maximum flooding per culture is shown in Table 8.

Table 8. Agricultural production and potential losses due to flooding.

Culture	Flooded area [ha]	Percentage of total
Corn	3,748.5	61.2%
Potatoes	1,288.2	21%
Apples	789.5	12.9%
Unbaled hay	293.9	4.8%
TOTAL	6,120.1	100%

3.1.2.3 Transportation infrastructure

As indicated in section 2.4.3, the only transportation infrastructure losses considered in the Tamnava watershed are the flood-related damages to roadway infrastructure. For the purpose of this study, only the official state roadways (category Ib, IIa, and IIb) were analyzed within the Tamnava river watershed. In the study area, there are approximately 296 km of state roadways (Figure 19).

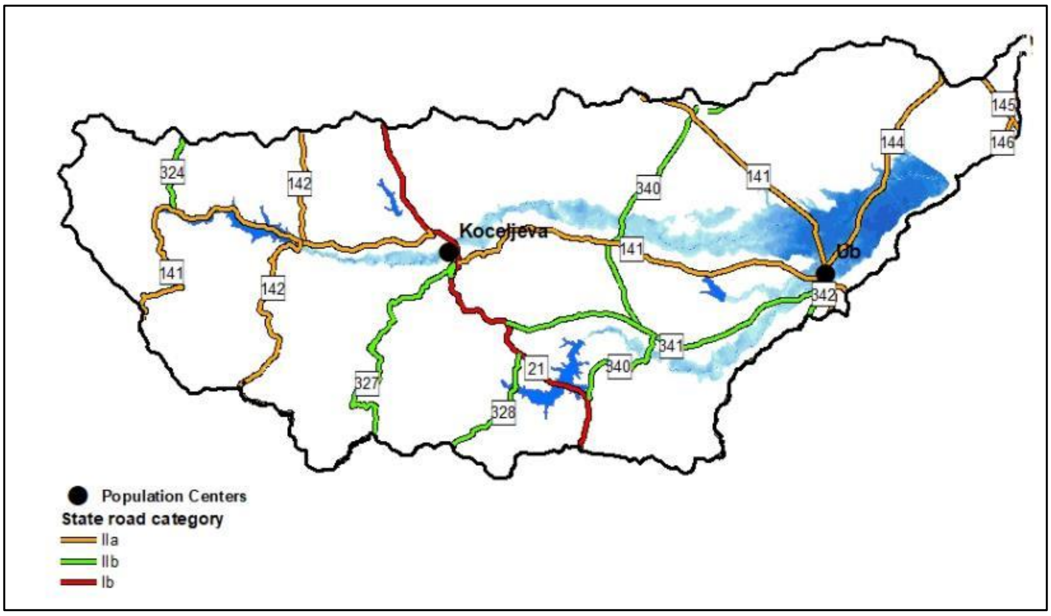


Figure 19. Network of State roads within the Tamnava watershed. 1,000-year recurrence interval flood boundaries illustrate sections of the network exposed to flooding

Of the 296 kilometers of State roads, only a fraction (approximately 16 km) is exposed to the potential maximum (1,000-year recurrence interval) flood waters of Tamnava, Gračica and Ub. Many more local roads within the study area are exposed to flooding, but they are not built, or regulated by the standards so their damages are hard to quantify and forecast. The identified State roads of category Ib, IIa, and IIb, all have relatively similar width specifications (two lanes 3.0-3.5 m wide, with shoulders 0.25-0.50 wide).

For the simplicity of calculations, it was assumed that the roads will have a uniform width of eight (8) meters. Table 9 depicts breakdown of roads by the category and their exposure to the 1,000-year floods.

Table 9. Roadway infrastructure and maximum potential flood exposure

State road category	Total road length [km]	Flooded road length [km]	Percentage of total
Ib	37.79	0.38	1.0%
IIa	140.50	12.0	8.5%
IIb	118.25	3.95	3.3%
TOTAL	296.54	16.32	5.5%

3.1.2.4 Population affected by flooding

As stated in section 2.4.4, the population displacement is considered only for the inhabitants whose residencies are directly affected by flooding. The number of inhabitants is based on the official affected population records from the Kolubara study. The population exposed to flooding within the study area is estimated at 9,155, with 3,800 residential structures in the same domain, producing an average of 2.41 inhabitants per structure. This number is conservative when compared to the official 2011 census numbers for Ub and Koceljeva municipalities (RZS, 2015), but is study-specific and is used to project population displacement for all other recurrence interval flood events.

3.1.3 Flood-related damages

3.1.3.1 Direct losses to building stock and contents

To achieve higher level of detail, calculations of flood-related damages to the building stock in this research are performed on a level of individual structures, as previously indicated in sections 2.4.1 and 2.5.1.

The depth-damage functions (DDFs) used in calculations are taken from the global data base (Huizinga et al., 2017) in their relative form (with damages expressed as a percentage of a maximum potential damage). Different DDFs are used for residential buildings, commercial, industrial, transportation facilities, and agricultural buildings and facilities (see Figure 20). To make the DDFs representative of structures in the study area, the maximum value of damages (the buildings replacement costs) was modified for Serbian economic profile and for inflation.

The same DDFs are also utilized for calculation of the content damages for corresponding occupational classes. The maximum damage value of the contents range between 50% and 150% of the maximum damage value for the corresponding structure, depending on its occupational class and type of its equipment.

Table 10 presents maximum value of flood-related damages to buildings and their contents, corresponding to losses caused by the 1,000-year flood under existing conditions. Flood damages to buildings and contents for all recurrence intervals are presented in Appendix B.

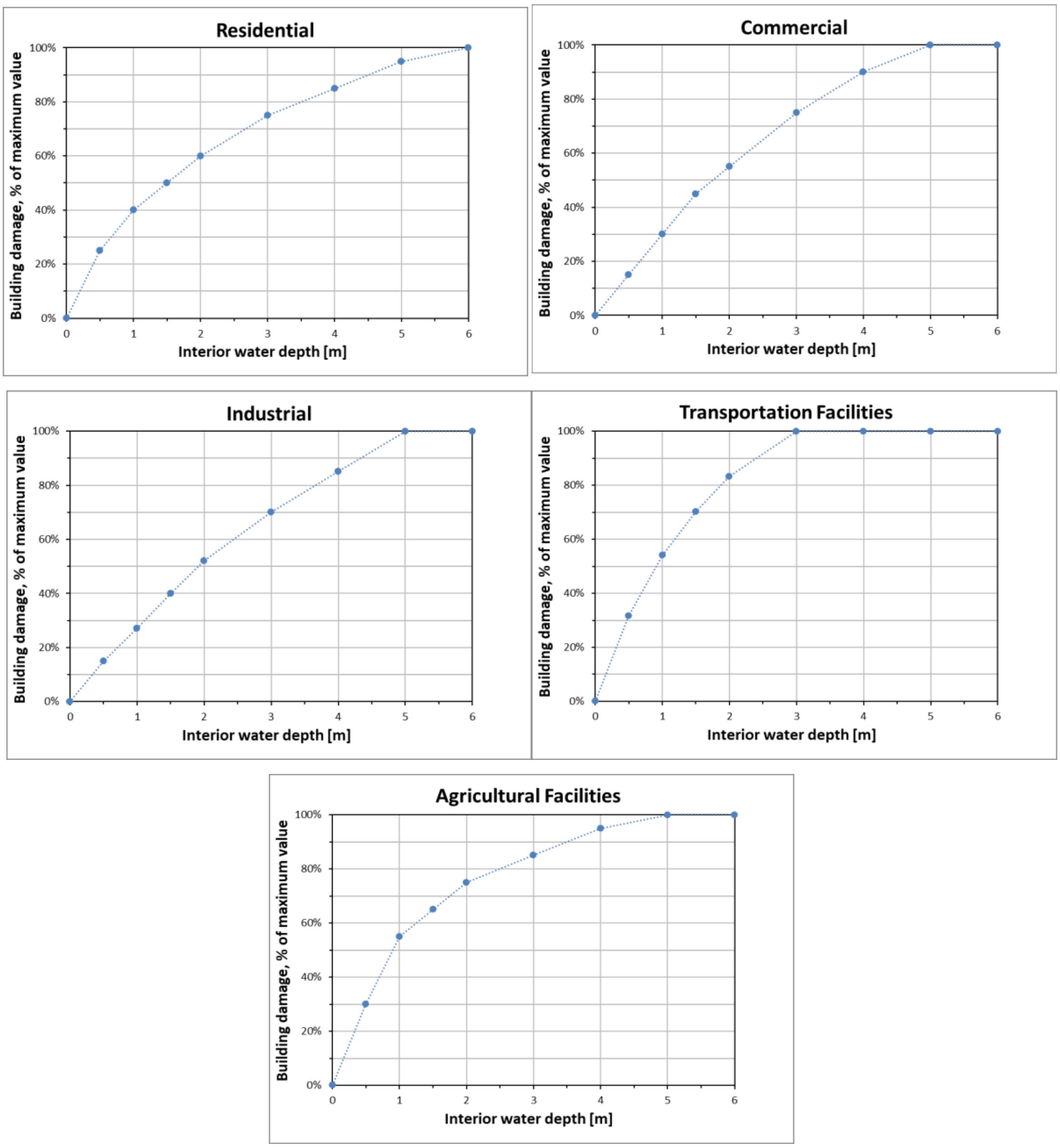


Figure 20. Depth Damage Functions used in Tamnava watershed calculations; as adopted from JRC Global DDF database for Europe

Table 10. Maximum estimated flood-related direct losses to buildings and contents in the Tamnava watershed

Building occupational class	Building count	Building losses [€]	Content losses [€]
• Residential (all types)	3,800	42,831,274	21,415,637
• Commercial, educational, governmental, institutional	380	11,096,244	11,096,244
• Manufacturing and light industrial	140	7,535,970	11,303,955
• Transportation facilities	3	187,646	187,646
• Agricultural facilities	1,661	13,302,035	12,129,461
TOTAL	5,984	74,953,168	56,132,943

3.1.3.2 Agricultural losses

As noted in sections 2.4.2, 2.5.2, and 3.1.2.2, agricultural losses are counted for four cultures (three principal crops and unbaled hay), using and modifying some of the relevant cost data from the Kolubara study and land cover information from 2012 CORINE land cover data base. Losses are calculated for each of the flood sectors, for all considered recurrence intervals (2, 10, 20, 50, 100, 200 and 1,000 years). Table 11 presents maximum value of flood-related losses for each of flood sectors for a 1,000-year recurrence interval flood. Appendix B contains flood-related agricultural losses for all recurrence intervals.

Table 11. Maximum estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors

Sector	Corn [€]	Potato [€]	Apples [€]	Unbaled hay [€]	Total per sector [€]
7	291,095	3,053	3,555	0	297,703
7'	15,916	0	0	0	15,916
8	1,278,879	1,633,839	1,902,750	23,309	4,838,777
9	520,852	1,093,111	1,273,024	31,094	2,918,081
11	297,755	874,354	1,018,263	1,234	2,191,605
11'	57,125	6,795	7,913	0	71,833
11''	17,319	4,705	5,479	1,247	28,750
12	292,621	972,560	1,132,633	4,226	2,402,040
13	33,250	225,530	262,650	0	521,429
13'	80,949	147,110	171,322	0	399,381
TOTAL	2,885,759	4,961,056	5,777,590	61,110	13,685,515

Table 12. Maximum estimated flood-related roadway losses in the Tamnava watershed, distributed by road category

State road category	State road number	Total flooded length [km]	Average water depth [m]	Level of damage [%]	Roadway damage [€]
Ib	21	0.38	0.62	29%	21,759
IIa	141	4.98	2.16	64%	632,723
	142	0.27	0.85	37%	20,207
	144	6.75	2.35	70%	948,080
IIb	340	1.49	0.67	31%	91,429
	341	1.94	0.71	32%	125,193
	342	0.52	1.28	49%	50,799
TOTAL		16.32			1,890,190

3.1.3.3 Transportation infrastructure losses

Calculation of flood-related losses to roadway infrastructure is limited to direct flood-damages to state roads. This scope is dictated by the limited amount of available information and by the generally low contribution of the roadway losses in an overall watershed flood loss analysis. Roadway flood damages are estimated for all considered recurrence intervals (2, 10, 20, 50, 100, 200 and 1,000 years). Table 12 presents maximum value of flood-related losses for each of roadway categories, including average depth of flooding, length of flooded road sections, and overall level of road damages, as produced by the methodology described in section 2.5.3. Flood-related damages to roadway infrastructure for all recurrence intervals are located in Appendix B.

3.1.3.4 Population displacement costs

As described in previous sections (2.4.4, 2.5.4, and 3.1.2.4), the costs to relocate flood-affected population generally include one-time evacuation costs and the expenses related to temporary housing, but only the latter is considered in this study (estimated at approximately 10 € per person per day (UNHCR Serbia, personal communication).

The number of inhabitants affected by flooding is estimated as a function of residential structures (households) within the flooded area, based on data from the 2014 flood. It is estimated that during the 1,000-year recurrence interval flood, approximately 3,180 residential structures would be affected, with population in excess of 7,600 displaced for various periods of time, ranging between 7 and 420 days. The maximum estimated displacement losses are in excess of 16 million euros. Losses are estimated per individual stream sectors and for all considered recurrence intervals. Table 13 lists the maximum estimated number of affected residential buildings and population displacement costs for the study area, corresponding to the 1,000-year flood under existing conditions. Appendix B contains population-displacement costs for all recurrence intervals.

Table 13. Maximum estimated displacement cost in the Tamnava watershed, distributed by flood sectors

Sector	Count of affected residencies	Displacement losses [€]
7	32	38,954
7'	310	497,471
8	314	1,335,514
9	643	5,749,410
11	54	65,686
11'	119	471,419
11''	752	3,446,512
12	70	573,470
13	20	15,010
13'	870	4,446,024
TOTAL	3,184	16,639,470

3.1.4 Valuation of ecosystem services

As discussed in section 2.6.2, five principal land cover categories (biomes) are identified in the study area of the Tamnava River watershed: agricultural, pasture, forest, wetlands, and lakes and streams. These five categories provide a range of ecosystem services (ESS), shown in Table 5 in the same section.

The valuation of the ESS in this study uses information on monetary values of ESS from several ecosystem databases and studies, including the ESVD database (ESVD, 2020) and other related studies. The ESS values refer to smaller agricultural watersheds, located mainly in Europe and North America. Where multiple studies or sources were available, the values are presented as a range, with minimum and maximum values, in 2020 €/ha/year.

The only value of ESS specifically derived from the Tamnava River watershed is the value for soil erosion control by forested areas, as described in subsection 3.1.4.1. The final results of the ESS valuation in the Tamnava watershed are shown in subsection 3.1.4.2.

3.1.4.1 Estimating secondary benefits from counter-erosion measures and site-specific value of ESS for soil erosion control

The proposed mitigation strategies within the Tamnava watershed in the Kolubara study include basin-wide measures aimed at watershed improvement, namely towards reduction of storm runoff and soil erosion. Most of the counter-erosion measures are located in the upper reaches of the three proposed detention basins: Kamenica, Pambukovica, and Gračica. The principal proposed non-point (land cover) measures include forestation, reforestation (fill), and grassing/regrassing of pastures. The breakdown of measures per each detention basin drainage area is listed in Table 14; the location of measures is depicted in Figure 21.

The proposed counter-erosion measures are designed to alleviate sediment loads entering the three detention basins for very high-volume storms, from 100-year recurrence intervals and above. Sediment loads for such storms are a function of the total runoff volume. The Kolubara study estimates the maximum concentration of suspended sediment in flood hydrograph entering the detention basin, $C_{\max}$, at 50 kg/m^3 of runoff volume. The total sediment load, G_{tot}, can be calculated as:

$$G_{\text{tot}} = C_{\max} \cdot V_{\text{tot}} \tag{6}$$

where total runoff volume, V_{tot}, is calculated from the simulated hydrograph of the inflow into the detention basins. Hydrologic calculations in the Kolubara study, using HEC-HMS model, were used to simulate the effects of the proposed counter-erosion measures by modifying the CN runoff coefficients, and consequently, the inflow hydrographs to the three detention basins.

Table 14. Breakdown of counter-erosion measures per the detention basin drainage area

Reservoir	Forestation [ha]	Filling [ha]	Regrassing [ha]	Total area [ha]
Kamenica	194.92	398.14	19.66	612.72
Pambukovica	216.99	724.21	13.50	954.70
Gračica		118.61		118.61
TOTAL	412	1,241	33	1,686

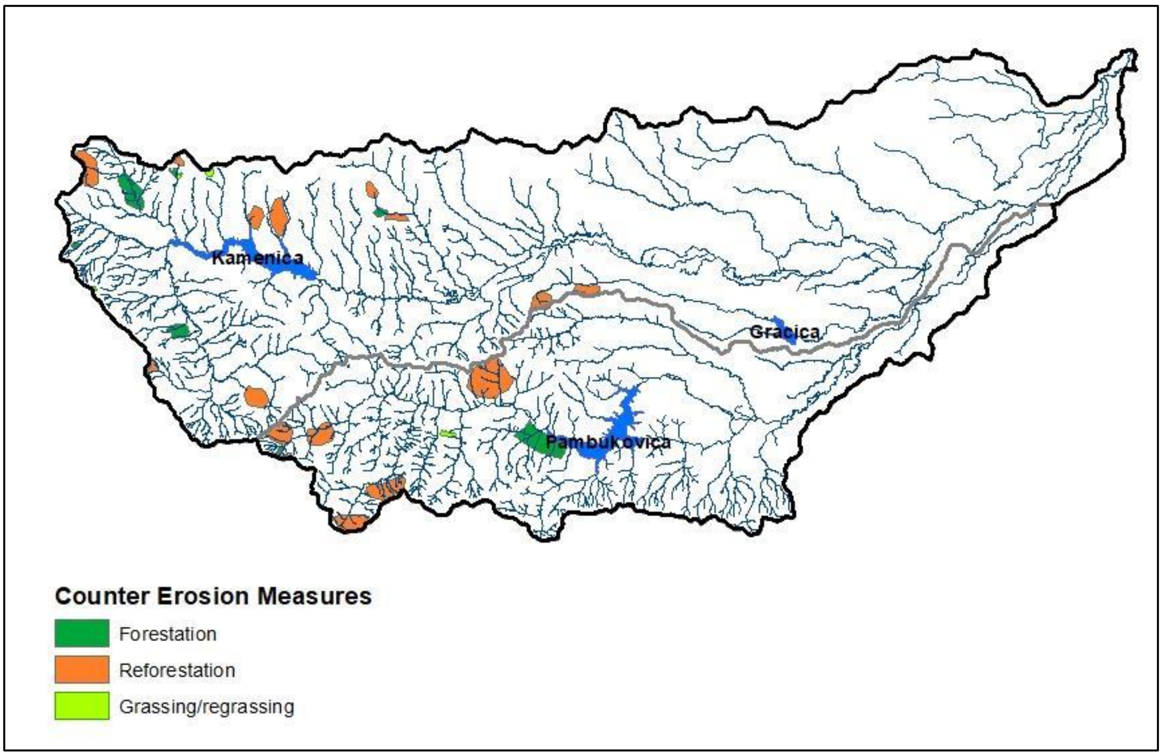


Figure 21. Location of non-point, counter-erosion measures in upper reaches of Tamnava, Ub and Gračica rivers.

The predicted sediment loads for the 100-year, 200-year, and 1,000-year recurrence interval floods, without counter-erosion measures, are presented in Table 15. When using a typical cost of €10/m^3 for similar sediment dredging operations, the maximum estimated expenses of dredging/sediment removal are approximately €10.4 million, for the 1,000-year event.

Table 15. Estimated sediment loads without counter-erosion measures in Kamenica, Pambukovica, and Gračica drainage areas

Sediment loads – existing conditions					
Recurrence interval	Kamenica basin	Pambukovica basin	Gračica basin	All basins	Sediment removal
[years]	[m^3]	[m^3]	[m^3]	[m^3]	[€]
1,000	556,290	389,579	94,050	1,039,919	10,399,190
200	381,276	255,087	63,954	700,317	7,003,170
100	317,219	207,203	52,979	577,401	5,774,010

Table 16 presents estimates for the counter-erosion measures in place. The erosion process for higher frequency events is considered not nearly as intense (UNDP Serbia, 2016, Petković et al ,1992) and is not calculated in this thesis. The resulting sediment reductions (compared to the existing conditions) are annualized to obtain the expected erosion reduction (last row for each reservoir in Table 16). Total annualized difference in sediment load with the counter-erosion measures in place is 2,828.6 m^3/year.

Table 16. Calculation of annualized sediment load reductions due to application of the counter-erosion measures in Kamenica, Pambukovica, and Gračica drainage areas

Kamenica basin sediment load

Recurrence interval	Existing conditions	Measures in place	Difference	Reduction	Annualized difference
[years]	[m^3]	[m^3]	[m^3]	[%]	[m^3/year]
1,000	556,290	438,620	117,671	21.2	118
200	381,276	283,667	97,609	25.6	488
100	317,219	228,744	88,475	27.9	885
TOTAL					**1,490**

Pambukovica basin sediment load

Recurrence interval	Existing conditions	Measures in place	Difference	Reduction	Annualized difference
[years]	[m^3]	[m^3]	[m^3]	[%]	[m^3/year]
1,000	389,579	295,929	93,649	24.0	94
200	255,087	181,350	73,737	28.9	369
100	207,203	142,133	65,070	31.4	651
TOTAL					**1,113**

Gračica basin sediment load

Recurrence interval	Existing conditions	Measures in place	Difference	Reduction	Annualized difference
[years]	[m^3]	[m^3]	[m^3]	[%]	[m^3/year]
1,000	94,050	76,194	17,856	19.0	18
200	63,954	49,203	14,751	23.1	74
100	52,979	39,632	13,347	25.2	133
TOTAL					**225**

The benefits of the reduction of the sediment load entering the detention basins are quantified as savings using documented costs for sediment dredging from canals and reservoirs. Using a unit cost of €10/m^3, the soil-erosion control measures for all three basins produce approximately € 28,286 in savings on an annual basis. In terms of ecological benefits/ESS, this is converted to a saving per unit area of land with the measures applied (total of 1,686 ha), yielding a value of 16.8 €/ha annually. Because of the dams regulating the flow from the basins, the benefits stemming from the counter-erosion measures remain localized and cannot be counted through the conventional loss estimates.

The above obtained value of the soil erosion control ESS is used in an updated valuation of the Tamnava watershed in the next subsection. It should be noted that the counter-erosion measures also contribute to the flood risk reduction ESS; the suspended sediment reduction stems from a sizable discharge reduction (20-30%) as well. For the sake of simplicity, these additional benefits were not included in the overall ecosystem function calculations.

3.1.4.2 Ecosystem valuation of the Tamnava river watershed

Valuations are made for ESS from five principal land cover categories shown in Table 5 in section 2.6.2. The annual value of ESS per unit area for the Tamnava River watershed are estimated with low and high values, with special consideration to flood risk mitigation and soil erosion control ESS, shown in Table 17. As noted previously, the low and high monetary estimates are based on the literature values for all ESS, except for the value of soil erosion control, estimated in the previous subsection.

Annual benefits from ESS in the Tamnava River watershed with a range of low and high values are presented in Table 18. It indicates that the annual contribution of ecosystems within the Tamnava River watershed ranges between 111 and 329 million euros. The wide range of annual values is the reflection of utilizing the results from the multiple studies, most of them non-specific to the Tamnava watershed. Despite that, the economic valuation of the Tamnava ecosystem services gives a good understanding of the watershed's intrinsic natural value for the projection of its future benefits.

Table 17. Low and high value for ecosystem services per unit area within the Tamnava River watershed, per land cover categories (* denotes ecosystem service values specific for the Tamnava River watershed)

	Agricultural		**Pasture**		**Forest**	
Ecosystem service	**Low value**	**High value**	**Low value**	**High value**	**Low value**	**High value**
Food production	1.4	20.5			0.1	16.3
Water supply	0.1	50.8			4,732.2	6,000.6
Climate regulation	95.4	95.4	3.1	16.8	52.2	860.9
Flood risk mitigation	0.1	3,102.6				
Soil erosion control	19.8	19.8			16.8*	16.8*
Water regulation					11.0	143.1
Biological control	51.8	51.8	97.8	97.8	32.8	32.8
Water quality			7.7	7.7		
Soil formation	19.7	19.7	21.7	21.7		
Nutrient cycling	75.7	75.7				
Habitat refugium					2,007.0	2,007.0
Total [€/ha/year]	264	3,436	130	144	6,835	9,061
Flood risk mitigation /soil erosion control only [€/ha/year]	20	3,122	0	0	16.8	16.8

Table 17 (continued). Low and high value for ecosystem services per unit area within the Tamnava River watershed, per land cover categories

	Wetlands		Rivers and lakes	
Ecosystem service	**Low value**	**High value**	**Low value**	**High value**
Food production	0.3	1,255.1	26.2	46.2
Water supply	57.8	5,236.5	86.5	3,505.8
Climate regulation	2.4	610.6	35.1	45.5
Flood risk mitigation	312.4	10,238.9	9.1	1,055.1
Soil erosion control	1,082.4	16,008.7		
Water regulation	96.5	357.3	51.4	51.4
Biological control	197.8	197.8		
Water quality	43.6	5,922.4	124.6	2,260.7
Soil formation				
Nutrient cycling				
Habitat refugium	218.0	2,225.6	7.9	63.5
Total [€/ha/year]	2,011	42,053	341	7,028
Flood risk mitigation /soil erosion control only [€/ha/year]	1,395	26,248	9	1,055

Table 18. Annual values for ecosystem services produced in the Tamnava River watershed (with updated ESS for forest land cover)

		Annual value per unit area [€/ha]		**Annual value [€]**	
Land cover category	**Area [ha]**	**Low value**	**High value**	**Low value**	**High value**
Agricultural	56,625	264.00	3436.30	14,949,000	194,580,488
Pasture	974	130.3	144.0	126,912	140,256
Forest	13,955	6,835	9,061	95,386,612	126,442,069
Wetlands	171	2,011	42,053	343,915	7,191,046
Rivers and lakes	33	340.8	7,028.2	11,246	231,931
Total	71,758			110,817,685	328,585,789

3.1.5 Evaluation of benefits from flood mitigation strategies

3.1.5.1 Flood mitigation scenarios

Four alternative scenarios (baseline, grey, green, and grey-green) for flood mitigation in the Tamnava watershed are defined in section 2.7.1. All proposed future scenarios are measured against the existing (baseline) conditions.

Grey scenario implies raising the existing levees in river sectors 7′ (urban, through Koceljeva), and 9 and 12 (agricultural levees). Grey scenario also includes construction of the Gračica-Ub bypass canal, as proposed in UNDP study.

Green scenario includes three proposed detention basins (Kamenica, Pambukovica, and Gračica), with the counter-erosion measures in the headwaters of their drainage areas. The green scenario also includes all existing urban and agricultural levees with the levels of flood protection they currently provide.

The hybrid, grey-green scenario includes implementation of both green (detention basins and counter-erosion measures) and grey measures (heightened levees and the Gračica-Ub bypass canal) in the watershed.

The baseline conditions and the three mitigation scenarios are summarized in the tables 19 through 22 below, with respect to the individual river sectors and corresponding levels of flood protection.

Table 19. Tamnava River watershed – flood protection measures in existing (baseline) conditions

Stream	Sector	General description	Flood protection measures
Tamnava	Headwaters	Undisturbed / rural	-
	7	Rural	-
	7'	Urban	Urban levees, 50-year protection
	8	Rural	-
	9	Rural	Agricultural levees, 50-year protection
Ub	Headwaters	Undisturbed / rural	-
	11	Rural	-
	11'	Urban	Urban levee, 100-year protection
	11''	Urban	Urban levee, 100-year protection
	12	Rural	Agricultural levees, 25-year protection
Gračica	Headwaters	Undisturbed / rural	-
	13	Rural	-
	13'	Semi-urban	-

Table 20. Tamnava River watershed – flood protection measures in grey infrastructure scenario

Stream	Sector	General description	Flood protection measures
Tamnava	Headwaters	Undisturbed / rural	-
	7	Rural	-
	7'	Urban	Urban levees, 100-year protection
	8	Rural	-
	9	Rural	Agricultural levees, 100-year protection
Ub	Headwaters	Undisturbed / rural	-
	11	Rural	-
	11'	Urban	Urban levee, 100-year protection
	11''	Urban	Urban levee, 100-year protection
	12	Rural	Agricultural levees, 100-year protection
Gračica	Headwaters	Undisturbed / rural	-
	13	Rural	-
	13'	Semi-urban	Bypass canal Gračica-Ub

Table 21. Tamnava River watershed – flood protection measures in green infrastructure scenario

Stream	Sector	General description	Flood protection measures
Tamnava	Headwaters	Undisturbed / rural	Kamenica detention basin and counter-erosion measures
	7	Rural	-
	7'	Urban	Urban levees, 50-year protection
	8	Rural	-
	9	Rural	Agricultural levees, 50-year protection
Ub	Headwaters	Undisturbed / rural	Pambukovica detention basin and counter-erosion measures
	11	Rural	-
	11'	Urban	Urban levee, 100-year protection
	11''	Urban	Urban levee, 100-year protection
	12	Rural	Agricultural levees, 25-year protection
Gračica	Headwaters	Undisturbed / rural	Gračica detention basin and counter-erosion measures
	13	Rural	-
	13'	Semi-urban	-

Table 22. Tamnava River watershed – flood protection measures in grey-green infrastructure scenario

Stream	Sector	General description	Flood protection measures
Tamnava	Headwaters	Undisturbed / rural	Kamenica detention basin and counter-erosion measures
	7	Rural	-
	7'	Urban	Urban levees, 100-year protection
	8	Rural	-
	9	Rural	Agricultural levees, 100-year protection
Ub	Headwaters	Undisturbed / rural	Pambukovica detention basin and counter-erosion measures
	11	Rural	-
	11'	Urban	Urban levee, 100-year protection
	11''	Urban	Urban levee, 100-year protection
	12	Rural	Agricultural levees, 100-year protection
Gračica	Headwaters	Undisturbed / rural	Gračica detention basin and counter-erosion measures
	13	Rural	-
	13'	Semi-urban	Bypass canal Gračica-Ub

3.1.5.2 Validation of the damage assessment model using the 2014 flood event data

The losses from the May 2014 flood are estimated using the micro-scale damage assessment approach, described in section 2.5 and compared to the corresponding post-event damage assessments given in the Kolubara study. The comparison is possible for two asset categories: combined residential damages for building structures and content, and agricultural losses. Population displacement was not considered in the Kolubara study, while the 2014 roadway damages were not itemized in a format correspondent to the results in this thesis.

Table 23 shows damage estimates of the 2014 flood for residential structures and contents and three other loss categories considered in this case study. The difference between the estimated damages to the residential structures and contents in two assessments is within 2.5% (the estimate of € 37,897,822 in this study largely corresponds to the estimate of € 38,869,942 from the Kolubara Study). The two estimates of agricultural damages also are in good agreement (€ 13,113,716 in this thesis vs. the estimate of € 13,110,157 in the Kolubara study).

Table 23. Assessment of 2014 floods in Tamnava River watershed under baseline conditions for selected damage categories

Residential building losses	Residential content losses	Agricultural losses	Roadway losses	Displacement losses
[€]	[€]	[€]	[€]	[€]
25,265,215	12,632,607	13,113,716	977,420	8,091,897

The validation results suggest that the flood losses estimated in this study can be considered valid and can provide reasonably realistic assessments of benefits gained by implementing various flood mitigation measures. Table 24 presents 2014 damage assessment for all damage categories considered in this thesis. The losses for non-residential structures add approximately € 18.5 million, with an additional € 19.5 million in non-residential contents losses. The total estimated damages for the 2014 floods are € 98,198,729.

Table 24. Assessment of 2014 floods in Tamnava River watershed under baseline conditions for all damage categories considered in this thesis

All building losses	All content losses	Agricultural losses	Roadway losses	Displacement losses
[€]	[€]	[€]	[€]	[€]
43,734,883	32,280,813	13,113,716	977,420	8,091,897

3.1.5.3 Assessment of damages

The results of flood damage assessment under the baseline conditions in the Tamnava River watershed for the considered recurrence intervals are shown in Table 25. The results for the grey, green, and grey-green scenarios are shown in Tables 26, 27, and 28.

Table 25. Baseline conditions - calculation of five damage categories and sediment removal expenses for different flood recurrence intervals in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Agricultural losses	Roadway losses	Displacement losses	Sediment removal
[years]	[€]	[€]	[€]	[€]	[€]	[€]
1,000	74,953,168	56,132,943	13,685,515	1,890,190	16,639,470	10,399,190
200	48,600,995	36,186,557	13,004,008	1,292,758	9,492,074	7,003,170
100	34,630,968	27,598,839	12,725,355	1,012,275	6,033,820	5,774,010
50	9,881,742	8,155,595	9,082,722	72,819	1,457,801	-
20	2,467,790	1,869,942	5,839,652	47,150	395,142	-
10	1,159,178	934,439	4,362,976	32,427	191,423	-
2	311,980	283,531	1,446,811	11,371	50,360	-

Table 26. Grey scenario - calculation of five damage categories and sediment removal expenses for different flood recurrence intervals in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Agricultural losses	Roadway losses	Displacement losses	Sediment removal
[years]	[€]	[€]	[€]	[€]	[€]	[€]
1,000	74,953,168	56,132,943	13,685,515	1,890,190	16,639,470	10,399,190
200	48,600,995	36,186,557	13,004,008	1,292,758	9,492,074	7,003,170
100	8,853,725	6,661,773	7,288,884	445,579	1,423,808	5,774,010
50	1,911,305	1,606,457	6,397,908	56,892	280,218	-
20	1,238,122	1,059,726	5,578,745	38,162	171,785	-
10	837,251	719,954	4,186,937	27,578	125,264	-
2	267,662	247,717	1,390,538	11,344	46,044	-

Table 27. Green scenario - calculation of five damage categories and sediment removal expenses for different flood recurrence intervals in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Agricultural losses	Roadway losses	Displacement losses	Sediment removal
[years]	[€]	[€]	[€]	[€]	[€]	[€]
1,000	62,438,328	46,891,002	13,402,702	1,681,369	13,284,734	8,107,430
200	2,170,556	1,704,975	6,056,455	347,443	344,140	5,142,200
100	995,355	842,357	4,849,636	28,892	145,953	4,105,090
50	486,800	425,097	3,609,696	27,240	78,427	-
20	194,454	181,767	1,923,343	3,982	32,152	-
10	84,438	82,947	666,556	2,596	14,424	-
2	3,598	2,791	74,342	1,375	-	-

Table 28. Grey-green scenario - calculation of five damage categories and sediment removal expenses for different flood recurrence intervals in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Agricultural losses	Roadway losses	Displacement losses	Sediment removal
[years]	[€]	[€]	[€]	[€]	[€]	[€]
1,000	62,438,328	46,891,002	13,402,702	1,681,369	13,284,734	8,107,430
200	1,566,043	1,322,439	5,843,714	45,947	227,690	5,142,200
100	870,214	744,778	4,701,335	26,954	128,996	4,105,090
50	436,085	383,569	3,510,551	27,108	73,399	-
20	176,164	165,270	1,860,745	3,982	29,680	-
10	83,484	81,993	641,669	2,596	14,256	-
2	3,598	2,791	72,750	1,375	-	-

In addition to losses for asset categories from section 3.1.3, these tables also include the expenses for sediment removal estimated in section 3.1.4.1. Sediment removal expenses in scenarios with no counter-erosion measures (baseline and grey scenario) are greater than those with these measures in place (green and grey-green scenario). It should be noted that the sediment removal expenses for existing conditions, with no counter-erosion measures (the baseline and grey scenarios), would still be incurred in river reaches downstream of the planned detention basins. Furthermore, the benefits from the counter-erosion measures cannot be attributed to any particular river sector, as they contribute to the overall watershed benefits of the green and grey-green mitigation scenarios.

Total losses due to floods of different recurrence intervals and under different flood mitigation scenarios are computed for each river sector in the Tamnava watershed by summing the losses over the five considered loss categories (building structures and their content, agriculture, population displacement, roadway damages) and projected expenses for sediment removal, as shown in Table 29. The total losses are presented in Figure 22 in function of the flood recurrence interval, representing the probability distribution of the total damage for each scenario.

The grey scenario exhibits notable improvement over the baseline conditions, for the losses are significantly reduced up to the 100-year recurrence interval. For floods exceeding the 100-year recurrence interval, which is the design criterion for the elevated levees in grey scenario, the losses revert to those for the baseline conditions. The green scenario losses, on the other hand, are smaller to the ones for the baseline and grey scenarios for all recurrence intervals including for the 1,000 years. Finally, the losses for the grey-green scenario show just a marginal improvement in comparison to the green scenario.

Total damages per river sector are shown in Appendix C. The sectoral damage distributions exhibit somewhat different patterns depending on the relative improvement of protection for a particular sector, but they generally show that the green scenario is superior to the grey scenario, while just marginally below the grey-green scenario.

Table 29. Overview of total losses for four flood mitigation scenarios and sediment removal expenses for different flood recurrence intervals in the Tamnava River watershed.

Recurrence interval	Baseline scenario	Grey scenario	Green scenario	Grey-green scenario
[years]	[€]	[€]	[€]	[€]
1,000	173,700,477	173,700,477	145,805,565	145,805,565
200	115,579,561	115,579,561	15,765,770	14,148,033
100	87,775,268	30,447,779	10,967,284	10,577,367
50	28,650,678	10,252,781	4,627,260	4,430,712
20	10,619,676	8,086,540	2,335,699	2,235,841
10	6,680,443	5,896,983	850,962	823,997
2	2,104,052	1,963,306	82,106	80,514

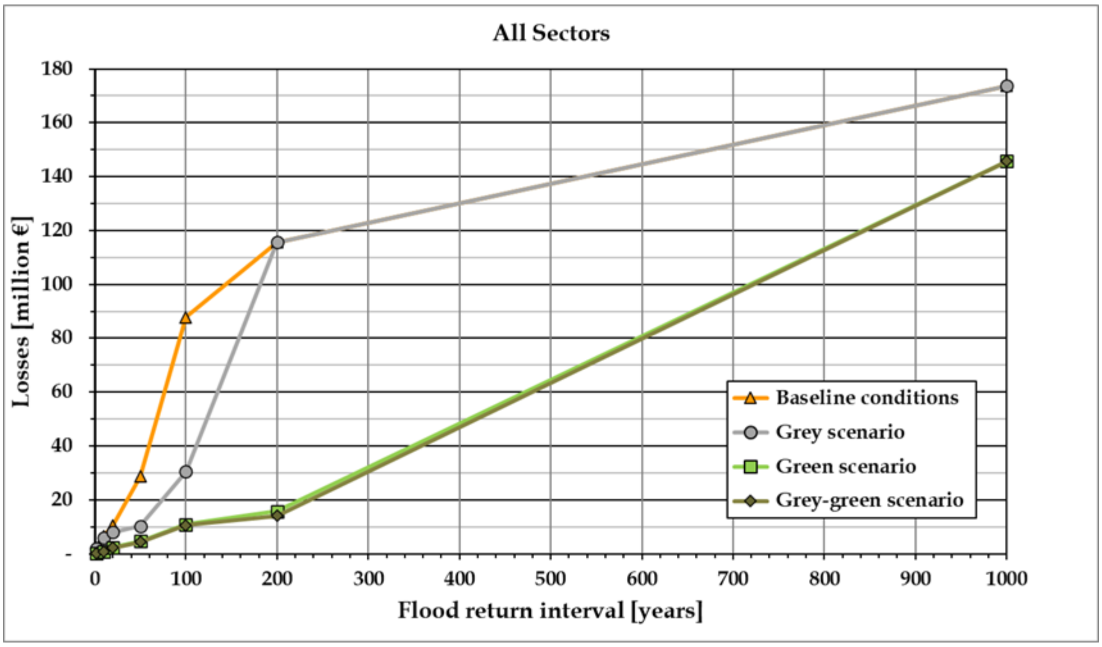


Figure 22. Distribution of total flood-related losses in the Tamnava River watershed for baseline conditions and three proposed flood mitigation scenarios.

The expected annual damages (EAD) for the four scenarios are presented in Table 30, together with their breakdown per loss categories considered. Share of the loss categories in EAD varies across the scenarios, but on average, the agricultural losses are the greatest, at 47% of the total EAD per scenario. Losses related to more expensive commodities, like buildings and contents are at 24.4% and 19.6%, respectively. That could be expected, given that the Tamnava watershed is predominantly rural, agricultural watershed, with low percentage of urbanized and industrial areas. Consequently, the population displacement costs are relatively small, at the average of 4.3%. The lowest losses are attributed to physical damages of the state roads within the watershed, at less than 1%. The annual sediment removal costs are on average 4% of the total EAD.

Table 30. Expected annual damages (EADs) and their breakdown per loss category, including sediment removal, under different flood mitigation scenarios.

Damage categories	EAD for flood mitigation scenarios [€]				Average share of total EAD
	Baseline	Grey	Green	Grey-green	
Buildings	1,257,200	724,184	112,946	106,648	24.4%
Contents	1,004,872	584,653	91,120	86,481	19.6%
Displacement	217,674	128,080	21,084	20,091	4.3%
Agriculture	1,839,299	1,672,453	364,369	353,425	47.0%
Roadways	31,219	24,286	5,398	3,869	0.7%
Sediment removal	103,155	103,155	74,869	74,869	4.0%
TOTAL	4,453,419	3,236,810	669,787	645,383	100%

Figures 23 and 24 extend the above discussion per mitigation scenarios. Compared to the baseline conditions, grey scenario exhibits smallest drop in losses across all five categories, but the least drop is in agriculture. Some of agricultural sectors (to be discussed in detail later) already have some existing protection; grey scenario only elevates the existing levees, while the previously unprotected sectors remain as such. The green and the grey-green scenarios feature reduction in flood discharges and thus, the reduction in flood hazards. As mentioned earlier, the displacement costs and the roadway damages are small, both in absolute value and in relative share of the EAD, for each of the scenarios. Annual costs of the sediment removal are also relatively low for all the scenarios, but they constitute large EAD share (11%) for green and grey-green scenarios, even with the counter-erosion measures in place.

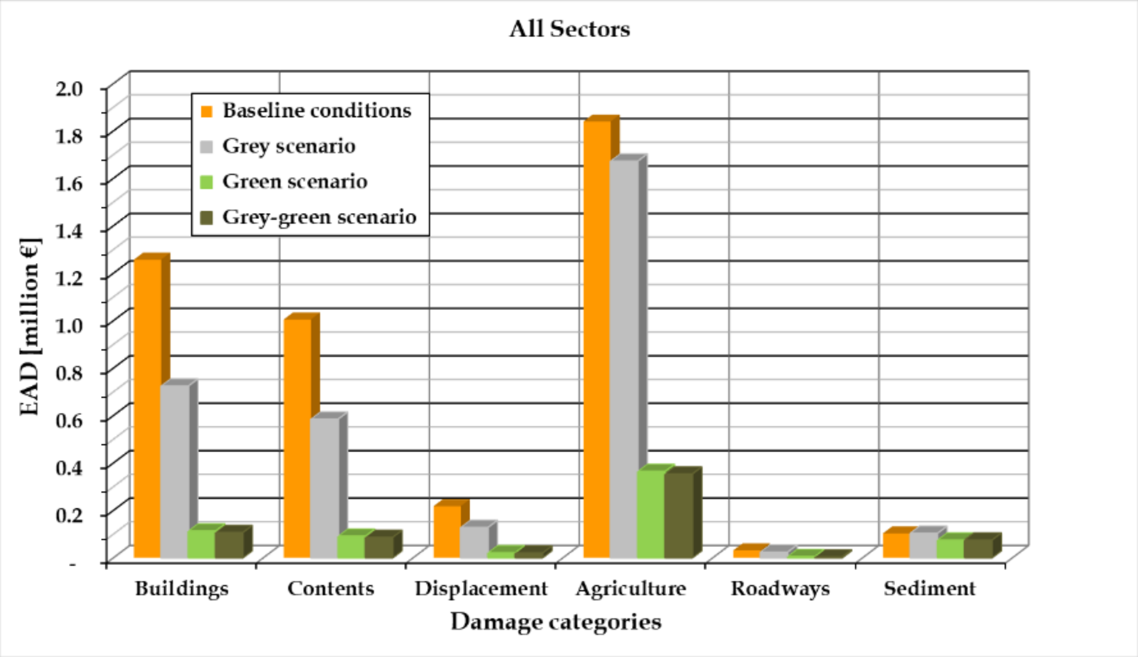


Figure 23. Expected annual damages (EADs) and their breakdown per loss category under different flood mitigation scenarios.

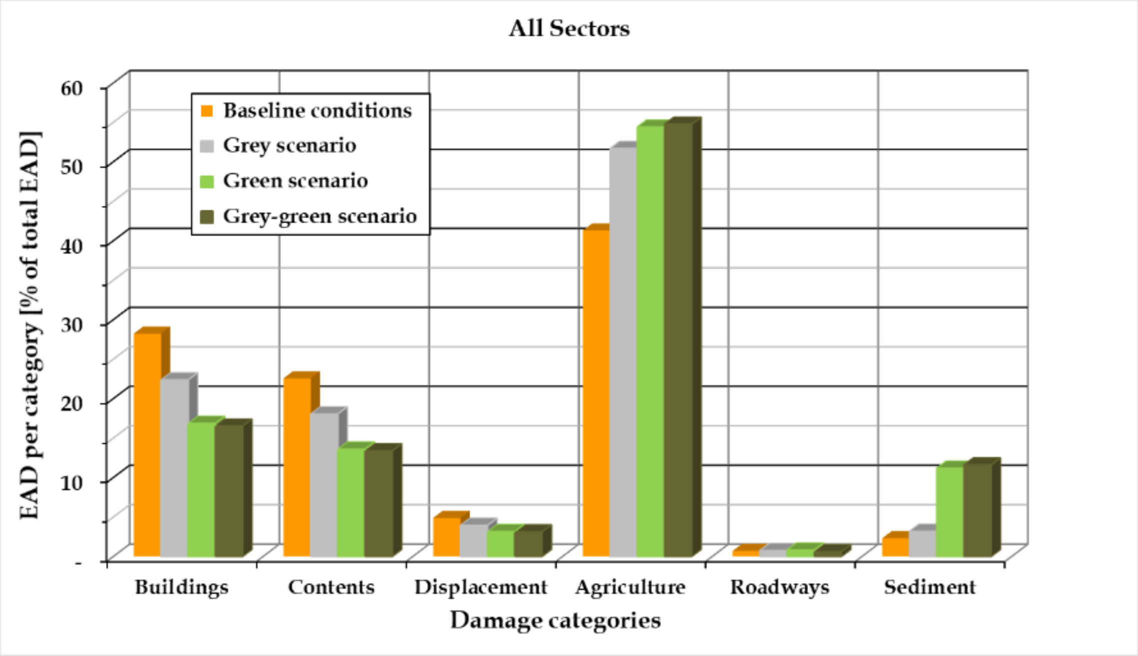


Figure 24. Expected annual damages (EADs) per loss category as percentage of total EAD under different flood mitigation scenarios.

Figure 25 shows EAD for individual river sectors for baseline conditions and all flood mitigation scenarios. The greatest losses under the baseline scenario are in sectors 8, 9, 11 and 13′, confirming high flood hazard in these sectors (see Figure 12). In addition, these sectors are characterized by large areas (e.g., sector 8) or by presence of urbanized or industrial zones (e.g., sector 13′), with little existing flood protection. Sectors 8, 11, and 13 are not protected by any existing or proposed grey measures, so EAD for the grey scenario is the same as for the existing conditions. Figure 25 also shows that measures of the green and grey-green scenarios result in lower damages than under grey measures, especially in the most downstream sectors 9 and 12. Under the grey scenario, the heightened levees in these sectors provide protection from the 100-year flood, so the EAD is the result of levee overtopping by more extreme events (200- and 1,000-year floods). On the other hand, the detention basins in the green and grey-green scenarios efficiently reduce damages due to such extreme flood events in these sectors, and consequently result in lower EAD than under the grey scenario.

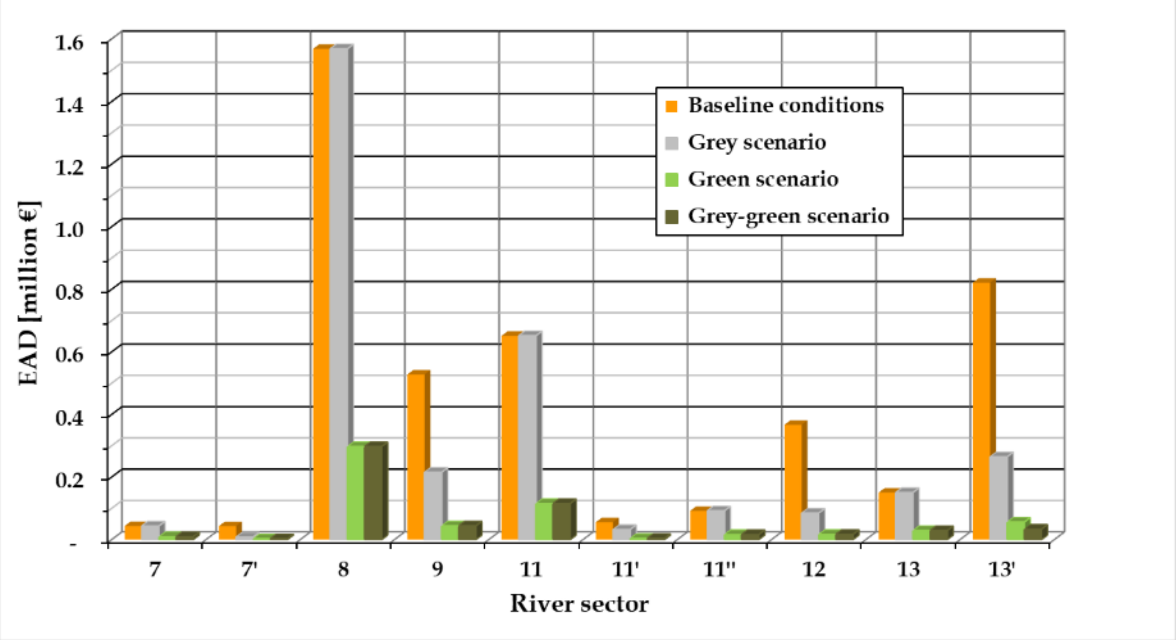


Figure 25. Expected annual damages (EAD) under different flood mitigation scenarios in different river sections across the Tamnava River watershed. Roadway damages and sediment removal costs are not included.

3.1.5.4 Assessment of benefits

As can be seen in Table 30 and Figures 22, 23, 24, and 25, the greatest benefits, i.e., reduction of losses relative to the baseline scenario, are obtained under the green and grey-green scenarios. Figure 26 shows the benefits for different recurrence intervals and indicates that the grey scenario has lower benefits than the remaining two scenarios for floods of 100-year recurrence interval and smaller. For more extreme floods, grey scenario exhibits no benefits at all, which is in agreement with the designed heightening of the levees to the 100-year protection level only.

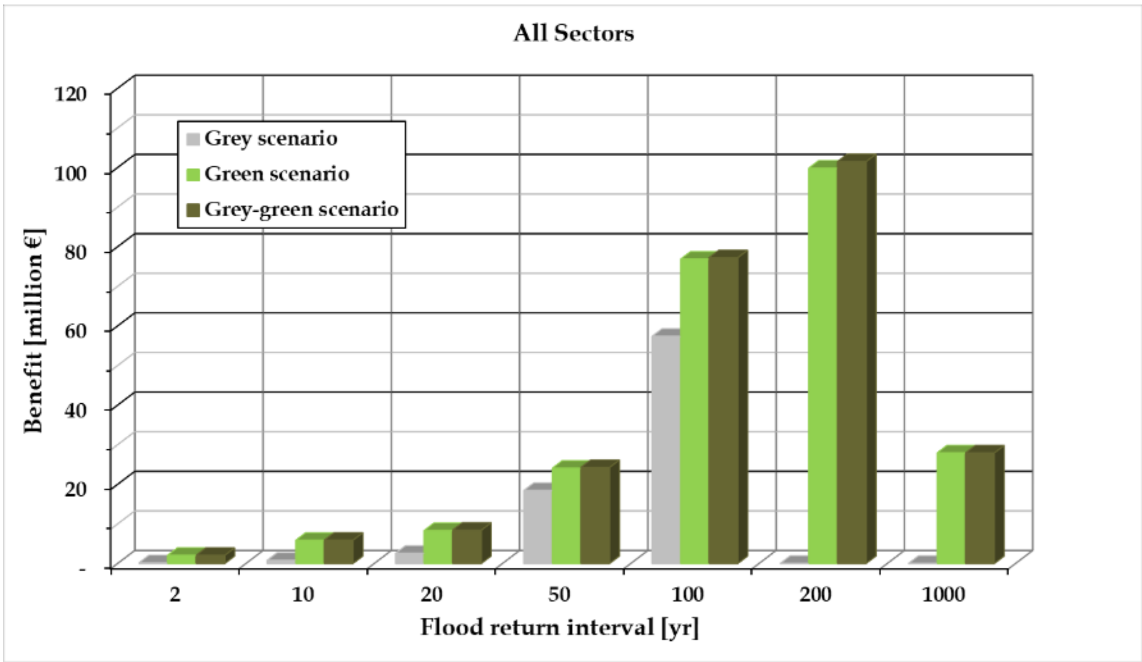


Figure 26. Benefits (loss reduction relative to baseline scenario) in the Tamnava River watershed under three proposed flood mitigation scenarios depending on the flood recurrence interval.

Table 31. Expected annual benefits (EABs) under three flood mitigation scenarios and their breakdown per loss category.

Damage categories	**EAB for flood mitigation scenarios [€]**					
	Grey scenario		**Green scenario**		**Grey-green scenario**	
Buildings	533,016	43.8%	1,144,254	30.2%	1,150,552	30.2%
Contents	420,220	34.5%	913,752	24.2%	918,392	24.1%
Displacement	89,594	7.4%	196,590	5.2%	197,583	5.2%
Agriculture	166,846	13.7%	1,474,930	39.0%	1,485,874	39.0%
Roadways	6,933	0.6%	25,820	0.7%	27,350	0.7%
Sediment removal	0	0.0%	28,286	0.7%	28,286	0.7%
TOTAL	1,216,609		3,783,632		3,808,036	

Table 31 presents expected annual benefits (EAB, section 2.7.3) for the considered scenarios. This table also suggests that the greatest benefits are obtained under the green and grey-green scenarios, which include detention basins that generally have greater effects on flood hazard and loss reduction than the levees. Hence, the benefits from implementing measures within the grey scenario are considerably smaller and reflect primarily in reduction of losses to building structures and contents. This can be explained by the fact that the grey measures are intended for protection of settlements in which buildings represent the most valuable assets. Since the grey measures make local impact on flood hazard and loss mitigation, reduction in the remaining, more remote, agricultural parts of the watershed are substantially smaller compared to the other two scenarios. Costs of temporary displacement of population are considerably lower than losses in other categories considered, and this pattern is also exhibited in the benefits. The damages caused to transportation infrastructure are also low, and without including indirect detour costs, the benefits share remain below 1% of the total. Similarly, the benefits resulting from reduction in erosion and subsequent sediment removal cost have a small share of less than 1% of the EAB.

The difference in benefits between green and grey-green scenarios is minor. This is because the detention basins reduce flood peaks efficiently in the downstream sections so that there is no overtopping of the existing systems of levees. In other words, the levee heightening included in the grey-green scenario has minor effect in combination with implementation of the detention basins.

Table 32. Benefits (reduction of losses) due to implementing flood protection measures under different scenarios, relative to the baseline conditions over a 50-year planning horizon

Sector	General description	Existing flood protection measures	50-year planning horizon			
			NPV, baseline scenario [€]	Benefits [% of NPV baseline]		
				Grey scenario	Green scenario	Grey-green scenario
7	Rural	No	596,964	0.0%	79.3%	79.3%
7'	Urban	Yes	592,891	81.0%	93.8%	93.8%
8	Rural	No	21,643,905	0.0%	81.0%	81.0%
9	Rural	Yes	7,282,655	59.2%	91.7%	91.7%
11	Rural	No	8,987,822	0.0%	82.3%	82.3%
11'	Urban	Yes	767,464	42.2%	93.3%	93.3%
11''	Urban	Yes	1,266,275	0.0%	82.5%	82.5%
12	Rural	Yes	5,061,185	76.9%	95.5%	95.5%
13	Rural	No	2,074,249	0.0%	80.7%	80.7%
13'	Semi-urban	No	11,332,632	67.8%	93.2%	96.0%
Total (attributable to sectors)			59,606,041	28.0%	86.4%	86.9%
Roadway damages			430,841	22.2%	82.7%	87.6%
Sediment removal			1,423,618	0.0%	27.4%	27.4%
GRAND TOTAL			61,460,499	27.3%	85.0%	85.5%

The benefits produced in each sector by implementing grey, green and grey-green measures, and compared relative to the baseline scenario, are presented in Table 32 in terms of benefits over the 50-year planning horizon (NPV), as discussed in section 2.7.3, and illustrated in Figure 27 in terms of EAB. Five river sectors (7, 8, 11, 13, 13′) are not being protected by levees, nor will be under the grey scenario, so there are no benefits under this scenario in these sections. Sector 11″ is already protected by the urban 100-year levee, so no additional grey measures were applied. The benefits under the green and grey-green scenarios are the same in all sections, except for section 13′, where the bypass canal is proposed (see Figure 5). As already discussed, levee heightening is not so beneficial if detention basins are implemented in the watershed. Benefits stemming from the reduction in roadway damages and sediment removal costs are not attributable to any river sector in particular, but to the overall Tamnava watershed. The benefits for sediment removal are assumed to start accruing eight years after implementing the counter-erosion measures, and they are computed for the remaining 42 years of the planning horizon. Table 33 presents a final, watershed-level comparison of losses and benefits for each of the scenarios, over the long-term, 50-year project horizon.

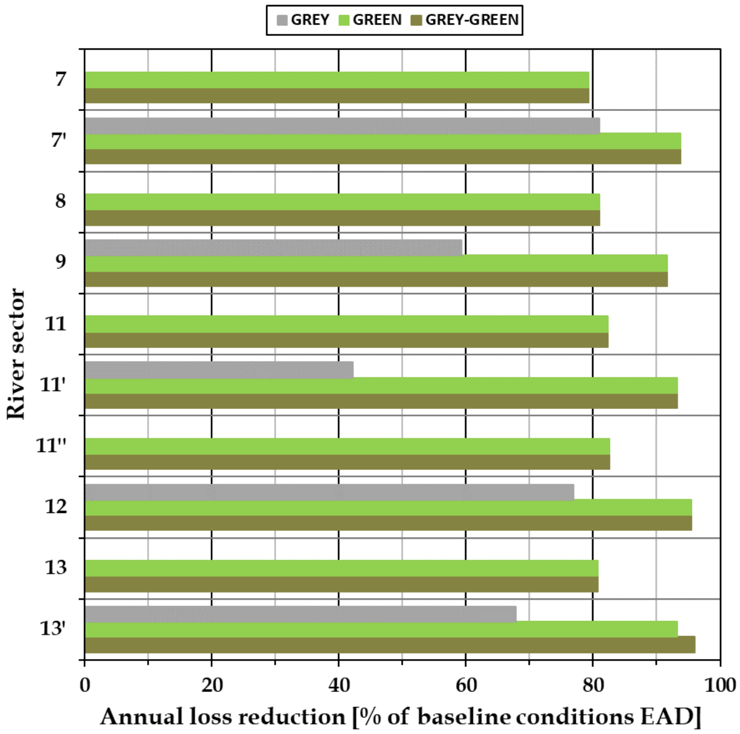


Figure 27. Expected annual benefits EAB (annual loss reduction), sectors expressed relative to the baseline EAD, per mitigation scenario and per river sector within the Tamnava River watershed [sectors 7,8,11,13 - no grey infrastructure, sector 11" - no benefits for grey scenario]

Table 33. Watershed-level comparison of losses and benefits for 50-year planning horizon

	Baseline conditions	**Grey scenario**	**Green scenario**	**Grey-green scenario**
	[€]	**[€]**	**[€]**	**[€]**
Losses	61,460,499	44,670,391	9,243,555	8,906,761
Benefits		16,790,108	52,216,944	52,553,738

3.2 Discussion

The assessment of the current flood hazard conditions within the Tamnava watershed indicates moderate levels of protection (LOP) in populated areas, and little or no flood protection in agricultural areas. Application and comparison of the three flood mitigation scenarios indicates that the ones utilizing green infrastructure (green and grey-green scenarios) exhibit the most benefits for all asset categories. Benefits are more pronounced in urban sectors, where the reduction of expected annual damages (EAD) ranges between 82.5% and 95% of the baseline (before-mitigation) levels. That is to be expected, since the value of the exposed urban assets (structures and contents) is much higher than the assets in rural sectors. In the same urban sectors, additional grey infrastructure (grey scenario) also provides considerable loss reductions, albeit at a lower rate (13%-51% lower) than the green scenarios.

In rural sectors with no existing flood protection, the green infrastructure scenarios provide excellent savings, reducing up to 82% of baseline EADs. This rate is even higher in sectors with the existing agricultural levees, where the reduction is up to 95.5%. Bolstering the existing levees (grey scenario) in these agricultural sectors also considerably reduces flood losses, but at the lower rate (19%-33% less) than the green scenario.

In this particular analysis, the grey-green scenario exhibits marginally higher benefits (85.5% vs 85.0% of EAB) than the pure green scenario. The grey-green scenario already comprises the green scenario, with additional grey infrastructure implementation. If the cost of grey measures is considerable, it may outweigh these benefits, and become a deciding factor when selecting an optimum between the two scenarios with fairly comparable mitigation efficiency.

The overall conclusion from comparing the three scenarios in this case study is that maintaining the existing flood protection system, and complementing it with larger scale green measures can be the optimal flood protection setup for predominately rural watersheds. Grey infrastructure elements alone can provide adequate LOP on a localized level (within a specific river sector), but may possibly transfer the flood hazard downstream. The green infrastructure scenarios, utilizing detention basins and counter-erosion measures, may provide a more comprehensive flood protection. By reducing the peak and the volume of the watershed headwater hydrographs further downstream, the green scenarios affect more assets within a larger area of influence. The green infrastructure approach may be further refined by specifically addressing flooding events of higher frequency (i.e., lower magnitude). As indicated in section 3.1.5.4, the existing grey infrastructure has a LOP limit of 50 to 100 years, which will further diminish over time. For the lower magnitude events, small-scale green infrastructure elements may be successfully applied to replace the function of the grey infrastructure (Vojinovic et al, 2021), without losing its effectiveness over time. Such small-scale NBS may be rural wetlands, lateral detentions, smaller detention basins, riparian buffers etc. A combination of the mutually complementing small-scale and large-scale NBS may provide a better flexibility and applicability, especially in the rural areas with smaller centers of population. Such flood protection systems can provide a superior scalability and flood protection efficiency, with the green infrastructure benefits actually growing over time.

It is important to point out that the flood loss estimation includes the inherent uncertainties in both flood hazard and flood damage assessments. In general, the accuracy of flood hazard modelling is influenced by the terrain information, morphological features, hydrologic and hydraulic models etc. The accuracy of damage estimations depends on the accuracy of assets' inventory, their flood vulnerability (depth-damage) functions, and if the proposed structural measures (in grey and grey-green scenarios) would perform as designed.

Application of the micro-scale damage model, developed for the Tamnava basin, can be characterized as the "lower boundary" damage assessment, due to a limited number of vulnerability categories taken into account. Some of the additional categories that could be considered include expanded number of crop cultures, transportation and energy infrastructure losses, traffic delays, loss of critical facilities (water and wastewater, hospitals, communications, emergency service facilities), lost productivity, business displacement, etc. While taking more vulnerability categories into consideration is generally expected to provide more comprehensive flood loss estimates, using uncertain or generalized data would also lead to uncertain results. This is the reason for applying the "lower boundary" assessment in this study. The mitigation strategies proven to be effective using the limited number of vulnerability categories, would have their mitigation benefits increased further, inclusive of additional categories. Despite the limited number of vulnerability categories used, the proposed flood mitigation scenarios are compared in relative terms, allowing their unbiased ranking.

The damage assessment approach in this study is validated successfully for the case of the flood event in May 2014, leading to a conclusion that the approach yields plausible damage estimates. As a result, it is expected that the uncertainties in flood hazard and limited number of vulnerability categories do not affect the relative ranking of the scenarios.

The application of nature-based solutions is also characterized by the value of eco-system services these measures provide. In this thesis research, one of the green measures comprises reforestation/restoration of approximately 1,700 hectares in headwaters of the Tamnava River watershed. The benefits of the green measures are not only important in their conventional economic analyses and subsequent selection of the optimal mitigation scenario. Green measures and their ESS are instrumental in a long-term valuation of flood losses and of the watershed itself, as an overall ecosystem. The long term (50-year horizon) forecasts of losses avoided will have ESS valuations of the green measures factored in as an *added value* to the watershed, whereas alternatively, the grey infrastructure will provide no ecological benefits. The grey infrastructure scenarios will have the cost of maintenance and repair of the levees *subtracted* from the future flood protection benefits.

The findings of this research are to be tested in different watersheds and for various flood mitigation scenarios that would include a wide variety of measures with special emphasis on green, nature-based solutions. Further refinement of information and continued valuation of the site-specific ESS can provide a reliable methodology for improved, initial ecosystem estimates of similar watersheds on a local or regional level. Building upon the basis of more site-specific ESS and their primary benefits, an additional potential area of further research would focus on exploring nature-related co-benefits. This phase would require additional information on the affected natural assets, and their role in the particular ecosystem of interest. The research can analyze their intercorrelation and specifically, their contribution to the watershed's overall ESS value in the long-term projection framework.

The human well-being and intrinsic improvement of the quality of life can be corner stone of the future research that incorporates public outreach, and interaction with stakeholders. The specific eco-system functions that concern human well-being are valued differently than using conventional market- and cost-based methods from this research (de Groot et al., 2012). The methodologies for their determination would be carefully tailored to the specific cultural and demographic conditions, and valued with the active input from local stakeholders.

4 CONCLUSIONS

Nature-based solutions for flood risk mitigation are becoming more attractive as resilient and adaptive measures that can also contribute greatly to restoration of natural ecosystems, as well as to human well-being and socio-economic characteristics of a focus area. However, the economic effectiveness of NBS is not yet clearly understood from the existing studies. For that reason, more applications of these solutions are needed, and more systematic research is also necessary to develop and refine robust methodologies for their economic valuation. At the same time, the traditional grey infrastructure for flood mitigation is already implemented in many watersheds and is still a predominant approach in engineering applications. It is therefore important that the methodologies for evaluating flood mitigation strategies are capable of analyzing a wide range of measures: green, grey, or combined grey-green.

This thesis presents a comprehensive micro-scale flood damage assessment methodology, applied under various scenarios of flood mitigation in a predominately rural, agricultural watershed. The model evaluates the benefits from the proposed flood protection measures, including the primary benefits related to flood risk reduction, and the secondary benefits related to the contribution of the measures to the value of ecosystem services in the watershed.

The specificity of the micro-scale damage modelling is that all economic calculations are performed at an individual asset-level, instead of an asset-class level. The high degree of detail in both the input data, and the specific depth-damage relations, allows for flexibility in specifying mitigation options and for better interpretation of the modelling and the economic results, expressed in the form of annualized damages.

Evaluating mitigation scenario losses in an annualized format provides a clear advantage over the conventional approaches, where mitigation comparisons are usually conducted for a singular event, historic or probabilistic. Annualized damages present a universal, normalized evaluation of a series of multiple frequency events, well suited for the scenario efficiency comparisons, specific mitigation improvements, and long-term economic projections.

The objective of the proposed methodology, which is mainly aimed at smaller rural watersheds, is not only to identify the flood protection strategy that would result in maximum avoidance of losses due to floods, but also to allow evaluating the benefits for the watershed ecosystem services from NBS. Hence, the proposed methodology builds on the relationship between NBS, restoration of natural ecosystems, and overall reduction of their flood risk.

Application of the proposed methodology on the small agricultural watershed of the Tamnava River demonstrates that the detention basins, as an example of green flood mitigation measures that reduce peak flood flows in downstream river sections, can significantly decrease flood hazard and consequently the flood-induced losses. In the case of Tamnava watershed, this peak flow reduction is sufficient to enable the existing system of protection levees to operate without failure and to control the design floods without overtopping. On the other hand, heightening of the levees, as an example of grey flood protection measures, increases flood protection only locally, does not attenuate peak discharges and may actually exacerbate the damages further downstream. Unlike the urban areas, where levees may be economically acceptable due to high-priced assets in relatively small spaces, rural watersheds are characterized by larger floodplains and long river banks that would require extensive and excessively expensive levee systems. Additionally, with the lower-valued crops being the biggest commodity in rural watersheds, the flood losses per unit area are lower than in urban settings, as demonstrated by a fine-scale detailed damage assessment in this study.

Consequently, in rural watersheds, the purely grey flood protection measures (such as levees) prove not to be as effective in reducing flood risk as the green measures. A combination of grey and green measures, i.e., implementation of forestation and detention basins, together with the levee improvements, provides a small margin of benefits over purely green scenario, insufficient to justify the costs of an additional grey infrastructure, its projected degradation, maintenance, and repair. It is therefore confirmed that the hybrid-type flood mitigation setups, i.e., combinations of large-scale, far-reaching green mitigation solutions that reduce peak flood flows with the existing smaller-scale conventional flood protection measures, can be the most effective solution for rural watersheds with prevalent agricultural land use and production.

Implementation of mitigation scenarios comprising NBS provides additional long-term benefits, through an increased overall watershed ecosystem value, and bringing savings through reduced cost of repairs and maintenance of the alternative grey infrastructure. The high-resolution valuation of these benefits is made possible by annualized damage estimates from the micro-scale modelling, whose framework fits seamlessly with the concept of ecosystem service annual valuations.

Albeit this research focuses on a relatively small example (forestation of the Tamnava headwaters), the derived result is a reliable, localized ESS value, related specifically to the control of erosion and overall restoration of the considered watershed. A higher-resolution analysis would be achievable with an addition of more asset categories and more quantifiable benefits, thus producing localized valuations for more eco-system functions.

The methodology described herein is a framework that can be applied to other rural, agricultural watersheds. The vulnerability functions for man-made and natural assets may be modified to better suite local conditions. The ESS values derived and refined by this methodology are site- and region-specific, and can be utilized for an improved initial valuation of watersheds within the same geographic realm.

Finally, the analysis presented in this research indicates that the inclusion of NBS through green mitigation scenarios in rural watersheds clearly demonstrates high level of engineering and economic efficiency in reducing their flood hazards, and flood-related losses. In addition to inherently increasing flood resiliency of the rural watersheds, the application of NBS restores their fluvial eco-systems and increases their ecological valuation in long-term time horizons.

5 REFERENCES

Akter, T., & Simonovic, S. P. (2005). Aggregation of fuzzy views of a large number of stakeholders for multi-objective flood management decision-making. *Journal of Environmental Management*, 77(2), 133–143. DOI: 10.1016/j.jenvman.2005.02.015

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, *239*, 244–254. DOI: 10.1016/j.jenvman.2019.03.036

Alves, A., Vojinovic, Z., Kapelan, Z., Sanchez, A., & Gersonius, B. (2020). Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. *Science of The Total Environment*, *703*, 134980. DOI: 10.1016/j.scitotenv.2019.134980

Butler, C., & Pidgeon, N. (2011). From 'Flood Defence' to 'Flood Risk Management': Exploring Governance, Responsibility, and Blame. *Environment and Planning C: Government and Policy*, *29*(3), 533–547. DOI: 10.1068/c09181j

Cohen, J. P., Field, R., Tafuri, A. N., & Ports, M. A. (2012). Cost Comparison of Conventional Gray Combined Sewer Overflow Control Infrastructure versus a Green/Gray Combination. *Journal of Irrigation and Drainage Engineering*, *138*(6), 534–540. DOI: 10.1061/(ASCE)IR.1943-4774.0000432

Collentine, D., & Futter, M. N. (2018). Realising the potential of natural water retention measures in catchment flood management: trade-offs and matching interests. *Journal of Flood Risk Management*, *11*(1), 76–84. DOI: 10.1111/jfr3.12269

CLC (2012). Corine Land Cover (CLC) 2012. Available online: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012?tab=mapview (accessed on Jul 28, 2020).

CRED & UNISDR (2015). *The Human Cost of Weather Related Disasters 1995-2015*. Centre for Research on the Epidemiology of Disasters (CRED) and United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR). https://www.undrr.org/publication/human-cost-weather-related-disasters-1995-2015.

Daily, G.C. (1997). *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington, DC, USA.

Daly, H.E., & Farley, J. (2004). *Ecological Economics: Principles and Applications*. Island Press, Washington DC, USA.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L. C., ten Brink, P., & van Beukering, P. (2012). Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services*, 1(1), 50–61. DOI: 10.1016/j.ecoser.2012.07.005

Depietri, Y., & McPhearson, T. (2017). Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), *Nature-based Solutions to Climate Change Adaptation in Urban Areas* (pp. 91–109). DOI: 10.1007/978-3-319-56091-5_6

Dong, X., Guo, H., & Zeng, S. (2017). Enhancing future resilience in urban drainage system: Green versus grey infrastructure. *Water Research*, *124*, 280–289. DOI: 10.1016/j.watres.2017.07.038

EASAC (European Academies' Science Advisory Council). (2018). *Extreme Weather Events in Europe: Preparing for Climate Change Adaptation: An Update on EASAC's 2013 Study*. Halle, Germany, EASAC. Available at: https://easac.eu/publications/details/extreme-weather-events-in-europe/.

EEA (2015). Exploring nature-based solutions: The role of green infrastructure in mitigating the impacts of weather- and climate change-related natural hazards; European Environment Agency, ISBN 9789292136932.

ESVD (2020). Ecosystem Services Valuation Database (ESVD), Ecosystem Partnership. Available at: www.es-partnership.org/esvd.

FEMA (2011). *Supplement to the Benefit-Cost Analysis Reference Guide*. Federal Emergency Management Agency, Washington, DC, USA.

Fuchs, S., Birkmann, J., & Glade, T. (2012). Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. *Natural Hazards*, *64*(3), 1969–1975. DOI: 10.1007/s11069-012-0352-9

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., & Nanu, F. (2020). Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Sci. Tot. Environ.*, 713, 136552, DOI: 10.1016/j.scitotenv.2020.136552

Huizinga, J., Moel, H. de, & Szewczyk, W. (2017). *Global flood depth-damage functions. Methodology and the database with guidelines*. Joint Research Centre (European Commission). DOI: 10.2760/16510.

IPCC (Intergovernmental Panel on Climate Change). (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). www.ipcc.ch/sr15/.

Jonkman, S. N., Brinkhuis-Jak, M., & Kok, M. (2004). Cost benefit analysis and flood damage mitigation in the Netherlands. *Heron*, *49*(1), 95–111.

Jovanović, M., Prodanović, D., Plavšić, J., Rosić, N., Srna, P., & Radovanović, M. (2014). Jedan primer kartiranja rizika od poplava u Srbiji. *Voda i sanitarna tehnika*, 44(5–6), 63–70.

Jovanović Popović, M., Ignjatović, D., Radivojević, A., Rajčić, A., Đukanović, L., Ćuković Ignjatović, N., & Nedić, M. (2012). *Atlas of Family Housing in Serbia*. University of Belgrade - Faculty of Architecture and GIZ - Deutsche Gesellschaft fur internationale Zusammenarbeit.

Karrasch, L., Restemeyer, B., & Klenke, T. (2021). The 'Flood Resilience Rose': A management tool to promote transformation towards flood resilience. *Journal of Flood Risk Management*. DOI: 10.1111/jfr3.12726

Kocian, M., Traughber, B., & Batker, D. (2012). Valuing Nature's Benefits: An Ecological Economic Assessment of Iowa's Middle Cedar Watershed. Earth Economics. Tacoma, WA.

Kopsieker L., Gerritsen E., Stainforth T., Lucic A., Costa Domingo G., Naumann S., Röschel L. and Davis Mc. (2021). *Nature-based solutions and their socio-economic benefits for Europe's recovery: Enhancing the uptake of nature-based solutions across EU policies*. Policy briefing by the Institute for European Environmental Policy (IEEP) and the Ecologic Institute. https://ieep.eu/publications/nature-based-solutions-and-their-socio-economic-benefits-for-europe-s-recovery.

Kron, W. (2005). Flood Risk = Hazard • Values • Vulnerability. *Water International*, *30*(1), 58–68. DOI: 10.1080/02508060508691837

Lehman, W., & Hasanzadeh Nafari, R. (2016). An Empirical, Functional approach to Depth Damages. *E3S Web of Conferences*, *7*, 05002. DOI: 10.1051/e3sconf/20160705002

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Assessment of economic flood damage. *Natural Hazards and Earth System Sciences*, *10*(8), 1697–1724. DOI: 10.5194/nhess-10-1697-2010

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., & Van Der Veen, A. (2007). *Evaluating flood damages: guidance and recommendations on principles and methods*. FLOODsite Project Deliverable D9.1. http://www.floodsite.net/

MEA (2005). *Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC., USA.

NWRM (2015). *Natural Water Retention Measures, Catalogue of NWRM*. Available at: http://nwrm.eu/measures-catalogue.

Olesen, L., Löwe, R., & Arnbjerg-Nielsen, K. (2017). *Flood damage assessment – Literature review and recommended procedure*. Cooperative Research Centre for Water Sensitive Cities, Clayton, Vic., Australia.

Olsen, A., Zhou, Q., Linde, J., & Arnbjerg-Nielsen, K. (2015). Comparing Methods of Calculating Expected Annual Damage in Urban Pluvial Flood Risk Assessments. *Water*, 7(12), 255–270. DOI: 10.3390/w7010255

Peh, K. S.-H., Balmford, A., Bradbury, R. B., Brown, C., Butchart, S. H. M., Hughes, F. M. R., Stattersfield, A., Thomas, D. H. L., Walpole, M., Bayliss, J., Gowing, D., Jones, J. P. G., Lewis, S. L., Mulligan, M., Pandeya, B., Stratford, C., Thompson, J. R., Turner, K., Vira, B., … Birch, J. C. (2013). TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. *Ecosystem Services*, *5*, 51–57.

Perosa, F., Gelhaus, M., Zwirglmaier, V., Arias-Rodriguez, L. F., Zingraff-Hamed, A., Cyffka, B., & Disse, M. (2021). Integrated Valuation of Nature-Based Solutions Using TESSA: Three Floodplain Restoration Studies in the Danube Catchment. *Sustainability*, *13*(3), 1482. DOI: 10.3390/su13031482

Petković, S., & Milišić, V. (1992). Modelling of runoff and soil loss for the small watershed. Proceeding of 5th International Symposium on River Sedimentation, Karlsruhe, 1992.

Pistrika, A., Tsakiris, G., & Nalbantis, I. (2014). Flood Depth-Damage Functions for Built Environment. *Environmental Processes*, *1*(4), 553–572. DOI: 10.1007/s40710-014-0038-2

Plavšić, J., Vladiković, D., & Despotović, J. (2014). Floods in the Sava River Basin in May 2014. In E. Ferrari & P. Versace (Eds.), *Mediterranean Meeting on Monitoring, modelling, early warning of extreme events triggered by heavy rainfall*, E. Ferrari & P. Versace (eds), pp. 241–251.

Pudar, R., Plavšić, J., & Todorović, A. (2020). Evaluation of Green and Grey Flood Mitigation Measures in Rural Watersheds. *Applied Sciences*, 10(19), 6913. DOI: 10.3390/app10196913.

Ristic, R., Radic, B., Miljanovic, V., Trivan, G., Ljujic, M., Letic, L., & Savic, R. (2013). „Blue-green“ corridors as a tool for mitigation of natural hazards and restoration of urbanized areas: A case study of Belgrade city. *Spatium*, *30*, 18–22. DOI: 10.2298/SPAT1330018R

Ristić, R., & Macan, G. (1997). The impact of erosion control measures on runoff processes. In *Human Impact on Erosion and Sedimentation* (Proceedings of Rabat Symposium S6), IAHS Publ. no. 245, pp. 191-194.

Rozos, E., Makropoulos, C., & Maksimović, Č. (2013). Rethinking urban areas: an example of an integrated blue-green approach. *Water Supply*, *13*(6), 1534–1542. DOI: 10.2166/ws.2013.140

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L. S., Capobianco, V., Oen, A. M. P., McClain, M. E., & Lopez-Gunn, E. (2020a). Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. *Natural Hazards and Earth System Sciences*, 20(1), 243–270. DOI: 10.5194/nhess-20-243-2020

Ruangpan, L., Vojinovic, Z., Plavšić, J., Doong, D.-J., Bahlmann, T., Alves, A., Tseng, L.-H., Randelović, A., Todorović, A., Kocic, Z., Beljinac, V., Wu, M.-H., Lo, W.-C., Perez-Lapeña, B., & Franca, M. J. (2020b). Incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale Nature-Based Solutions. *Ambio*. DOI: 10.1007/s13280-020-01419-4

RZS (2015). Census 2011, Statistical Office of the Republic of Serbia (Republicki zavod za statistiku, RZS), available at: https://www.stat.gov.rs/en-US/oblasti/popis/popis-2011

Schrier, A. V., Bronfin, J., Harrison-Cox, J. (2013). *What is your planet worth? A handbook for understanding natural capital*. Earth Economics. Tacoma, WA.

Schubert, J. E., Burns, M. J., Fletcher, T. D., & Sanders, B. F. (2017). A framework for the case-specific assessment of Green Infrastructure in mitigating urban flood hazards. *Advances in Water Resources*, *108*, 55–68. DOI: 10.1016/j.advwatres.2017.07.009

Schumacher, E. F. (1973). *Small is beautiful: Economics as if people mattered*. New York: Harper & Row.

Stanić, M., Todorović, A., Vasilić, Ž., & Plavšić, J. (2018). Extreme flood reconstruction by using the 3DNet platform for hydrological modelling. *Journal of Hydroinformatics*, 20(4), 766–783. DOI: 10.2166/hydro.2017.050.

TEEB (2010a). The Economics of Ecosystems and Biodiversity – Ecological and Economic Foundations, P. Kumar (Ed.), Earthscan, London, Washington.

TEEB (2010b). The Economics of Ecosystems and Biodiversity – Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB. Available at: http://teebweb.org/publications/teeb-for/synthesis.

Thomas, F., & Knüppe, K. (2016). From Flood Protection to Flood Risk Management: Insights from the Rhine River in North Rhine-Westphalia, Germany. *Water Resources Management*, *30*(8), 2785–2800. DOI: 10.1007/s11269-016-1323-9

UNDP Serbia. (2016). *Studija unapređenja zaštite od voda u slivu reke Kolubare* (in Serbian). Institute "Jaroslav Černi" for the United Nations Development Programme in Serbia and Public Water Management Company "Srbijavode".

UNHCR Serbia. (2019). United Nations High Commissioner for Refugees, Representation in Serbia, personal communication.

Vojinovic, Z., Keerakamolchai, W., Weesakul, S., Pudar, R., Medina, N., & Alves, A. (2016). Combining Ecosystem Services with Cost-Benefit Analysis for Selection of Green and Grey Infrastructure for Flood Protection in a Cultural Setting. *Environments*, 4(1), 3. DOI: 10.3390/environments4010003

Vojinovic, Z., Alves, A., Gómez, J. P., Weesakul, S., Keerakamolchai, W., Meesuk, V., & Sanchez, A. (2021). Effectiveness of small- and large-scale Nature-Based Solutions for flood mitigation: The case of Ayutthaya, Thailand. *Science of The Total Environment*, *789*, 147725. DOI: 10.1016/j.scitotenv.2021.147725

Vorhies, F., & Wilkinson, E. (2016). *Co-Benefits of Disaster Risk Management*. Policy Research Working Paper No. 7633. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/24207

Wagenaar, D., Lüdtke, S., Schröter, K., Bouwer, L. M., & Kreibich, H. (2018). Regional and Temporal Transferability of Multivariable Flood Damage Models. *Water Resources Research*, *54*(5), 3688–3703. DOI: 10.1029/2017WR022233

Watkin, L. J., Ruangpan, L., Vojinovic, Z., Weesakul, S., & Torres, A. S. (2019). A framework for assessing benefits of implemented nature-based solutions. *Sustainability*, *11*(23): 6788. DOI: 10.3390/su11236788

Wong, S. M., & Montalto, F. A. (2020). Exploring the Long-Term Economic and Social Impact of Green Infrastructure in New York City. *Water Resources Research*, *56*(11). DOI: 10.1029/2019WR027008

World Bank. (2017). *Implementing nature-based flood protection: Principles and implementation guidance*. World Bank, Washington, DC.

APPENDICES

Appendix A – Flood boundaries and depth grids in the Tamnava watershed

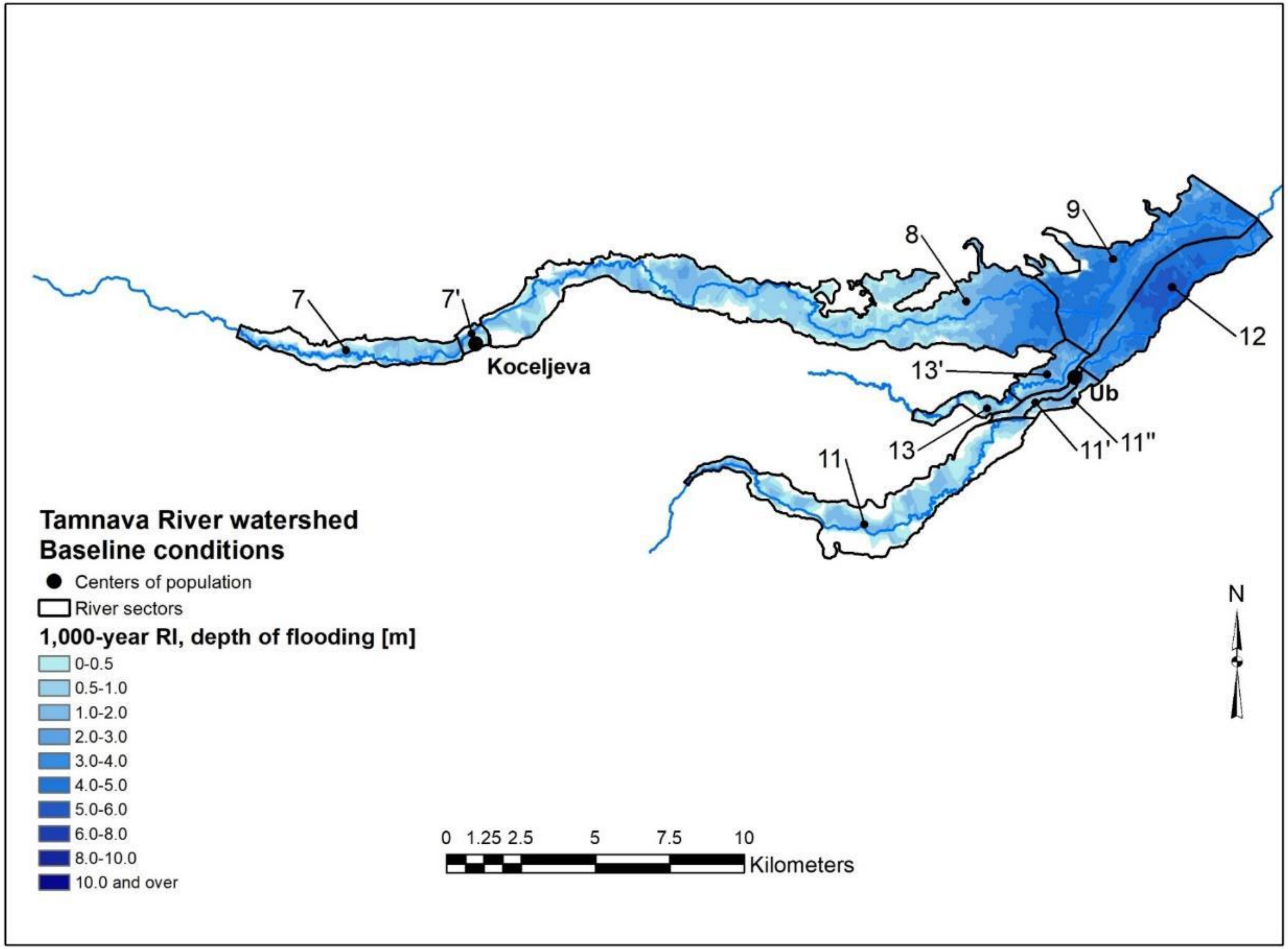


Figure A.1. Flood hazard: 1,000-year recurrence interval flood in the Tamnava watershed under the baseline scenario

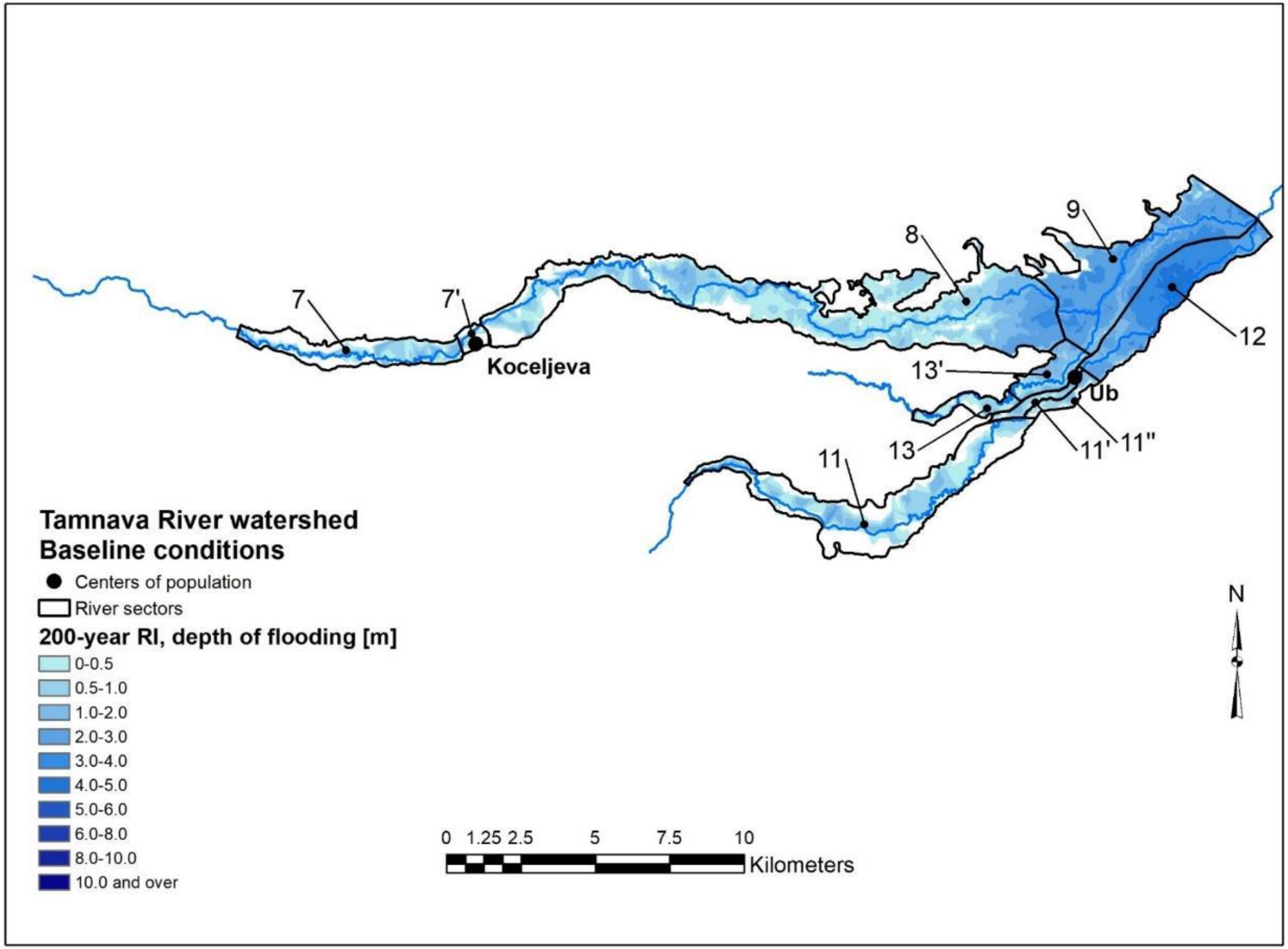


Figure A.2. Flood hazard: 200-year recurrence interval flood in the Tamnava watershed under the baseline scenario

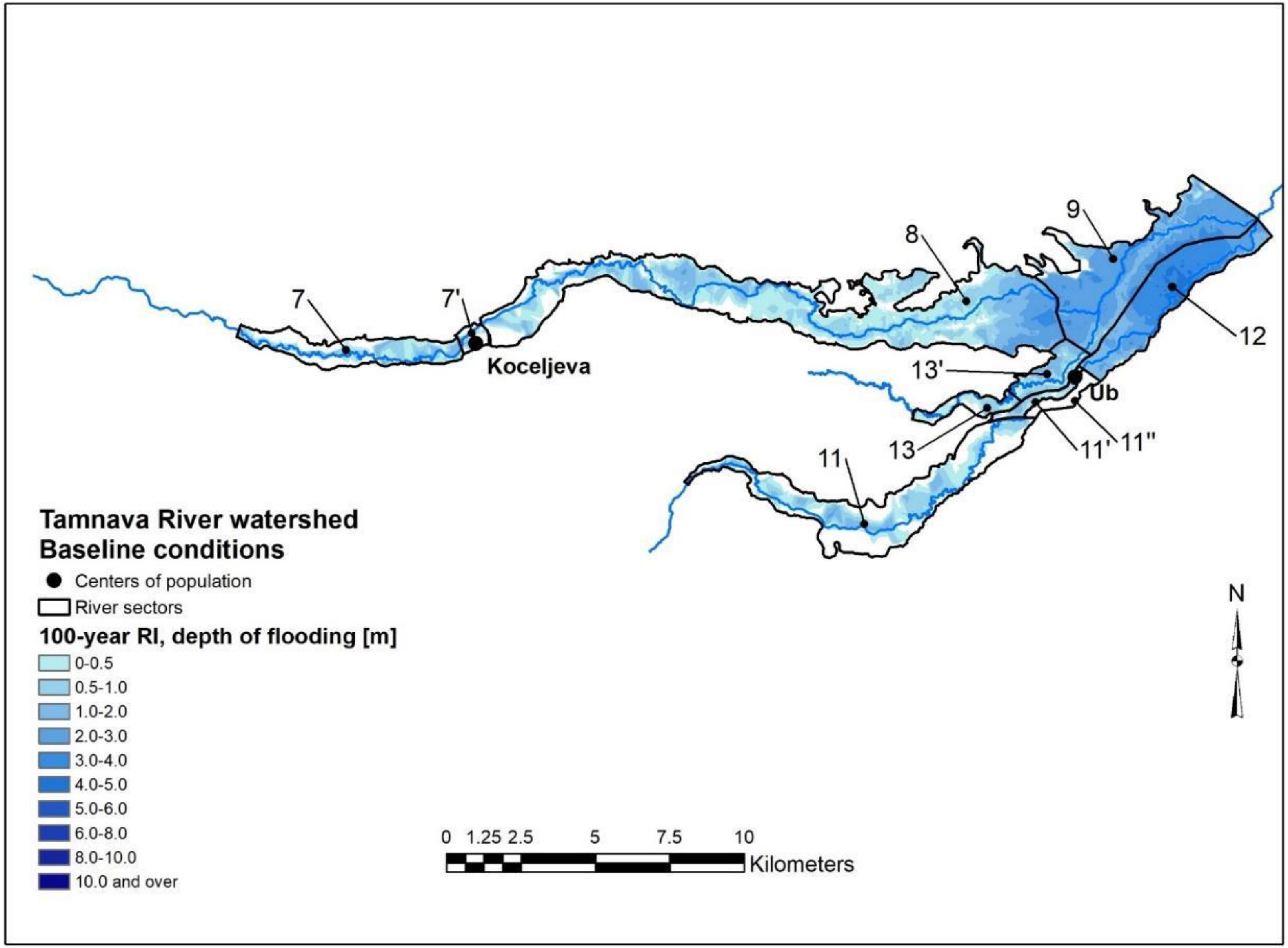


Figure A.3. Flood hazard: 100-year recurrence interval flood in the Tamnava watershed under the baseline scenario

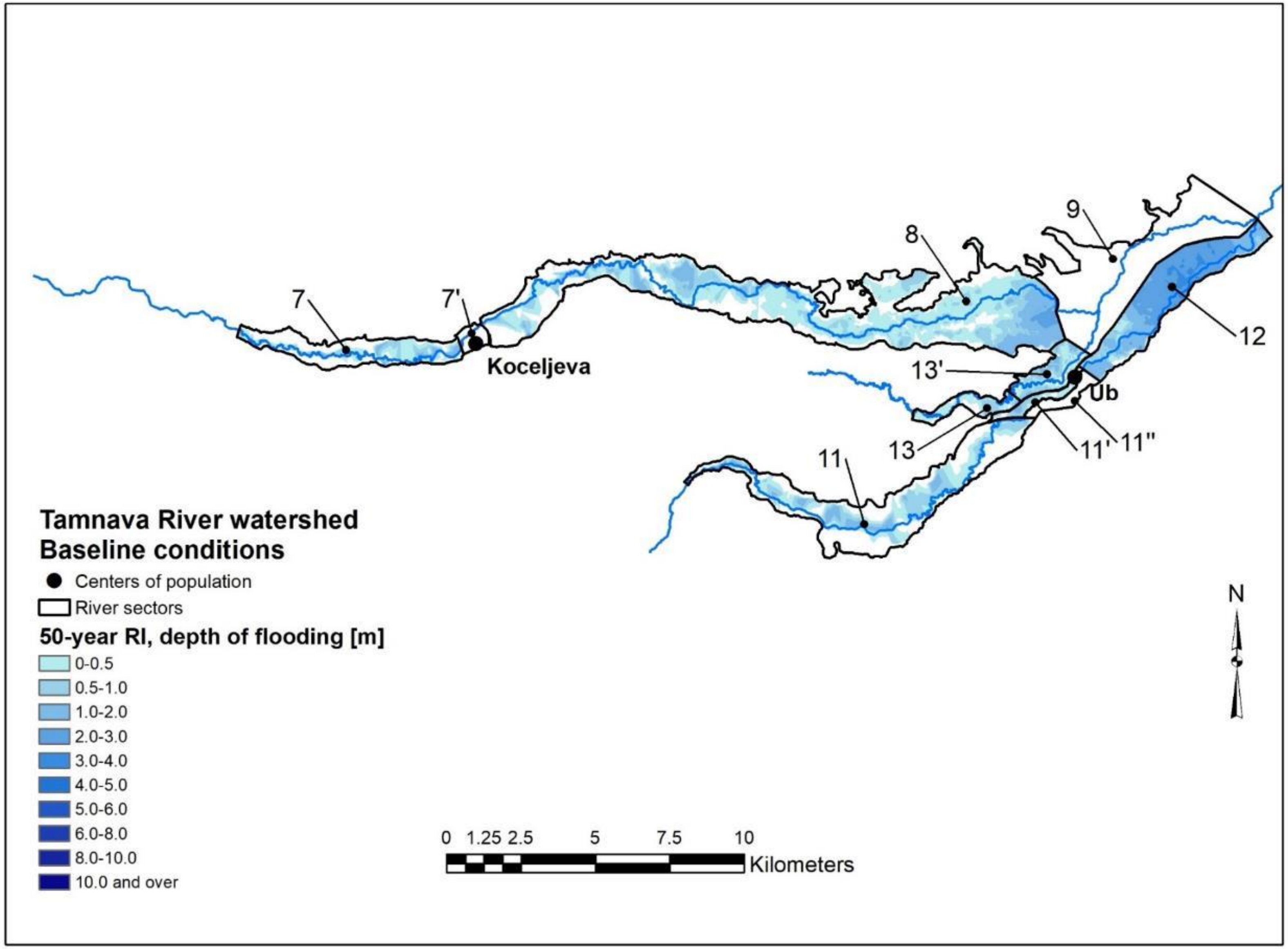


Figure A.4. Flood hazard: 50-year recurrence interval flood in the Tamnava watershed under the baseline scenario

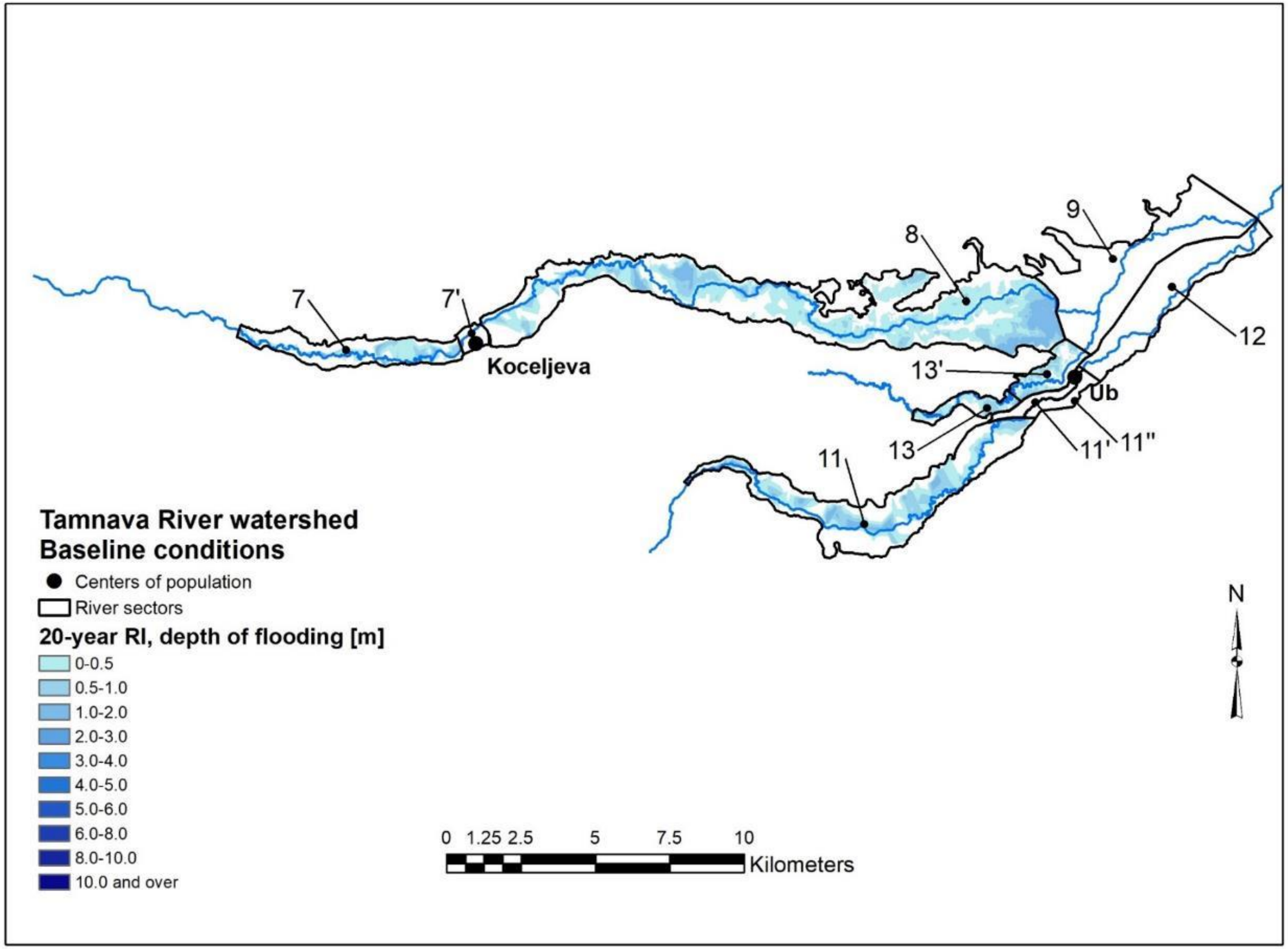


Figure A.5. Flood hazard: 20-year recurrence interval flood in the Tamnava watershed under the baseline scenario

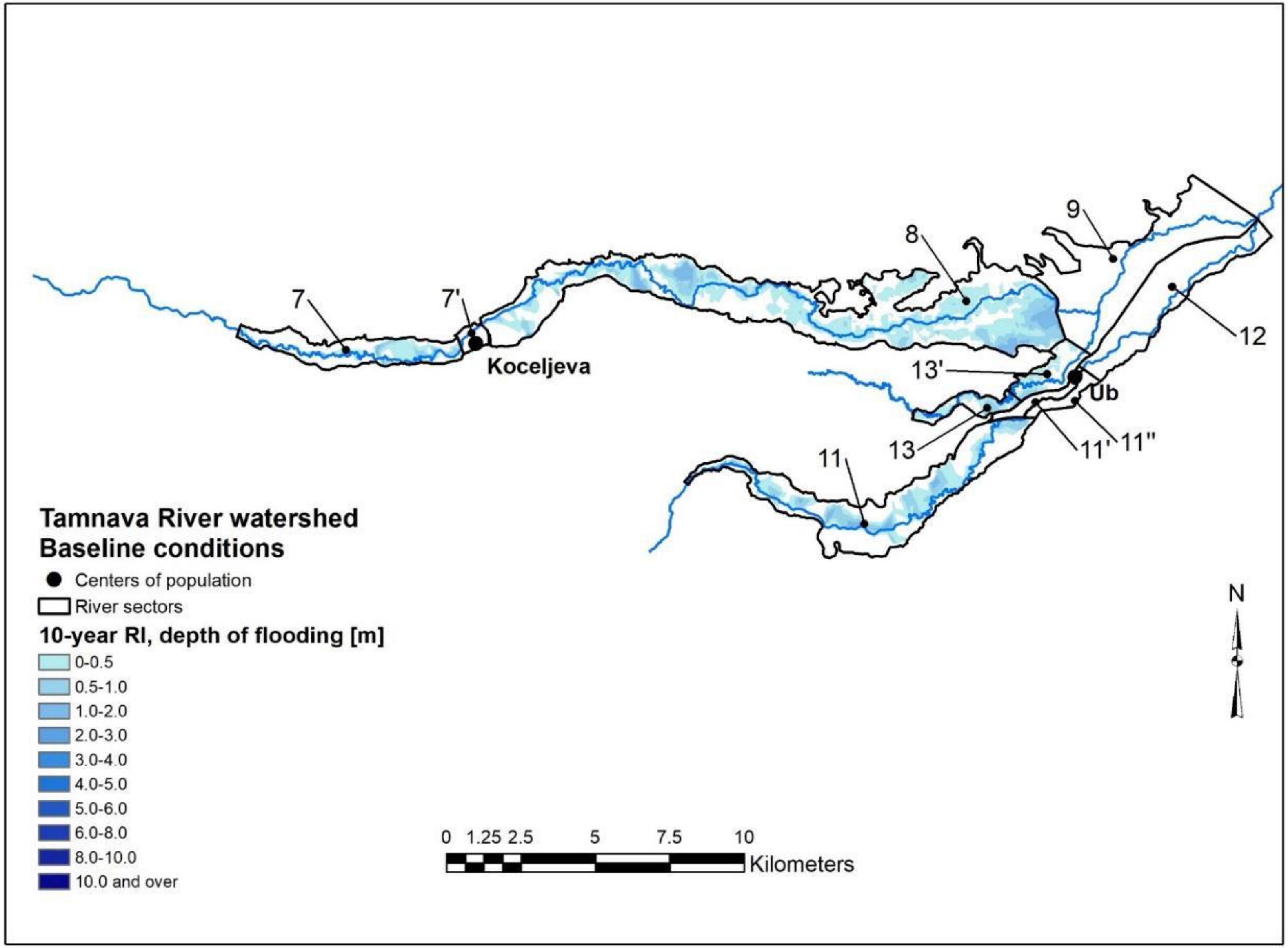


Figure A.6. Flood hazard: 10-year recurrence interval flood in the Tamnava watershed under the baseline scenario

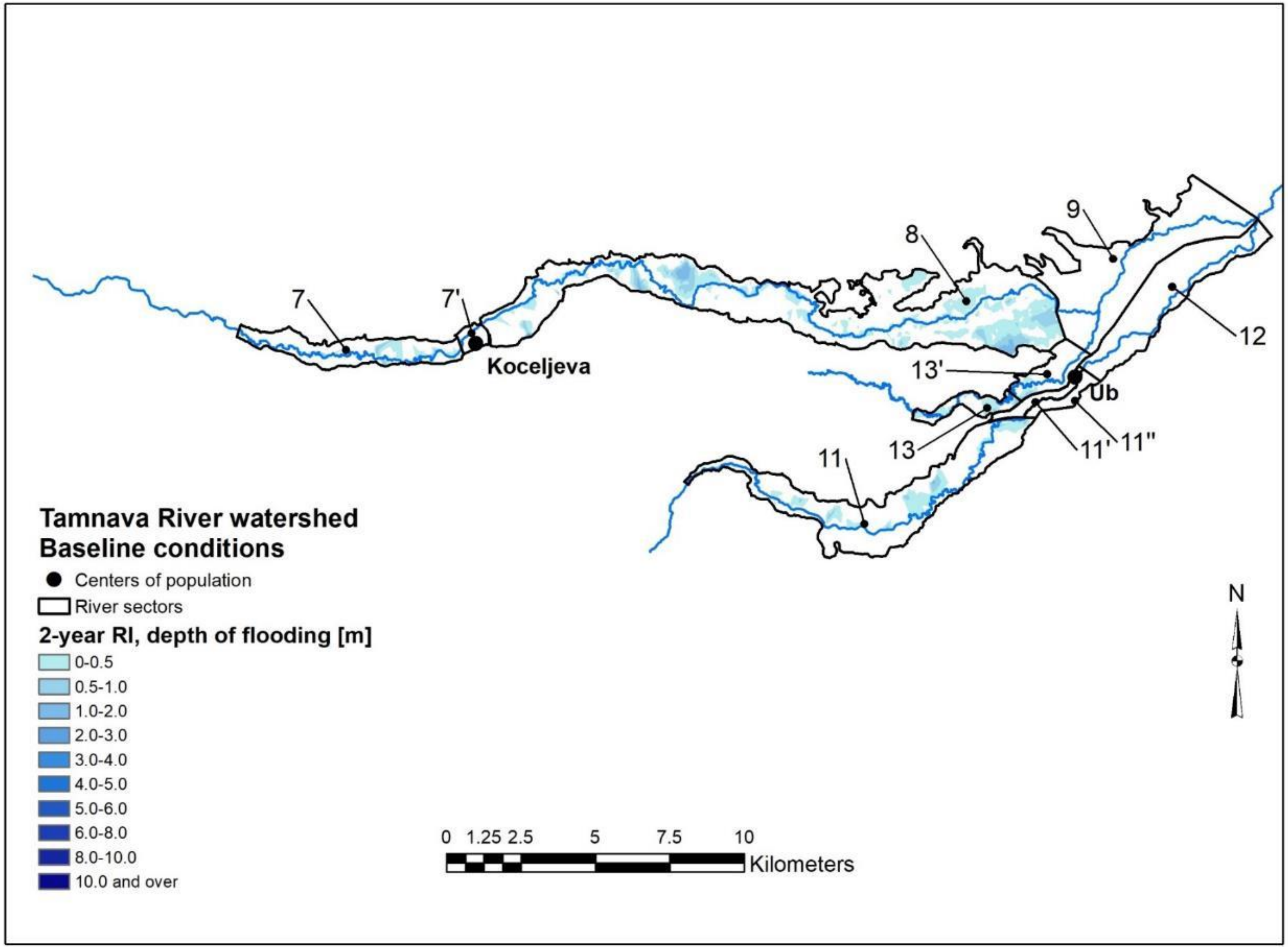


Figure A.7. Flood hazard: 2-year recurrence interval flood in the Tamnava watershed under the baseline scenario

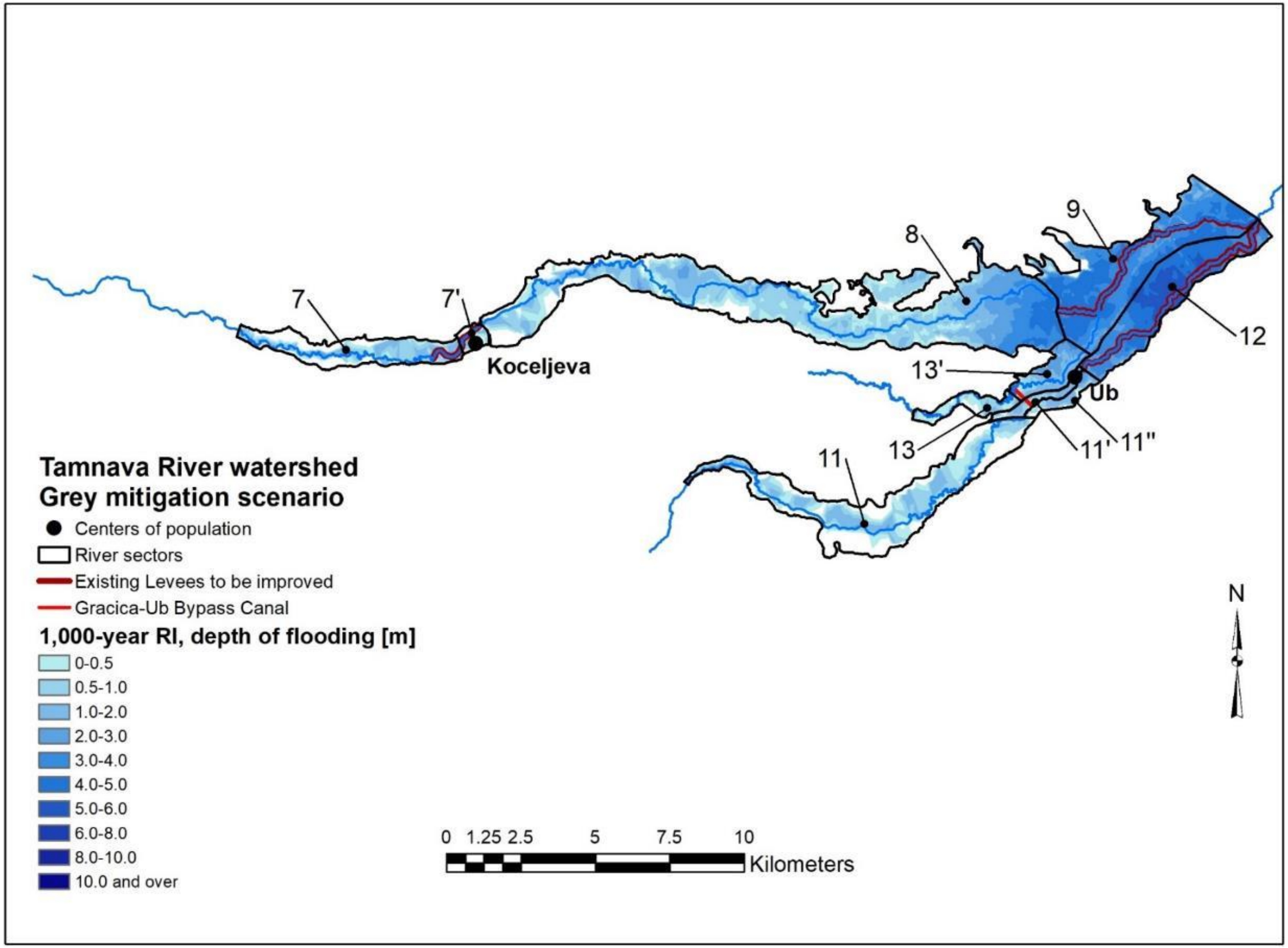


Figure A.8. Flood hazard: 1,000-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

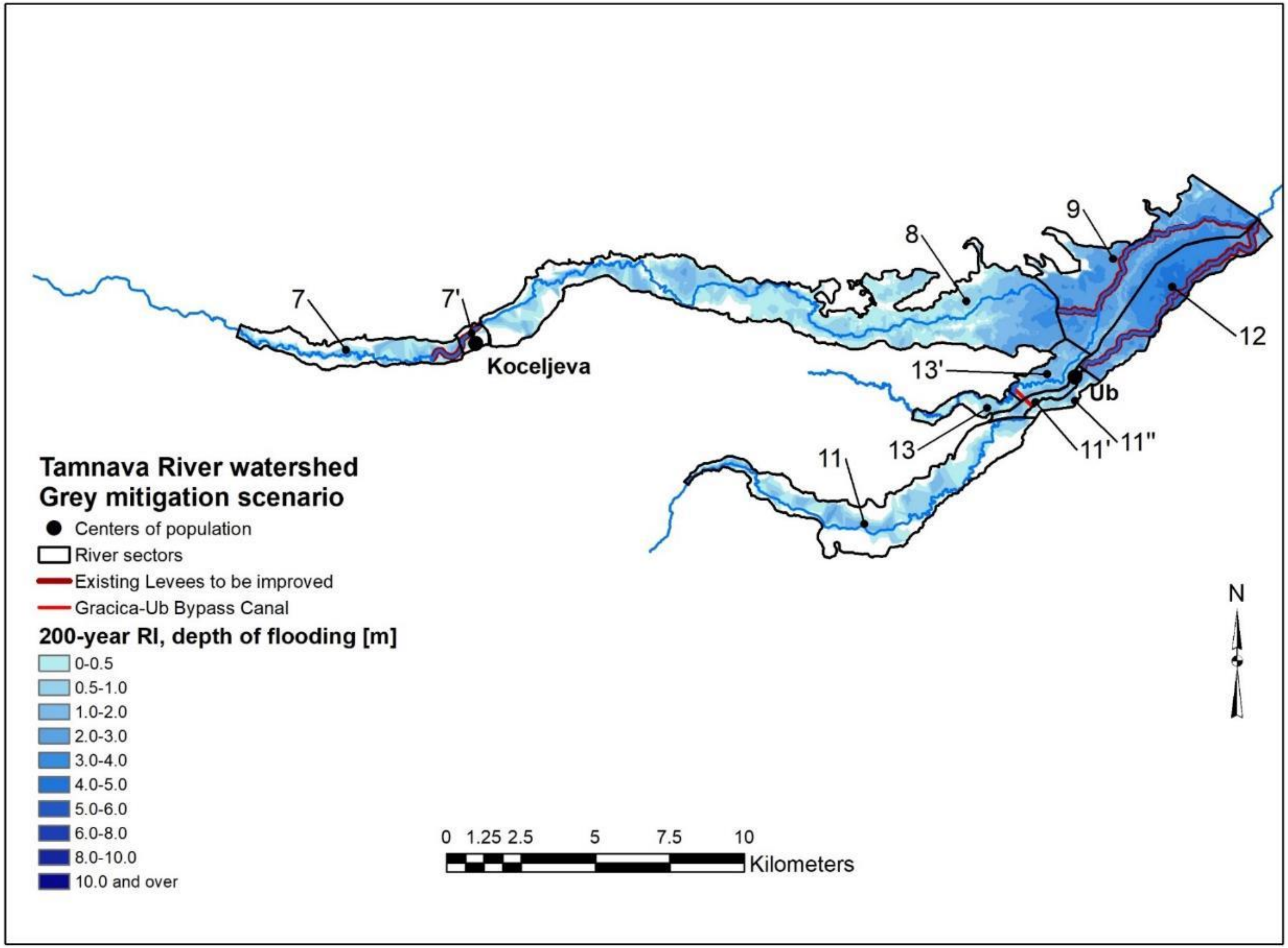


Figure A.9. Flood hazard: 200-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

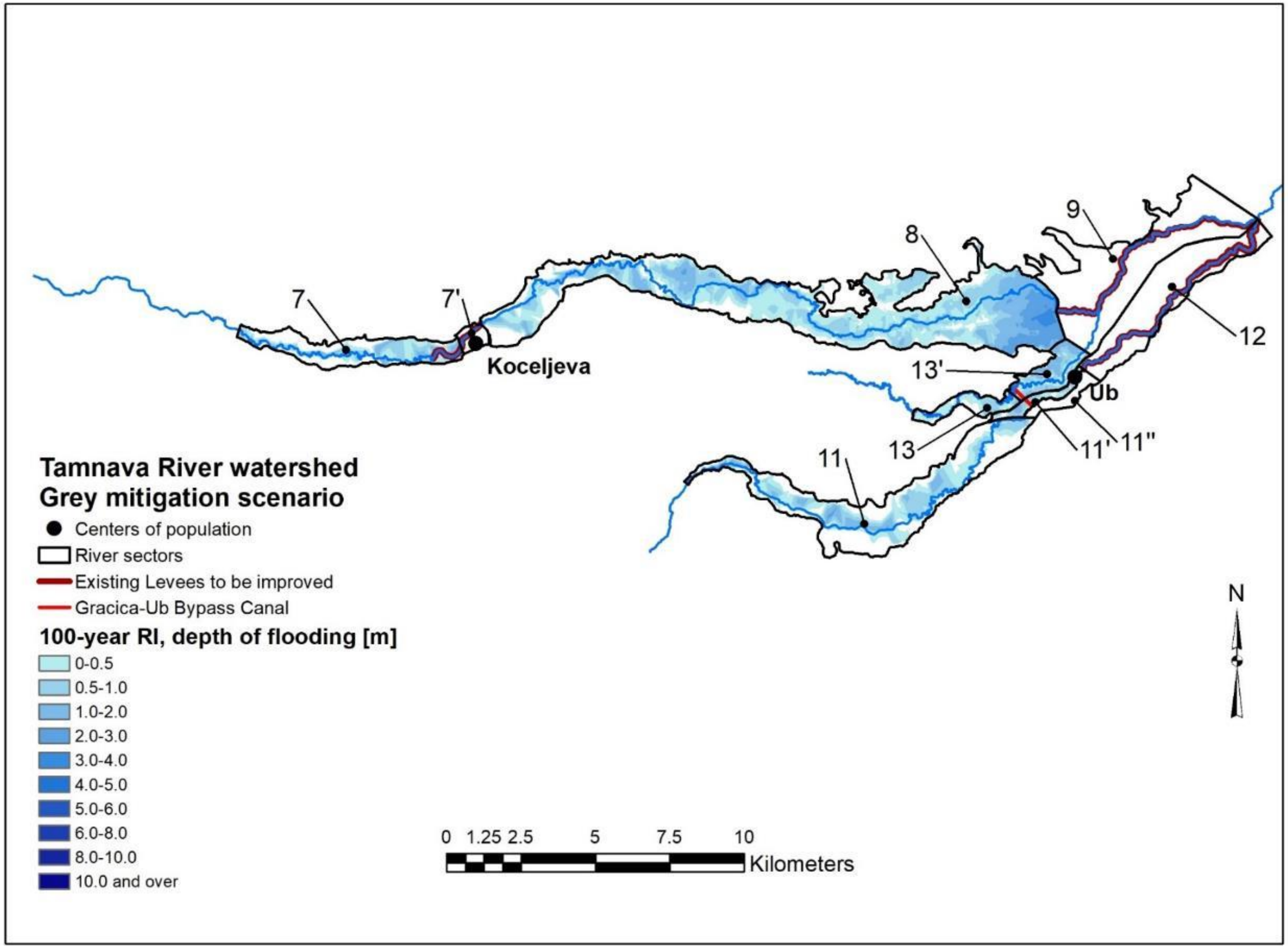


Figure A.10. Flood hazard: 100-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

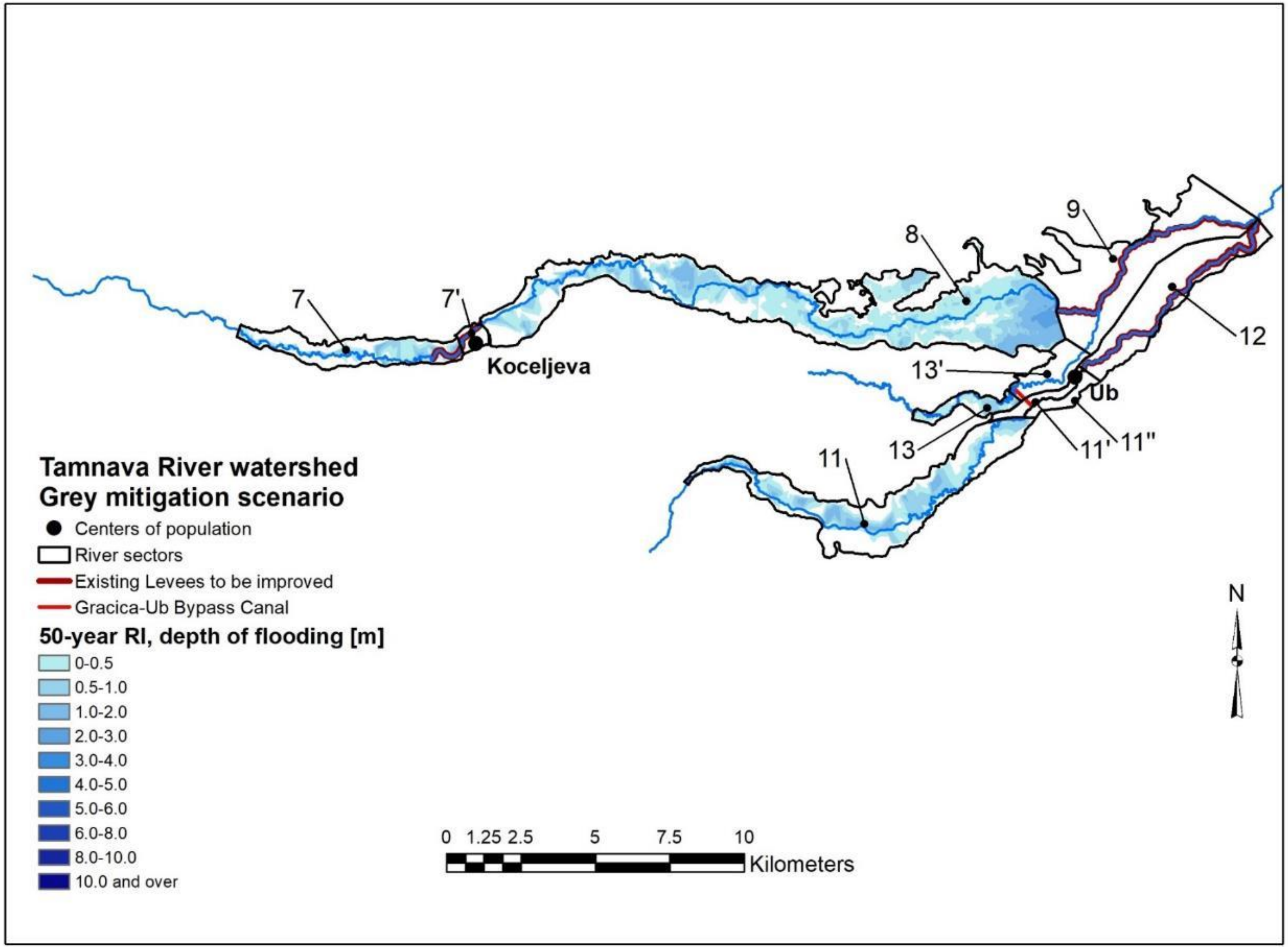


Figure A.11. Flood hazard: 50-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

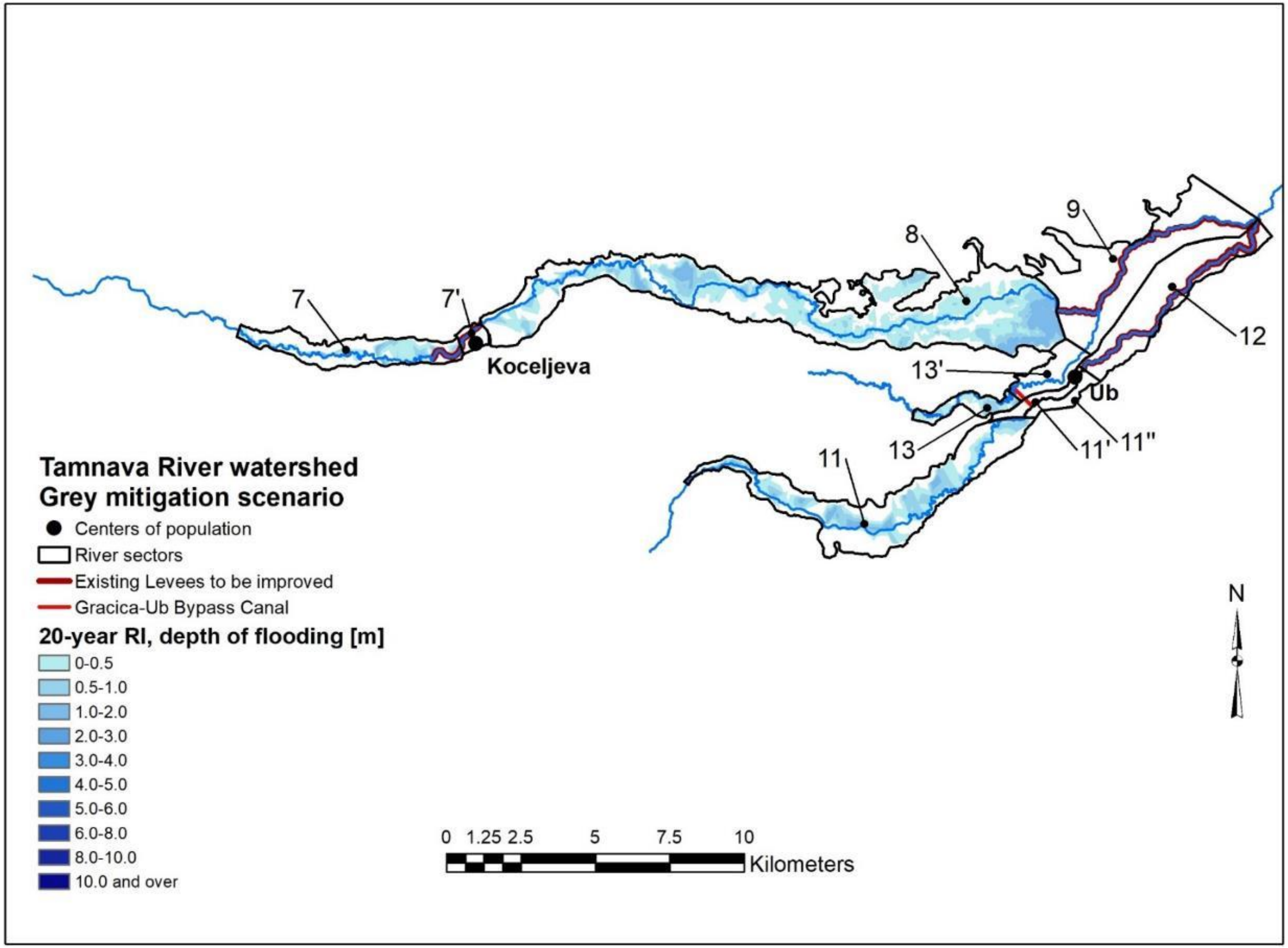


Figure A.12. Flood hazard: 20-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

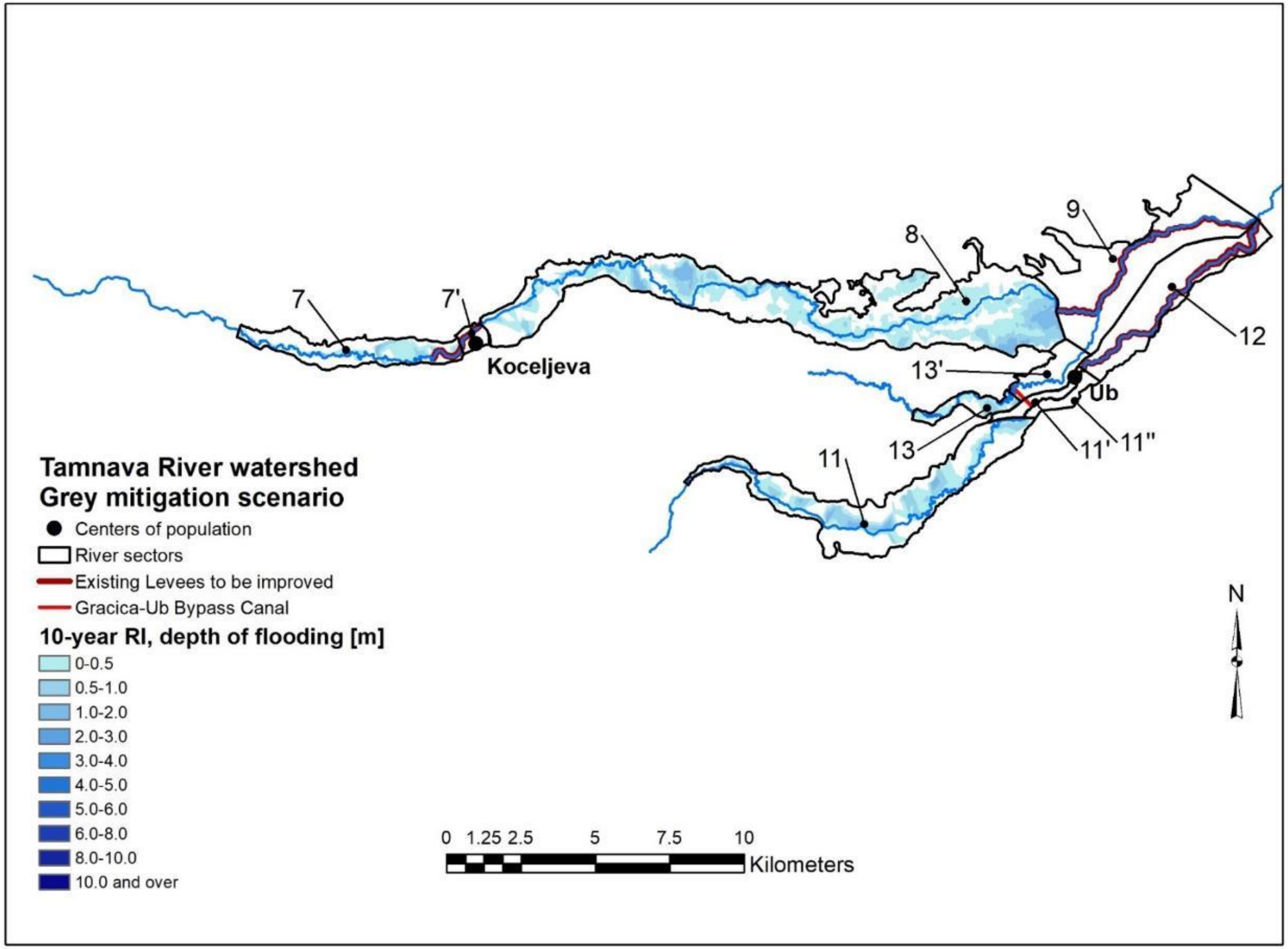


Figure A.13. Flood hazard: 10-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

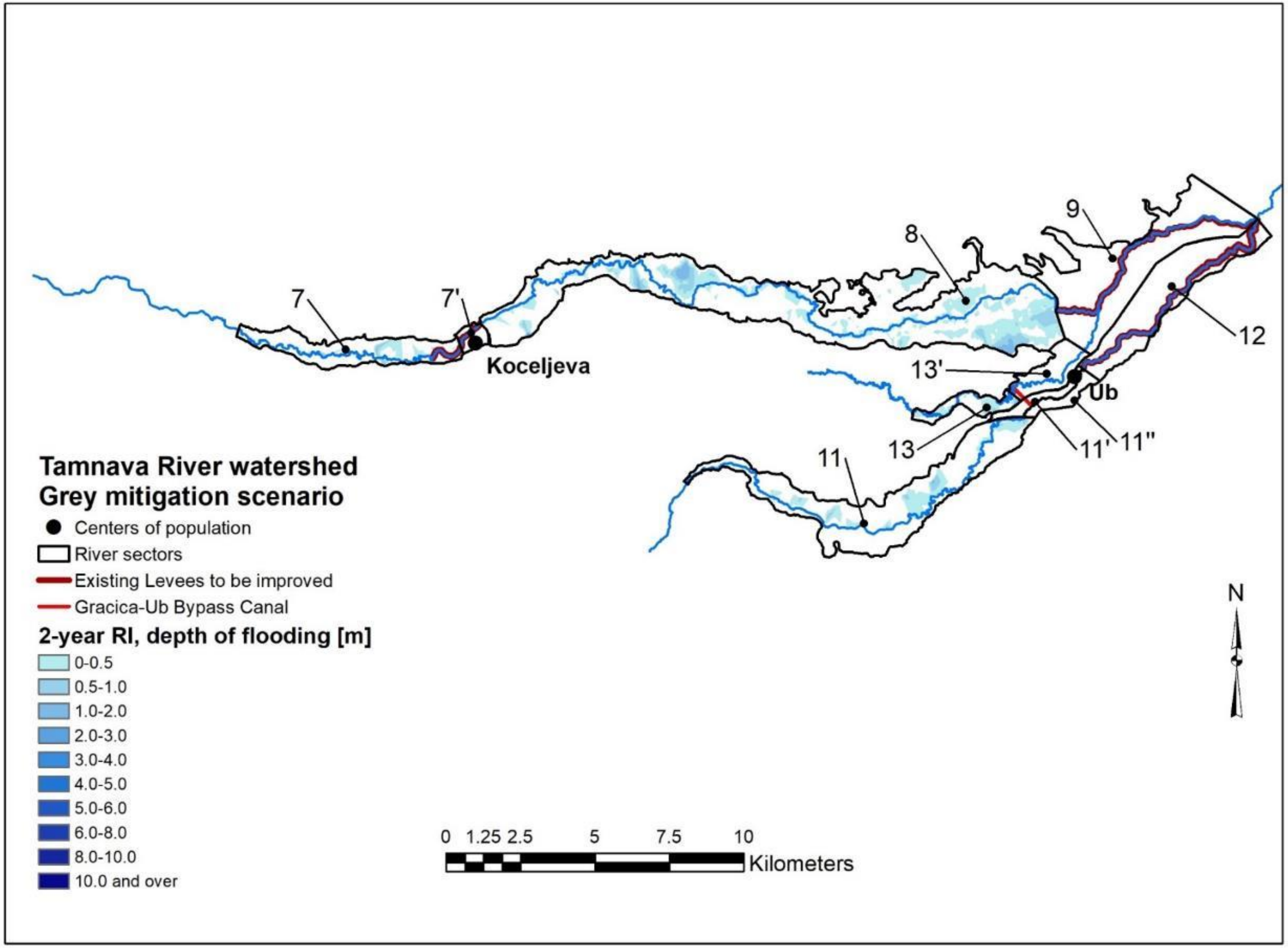


Figure A.14. Flood hazard: 2-year recurrence interval flood in the Tamnava watershed under the grey mitigation scenario

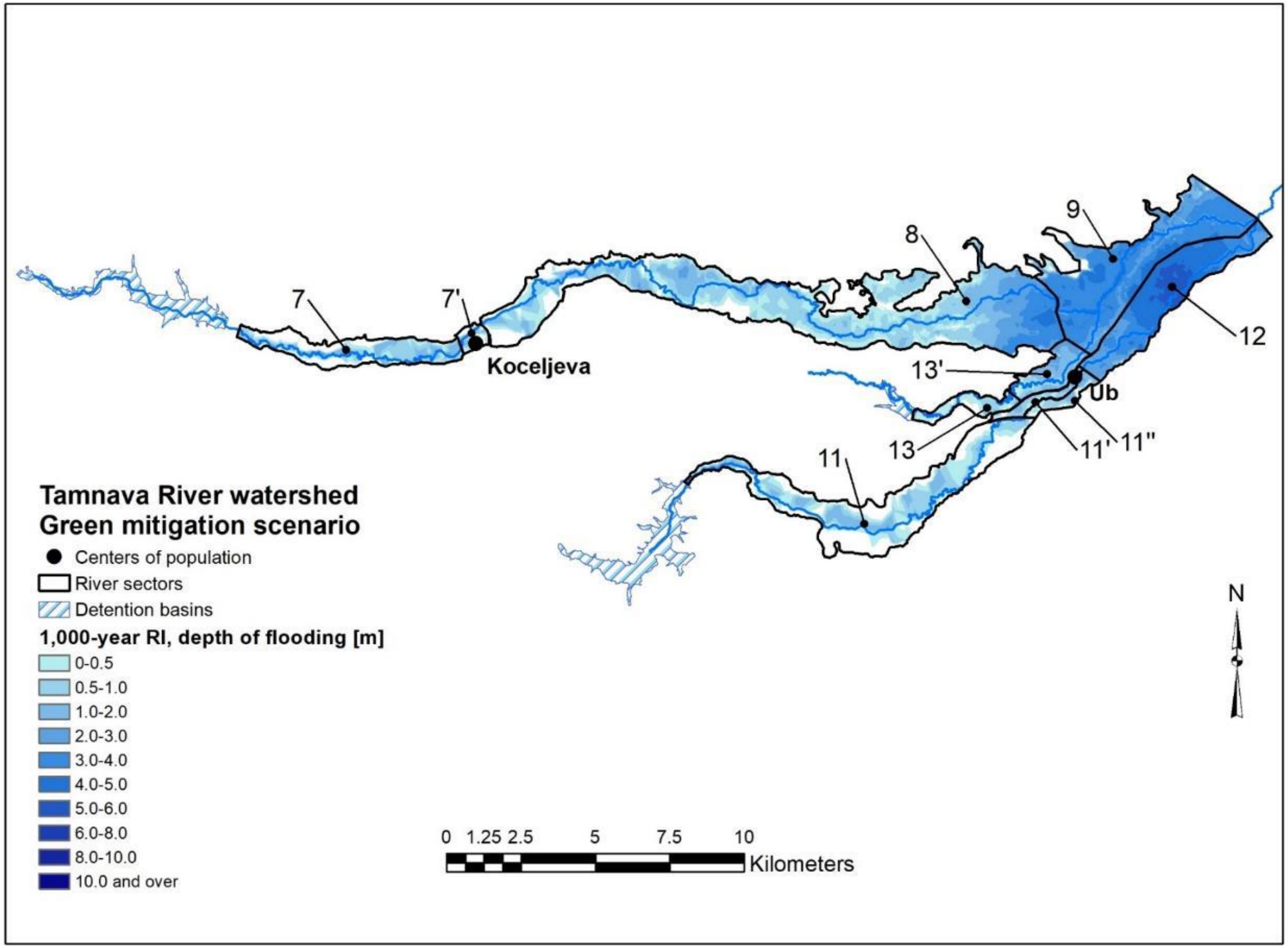


Figure A.15. Flood hazard: 1,000-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

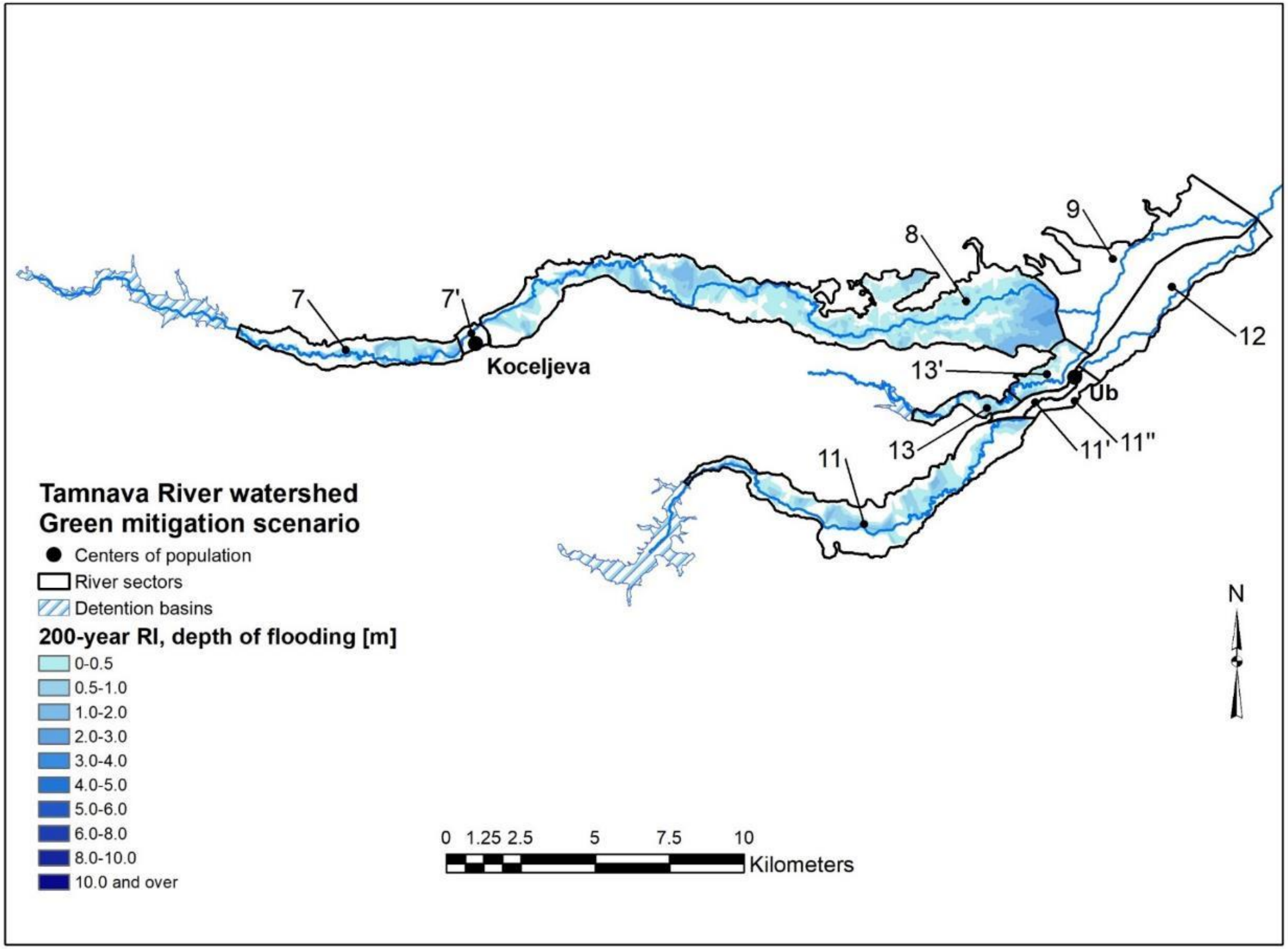


Figure A.16. Flood hazard: 200-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

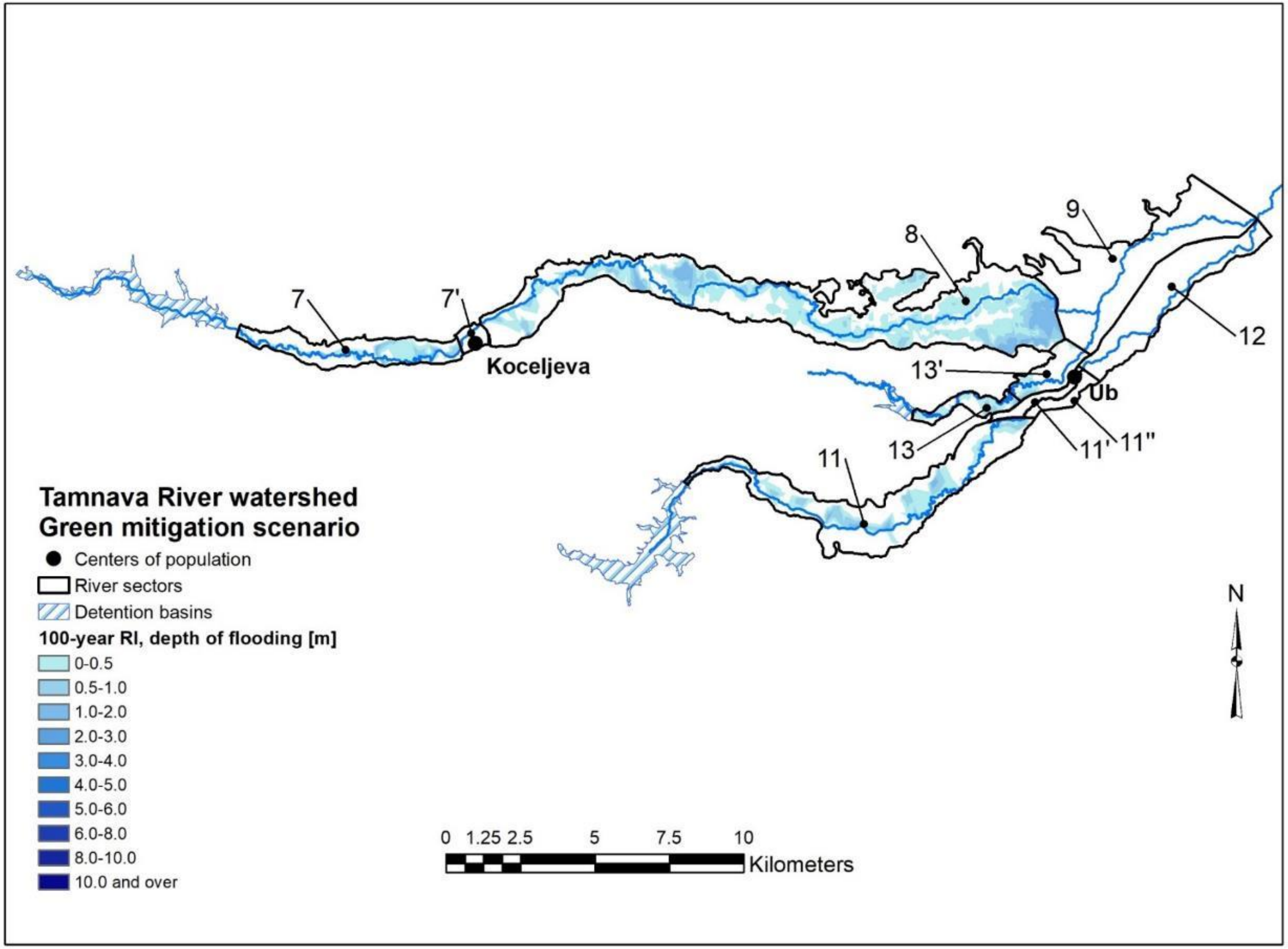


Figure A.17. Flood hazard: 100-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

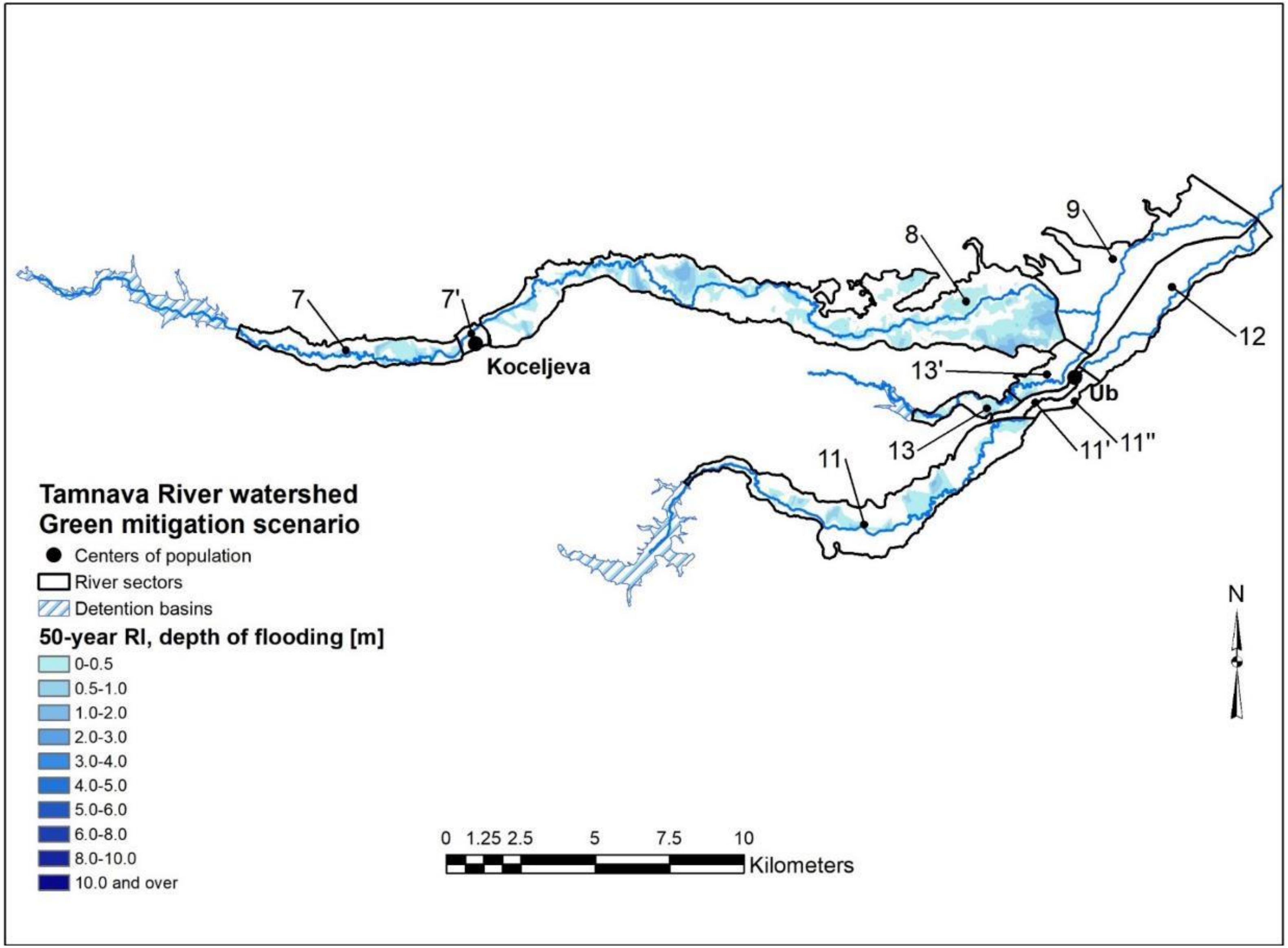


Figure A.18. Flood hazard: 50-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

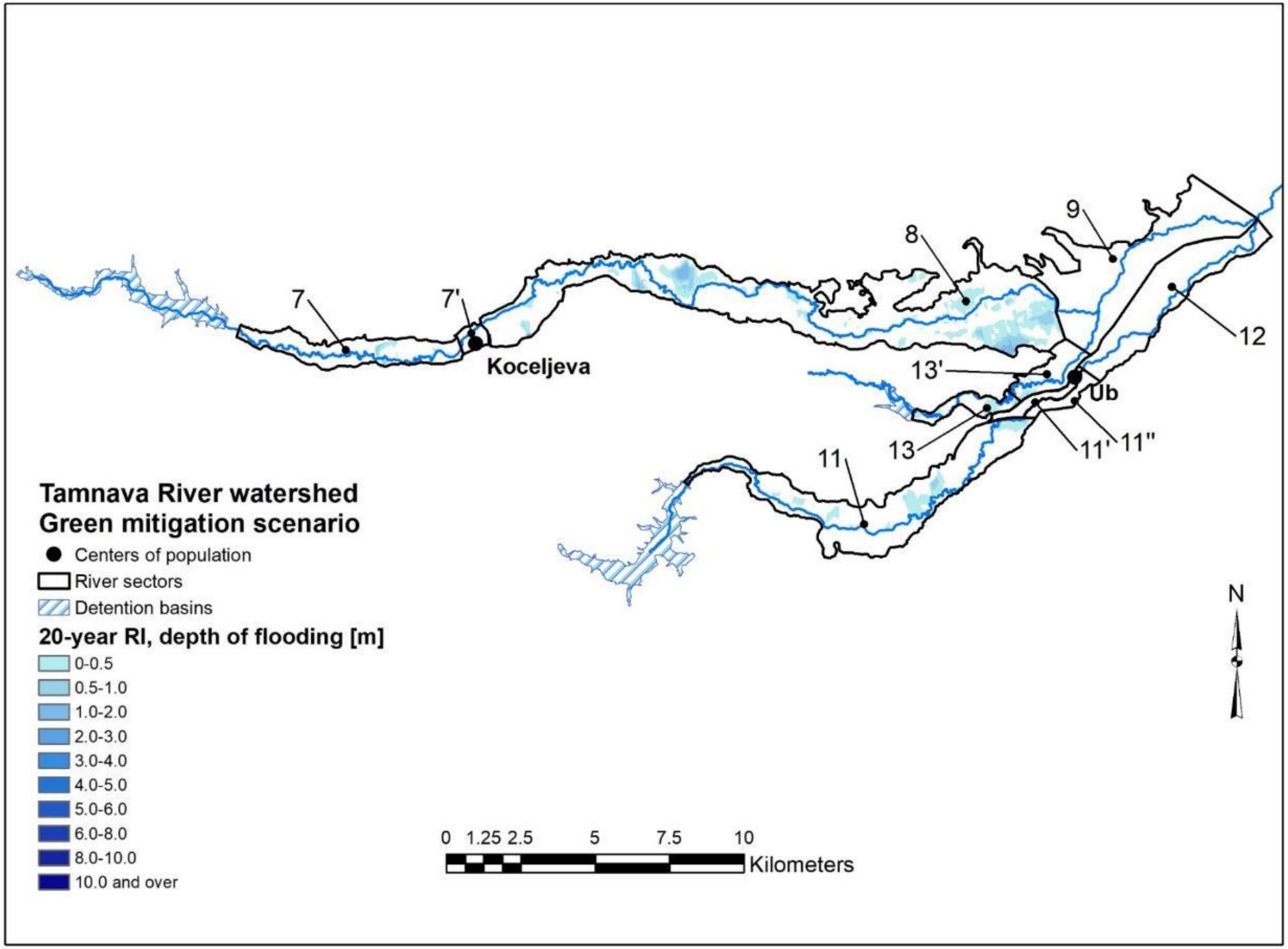


Figure A.19. Flood hazard: 20-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

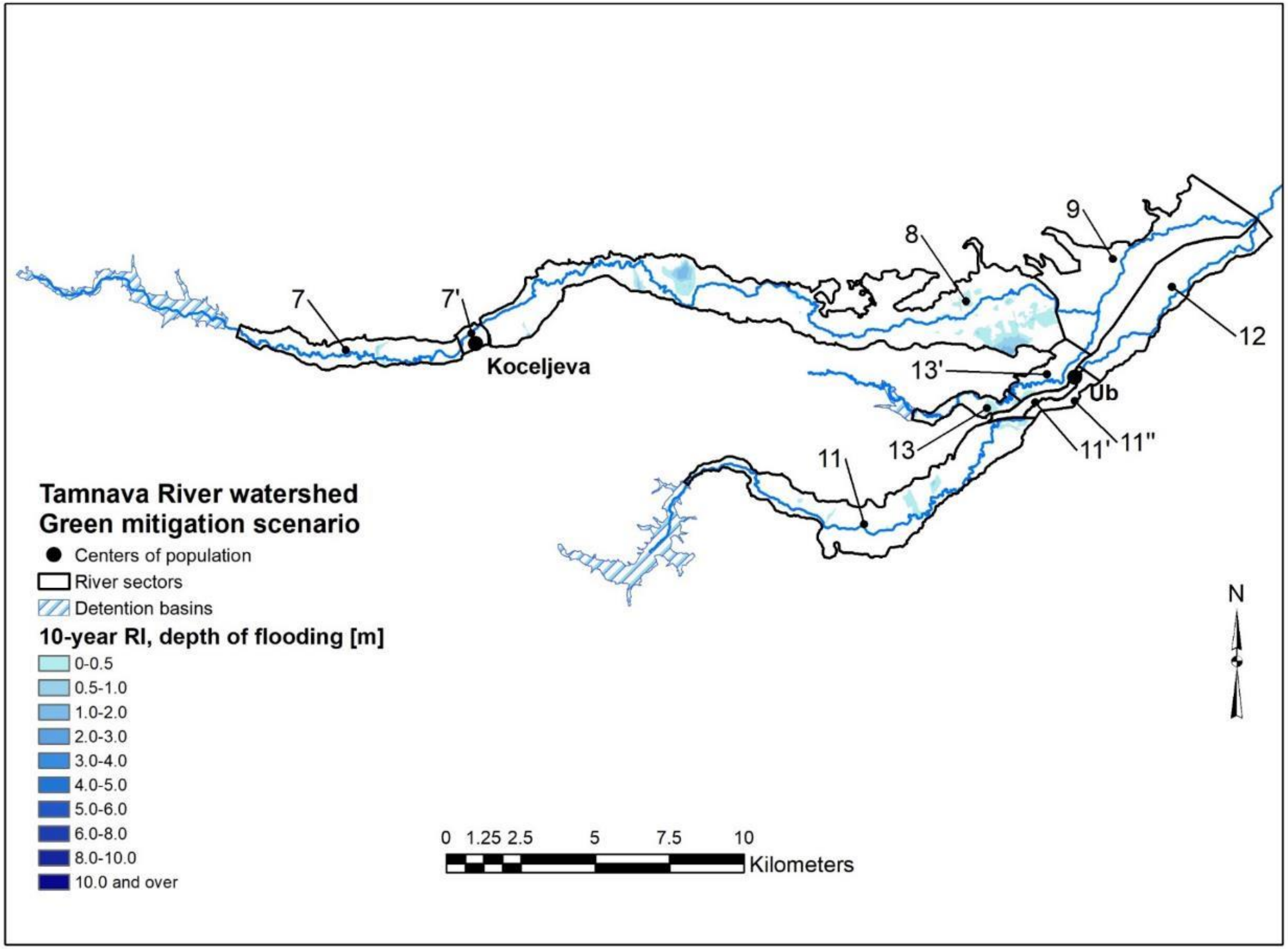


Figure A.20. Flood hazard: 10-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

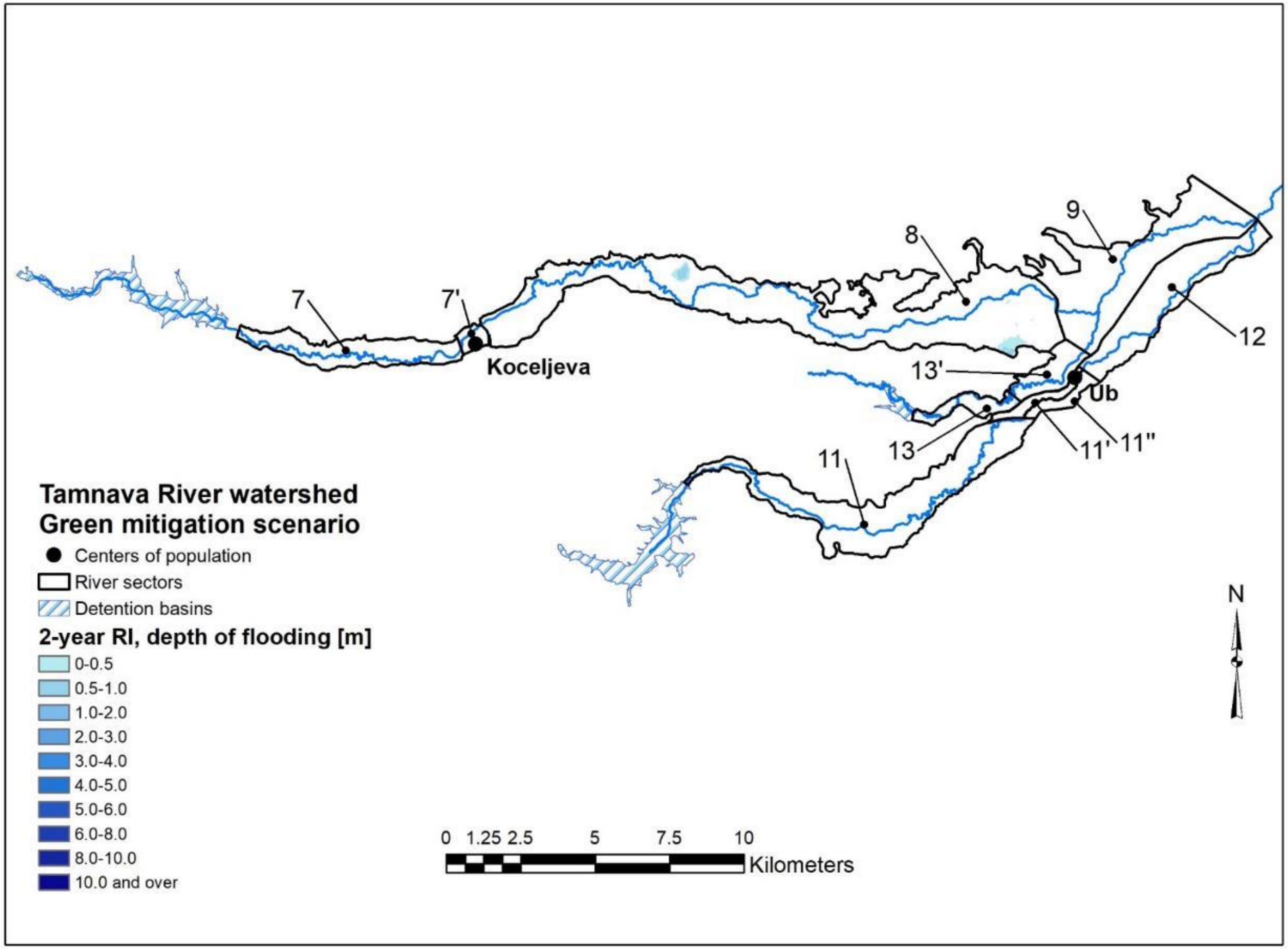


Figure A.21. Flood hazard: 2-year recurrence interval flood in the Tamnava watershed under the green mitigation scenario

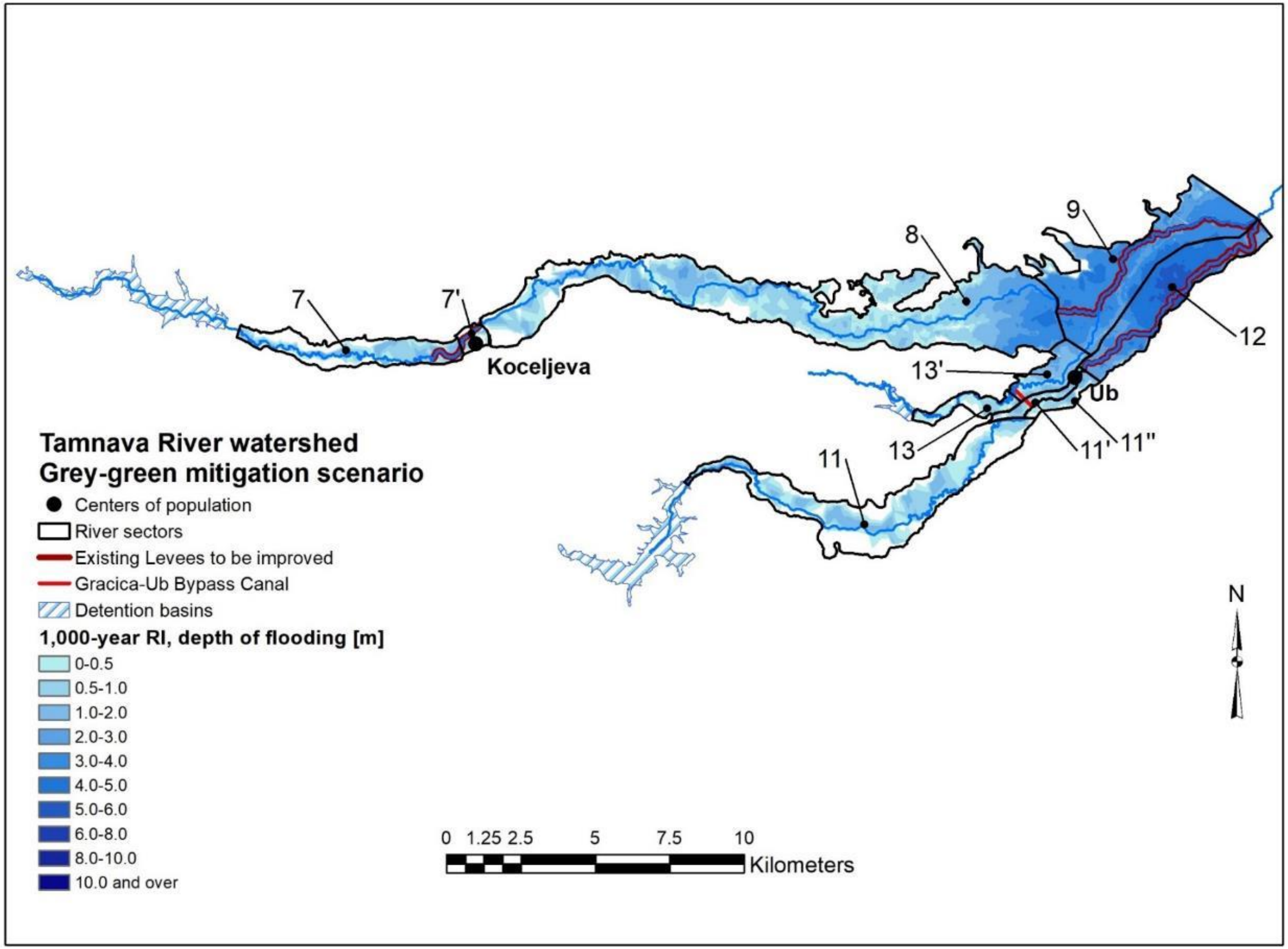


Figure A.22. Flood hazard: 1,000-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

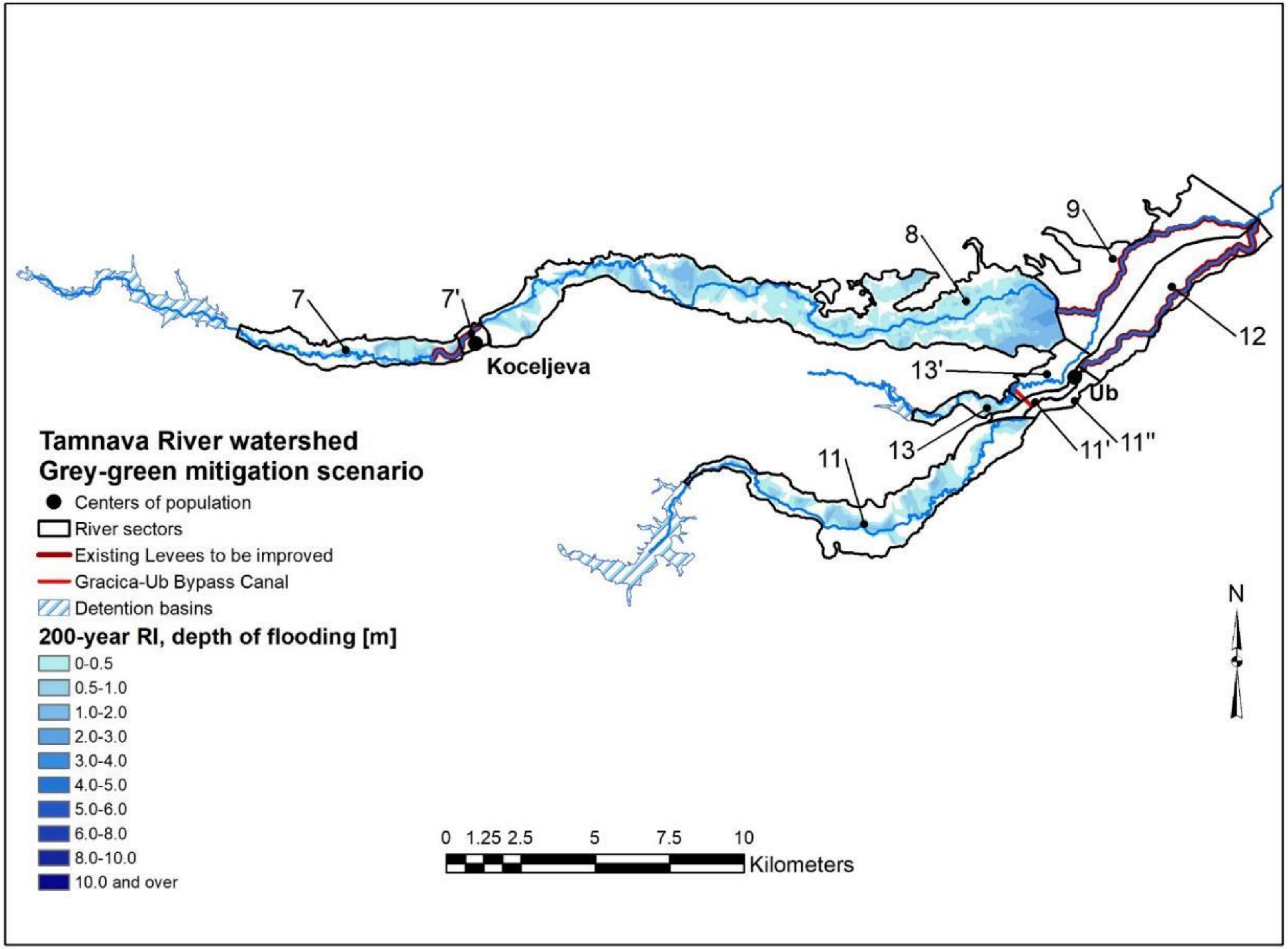


Figure A.23. Flood hazard: 200-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

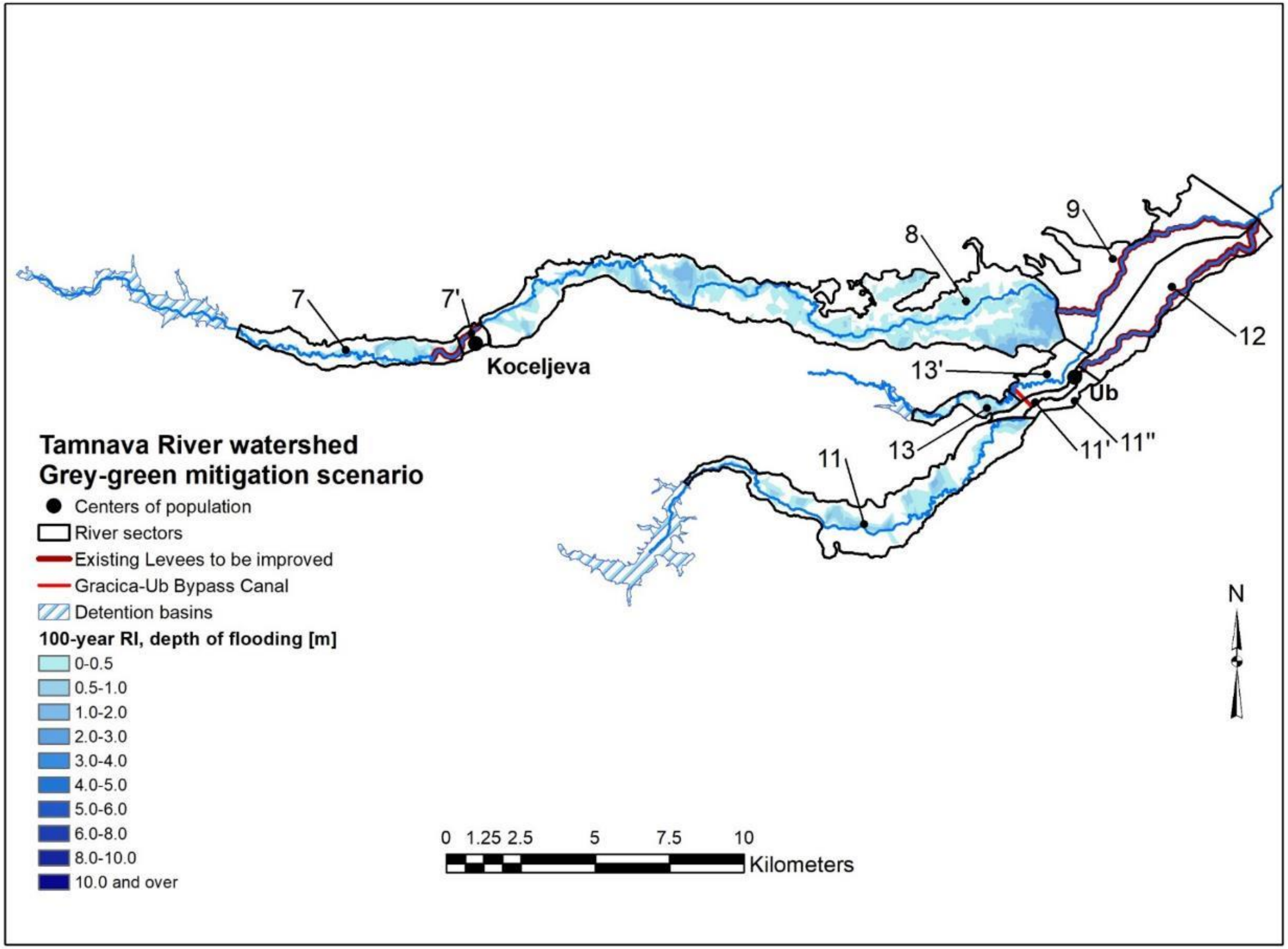


Figure A.24. Flood hazard: 100-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

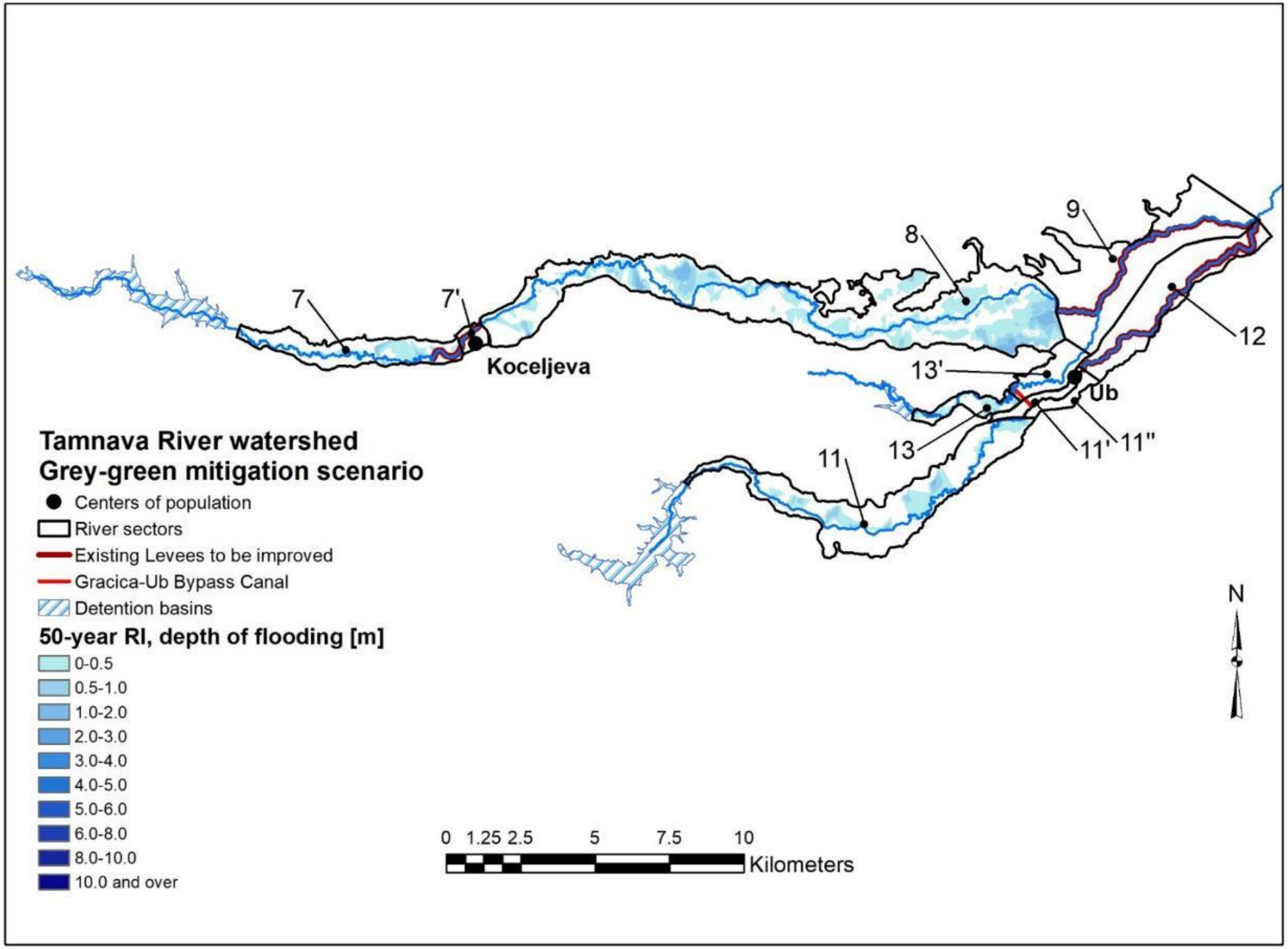


Figure A.25. Flood hazard: 50-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

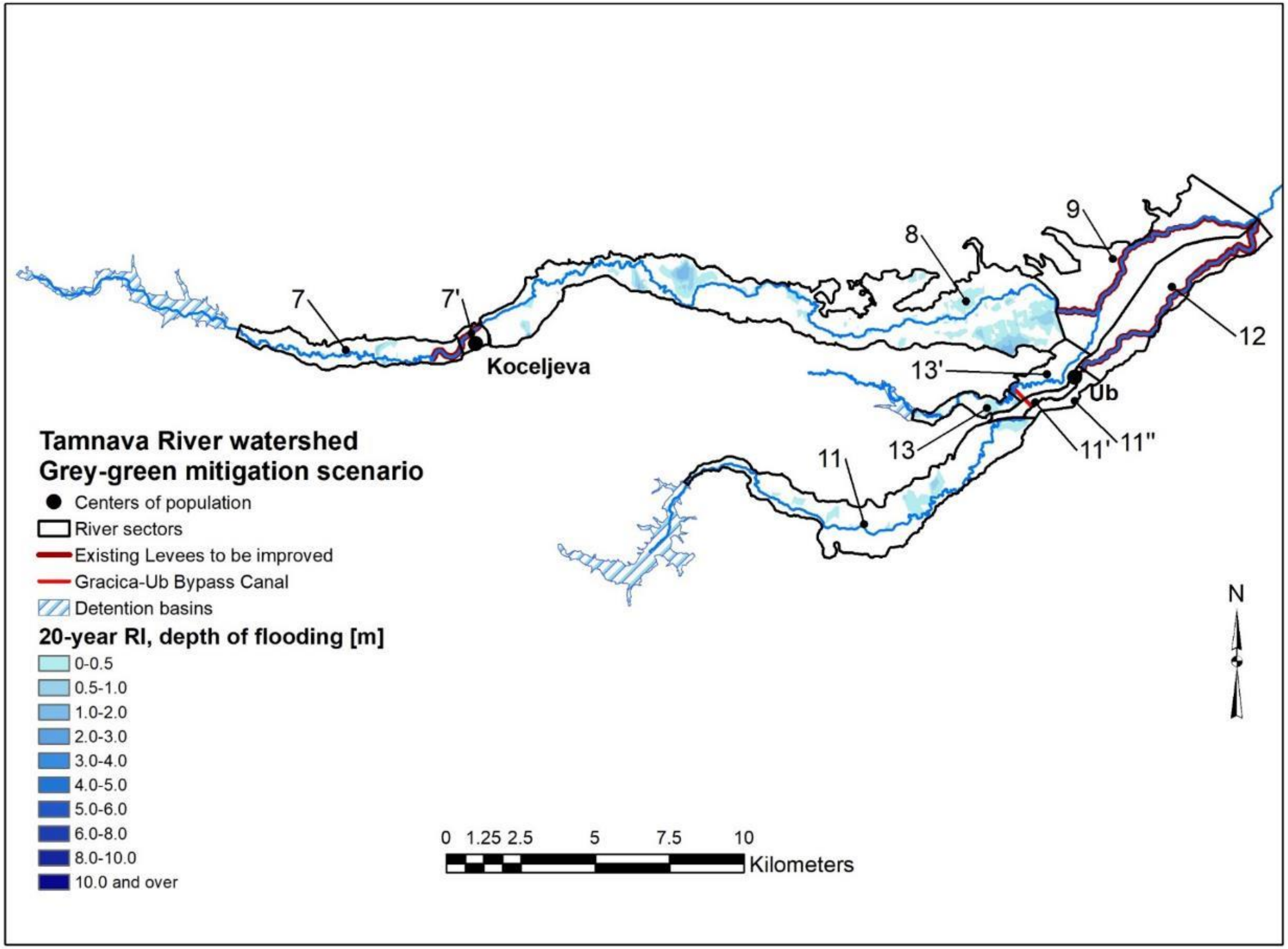


Figure A.26. Flood hazard: 20-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

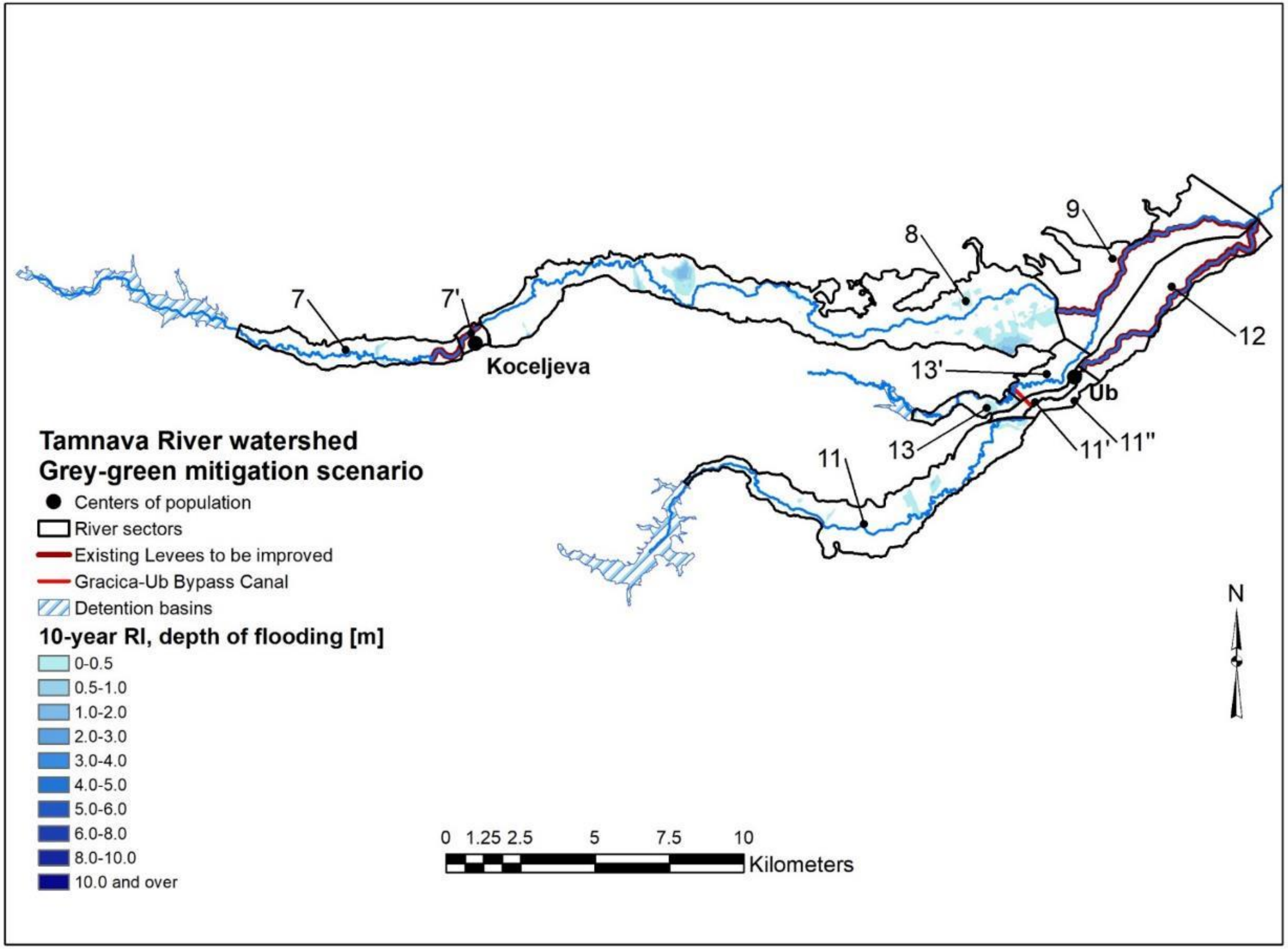


Figure A.27. Flood hazard: 10-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

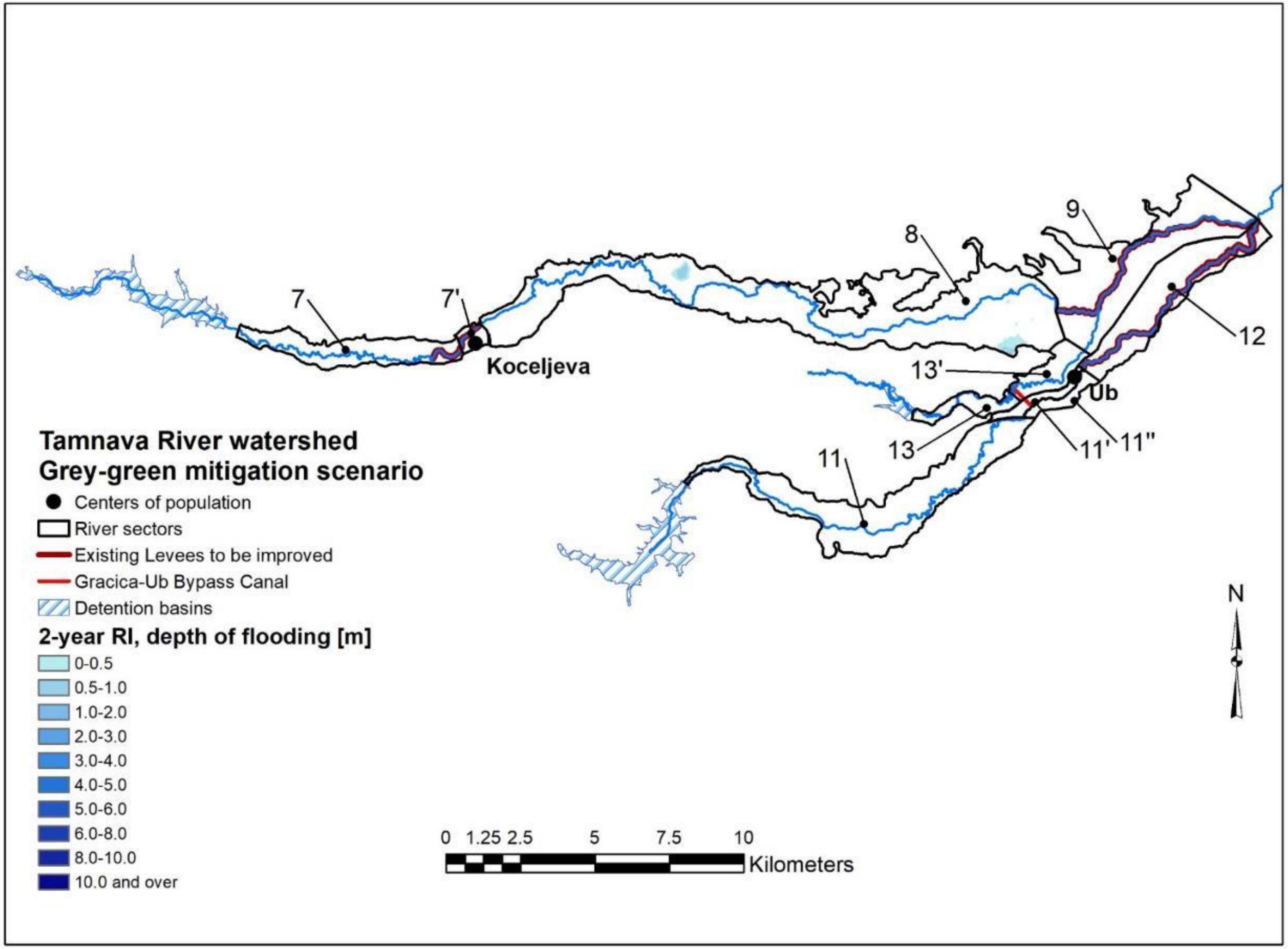


Figure A.28. Flood hazard: 2-year recurrence interval flood in the Tamnava watershed under the grey-green mitigation scenario

Appendix B - Flood damages per loss categories in the Tamnava watershed

Table B.1. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 1,000-year recurrence interval

	Existing conditions			Grey scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	3,030	42,831,274	21,415,637	3,030	42,831,274	21,415,637
• Commercial, educational, governmental, institutional	339	11,096,244	11,096,244	339	11,096,244	11,096,244
• Manufacturing and light industrial	109	7,535,970	11,303,955	109	7,535,970	11,303,955
• Transportation facilities	3	187,646	187,646	3	187,646	187,646
• Agricultural facilities	1,234	13,302,035	12,129,461	1,234	13,302,035	12,129,461
TOTAL	4,715	74,953,168	56,132,943	4,715	74,953,168	56,132,943

	Green scenario			Grey-green scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	2,817	35,261,615	17,630,807	2,817	35,261,615	17,630,807
• Commercial, educational, governmental, institutional	302	8,850,637	8,850,637	302	8,850,637	8,850,637
• Manufacturing and light industrial	103	6,219,586	9,329,379	103	6,219,586	9,329,379
• Transportation facilities	3	167,156	167,156	3	167,156	167,156
• Agricultural facilities	1,148	11,939,334	10,913,022	1,148	11,939,334	10,913,022
TOTAL	4,373	62,438,328	46,891,002	4,373	62,438,328	46,891,002

Table B.2. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 200-year recurrence interval

	Existing conditions			Grey scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	2,597	27,812,172	13,906,086	2,597	27,812,172	13,906,086
• Commercial, educational, governmental, institutional	288	6,449,330	6,449,330	288	6,449,330	6,449,330
• Manufacturing and light industrial	94	4,495,287	6,742,930	94	4,495,287	6,742,930
• Transportation facilities	3	155,732	155,732	3	155,732	155,732
• Agricultural facilities	1,006	9,688,474	8,932,479	1,006	9,688,474	8,932,479
TOTAL	3,988	48,600,995	36,186,557	3,988	48,600,995	36,186,557

	Green scenario			Grey-green scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	251	962,554	481,277	148	546,719	273,360
• Commercial, educational, governmental, institutional	21	172,277	172,277	9	129,050	129,050
• Manufacturing and light industrial	16	97,424	146,135	15	94,623	141,934
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	223	938,303	905,287	182	795,651	778,095
TOTAL	511	2,170,556	1,704,975	354	1,566,043	1,322,439

Table B.3. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 100-year recurrence interval

	Existing conditions			Grey scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	1,819	17,152,294	8,576,147	1,047	4,656,758	2,328,379
• Commercial, educational, governmental, institutional	229	4,184,035	4,184,035	149	1,200,683	1,200,683
• Manufacturing and light industrial	81	4,401,710	6,602,565	27	568,842	853,263
• Transportation facilities	3	120,292	120,292	2	43,437	43,437
• Agricultural facilities	940	8,772,637	8,115,801	476	2,384,005	2,236,011
TOTAL	3,072	34,630,968	27,598,839	1,701	8,853,725	6,661,773

	Green scenario			Grey-green scenario		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	120	346,904	173,452	106	293,191	146,595
• Commercial, educational, governmental, institutional	6	40,111	40,111	5	37,930	37,930
• Manufacturing and light industrial	10	60,084	90,126	10	60,084	90,126
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	162	548,257	538,668	148	479,010	470,127
TOTAL	298	995,355	842,357	269	870,214	744,778

Table B.4. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 50-year recurrence interval

	Existing conditions			**Grey scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	840	4,690,279	2,345,140	171	673,814	336,907
• Commercial, educational, governmental, institutional	139	1,224,967	1,224,967	11	160,182	160,182
• Manufacturing and light industrial	57	1,474,297	2,211,445	14	112,532	168,798
• Transportation facilities	2	31,059	31,059	0	0	0
• Agricultural facilities	438	2,461,140	2,342,984	219	964,776	940,571
TOTAL	1,476	9,881,742	8,155,595	415	1,911,305	1,606,457

	Green scenario			**Grey-green scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	79	157,847	78,924	73	139,473	69,736
• Commercial, educational, governmental, institutional	1	3,920	3,920	1	3,920	3,920
• Manufacturing and light industrial	5	46,555	69,833	5	46,555	69,833
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	102	278,478	272,421	98	246,137	240,079
TOTAL	187	486,800	425,097	177	436,085	383,569

Table B.5. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 20-year recurrence interval

	Existing conditions			**Grey scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	288	1,302,646	651,323	125	418,962	209,481
• Commercial, educational, governmental, institutional	28	127,704	127,704	10	74,243	74,243
• Manufacturing and light industrial	19	159,451	239,177	15	83,659	125,488
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	233	877,989	851,738	169	661,258	650,514
TOTAL	568	2,467,790	1,869,942	319	1,238,122	1,059,726

	Green scenario			**Grey-green scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	24	56,144	28,072	21	52,559	26,279
• Commercial, educational, governmental, institutional	0	0	0	0	0	0
• Manufacturing and light industrial	4	37,049	55,574	4	37,049	55,574
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	54	101,260	98,121	53	86,556	83,417
TOTAL	82	194,454	181,767	78	176,164	165,270

Table B.6. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 10-year recurrence interval

	Existing conditions			**Grey scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	168	485,611	242,805	107	278,643	139,322
• Commercial, educational, governmental, institutional	8	34,709	34,709	6	25,062	25,062
• Manufacturing and light industrial	9	61,091	91,636	9	61,091	91,636
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	168	577,767	565,289	141	472,455	463,934
TOTAL	353	1,159,178	934,439	263	837,251	719,954

	Green scenario			**Grey-green scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	11	24,589	12,294	11	24,589	12,294
• Commercial, educational, governmental, institutional	0	0	0	0	0	0
• Manufacturing and light industrial	4	25,745	38,617	4	25,745	38,617
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	25	34,105	32,035	24	33,150	31,081
TOTAL	40	84,438	82,947	39	83,484	81,993

Table B.7. Estimated flood-related direct losses to buildings and contents in the Tamnava watershed for a 2-year recurrence interval

	Existing conditions			**Grey scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	44	95,063	47,531	39	78,055	39,027
• Commercial, educational, governmental, institutional	0	0	0	0	0	0
• Manufacturing and light industrial	4	46,239	69,358	4	46,239	69,358
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	86	170,678	166,641	83	143,368	139,331
TOTAL	134	311,980	283,531	126	267,662	247,717

	Green scenario			**Grey-green scenario**		
Building occupational class	**Building count**	**Building losses [€]**	**Content losses [€]**	**Building count**	**Building losses [€]**	**Content losses [€]**
• Residential (all types)	0	0	0	0	0	0
• Commercial, educational, governmental, institutional	0	0	0	0	0	0
• Manufacturing and light industrial	1	992	1,488	1	992	1,488
• Transportation facilities	0	0	0	0	0	0
• Agricultural facilities	1	2,606	1,303	1	2,606	1,303
TOTAL	2	3,598	2,791	2	3,598	2,791

Table B.8. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 1,000-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	297,703	297,703	285,423	285,423
7'	15,916	15,916	15,096	15,096
8	4,838,777	4,838,777	4,761,661	4,761,661
9	2,918,081	2,918,081	2,903,356	2,903,356
11	2,191,605	2,191,605	2,081,770	2,081,770
11'	71,833	71,833	69,148	69,148
11''	28,750	28,750	26,182	26,182
12	2,402,040	2,402,040	2,399,053	2,399,053
13	521,429	521,429	484,221	484,221
13'	399,381	399,381	376,793	376,793
TOTAL	13,685,515	13,685,515	13,402,702	13,402,702

Table B.9. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 200-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	258,260	258,260	201,358	201,358
7'	12,531	12,531	0	0
8	4,513,223	4,513,223	3,746,252	3,746,252
9	2,847,812	2,847,812	0	0
11	2,010,014	2,010,014	1,521,056	1,521,056
11'	69,497	69,497	0	0
11''	26,097	26,097	0	0
12	2,385,869	2,385,869	0	0
13	498,437	498,437	375,048	375,048
13'	382,268	382,268	212,741	0
TOTAL	13,004,008	13,004,008	6,056,455	5,843,714

Table B.10. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 100-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	252,319	252,319	164,202	164,202
7'	14,233	0	0	0
8	4,465,396	4,465,396	3,024,910	3,024,910
9	2,836,097	0	0	0
11	1,886,473	1,886,473	1,174,072	1,174,072
11'	66,330	33,165	0	0
11''	0	0	0	0
12	2,379,844	0	0	0
13	478,399	478,399	338,150	338,150
13'	346,265	173,132	148,301	0
TOTAL	12,725,355	7,288,884	4,849,636	4,701,335

Table B.11. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 50-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	209,645	209,645	124,851	124,851
7'	0	0	0	0
8	3,916,295	3,916,295	2,285,312	2,285,312
9	0	0	0	0
11	1,803,189	1,803,189	862,251	862,251
11'	31,446	0	0	0
11''	0	0	0	0
12	2,332,756	0	0	0
13	468,779	468,779	238,136	238,136
13'	320,613	0	99,144	0
TOTAL	9,082,722	6,397,908	3,609,696	3,510,551

Table B.12. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 20-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	178,879	178,879	40,024	40,024
7'	0	0	0	0
8	3,288,746	3,288,746	1,167,865	1,167,865
9	0	0	0	0
11	1,669,634	1,669,634	493,534	493,534
11'	0	0	0	0
11''	0	0	0	0
12	0	0	0	0
13	441,486	441,486	159,322	159,322
13'	260,907	0	62,598	0
TOTAL	5,839,652	5,578,745	1,923,343	1,860,745

Table B.13. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 10-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	115,942	115,942	9,837	9,837
7'	0	0	0	0
8	2,446,214	2,446,214	384,789	384,789
9	0	0	0	0
11	1,279,852	1,279,852	176,535	176,535
11'	0	0	0	0
11''	0	0	0	0
12	0	0	0	0
13	344,928	344,928	70,509	70,509
13'	176,039	0	24,887	0
TOTAL	4,362,976	4,186,937	666,556	641,669

Table B.14. Estimated flood-related agricultural losses in the Tamnava watershed, distributed by stream sectors for a 2-year recurrence interval

Sector	Existing conditions [€]	Grey scenario [€]	Green scenario [€]	Grey-green scenario [€]
7	18,743	18,743	0	0
7'	0	0	0	0
8	864,108	864,108	52,323	52,323
9	0	0	0	0
11	370,451	370,451	14,459	14,459
11'	0	0	0	0
11''	0	0	0	0
12	0	0	0	0
13	137,236	137,236	5,968	5,968
13'	56,272	0	1,592	0
TOTAL	1,446,811	1,390,538	74,342	72,750

Table B.15. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 1,000-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.38	21,759	0.38	21,759	0.19	13,107	0.19	13,107
IIa	141	4.98	632,723	4.98	632,723	4.88	553,136	4.88	553,136
	142	0.27	20,207	0.27	20,207	0.26	18,376	0.26	18,376
	144	6.75	948,080	6.75	948,080	6.74	888,340	6.74	888,340
IIb	340	1.49	91,429	1.49	91,429	1.45	83,037	1.45	83,037
	341	1.94	125,193	1.94	125,193	1.76	86,328	1.76	86,328
	342	0.52	50,799	0.52	50,799	0.46	39,045	0.46	39,045
	TOTAL	16.32	1,890,190	16.32	1,890,190	15.75	1,681,369	15.75	1,681,369

Table B.16. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 200-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.07	7,418	0.07	7,418	0.00	0	0.00	0
IIa	141	4.71	449,135	4.71	449,135	2.35	165,873	0.01	50
	142	0.22	14,381	0.22	14,381	0.19	8,806	0.19	8,806
	144	6.68	635,430	6.68	635,430	3.02	135,672	0.00	0
IIb	340	1.37	69,976	1.37	69,976	1.09	37,091	1.09	37,091
	341	1.79	85,252	1.79	85,252	0.00	0	0.00	0
	342	0.36	31,166	0.36	31,166	0.00	0	0.00	0
	TOTAL	15.21	1,292,758	15.21	1,292,758	6.65	347,443	1.29	45,947

Table B.17. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 100-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.07	7,012	0.07	7,012	0.00	0	0.00	0
IIa	141	4.24	383,261	3.29	356,679	0.12	1,938	0.00	0
	142	0.21	13,677	0.21	13,677	0.15	5,631	0.15	5,631
	144	5.90	540,114	0.00	0	0.00	0	0.00	0
IIb	340	1.36	68,211	1.36	68,211	0.96	21,323	0.96	21,323
	341	0.00	0	0.00	0	0.00	0	0.00	0
	342	0.00	0	0.00	0	0.00	0	0.00	0
	TOTAL	11.78	1,012,275	4.93	445,579	1.23	28,892	1.11	26,954

Table B.18. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 50-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.00	0	0.00	0	0.00	0	0.00	0
IIa	141	0.57	16,035	0.01	109	0.03	132	0.00	0
	142	0.20	9,822	0.20	9,822	0.14	3,275	0.14	3,275
	144	0.00	0	0.00	0	0.00	0	0.00	0
IIb	340	1.21	46,961	1.21	46,961	0.69	23,833	0.69	23,833
	341	0.00	0	0.00	0	0.00	0	0.00	0
	342	0.00	0	0.00	0	0.00	0	0.00	0
	TOTAL	1.98	72,819	1.43	56,892	0.85	27,240	0.83	27,108

Table B.19. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 20-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.00	0	0.00	0	0.00	0	0.00	0
IIa	141	0.33	8,988	0.00	0	0.00	0	0.00	0
	142	0.17	6,859	0.17	6,859	0.07	675	0.07	675
	144	0.00	0	0.00	0	0.00	0	0.00	0
IIb	340	1.04	31,302	1.04	31,302	0.04	3,307	0.04	3,307
	341	0.00	0	0.00	0	0.00	0	0.00	0
	342	0.00	0	0.00	0	0.00	0	0.00	0
	TOTAL	1.54	47,150	1.21	38,162	0.11	3,982	0.11	3,982

Table B.20. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 10-year recurrence interval

		Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.00	0	0.00	0	0.00	0	0.00	0
IIa	141	0.24	4,850	0.00	0	0.00	0	0.00	0
	142	0.15	5,023	0.15	5,023	0.02	85	0.02	85
	144	0.00	0	0.00	0	0.00	0	0.00	0
IIb	340	0.98	22,555	0.98	22,555	0.03	2,511	0.03	2,511
	341	0.00	0	0.00	0	0.00	0	0.00	0
	342	0.00	0	0.00	0	0.00	0	0.00	0
	TOTAL	1.37	32,427	1.12	27,578	0.04	2,596	0.04	2,596

Table B.21. Estimated flood-related roadway losses in the Tamnava watershed, distributed by road category for a 2-year recurrence interval

		Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
State road category	**State road number**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**	**Total flooded length [km]**	**Roadway damage [€]**
Ib	21	0.00	0	0.00	0	0.00	0	0.00	0
IIa	141	0.00	26	0.00	0	0.00	0	0.00	0
	142	0.13	1,674	0.13	1,674	0.00	0	0.00	0
	144	0.00	0	0.00	0	0.00	0	0.00	0
IIb	340	0.51	9,670	0.51	9,670	0.02	1,375	0.02	1,375
	341	0.00	0	0.00	0	0.00	0	0.00	0
	342	0.00	0	0.00	0	0.00	0	0.00	0
	TOTAL	0.64	11,371	0.63	11,344	0.02	1,375	0.02	1,375

Table B.22. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 1,000-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	32	38,954	32	38,954	25	31,465	25	31,465
7'	310	497,471	310	497,471	214	298,712	214	298,712
8	314	1,335,514	314	1,335,514	291	1,079,342	291	1,079,342
9	643	5,749,410	643	5,749,410	620	5,354,109	620	5,354,109
11	54	65,686	54	65,686	46	50,838	46	50,838
11'	119	471,419	119	471,419	111	332,670	111	332,670
11''	752	3,446,512	752	3,446,512	715	2,298,068	715	2,298,068
12	70	573,470	70	573,470	69	530,881	69	530,881
13	20	15,010	20	15,010	17	9,878	17	9,878
13'	870	4,446,024	870	4,446,024	849	3,298,770	849	3,298,770
TOTAL	3,184	16,639,470	3,184	16,639,470	2,957	13,284,734	2,957	13,284,734

Table B.23. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 200-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	14	17,222	14	17,222	7	7,016	7	7,016
7'	109	96,918	109	96,918	0	0	0	0
8	246	602,062	246	602,062	144	195,843	144	195,843
9	603	3,511,315	603	3,511,315	0	0	0	0
11	38	46,939	28	46,939	25	21,813	25	21,813
11'	111	283,543	111	283,543	0	0	0	0
11''	694	1,916,876	694	1,916,876	0	0	0	0
12	60	442,160	60	442,160	0	0	0	0
13	18	11,830	18	11,830	7	3,018	7	3,018
13'	851	2,563,209	851	2,563,209	145	116,450	0	0
TOTAL	2,744	9,492,074	2,734	9,492,074	328	344,140	183	227,690

Table B.24. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 100-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	12	14,650	12	14,650	3	3,209	3	3,209
7'	161	228,578	0	0	0	0	0	0
8	236	526,820	236	526,820	109	109,421	109	109,421
9	597	3,131,205	0	0	0	0	0	0
11	32	38,769	32	38,769	22	13,995	22	13,995
11'	98	171,399	98	85,699	0	0	0	0
11''	0	0	0	0	0	0	0	0
12	53	416,468	0	0	0	0	0	0
13	17	9,807	17	9,807	4	2,369	4	2,369
13'	780	1,496,124	780	748,062	27	16,958	0	0
TOTAL	1,986	6,033,820	1,175	1,423,808	165	145,953	138	128,996

Table B.25. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 50-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	7	8,093	7	8,093	3	2,170	3	2,170
7'	0	0	0	0	0	0	0	0
8	172	230,718	172	230,718	79	61,967	79	61,967
9	0	0	0	0	0	0	0	0
11	32	32,793	32	32,793	15	7,838	15	7,838
11'	94	57,757	0	0	0	0	0	0
11''	0	0	0	0	0	0	0	0
12	48	281,998	0	0	0	0	0	0
13	17	8,615	17	8,615	2	1,423	2	1,423
13'	668	837,827	0	0	8	5,028	0	0
TOTAL	1,038	1,457,801	228	280,218	107	78,427	99	73,399

Table B.26. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 20-year recurrence interval

	Existing conditions		Grey scenario		Green scenario		Grey-green scenario	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	4	4,232	4	4,232	0	0	0	0
7'	0	0	0	0	0	0	0	0
8	117	133,050	117	133,050	44	25,110	44	25,110
9	0	0	0	0	0	0	0	0
11	35	30,274	35	30,274	9	4,233	9	4,233
11'	0	0	0	0	0	0	0	0
11''	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	12	4,229	12	4,229	2	337	2	337
13'	267	223,356	0	0	5	2,472	0	0
TOTAL	435	395,142	168	171,785	60	32,152	55	29,680

Table B.27. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 10-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	3	2,914	3	2,914	0	0	0	0
7'	0	0	0	0	0	0	0	0
8	102	97,552	102	97,552	24	13,244	24	13,244
9	0	0	0	0	0	0	0	0
11	25	21,855	25	21,855	5	844	5	844
11'	0	0	0	0	0	0	0	0
11''	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	9	2,943	9	2,943	1	169	1	169
13'	102	66,159	0	0	1	169	0	0
TOTAL	241	191,423	139	125,264	31	14,424	30	14,256

Table B.28. Estimated displacement cost in the Tamnava watershed, distributed by flood sectors for a 2-year recurrence interval

	Existing conditions		**Grey scenario**		**Green scenario**		**Grey-green scenario**	
Sector	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**	**Count of affected residencies**	**Displacement losses [€]**
7	2	1,423	2	1,423	0	0	0	0
7'	0	0	0	0	0	0	0	0
8	64	37,024	64	37,024	0	0	0	0
9	0	0	0	0	0	0	0	0
11	11	6,885	11	6,885	0	0	0	0
11'	0	0	0	0	0	0	0	0
11''	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	1	712	1	712	0	0	0	0
13'	7	4,316	0	0	0	0	0	0
TOTAL	85	50,360	78	46,044	0	0	0	0

Appendix C - Flood damages per river sectors in the Tamnava watershed

River Sector 7

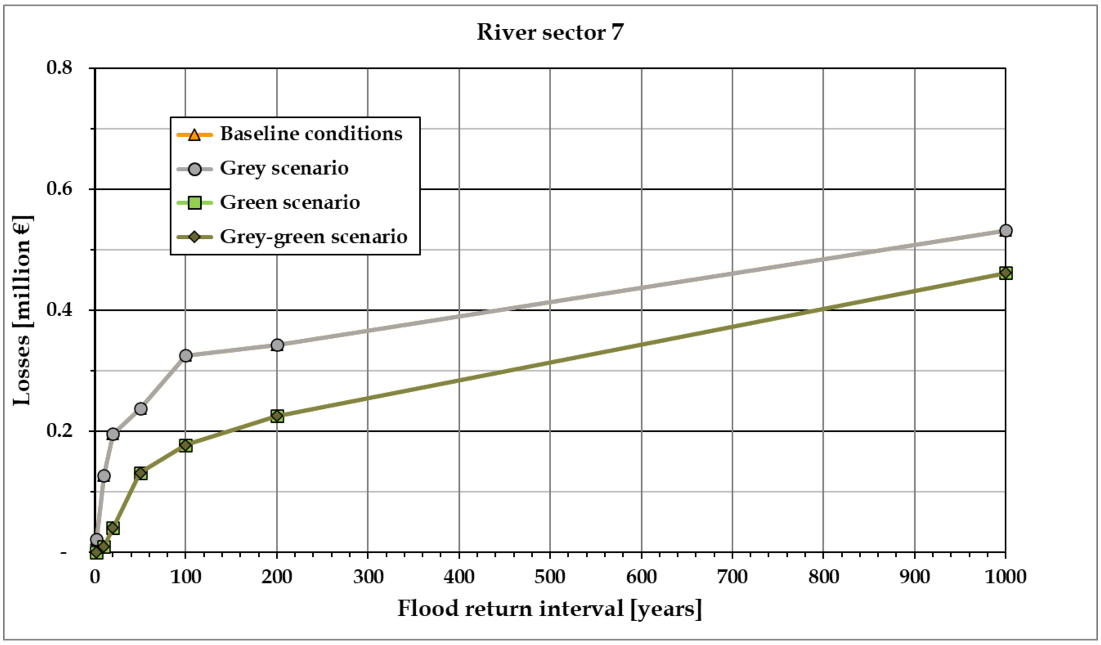


Table C.1. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 7 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	117,411	77,716	38,954	297,703
200	41,048	26,472	17,222	258,260
100	35,197	22,774	14,650	252,319
50	11,993	7,747	8,093	209,645
20	7,350	4,810	4,232	178,879
10	4,936	3,207	2,914	115,942
2	618	309	1,423	18,743

Table C.2. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	117,411	77,716	38,954	297,703
200	41,048	26,472	17,222	258,260
100	35,197	22,774	14,650	252,319
50	11,993	7,747	8,093	209,645
20	7,350	4,810	4,232	178,879
10	4,936	3,207	2,914	115,942
2	618	309	1,423	18,743

Table C.3. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	87,484	57,375	31,465	285,423
200	9,971	6,483	7,016	201,358
100	5,757	3,752	3,209	164,202
50	2,499	1,590	2,170	124,851
20	-	-	-	40,024
10	-	-	-	9,837
2	-	-	-	-

Table C.4. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	87,484	57,375	31,465	285,423
200	9,971	6,483	7,016	201,358
100	5,757	3,752	3,209	164,202
50	2,499	1,590	2,170	124,851
20	-	-	-	40,024
10	-	-	-	9,837
2	-	-	-	-

River Sector 7′

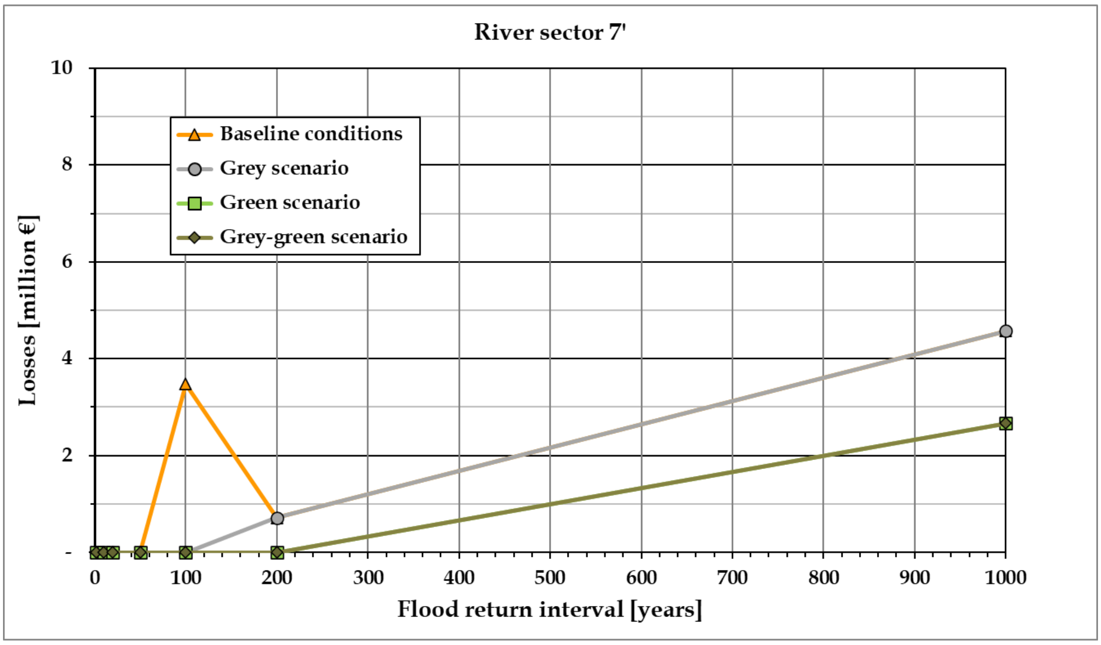


Table C.5. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 7′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	2,273,488	1,787,011	497,471	15,916
200	344,389	261,628	96,918	12,531
100	1,636,531	1,601,616	228,578	14,233
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.6. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	2,273,488	1,787,011	497,471	15,916
200	344,389	261,628	96,918	12,531
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.7. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	1,310,315	1,040,890	298,712	15,096
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.8. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 7′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	1,310,315	1,040,890	298,712	15,096
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

River Sector 8

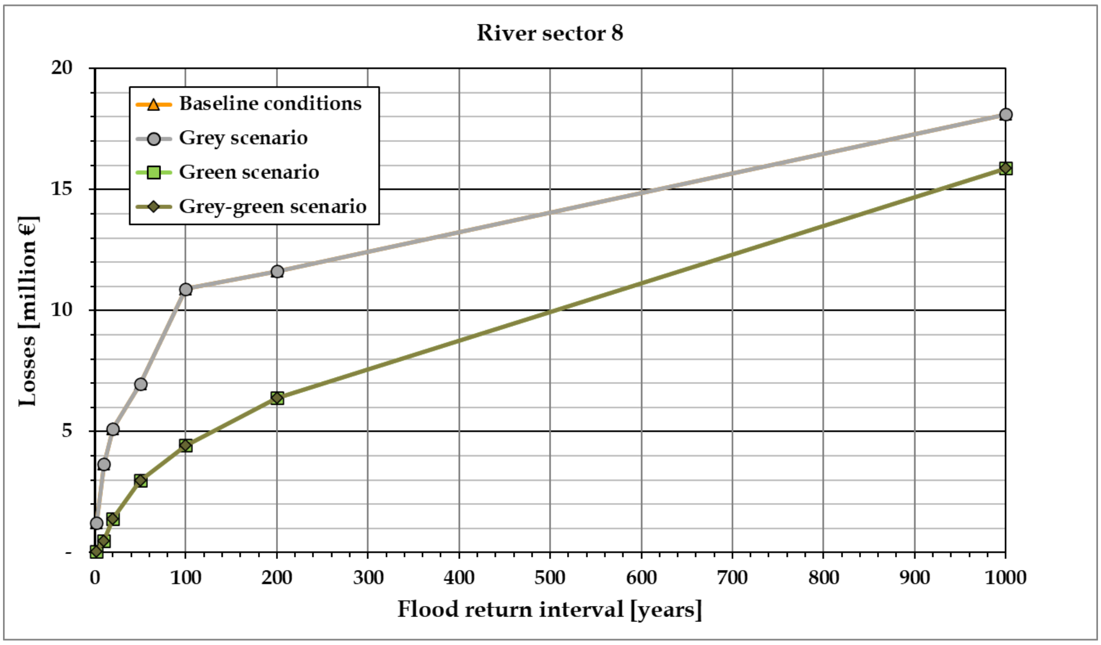


Table C.9. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 8 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	6,745,379	5,191,882	1,335,514	4,838,777
200	3,637,869	2,873,890	602,062	4,513,223
100	3,296,791	2,613,188	526,820	4,465,396
50	1,545,964	1,265,883	230,718	3,916,295
20	935,393	770,820	133,050	3,288,746
10	610,854	496,222	97,552	2,446,214
2	188,815	154,820	37,024	864,108

Table C.10. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 8 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	6,745,379	5,191,882	1,335,514	4,838,777
200	3,637,869	2,873,890	602,062	4,513,223
100	3,296,791	2,613,188	526,820	4,465,396
50	1,545,964	1,265,883	230,718	3,916,295
20	935,393	770,820	133,050	3,288,746
10	610,854	496,222	97,552	2,446,214
2	188,815	154,820	37,024	864,108

Table C.11. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 8 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	5,658,222	4,380,466	1,079,342	4,761,661
200	1,345,164	1,105,864	195,843	3,746,252
100	716,070	585,131	109,421	3,024,910
50	347,453	283,100	61,967	2,285,312
20	122,412	97,250	25,110	1,167,865
10	50,889	38,493	13,244	384,789
2	-	-	-	52,323

Table C.12. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 8 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	5,658,222	4,380,466	1,079,342	4,761,661
200	1,345,164	1,105,864	195,843	3,746,252
100	716,070	585,131	109,421	3,024,910
50	347,453	283,100	61,967	2,285,312
20	122,412	97,250	25,110	1,167,865
10	50,889	38,493	13,244	384,789
2	-	-	-	52,323

River Sector 9

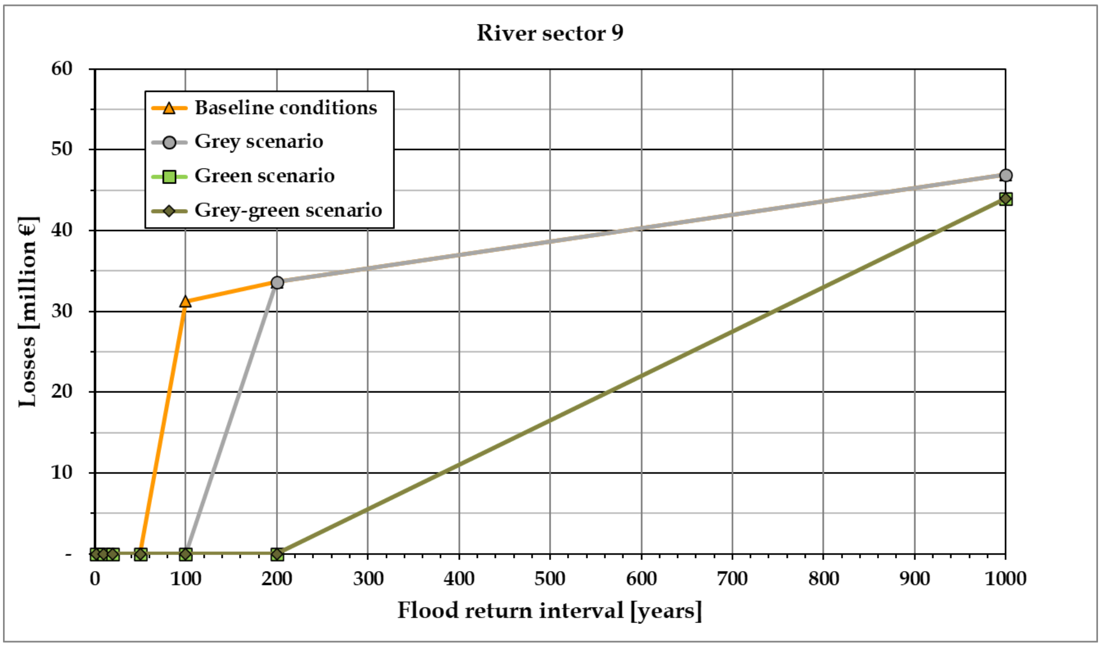


Table C.13. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 9 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	21,991,894	16,248,161	5,749,410	2,918,081
200	15,656,193	11,624,706	3,511,315	2,847,812
100	14,510,019	10,781,918	3,131,205	2,836,097
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.14. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 9 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	21,991,894	16,248,161	5,749,410	2,918,081
200	15,656,193	11,624,706	3,511,315	2,847,812
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.15. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 9 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	20,565,354	15,154,158	5,354,109	2,903,356
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.16. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 9 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	20,565,354	15,154,158	5,354,109	2,903,356
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

River Sector 11

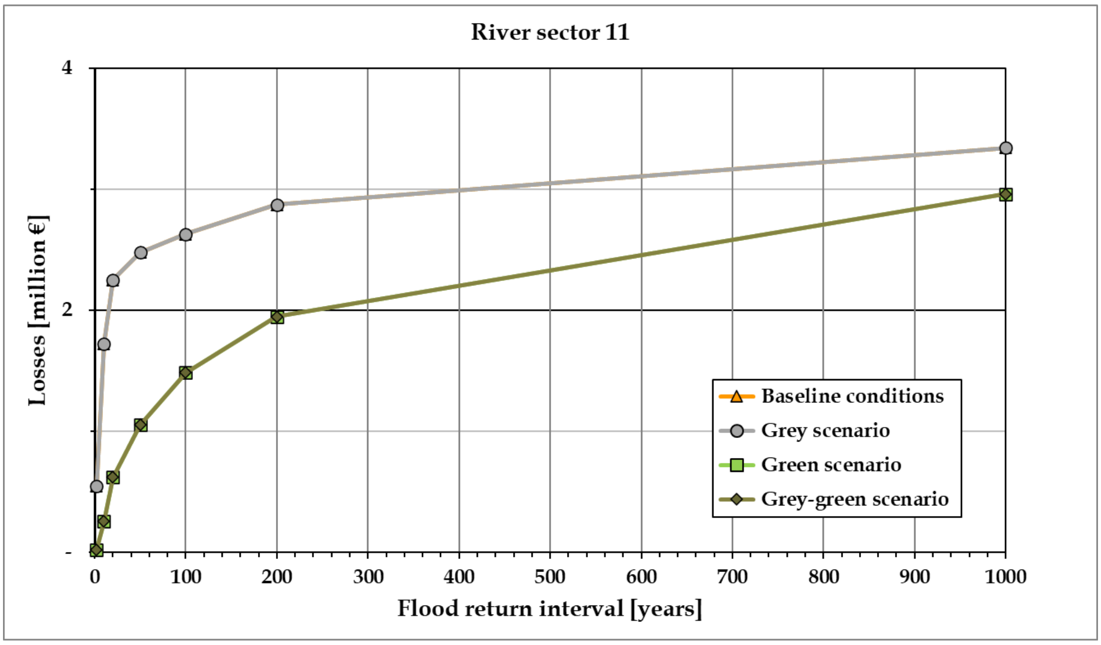


Table C.17. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 11 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	565,191	517,490	65,686	2,191,605
200	420,937	392,515	46,939	2,010,014
100	361,129	340,730	38,769	1,886,473
50	327,833	311,295	32,793	1,803,189
20	279,220	270,688	30,274	1,669,634
10	210,904	212,321	21,855	1,279,852
2	76,536	91,741	6,885	370,451

Table C.18. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	565,191	517,490	65,686	2,191,605
200	420,937	392,515	46,939	2,010,014
100	361,129	340,730	38,769	1,886,473
50	327,833	311,295	32,793	1,803,189
20	279,220	270,688	30,274	1,669,634
10	210,904	212,321	21,855	1,279,852
2	76,536	91,741	6,885	370,451

Table C.19. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	429,967	395,885	50,838	2,081,770
200	201,836	203,242	21,813	1,521,056
100	142,537	152,056	13,995	1,174,072
50	83,684	97,339	7,838	862,251
20	53,752	68,020	4,233	493,534
10	32,594	43,499	844	176,535
2	3,598	2,791	-	14,459

Table C.20. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	429,967	395,885	50,838	2,081,770
200	201,836	203,242	21,813	1,521,056
100	142,537	152,056	13,995	1,174,072
50	83,684	97,339	7,838	862,251
20	53,752	68,020	4,233	493,534
10	32,594	43,499	844	176,535
2	3,598	2,791	-	14,459

River Sector 11′

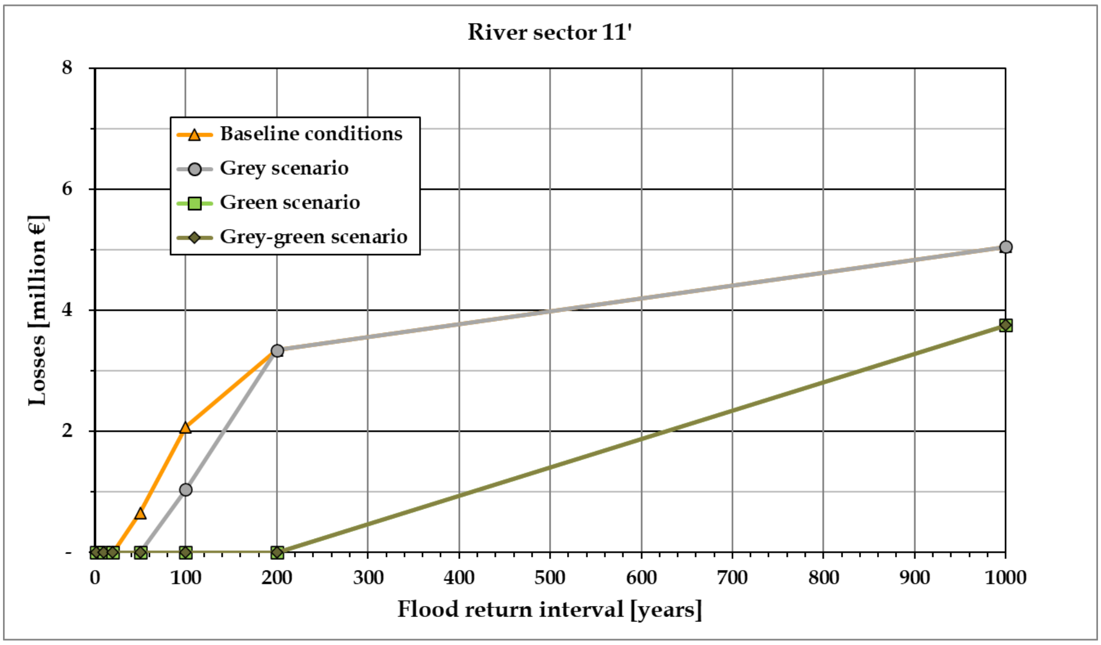


Table C.21. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 11′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	2,648,949	1,858,076	471,419	71,833
200	1,764,030	1,226,336	283,543	69,497
100	1,093,371	742,861	171,399	66,330
50	338,061	227,906	57,757	31,446
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.22. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	2,648,949	1,858,076	471,419	71,833
200	1,764,030	1,226,336	283,543	69,497
100	546,685	371,431	85,699	33,165
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.23. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	1,972,876	1,378,689	332,670	69,148
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.24. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	1,972,876	1,378,689	332,670	69,148
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

River Sector 11″

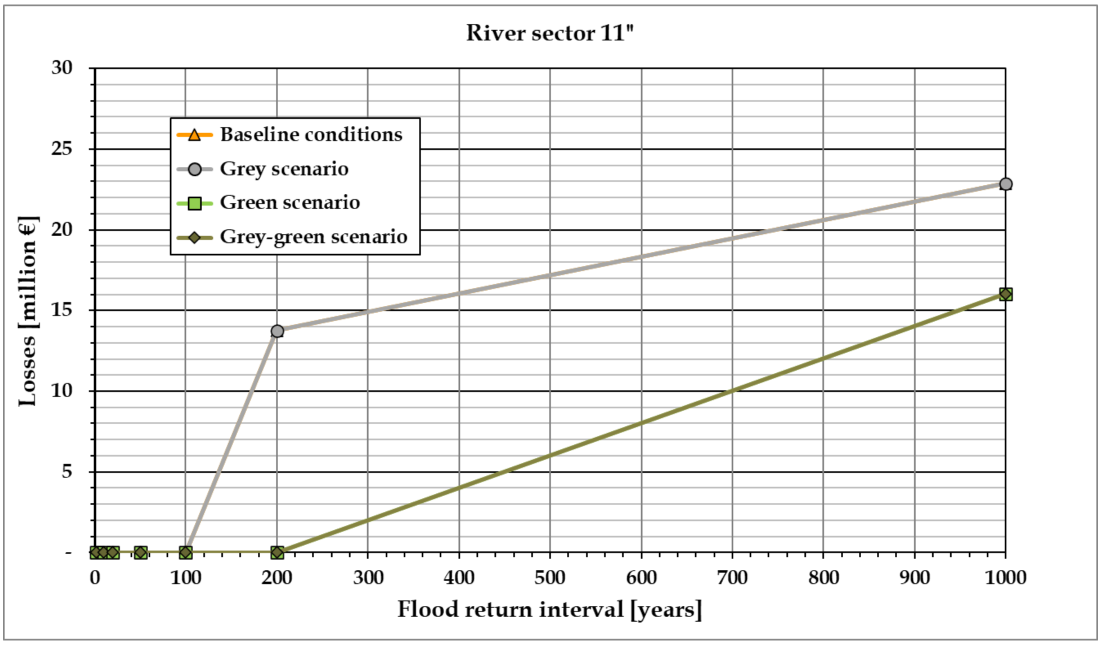


Table C.25. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 11″ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	12,195,446	7,221,146	3,446,512	28,750
200	7,534,841	4,294,630	1,916,876	26,097
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.26. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11″ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	12,195,446	7,221,146	3,446,512	28,750
200	7,534,841	4,294,630	1,916,876	26,097
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.27. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11″ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	8,720,726	5,001,573	2,298,068	26,182
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.28. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 11″ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	8,720,726	5,001,573	2,298,068	26,182
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

River Sector 12

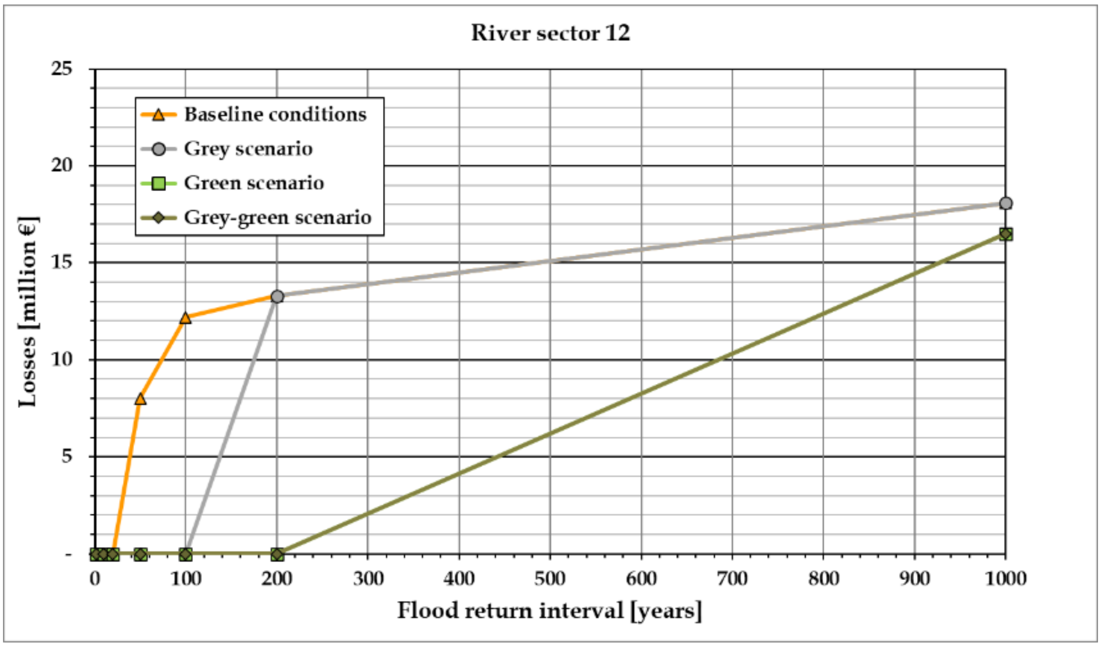


Table C.29. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 12 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	7,162,981	7,951,790	573,470	2,402,040
200	5,005,468	5,455,444	442,160	2,385,869
100	4,501,443	4,894,719	416,468	2,379,844
50	2,652,686	2,746,209	281,998	2,332,756
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.30. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 12 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	7,162,981	7,951,790	573,470	2,402,040
200	5,005,468	5,455,444	442,160	2,385,869
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.31. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 12 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	6,454,234	7,126,697	530,881	2,399,053
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.32. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 12 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	6,454,234	7,126,697	530,881	2,399,053
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

River Sector 13

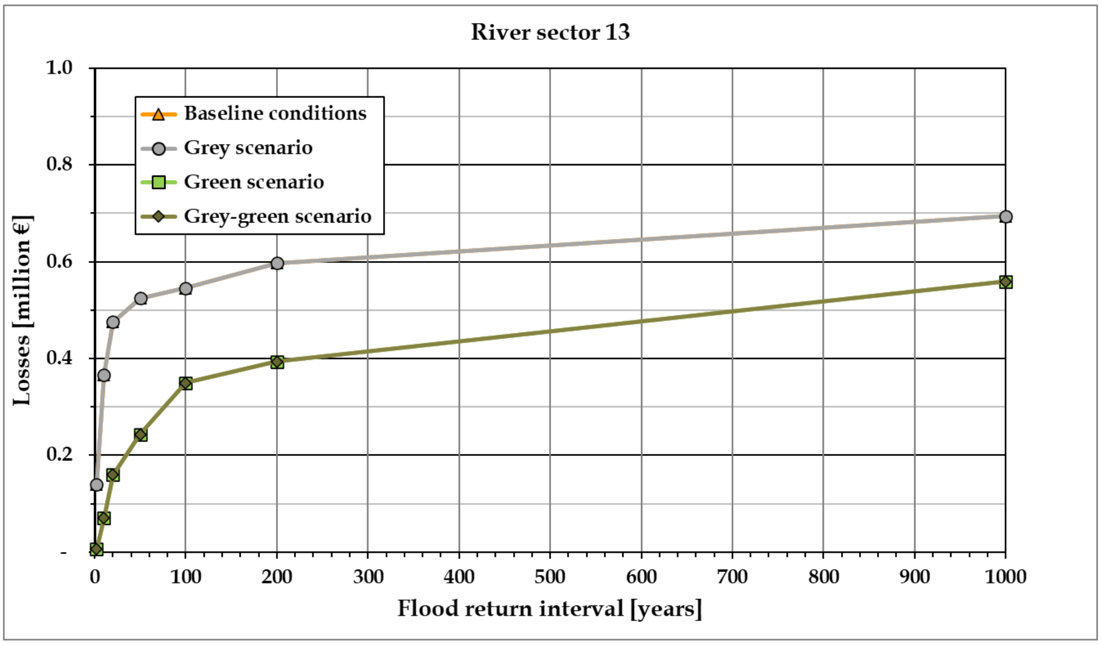


Table C.33. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 13 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	86,839	70,670	15,010	521,429
200	47,587	39,731	11,830	498,437
100	31,359	26,268	9,807	478,399
50	25,514	21,533	8,615	468,779
20	16,158	13,408	4,229	441,486
10	10,556	8,204	2,943	344,928
2	1,693	846	712	137,236

Table C.34. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	86,839	70,670	15,010	521,429
200	47,587	39,731	11,830	498,437
100	31,359	26,268	9,807	478,399
50	25,514	21,533	8,615	468,779
20	16,158	13,408	4,229	441,486
10	10,556	8,204	2,943	344,928
2	1,693	846	712	137,236

Table C.35. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	35,196	29,564	9,878	484,221
200	9,072	6,850	3,018	375,048
100	5,850	3,839	2,369	338,150
50	2,449	1,541	1,423	238,136
20	-	-	337	159,322
10	-	-	169	70,509
2	-	-	-	5,968

Table C.36. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13 in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	35,196	29,564	9,878	484,221
200	9,072	6,850	3,018	375,048
100	5,850	3,839	2,369	338,150
50	2,449	1,541	1,423	238,136
20	-	-	337	159,322
10	-	-	169	70,509
2	-	-	-	5,968

River Sector 13′

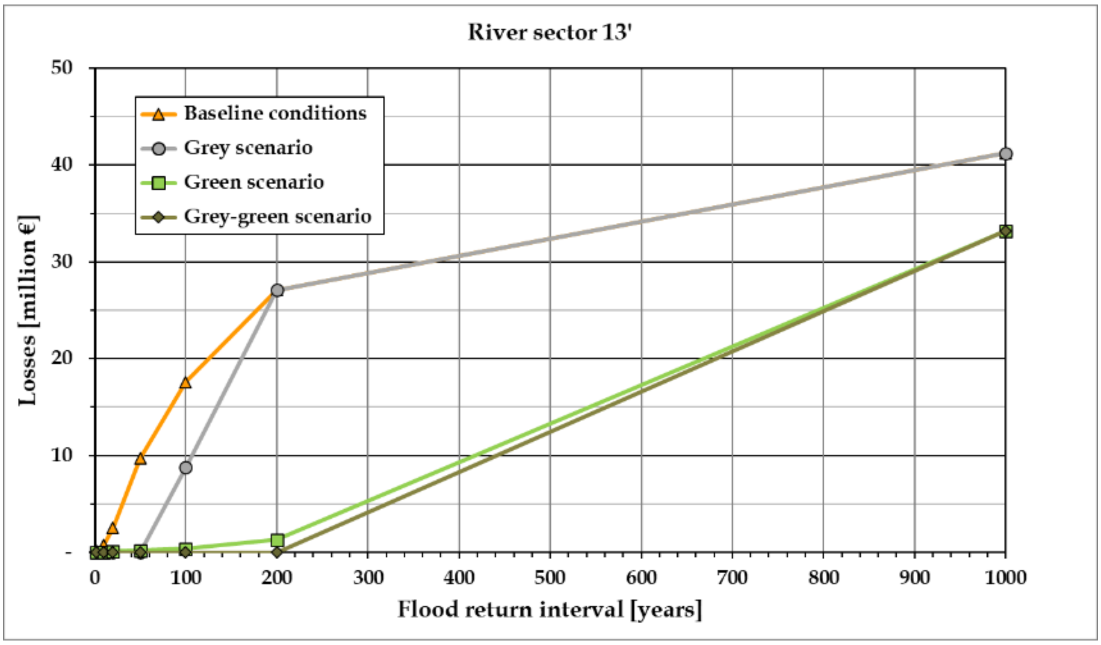


Table C.37. Baseline conditions - calculation of four damage categories for different flood recurrence intervals along river sector 13′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	21,165,590	15,208,999	4,446,024	399,381
200	14,148,633	9,991,204	2,563,209	382,268
100	9,165,128	6,574,763	1,496,124	346,265
50	4,979,690	3,575,022	837,827	320,613
20	1,229,669	810,216	223,356	260,907
10	321,927	214,486	66,159	176,039
2	44,318	35,814	4,316	56,272

Table C.38. Grey scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	21,165,590	15,208,999	4,446,024	399,381
200	14,148,633	9,991,204	2,563,209	382,268
100	4,582,564	3,287,382	748,062	173,132
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

Table C.39. Green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	17,203,954	12,325,705	3,298,770	376,793
200	604,514	382,537	116,450	212,741
100	125,141	97,579	16,958	148,301
50	50,716	41,528	5,028	99,144
20	18,290	16,497	2,472	62,598
10	954	954	169	24,887
2	-	-	-	1,592

Table C.40. Grey-green scenario - calculation of four damage categories for different flood recurrence intervals along river sector 13′ in the Tamnava River watershed.

Recurrence interval	Building losses	Content losses	Displacement losses	Agricultural losses
[years]	[€]	[€]	[€]	[€]
1,000	17,203,954	12,325,705	3,298,770	376,793
200	-	-	-	-
100	-	-	-	-
50	-	-	-	-
20	-	-	-	-
10	-	-	-	-
2	-	-	-	-

BIOGRAPHY

Ranko Pudar was born on March 15, 1963. He graduated from the Mathematical Gymnasium “Veljko Vlahović” in Belgrade, and enrolled in the Civil Engineering Faculty at the University of Belgrade in the Fall of 1982. He earned his B.Sc. degree in 1987, with a major in Water Resources and a GPA (Grade Point Average) of 8.36. For his thesis work titled “Numerical model for calculating dispersion in open channel flows”, he received the highest grade and an award for the best B.Sc. thesis in 1987. In August of 1991, Ranko received his Master of Science (M.S.) degree at Cornell University, School of Civil and Environmental Engineering (minor in applied mathematics), with a thesis titled “Numerical methods for finding leaks in pipe networks”. In summer of 1996, he received a second M.S. degree from Georgia Institute of Technology, School of Civil and Environmental Engineering (with a minor in numerical methods and turbulence). Ranko’s professional interests include natural hazards, flood risk assessment, benefit-cost analysis, and ecosystem services. He lives and works in Atlanta, Georgia, in the United States.

Ranko started his professional career in January 1988, by taking a position of hydraulic engineer in the Department of water and waste water at the Institute “Jaroslav Černi“ in Belgrade. In 1989, Ranko relocated to the United States, to pursue graduate studies in Civil Engineering. From 1991 to 1994 he worked with US Geological Survey, where he managed NPDES storm water management program for the City of San Antonio, Texas. Ranko joined URS Corporation in 1998, as the head of water resources group and regional director for FEMA (Federal Emergency Management Agency) contracts for south eastern United States. In 1998, he attained his PE (Professional Engineer) license. Since 2009, Ranko has been serving as a principal of his own consulting firm, Pudar Mitigation Consulting, where he manages projects related to hazard identification, flood risk assessment and mitigation, and floodplain management. He is a nationally recognized expert in benefit-cost analysis related to critical facilities, including hospital systems, wastewater treatment plants, dams, levee systems and other capital structures. Ranko is nationally accredited as a Certified Floodplain Manager (CFM), and Project Management Professional (PMP).

БИОГРАФИЈА

Ранко Пудар је рођен 15. марта 1963. године. У Београду је завршио основну школу и Математичку Гимназију "Вељко Влаховић". Грађевински факултет Универзитета у Београду, уписао је 1982. године. Основне студије, на Одсеку за хидротехнику, завршио је 1987. године са средњом оценом 8,36. За дипломски рад на тему „Рачунски модел линијске дисперзије у отвореним токовима", добио је највишу оцену и награду за најбољи дипломски рад у 1987. години. Магистарске (последипломске) студије, на Cornell универзитету у Сједињеним Америчким Државама, на грађевинском факултету, на Одсеку за хидраулику (специјализација за примењену математику), завршава у августу 1991. године, са тезом „Нумеричке методе за налажење губитака воде у водоводним системима" (изворно "Numerical methods for finding leaks in pipe networks"). У лето 1996. године добија још једно звање Магистра наука на универзитету Georgia Institute of Technology у Атланти, у Џорџији, у области нумеричких метода и турбуленције. Посебно је заинтересован за области природних ризика, и економских анализа у области водних ресурса. Живи и ради у Атланти (Џорџија) у Сједињеним Америчким Државама.

У јануару 1988, године запошљава се у Институту "Јарослав Черни", као инжењер у Одсеку за водовод и канализацију. У јесен 1989. године одлази на последипломске студије у Сједињеним Америчким Државама. Од 1991. године до 1994. године ради у US Geological Survey у Сан Антониу, у Тексасу, где се бави вођењем програма кишне канализације за град Сан Антонио. Од 1997. године је у консалтингу, где од 1998. године ради за URS Corporation, у звању директора групе за водне ресурсе и регионалног директора за југоисток за техничку сарадњу са Федералном Агенцијом за Интервентне Ситуације (Federal Emergency Management Agency - FEMA). Стручни испит положио је 1998. године. Од 2009. године, води своју приватну консултанску компанију, Pudar Mitigation Consulting, где води пројекте везане за идентификацију угрожености и квантификацију ризика од поплава, планирање управљања ризицима од поплава, и инжењерско-економске анализе везане за ризике критичне инфраструктуре, укључујући болнице, постројења за прераду отпадних вода, брана, насипских система и других капиталних објеката. Ранко је национално акредитован за управљање заштитом од поплава (Certified Floodplain Manager), и за управљање пројектима (Project Management Professional).

ИЗЈАВА О АУТОРСТВУ

Име и презиме аутора: Ранко С. Пудар

Изјављујем

да је докторска дисертација под насловом

VALUATION OF FLUVIAL ECOSYSTEMS RESTORATION IN FUNCTION OF FLOOD RISK MITIGATION

(Наслов на српском језику: ВРЕДНОВАЊЕ ОБНОВЕ РЕЧНИХ ЕКОЛОШКИХ СИСТЕМА У ФУНКЦИЈИ СМАЊЕЊА РИЗИКА ОД ПОПЛАВА)

- резултат сопственог истраживачког рада;
- да дисертација у целини ни у деловима није била предложена за стицање друге дипломе према студијским програмима других високошколских установа;
- да су резултати коректно наведени и
- да нисам кршио ауторска права и користио интелектуалну својину других лица.

Потпис аутора

У Београду, 9. јун 2021.

ИЗЈАВА О ИСТОВЕТНОСТИ ШТАМПАНЕ И ЕЛЕКТРОНСКЕ ВЕРЗИЈЕ ДОКТОРСКОГ РАДА

Име и презиме аутора:	Ранко С. Пудар
Наслов рада	VALUATION OF FLUVIAL ECOSYSTEMS RESTORATION IN FUNCTION OF FLOOD RISK MITIGATION (Наслов на српском језику: ВРЕДНОВАЊЕ ОБНОВЕ РЕЧНИХ ЕКОЛОШКИХ СИСТЕМА У ФУНКЦИЈИ СМАЊЕЊА РИЗИКА ОД ПОПЛАВА)
Ментор	др Јасна Плавшић, дипл.грађ.инж, редовни професор

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао ради похрањивања у **Дигиталном репозиторијуму Универзитета у Београду**.

Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

Потпис аутора

У Београду, 9. јун 2021.

ИЗЈАВА О КОРИШЋЕЊУ

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

VALUATION OF FLUVIAL ECOSYSTEMS RESTORATION IN FUNCTION OF FLOOD RISK MITIGATION

(Наслов на српском језику: ВРЕДНОВАЊЕ ОБНОВЕ РЕЧНИХ ЕКОЛОШКИХ СИСТЕМА У ФУНКЦИЈИ СМАЊЕЊА РИЗИКА ОД ПОПЛАВА)

која је моје ауторско дело.

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