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Risk based life-cycle planning for flood-resilient critical infrastructure

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Risk based life-cycle planning for flood-resilient critical infrastructure

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ABSTRACT: The paper presents a risk assessment model, developed in the project oVERFLOw and further implemented in the project CROSScade, for determining the direct and indirect impacts of flooding hazards. As a consequence of flooding, transport infrastructure and flood protection systems can be significantly damaged and cause cascading effects on other infrastructure. To achieve flood resilient infrastructure, it is necessary to assess the vulnerability of critical assets in the affected area. The model uses novel vulnerability assessment methods for embankments and bridges exposed to different flood hazard scenarios allowing the asset owners to understand risk and performance of their infrastructure. Scarce financial resources are allocated on the critical assets allowing significant cost savings and avoiding the waste of non-renewable resources in strengthening large sections which have sufficient resilience. The consequence analysis is based on an improved quantification model for direct and indirect impacts of different flood hazard scenarios used for risk mapping of the affected area.

1 INTRODUCTION

Climate change is leading to more extreme weather events in most parts of the world (EEA, 2016; World Economic Forum, 2019). High water levels caused by increased frequency of heavy rainfall are causing flooding hazards and higher impacts such as increased financial consequences and human losses. The complete life-cycle management for critical infrastructure needs to consider these new extreme loads by applying different climate change scenarios to prepare for future hazardous events. Infrastructure managers require tools to support decision-making and prioritize intervention measures, either during the response or during the prevention stage. A risk-based safety approach regarding flood events provides information by combining data about the chance of a flood event, vulnerability and exposure of community, property and infrastructure.

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The overall objective of the oVERFLOw project (https://projectoverflow.eu/) is strengthening resilience to climate change impacts, with the specific objective being the development of climate-resilient infrastructure. The key step to achieving the project objective focuses around the refinement of the risk-based approach for vulnerability assessment of levees (Rijkswaterstaat VNK Project Office, 2012, 2014) and using physical (sensor-based) real-time condition data rather than periodic visual condition assessment. Data-driven enhanced knowledge about the vulnerability of the weakest links in the flood protection systems and bridges led to the reduction of uncertainties and improved numerical models. This serves as the basis for decision-making processes regarding the prioritization of strategic investments and to further develop civil protection protocols for flooding events as prevention and response measures. The methodology developed in the oVERFLOw project was validated in a flood-prone case study areas of South Holland Region in the Netherlands and the city of Karlovac in Croatia. This paper presents the methodology validation on Croatian case study area, shown in Figure 1.

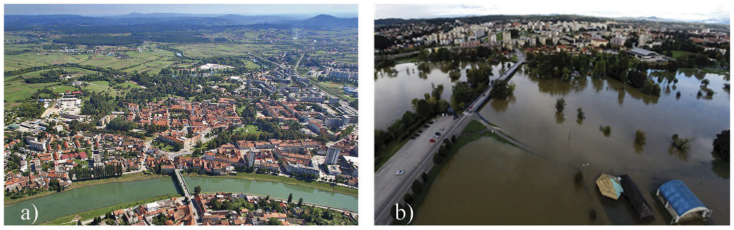

Figure 1. Karlovac city center next to the Kupa river: a) https://aktivirajkarlovac.net/); 2014 flood in Karlovac, b) https://www.jutarnji.hr/vijesti/hrvatska/).

2 FLOOD RISK ASSESSMENT

The intersection of a flood scenario for a specific return period and the area impacted by the hazard, for which vulnerability or damage functions are developed, forms the basis of flood risk assessment methodology. Using the framework presented in Figure 2, the vulnerability analysis results are combined with potential flood effects to create the risk forecasting tool. The tool provides information on the possible financial cost of flood consequences, as well as the population at risk, critical infrastructure, and evacuation routes in the flood-affected area.

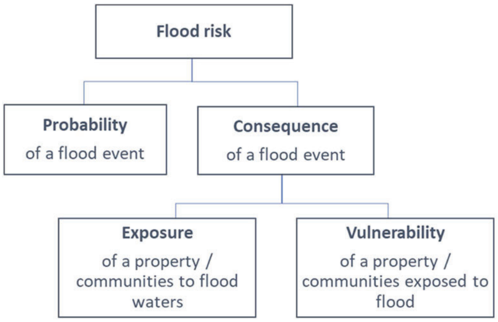

Figure 2. Risk assessment framework.

2.1 *Flood hazard scenarios*

Climate change is affecting the global mean temperature and the total amount of precipitation. However, the precipitation quantities are regionally significantly varying and have no clear trend compared to the temperature. Observations show that precipitation changes are occurring in the amount, intensity, frequency and type. Basic theory, climate model simulations and empirical evidence all confirm that warmer climates, owing to increased water vapour, lead to more intense precipitation events even when the total annual precipitation is reduced slightly, with prospects for even stronger events when the overall precipitation amounts increase. The warmer climate, therefore, increases the risks of both drought and floods (IPCC, 2014). The effect of climate change on precipitation is similar to that of the river flows. Future changes in the mean and extreme river flow will show regional variety.

In the development of flood scenarios, historical and predicted climatological and hydrological parameters were analyzed for a period of one hundred years from 1970 to 2070 for the case study in Croatia. A machine learning technique was applied to predict changes in water flow and water level using an ensemble of temperature and precipitation data from the regional climate change model RegCM4 (MZOE, 2017). The model was used to calculate change (projections) for the future climate in two periods: 2011 - 2040 and 2041 - 2070, assuming the IPCC scenarios RCP4.5 and RCP8.5. The RCP4.5 scenario (moderate scenario) predicts the medium level of greenhouse gas concentrations while for the RCP8.5 scenario (extreme scenario) there is continuous increase of greenhouse gas concentrations. Simulations of water flow and water level show that climate change is likely to impact the Kupa river's future flows and water levels. Although the changes in annual average flows and water levels are expected to be small and not significant, models predict a significant increase in flow and water level in winter months and its decrease in summer months for both moderate and extreme scenarios, with bigger changes in the extreme scenario, shown in Figure 3. The climate change data and flood maps obtained with this analysis were further used for vulnerability analysis of critical infrastructure (Burić&Grgurić, 2020).

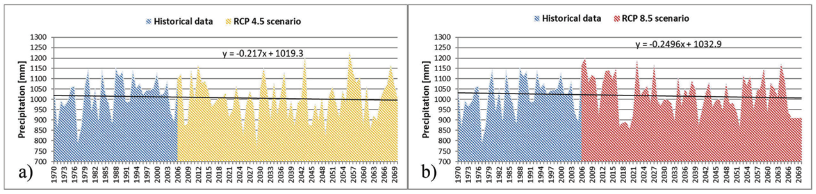

Figure 3. Modelled ensemble mean annual precipitation with RegCM4 for model point nearest to Karlovac 1970 – 2070; a) scenario RCP 4.5, b) scenario RCP 8.5. Data source: DHMZ (Burić&Grgurić, 2020).

2.2 *Vulnerability analysis of embankments and bridges*

Within the oVERFLOW project, the vulnerability analysis of critical assets focuses on the embankments and bridges, which are the most important components of the flood protection system and the transportation infrastructure as potential evacuation/emergency routes. The methodology is based on in-situ data collection and numerical models for bridges and embankments. The major outcomes of the proposed methodology are fragility curves for assessing the integrity of embankments and fragility surfaces for the serviceability and ultimate limit state for bridges. These data explicitly account for both material and loading uncertainty and can be used to interpret how likely a failure is, given a certain flood event.

The input data for the analysis of two bridges from the Karlovac case study area is obtained from archived projects, which were complemented with results of a drone and bathymetric survey and ambient vibration measurements (Kosič et al., 2021). The results of the drone and bathymetric surveys were used to define the geometry, whereas measurements of ambient vibration allowed the estimation of the bridge's modal properties. Due to specific hydraulic conditions, i.e. non-stationary flow (Burić&Grgurić, 2020), both velocity and water height are found to be necessary for precise estimation of the bridge performance, so the result of the vulnerability analysis is presented with fragility surfaces, which represents an extension of the classical fragility curve concept.

An advanced modelling approach for simulation of the bridge response considering soil-structure interaction is applied (Kosič et al. 2023a). The study examines different flood-loading scenarios, including hydrodynamic loads, debris and scour. Special attention is devoted to the explicit simulation of the effect of scouring on the distribution of forces in the structure. Several failure mechanisms are considered, and the most unfavorable mechanism for the given flooding scenario is identified. The vulnerability analysis is performed separately for the serviceability (SLS) and ultimate limit state (ULS). The results of the analyses indicate that the SLS of the bridges is affected significantly by the accumulation of debris, which constricts the flow of the water and leads to an amplification of scour due to the local increase of the flow velocity (Kosič et al., 2023b). The fragility surfaces provide crucial input for developing the risk forecasting tool with the so-called traffic light indicators, representing a safe/unsafe evacuation route during the response.

The implementation of the methodology to the Karlovac case study area includes calculating the probability of failure of 3 km of riverbanks on the left and right side of river Kupa. Riverbank stability is assessed for both rapid drawdown and seismic loading scenarios, for which fragility curves were developed (Bačić et al, 2022). Characteristic riverbank sections are identified from a remote photogrammetric survey, geometry for different sections and probabilistic calculations are performed on each of them. Calculated values of probability of failure for different scenarios provide the basis for classifying the embankments and riverbanks based on their vulnerability and developing an inventory of critical flood protection infrastructure in the case study area.

To evaluate the vulnerability of the riverbank slopes, global stability is identified as the relevant failure mechanism. For each riverbank section, analysis is performed so that the water level external to the riverbank slope experienced a rapid reduction in level while residual water levels (RWL) in the riverbank remained at higher levels. For the seismic stability during the increase of the pseudo-static loads (acceleration), the probability of stability failure also increases. The maximum considered value of peak horizontal acceleration is selected as 0.3g, which is double the value of the 475-year return period in the city of Karlovac (http://seizkarta.gfz.hr). These analyses are performed by using drained parameters in the first step analyses and undrained parameters in the second step analyses, in which upper clay was modelled with undrained parameters. In further project developments, these results are incorporated into the risk forecasting tool for the purpose of classification of the embankments and riverbanks based on their vulnerability and development of an inventory of critical flood protection infrastructure (Gavin&Reale, 2021).

2.3 *Direct and indirect consequences*

Flood effects may be both direct, through the immediate interaction of flood water with built, natural and human environments, and indirect, through damage or disruption of transportation and economic activities that impact people's livelihoods. Damage to buildings, economic assets, loss in agriculture, loss of human life, immediate health impacts and loss of ecological goods are generally applied quantifiable parameters. Indirect flood damages are damages caused by disruption of physical and economic linkages and the extra costs of emergency and other actions taken to prevent flood damage and other losses. This includes, for example, the loss of production of companies affected by the flooding, induced production losses of their suppliers and customers, the costs of traffic disruption or the costs of emergency services. Indirect damage is often measured as a loss of flow values (WMO, 2015).

oVERFLOw methodology for quantification of different flood impact categories includes two approaches developed for different types of users:

i. The quantification of impacts in monetary value to show direct flood damage to different assets can be used by infrastructure managers, owners or local authorities. This information can support decisions such as the prioritization of assets which need to be upgraded, identification of possible needed interventions and investments for flood protection systems, transport infrastructure or any other endangered asset. The model is used in the final risk assessment and can also be used for cost-benefit analysis (Bruijn et al., 2015).
ii. Mapping of the vulnerability of critical infrastructure and population density gives the insights of direct impacts on humans, especially important for Civil Protection Agencies (CPAs) and first responders about the endangered population, areas with low rise buildings or buildings with people without self-sufficiency (preschools, schools, retirement homes etc.) where their immediate attention is needed in case of floods. It also provides information about safety evacuation routes so they can reach certain areas without delay or endangerment.

The main parameters for the risk evaluation and calculation of direct economic damage are the value of elements at risk and water depth-damage curves (Moel&Aerts, 2011; Klijn et al., 2007). In the oVERFLOw methodology, damages of industrial and residential buildings, businesses, infrastructure and land per different usage types are quantified in monetary terms, using literature and historical values from the case study area (Huizinga et al. JRC, 2017; Kok et al., 2005, Wagenaar et. al, 2016;). For the oVERFLOw project, mainly for the case study area of the city of Karlovac, different categories for residence and industrial buildings are taken into account with damage curves developed for the analyzed area, see Figure 4.

Special assets and areas, including vulnerable assets (critical infrastructure such as transport, healthcare, electricity, and water supply), cultural heritage, installations, and vulnerable nature areas, are identified and mapped. The flooding of these assets is of relevance for flood risk managers, infrastructure managers and evacuation services. Also, mapping buildings per number of stories, provides with the information needed to prioritize evacuation in certain areas. Higher buildings mean more space for people to evacuate themselves on higher floors which is why buildings are mapped according to the number of stories and number of residents.

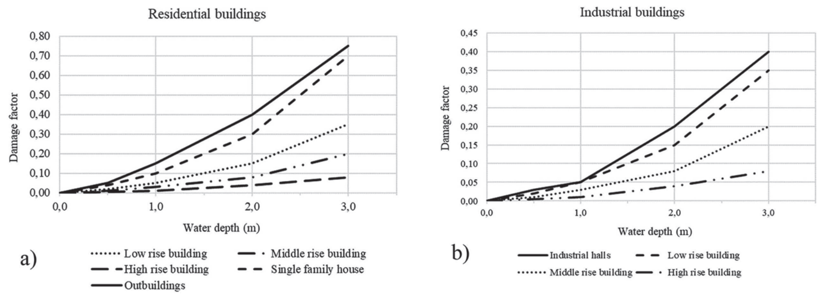

Figure 4. Proposed damage values for Croatian case study for a) Residential and b) Industrial buildings (Skaric&Stipanovic, 2022).

Safe evacuation routes and accessibility for first responders are determined by highlighting critical transport infrastructure. The safe evacuation routes are established based on reaching the nearest safe place within buildings, building blocks and city districts. Areas with higher buildings safer in case of a flood hazard can be highlighted. The main constraints associated with the emergency are structural vulnerabilities along escape routes (failure of bridges or flood protection structures), uncertain road conditions due to landslides, and parts of roads under the water, including traffic congestion, road blockage, etc. Optimal evacuation alternatives in the form of the safest and most efficient routes for evacuation of the population from the affected region are determined based on the results of the vulnerability assessment of bridges and embankments.

Losses to any business in the area affected by flood include loss of business value that would have been produced if a flood event had not occurred. Production is stopped due to the Material Damage (MD) of installations or disrupted supply chains. It could be that other businesses or productions, processes before or after, have also been stopped or delayed due to a hazardous flood event. These are indirect losses, defined as Loss due to Business Interruption (LBI), which do not include direct economic losses to a company caused directly by contact with water. Loss of business category implies the long-term economic effect of a flood due to business interruption. Indirect losses to a business are often expressed as a share of the material damage in flood (Vilier et.al, 2014). In the 1993 Netherlands flood, 75% of the damage to the industry was related to property, and 25% was related to productivity loss (Kok, 2001, Genovese, 2006).

Following the economic scenario that there is no income while the business is interrupted, but the expenditures remain, if the business is to be restored after the flood event, the economic loss due to business interruption (LBI) is calculated based on the following:

$$LBI = (I_{tot} + E_{tot}) \, x \, Nr_{emp} x \, T \tag{1}$$

where LBI = loss due to business interruption (€); I_{tot} = total income per employee per day; E_{tot} = total expenditure per employee per day; Nr_{emp} = a number of employees in the flood-affected area; T = time for the return of business to pre-flood conditions.

3 RISK MAPPING

Calculation of risk implies the combination of flood hazard scenarios with the exposed area, and the verification of direct and indirect consequences. The overall product is the spatial distribution of flood risks for selected areas. Direct impacts are quantified in monetary values, while indirect qualitative analysis with pre-designed risk classification and highlighting of different risk levels is proposed. The results are integrated into the existing GIS platforms as two different operational layers: for Infrastructure Managers (IMs) for future planning of investment measures and for CPAs in order to enhance the emergency response and ensure safe and efficient evacuation. Flood hazard maps, which show flood depths for different probabilities of occurrence of a flood, are overlapped with spatial data of area's exposure and vulnerability of critical assets.

3.1 *Hazard maps*

For the case study area in Croatia, the city of Karlovac, three different flood scenarios have been analyzed and compared. Flood scenarios are based on Croatian Waters flood hazard maps with three different return periods: high (HP), medium (MP) and low probability (LP) of occurrence, with return periods 25, 100 and 1000 years, respectively. Water depths are grouped into four categories: < 0.5 m, 0.5 – 1.5 m, 1.5 – 2.5 m and > 2.5 m (Croatian Waters, 2019).

3.2 *Risk tool layers for Civil Protection Agencies*

Based on the performed analysis, the following information is provided in the form of a GIS-based risk forecasting tool to be used by CPAs in a case of a flood event:

- Number of people to be evacuated, and their location in the affected area, see Figure 5;
- Crucial institutions affected by flood (hospitals, schools, retirement homes. . .);
- Available shelters for evacuation (flooded/not flooded);
- Safe and available evacuation routes (flooded roads; operating infrastructure – embankments and bridges that are safe or not safe for usage during flooding), see Figure 6.

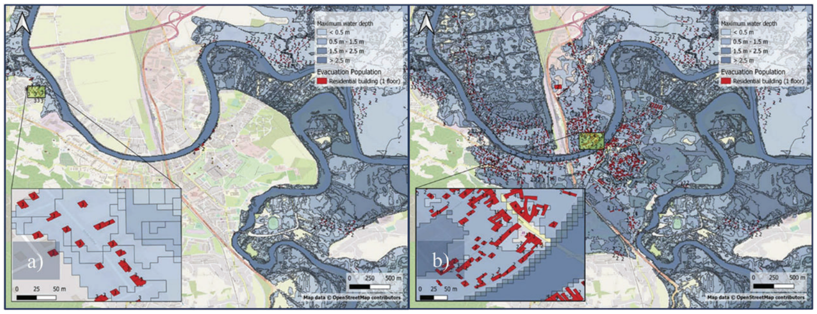

Figure 5. Population flood risk map – Map of low rise buildings (red) and number of residents overlapped with a) Flood map HP and b) Flood map LP.

3.3 *Risk tool layers for infrastructure managers*

Based on the performed analysis, information about possible direct and indirect impacts is provided through a risk forecasting tool to be used by IMs for prioritization and strategic planning. Direct impacts to transport infrastructure and to industrial and residential buildings, businesses, infrastructure and land per type, all quantified in monetary terms. Indirect impacts regarding loss of business disrupted due to the flood event.

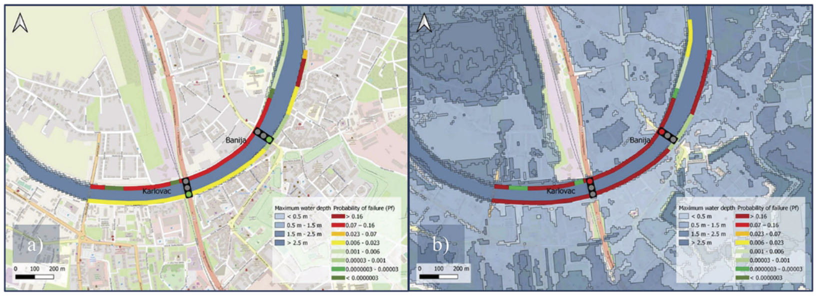

Figure 6. Results of the vulnerability analysis for embankments and bridges for a) HP of flood occurrence and b) LP of flood occurrence.

Figure 7 presents total estimated damage values (including direct and indirect damages) for different flood events for the City of Karlovac area. It can be seen from this graph that the total damage costs are increasing with the increase of the return period, or the extent of the flood event.

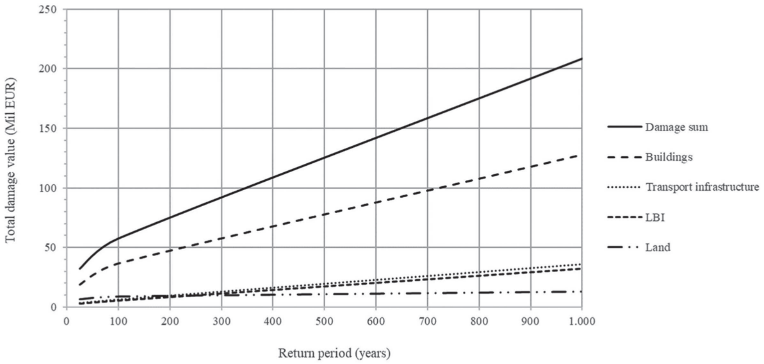

Figure 7. Graphical representation of economic damage (€) per category for three different flood probabilities for the city of Karlovac area.

4 CONCLUSIONS

Much effort is directed towards improving prevention and response measures for flood events to protect the population, their belongings, assets, businesses, and society at large. Experience has shown that, for the most part, consequences of flood hazard cannot be completely mitigated. As a result, the focus should be placed on reducing or avoiding adverse consequences on people, the environment, and property. Targeted data, which is frequently already available, can be used to extract relevant information from a range of users, including CPAs and IMs. This paper presents an overview of the risk assessment methodology developed within the oVERFLOw project and further implemented in the CROSScade project, which uses the improved vulnerability assessment of the critical infrastructure based on the actual monitoring data and consequence analysis of direct and indirect impacts using local exposure data. The main contribution of the methodology is a better prediction of the areas with the highest risk, which can be used to support decision-making during the response stage and to plan investments to strengthen most vulnerable parts of the critical infrastructure.

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