FLOOD RISKS TO CRITICAL INFRASTRUCTURE – CASE STUDY OF CITY OF KARLOVAC

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Abstract

Flooding is a significant threat to human-life, ecosystems, cultural heritage and society in general. A risk-based safety approach is necessary to support decision making and prioritize intervention measures, either during the response or during the prevention stage. As a consequence of flooding, transport infrastructure and flood protection system can be significantly damaged and cause cascading effects on other infrastructure. In this paper a risk assessment model will be presented for determining the direct and indirect impacts of flooding hazards in the case study area of city of Karlovac. The model is using the novel vulnerability assessment methods for embankments and bridges exposed to different flood hazard scenarios. The consequence analysis is using an improved quantification model for direct and indirect impacts of different flood hazard scenarios. These scenarios are then used for flood risk mapping, applied on the case study area.

Keywords: flood, critical infrastructure, vulnerability analysis, direct and indirect impacts

1 Introduction

Flooding is a significant threat to human-life, ecosystems, cultural heritage and society in general. In order to achieve flood resilient infrastructure it is necessary to assess the vulnerability of flood protection system and critical objects on the network, which will provide the information for risk-based safety approach and decision making which prioritizes intervention measures [1, 2]. The vulnerability assessment methodologies are used as an input into risk assessment models providing information on the critical infrastructure in the case of extreme weather and flooding events. The risk assessment models and tools assist decision making processes for various actors, i.e. Civil Protection Agencies (CPAs), Infrastructure Managers (IMs) related to planning and design measures for the improvement of safety and resilience of flood protection systems and transport infrastructure. In this paper a risk assessment model developed within oVERFLOw project [3] is presented for determining the direct and indirect impacts of flooding hazards and applied on a case study area. The model allows the asset owners to understand risk and performance of their infrastructure. This enables allocation of scarce financial resources to be focussed on the critical objects allowing significant cost savings and avoiding the waste of non-renewable resources in strengthening large sections which have sufficient resilience.

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In the case of a flood occurring before the resilience of a known weak-spot is increased, temporary reinforcements measures can be deployed by the asset owner or other mitigation strategies can be considered by the CPAs regarding evacuation routes. By increasing the resilience of the infrastructure the most vulnerable citizens will be protected from the impacts of climate change.

2 Flood risk assessment methodology

Flood risk assessment methodology is based on the intersection of flood hazard scenario for certain return period with the affected area, for which vulnerability or damage function are developed. Results of the vulnerability analysis are combined with possible consequences of a flood in the developed risk forecasting tool, using the framework shown in Figure 1. The tool provides information on the potential monetary value of flood damage together with the exposed population, critical infrastructure and evacuation routes in the area affected by flood.

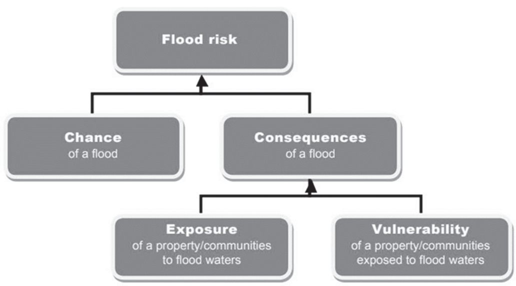

Figure 1 Risk assessment framework

2.1 Vulnerability analysis of critical infrastructure

Vulnerability analysis of critical infrastructure focused in the project on the embankments and bridges, as most critical elements of flood protection system and transport infrastructure. The analysis was based in-situ collected data was and numerical models for embankments and bridges [4, 5]. For bridges the focus was on foundation scouring potential due to flood events with the vulnerability assessed through vibration based methods and drones [4]. For the embankments sets of relevant loads based on the flooding scenarios were determined, covering wide range of possible actions for both ultimate and serviceability limit state. Flood embankments can fail through a variety of different mechanisms, while in oVERFLOw project four different mechanisms were considered, namely global stability, overtopping, piping and rapid drawdown. In Figure 2 fragility curve as probability of failure dependant on the residual water level height for rapid dropdown failure is presented. Vulnerability assessments were performed for two case studies, Oostmolendijk, a primary dyke situated just outside Dordrecht in the Netherlands and on riverbanks of Kupa river in the city centre of Karlovac in Croatia [5]. Those analysis enabled establishment of inventory of critical infrastructure assets in a case of a flood event.

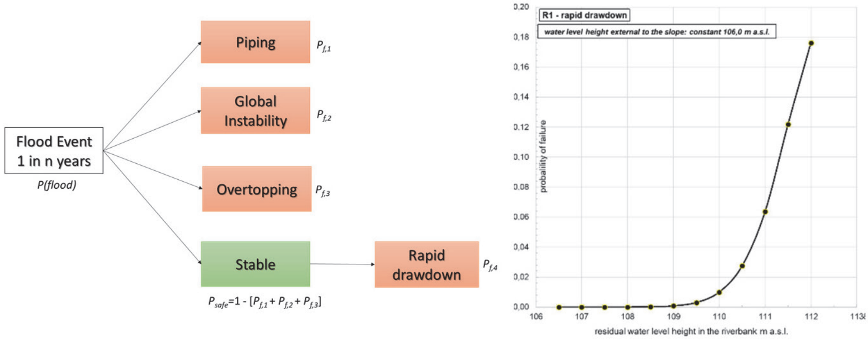

Figure 2 Event tree describing the different failure mechanisms (left), fragility curve for one of the sections in the case study area of city of Karlovac for rapid dropdown failure mechanism (right) [5]

2.2 Consequence analysis

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

- the identification of impacts that can be monetized in a way to show direct monetary value of flood damage to different assets which can then be used by infrastructure managers, owners or local authorities. This information can support decisions such as the identification of possible needed interventions and investments for flood protection infrastructure or transport infrastructure, through cost benefit analysis or risk assessment models.
- mapping of critical infrastructure gives the insight to CPAs and first responders about highly populated areas, areas with low rise buildings or buildings with people without self-sufficiency (preschools, schools, old-people homes etc.) where their immediate attention is needed in case of floods. It also provides them the information about safety routes so they can reach certain areas without delay or endangerment.

Impact categories are adopted from the Croatian disaster risk reduction strategy [6], developed for the purpose of reducing vulnerability of all categories of social values which are exposed to adverse impacts of different threats. There are three main categories for which consequences are quantified: a) economy (built environment, loss of business), b) human life and health (loss of life or injury, evacuation routes) and c) social stability and politics. Table 1 contains three main categories for quantification of flood impacts with data used for determination of exposure of a certain area to a flood hazard. The data is used to provide Infrastructure Managers and Civil Protection Agencies information needed for decision making prior and during a flood event.

Table 1 Quantification of flood impacts–exposure analysis [3]

Economy				Human health and Social stability		
Built environment			Loss of business	Population	Environment	Society
Land	Buildings	Infrastructure				
Type of land Value of land €/m^2	Type of building Value €/ m^2/unit Number of stories One-story buildings	Transport (e.g. bridges, roads) Flood protection - embankments Supply systems Value in €/m', m^2, unit	Loss due to business interruption because of flood (Nr of employees, total income, time to return to preflood…)	Potential loss of life and injury - evacuation possibilities and capabilities, flow m^3/s, water levels, population density	Potential pollutants in the area in case of flood – hazardous waste, mining, landfills, industry… o	Cultural heritage sites Critical objects /infrastructure (hospitals, schools, kindergardens, fire stations…)
IMs - Definition of maximum damage value, Flood damage factor regarding water depth CPAs – Information about buildings without dry floors, evacuation routes, supply outages				IMs – Awareness of highly populated areas, potential pollutants, sensitive areas CPAs – Population (evacuation priorities), potential pollutants		

2.3 Risk mapping

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

3 Case study: city of Karlovac

The city of Karlovac is located at the intersection of important road and railway routes from Zagreb to Rijeka and Split and therefore has an important role in transport and economy of the country. Karlovac is also situated at the intersection of four rivers, Kupa, Korana, Dobra and Mrežnica, making it extremely prone to floods. Many settlements, city districts, local roads and the state road D36 are regularly flooded with floods also threatening important international and regional rail lines. It is estimated that over the last several years floods along the Kupa river have caused direct and indirect costs of an average of 40 million EUR per year [8]. The flood protection system in Karlovac is designed to withstand floods with a 100-year return period, however, it has not yet been completed. An important element of this system (Kupa-Kupa channel) still needs to be optimized and is currently operating at only 20 % of maximum capacity [9].
The city of Karlovac has dozens of bridges many of them dating back to 19th century which are affected by flood loads and serve as evacuation routes during flooding events. Because of the lack of a proactive framework, authorities, IMs and CPAs deal with floods in a reactive manner and therefore improving the understanding of flood embankment and bridge vulnerability assessment procedures are critical.

3.1 Calculation of consequences for case study area

The main input as a flood parameter for an estimation of the flood damage is the water depth (relevant for certain return period). In the oVERFLOw methodology [3] damages of industrial and residential buildings, businesses, infrastructure and land per type are quantified in monetary terms. Special objects and areas including vulnerable objects (critical infrastructure such as transport network, healthcare institutions, educational institutions etc.), are identified and mapped. The flooding of these objects is of relevance for flood risk managers, infrastructure managers and evacuation services.

The research revealed that for certain types of assets a global depth damage function can be applied. This first of all goes for agriculture and infrastructure-roads since the damage curves in different countries across the world were quite similar [10]. Damage factors for other types of assets such as buildings, residential and industrial, and the associated land need to be assessed on a more local level. To calculate the monetary value of the damage, percentages are multiplied by the maximum damage value of properties.

Critical infrastructure includes a list of sectors such as energy, communication and information technology, health care, water management, food, finance, public sector etc. Calculation of direct economic loss on structures related to these sectors is similar to any other type of building. Critical infrastructure that is separately addressed in the oVERFLOw project is transport infrastructure, specifically bridges and embankments. A flooding event can cause direct damage to transport systems but can also have an economic impact on a wider area due to the disruption of communication links disabling movement of goods and people. Vulnerability assessment for embankments and bridges provides the information on behaviour of these types of structures in case of a flooding event dependant on the flood hazard intensity. The data is used to establish safe evacuation routes and for investment planning regarding infrastructure maintenance and development.

Maximum direct damage values are derived from construction cost of roads and rails, based on the assumption that the potential damage is 5-10 % of the construction cost [11]. The proposed values for Croatia are given in Table 5.

Table 2 Proposed direct damage values (left) and damage function (right) for Croatian transport infrastructure [3]

Transport category	**Maximum direct damage** [€/m]	**Depth** [m]	**Damage factor**
Highway	1500	<0.5	<0.2
Regional road	1000	0.5-1.5	0.2-0.7
Local road	700	1.5-2.5	0.7-0.9
Rail	8500	>2.5	0.9-1

3.2 Risk tool applied on the case study area

Criterions chosen to quantify consequences of a flood on human life and health are population density as a parameter describing vulnerability of the area, while water height depicts the hazardous event. In Figure 3 (left) consequence matrix is derived from the interdependence of population vulnerability, described by population density, and flood exposure, expressed with water height. The matrix enables visualization of risk with different colouring for consequence categories from negligible to catastrophic, which is used for GIS mapping. In Figure 3 (right) a map of flood hazard with low probability [12, 13] is overlapped with the population density map, providing the information of the most risky areas regarding the affected population.

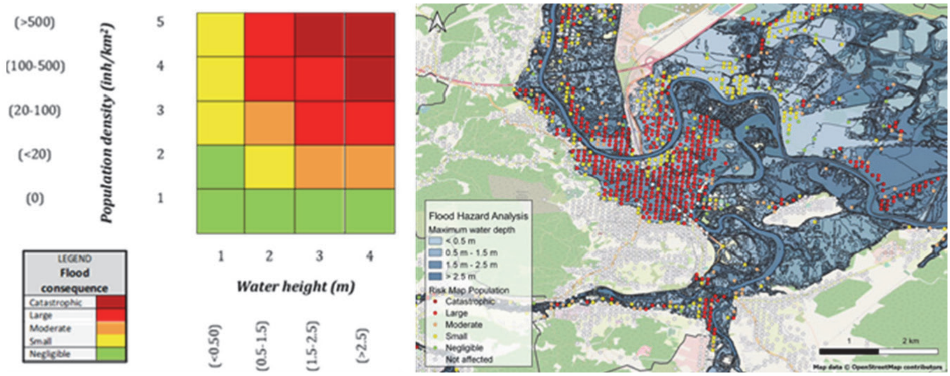

Figure 3 Flood consequences matrix (left) and population flood risk map (right)

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 district with areas with higher buildings safer in case of a flood hazard [14]. The main constraints for the safe evacuation routes are associated with the vulnerabilities of the structures along escape routes during the hazard event, such as potential scour of the bridge pier due to the high water level and water flow, uncertain road conditions due to the roads under water, road blockage, etc. Optimal evacuation alternatives in the form of safest and most efficient routes for evacuation of the population from the affected region will be determined based on the results of vulnerability assessment of bridges and embankments.

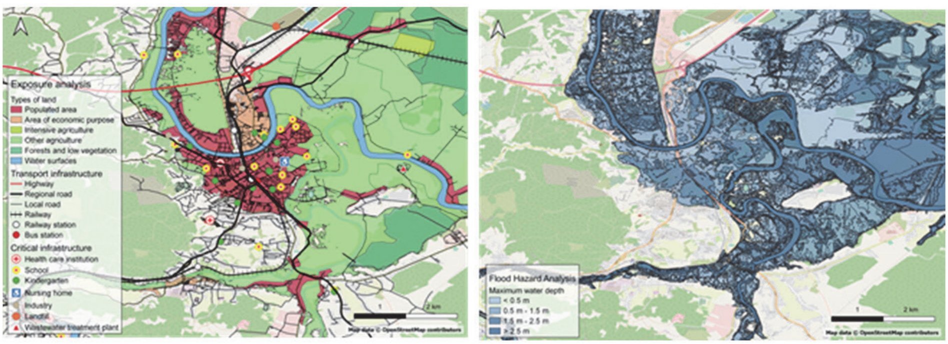

Figure 4 Map with exposure of case study Karlovac area (left) and flood hazard map (right)

Flood exposure analysis of case study area of City of Karlovac included land types, different transport infrastructure (highway, rail, regional and local roads) and different critical infrastructure such as health care institutions, schools, landfills etc. as is shown on map in Figure 4 (left). Exposure map is overlapped with flood hazard for low probability of occurrence [12] and presented in Figure 4 (right). The collection of data is still in the process for the quantification of direct impacts for all proposed categories. Currently available data revealed the following results: a total of 3.44 km highways, 13.94 km of regional road, 139.6 km of local road and 5.44 km of rail is flooded. Calculation of direct damage to transport infrastructure sums up to about 40 million € for low probability flood event. This number seems quite reasonable comparing to the estimated overall consequences over the last several years, which were estimated to the similar amount (direct and indirect costs of an average of 40 million EUR per year) for the events of high probability [13].

4 Conclusion

A flood is a natural hazard that, due to the intensity and unexpectedness can endanger the health and lives of large population, infrastructure, material goods and the environment. Floods can cause more damage than any other natural hazard, inflicting damage and losses that can last for a very long time period.
Flood management and control play a key role in protecting people, their property, industry and society as a whole. Practice has shown that in most cases it is impossible to completely eliminate the risk of floods. Therefore, efforts should be focused on reduction or mitigation of adverse consequences for people, the environment and properties. Targeted data, often already available, can be used to extract valuable information for different users such as CPAs and infrastructure managers. In this paper a summary of the risk assessment methodology developed within oVERFLOw project is presented, which can be used for the improved decision making during the response stage and planning of the investments to increase the resilience of the critical infrastructure.

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