Ref. Ares(2022)4858400 - 04/07/2022

Layman's report

oVERFLOw

VulnERability assessment of embankments and bridges exposed to FLOoding hazards

Funded by European Union Civil Protection
Grant Agreement Number 874421

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General information

Programme: UCPM 2019 PP AG , EU Civil Protection Mechanism

Project duration: 01-12-2019 – 30-11-2021

Total Cost : EUR 586 192

EU Contribution : EUR 498 260

Coordinator: University of Zagreb Faculty of Civil Engineering

www.projectoverflow.eu

Project background

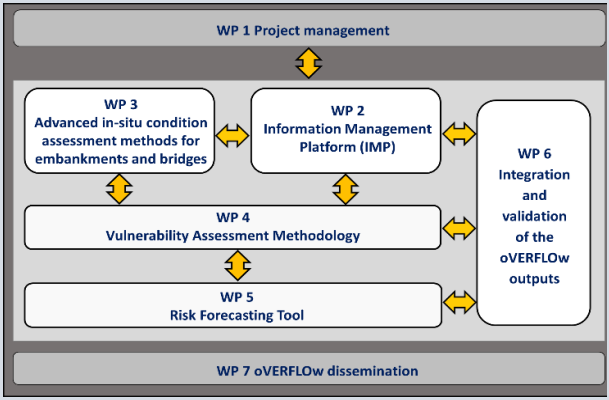
In recent years Europe has experienced some of the largest flood events in its history. The resilience of a flood defence system is controlled by the weakest link. Whilst the risk based method for assessing flood defences VNK2 developed in the Netherlands is the state of the art, the determination of the probability of failure is critically dependent on a number of highly uncertain parameters. A number of recent collapses of major bridges due to scour shortly after inspection highlight the limitation of risk assessments based on periodic inspection. During flood induced failures the condition of a bridge or flood defence changes in a matter of minutes. The oVERFLOw project implements a number of technologies to reduce these uncertainties and move to real-time risk assessment.

The overall objective of the oVERFLOw project, ***strengthening resilience to climate change impacts*** with the specific objective being the development of ***climate-resilient infrastructure,*** is achieved by:

1. Reducing the known uncertainties in the VNK2 approach using techniques and procedures, e.g. non-intrusive geophysical techniques to quantify length effects, image processing using drone data to identify piping and additional sensors to provide real-time response of a critical infrastructure object (levee of bridge) during a flood event.
2. The technology was deployed and demonstrated at two pilot sites, at flood prone areas in the Netherlands and Croatia in order to (i) validate the new technologies and increase the TRL levels, (ii) transfer the state of the art risk based approach from the Netherlands to Slovenia/Croatia and (iii) to provide validation and buy-in from a range of stakeholders including CPAs, infrastructure owners, regional authorities and responsible bodies for cultural heritage and the general public.

Project structure

The oVERFLOw project was organised using the interactive structure shown in the project structure below. The consortium is a multidisciplinary team, comprising two Civil Protection Agencies CPA's (in Slovenia and the Netherlands), research and educational institutions (University of Zagreb Faculty of Civil Engineering, Slovenian National Building and Civil Engineering Institute), and three research driven SMEs (Infra Plan Consulting, GEKOM and InGEO).



oVERFLOw project structure

Four technical Work Packages. (WP2 to WP5) were completed.

WP2 Information Management Platform – Developed a GIS web based platform to implement historical data, climate change and flooding scenarios.

WP3 Advanced in-situ condition assessment methods for embankments and bridges A number of technologies for assessing the condition of flood defences were demonstrated. For bridges the focus was on scouring potential due to flood events with the vulnerability assessed through vibration based methods and drones.

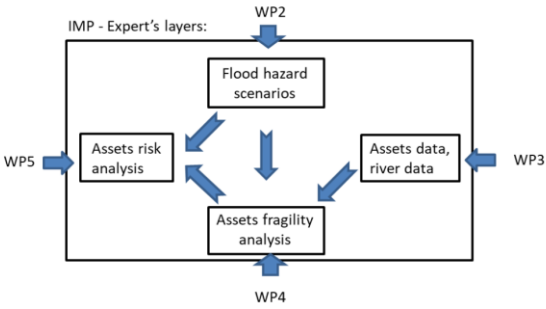
WP4 Vulnerability assessment methodology –Vulnerability of flood defences and bridges was quantified using numerical models. A range of condition and loading / hazard scenarios were considered.

WP5 Risk forecasting tool – A framework based on the VNK2 approach for the quantification of direct and indirect impacts of the hazard was developed. The project integrated the failure probabilities determined in WP4 into a multi attribute utility theory based risk forecasting tool which will take into account multiple socio-economic objectives and assess the cascading effects of critical assets' failures.

The last Work Package **WP6** was aimed at validation of the risk forecasting tool.

Information Management Platform, IMP

The IMP covers the case study areas in Croatia (city of Karlovac) and in the Netherlands (South Holland region), and operates in a GIS environment. The main purpose of the IMP is to facilitate the work of CPA's by providing more detailed information on the development of flood events and expected performance of critical infrastructure, such as bridges and flood defences. The platform also provides useful information to identify vulnerable assets, which can be important for the design of flood prevention activities and retrofitting actions.



Data transfer protocol between WPs

The figure above illustrates how the IMP acts as a common platform for data transfer between different WPs, or different stages in the risk assessment process for assets exposed to flood risk. Flood hazard scenarios consider different assumptions regarding the impact of climate change. This data is stored in the IMP and is made available to other experts working on flood fragility and risk analysis. Figure showing current and predicted flood in the Netherlands[1]. In-situ data regarding the examined assets (geometry, material, condition assessment and geotechnical data) is collected and stored in the platform together with the data regarding the river/channel profile and flow characteristic (e.g. water height vs. discharge relations). These data are obtained

Current flooding risk in the Netherlands in year 2019 (left) and prediction for the year 2050 (right)

[1] https://basisinformatie-overstromingen.nl/liwo/#/

based on existing project documentation, 3D drone survey, destructive and non-destructive testing of materials and soil, bathymetric survey of the riverbed, and measurements of the river flow. All data is then used as input for analyses resulting in fragility curves for the assets considered. The fragility curves are later used as input for risk analysis. For given flood hazard scenarios it is then possible to calculate consequences (direct and indirect impacts) expressed as risk for the selected assets.

Advanced in-situ condition assessment methods

Investigation works and monitoring of the **flood protection systems** of two case study areas were performed. The first case study is the system of riverbanks and embankments protecting Karlovac city centre in Croatia. In total, 3.0 km of riverbanks was investigated (1.5 km for each side of river), as well a 150 m region of an embankment next to the Kupa river. The second case study is the system of flood

3D point cloud of the riverbanks next to the Kupa river

defences called section 17-3 Oud-IJsselmonde-Oostendam in the Netherlands. It protects the eastern part of IJsselmonde against the influence of the North River. The flood protection system (dyke) in this area is 9.4 km long and consists entirely of engineered embankments. For this project, an evaluation of the condition of a critical 1.1 km section was analysed, known as Oostmolendijk. Aerial *photogrammetry* of both case study areas, in Croatia and the

Borehole drilling procedure and drilled core samples

Netherlands was performed. This allowed the generation of *3D point clouds* and *automatic generation of cross-sections* of the riverbanks and embankments. On both case study sites, a suite of geophysical approaches were applied consisting of the

DJI Matrice 300 RTK drone platform and scanning of bridges in Karlovac

combination of *seismic and geoelectrical investigations*. Determination of the subsoil conditions as well the variability of key soil parameters for vulnerability analysis: drilling was performed along with in-situ and laboratory geotechnical testing.

Investigation works and monitoring was also performed on bridges in Karlovac. Bridges were visually inspected with the help of a *drone survey*. A *bathymetric survey* was undertaken to scan the riverbed near the bridges. In addition, *in-situ ambient vibration measurements* were performed to obtain the modal frequencies and shapes of the two bridges, which were used for the calibration of numerical models.

Bathymetric survey of Banija bridge

Vulnerability assessment methodology

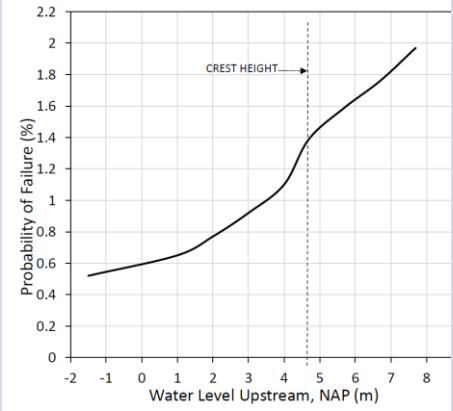
Vulnerability assessment using numerical models was performed to determine the vulnerability of flood defences and bridges to triggering values of external stress (including flood level) based on their condition and loading/hazard scenarios. The protocols for data fusion through integration of multiple data sources (investigation works, monitoring, historical data, downscaled scenarios) in order to produce more consistent input information for vulnerability assessment of embankments and bridges was established. Developed fragility curves represent the probability of

exceeding ultimate limit states (or serviceability limit states) for the given asset condition and triggering values.

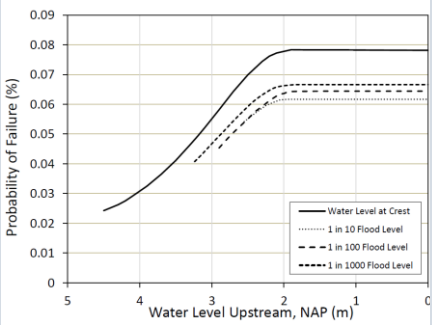
Based on developed flooding scenarios, sets of relevant loads on embankments and bridges were determined, covering wide range of possible actions for both ultimate and serviceability limit state. A sophisticated finite element analysis was conducted with overall aim of obtaining the fragility curves for both types of structures, where activities included various spatial and temporal analysis based on data.

Embankments

For the embankments sets of relevant loads based on the flooding scenarios were determined, covering a wide range of possible actions for both ultimate and serviceability limit state. Flood defences can fail through a variety of different mechanisms, while in the oVERFLOw project four different mechanisms were considered, namely global stability, overtopping, piping and rapid drawdown. Fragility curves were constructed determined as probability of failure dependant on the flood level height for different failure mechanisms, as can be seen in figures. These analysis enabled establishment of inventory of critical infrastructure assets in a case of a flood event.



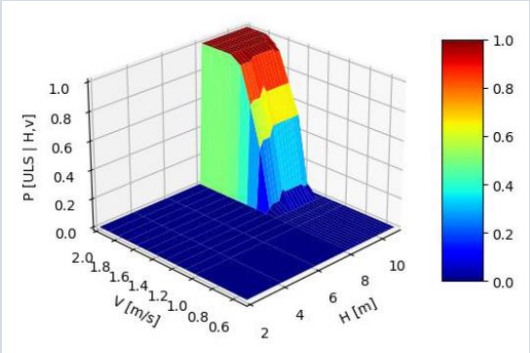
Fragility curve showing the change in global stability as flood level changes



Fragility curve showing the change in stability following rapid drawdown

Bridges

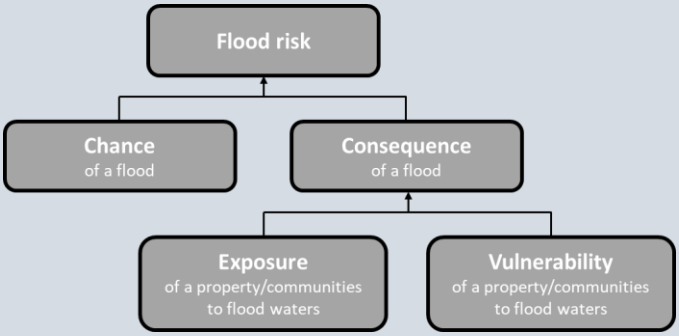
For bridges the focus was on the probability assessment of foundation scour caused by flood events, assessed through vibration based methods and drone recordings. The major outcome are fragility surfaces for the serviceability and ultimate limit states, which represent the probability of exceeding the designated limit states for a given combination of water height and water flow velocity. The results of the analyses indicate that the serviceability limit state of the bridges is affected significantly by the accumulation of debris, which constricts the flow of the water, which leads to an amplification of scour due to the local increase of the flow velocity.



Flood fragility surface for the ultimate limit state

Risk forecasting tool

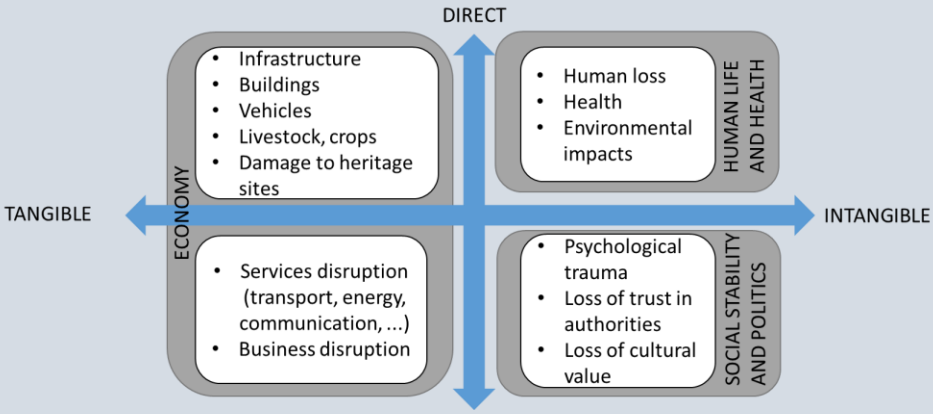
The risk forecasting tool overlaps the vulnerability assessment methodology and the methodology for quantification of direct and indirect impacts of a flood hazard. The improved and novel vulnerability assessment methodologies for embankments and bridges, determined failure triggering values based on their condition and loading / hazard scenarios. The risk forecasting tool developed was applied for two case study areas (city of Karlovac wider area in Croatia and Oostmolendijk in the Netherlands).



oVERFLOw risk assessment framework

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

a. The quantification of impacts in monetary value to show direct flood damage to different assets which 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 system, transport infrastructure or any other endangered asset. The model is used in final risk assessment and can be also used for cost benefit analysis.
b. Mapping of vulnerability of critical infrastructure and population density gives the insights of direct impacts on humans, especially important for CPAs and first responders about the endangered population, areas with low rise buildings or buildings with people without self-sufficiency (preschools, schools, homes for the elderly etc.) where their immediate attention is needed in case of floods. It also provides the information about safety evacuation routes so they can reach certain areas without delay or endangerment.



Framework to quantify direct and indirect impacts of a flood event

Calculation of risk implies a combination of flood hazard scenarios with the exposed area and verification of direct and indirect consequences. The output 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 oVERFLOw project results are integrated into the existing GIS platforms, as two different operational layers. The first for infrastructure owners for future planning of investment measures and the second 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. The results are shown for two case study areas, in Croatia and the Netherlands.

Case study area – Croatia

The city of Karlovac is situated in the central continental part of Croatia at the crossing of lowland and mountainous regions. It 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 the economy of the country. Karlovac is also situated at the intersection of four rivers, Kupa, Korana, Dobra and Mrežnica, making it extremely prone to flooding. Many settlements, city districts, local roads and the state road D36 are regularly flooded also threatening important international and regional rail lines.

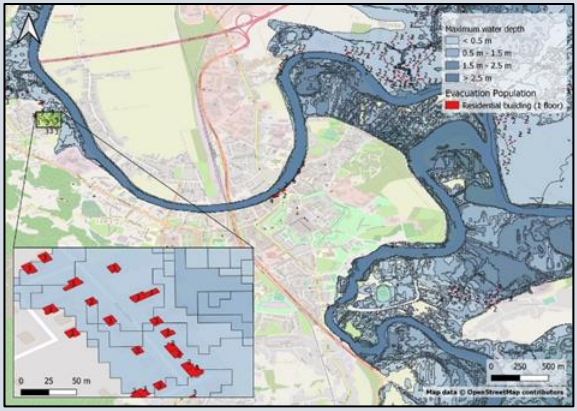
Historic area 'Karlovac Star' next to the Kupa river and 2014 flood in Karlovac

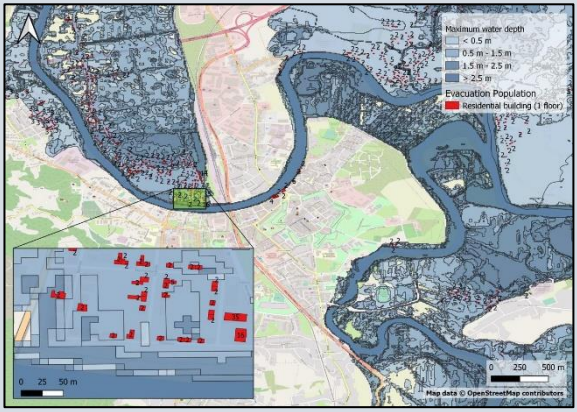
Three different flood scenarios have been analysed and compared. Flood scenarios are based on Croatian Waters flood hazard maps with three different probabilities of occurrence related to three different return periods high probability (HP) of occurrence (return period 25 years), medium probability (MP) of occurrence (return period 100 years) and low probability (LP) of occurrence (return period of 1000 years).

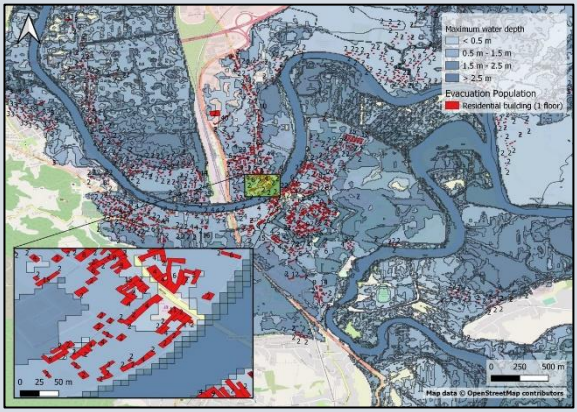
Risk tool layers for Civil Protection Agencies

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

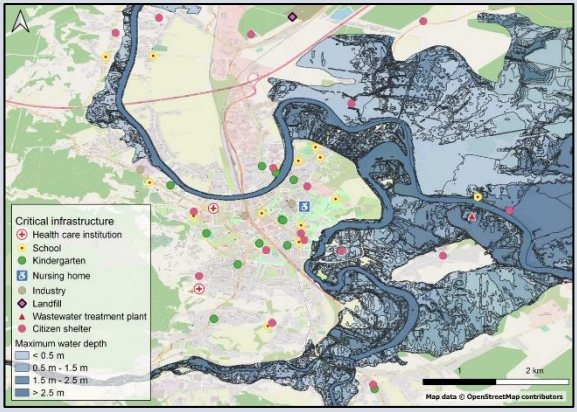
- Which evacuation routes are safe and available:
    a. Flooded roads – roads that can and cannot be used due to the flooding;
    b. Which critical infrastructure with the focus on embankments and bridges are safe or not safe to be used due to the flooding;
- How many people need to be evacuated and in which parts of the affected area they are located;
- Which critical objects are affected by flood (buildings with people without self-sufficiency – hospitals, preschools, schools, old-people homes etc.);
- Which shelters for evacuation are available or flooded.

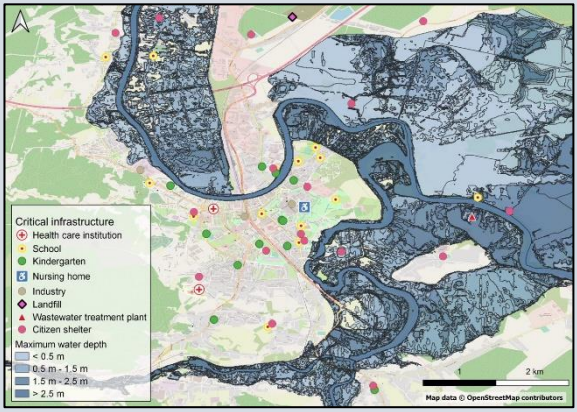


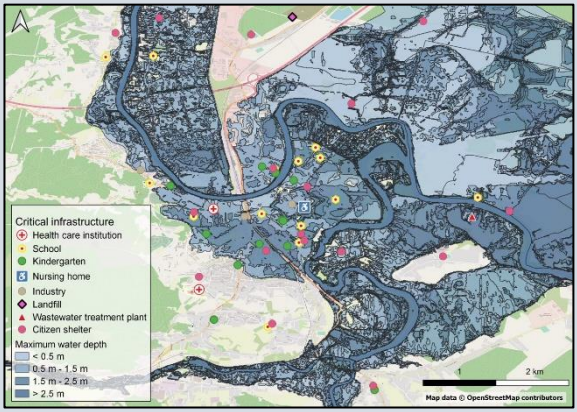




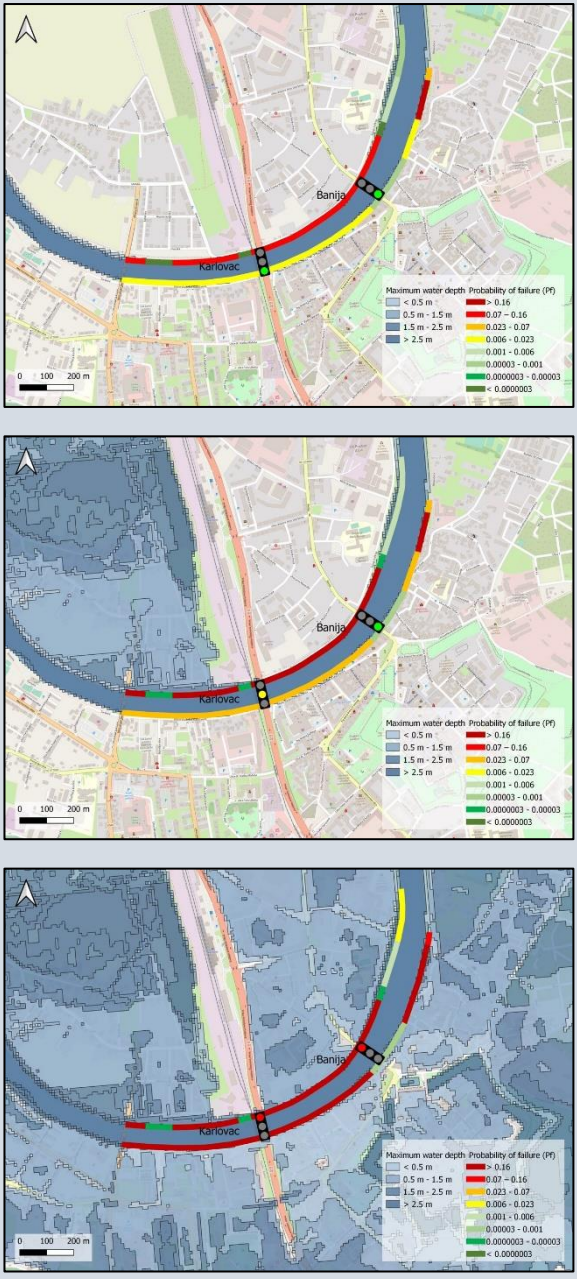
Population flood risk maps - Flood map for high/medium/low probability of flood occurrence overlapped with low rise buildings (red) and number of residents



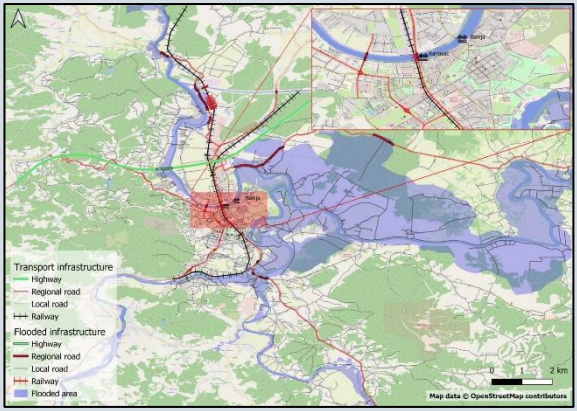


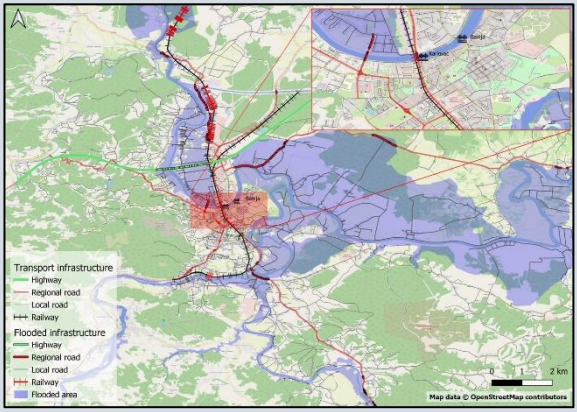


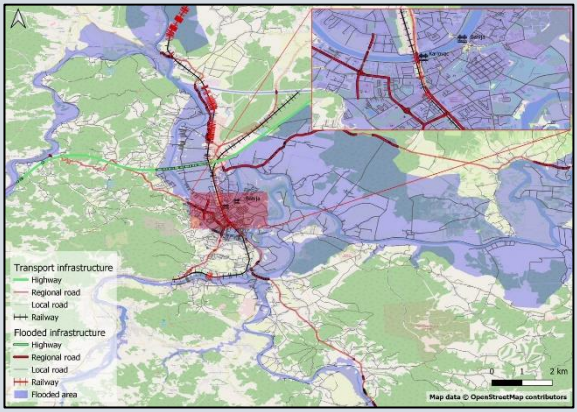
Critical infrastructure and locations of shelters for evacuation of population overlapped with flood map for high/medium/low probability of flood occurrence



Results of the vulnerability analysis for embankments and bridges for high/medium/low probability of flood occurrence – safe evacuation routes





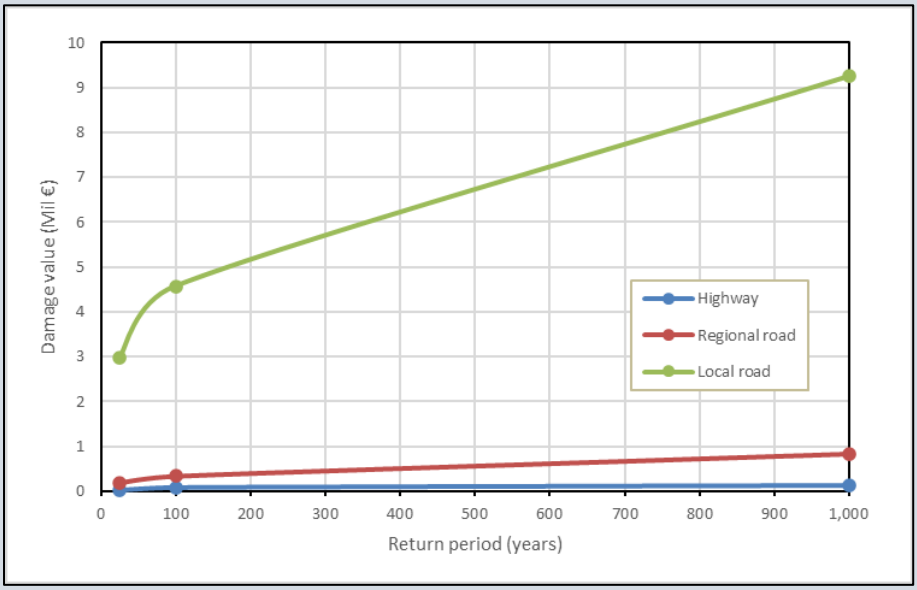


Flooded roads for high/medium/low probability of flood occurrence

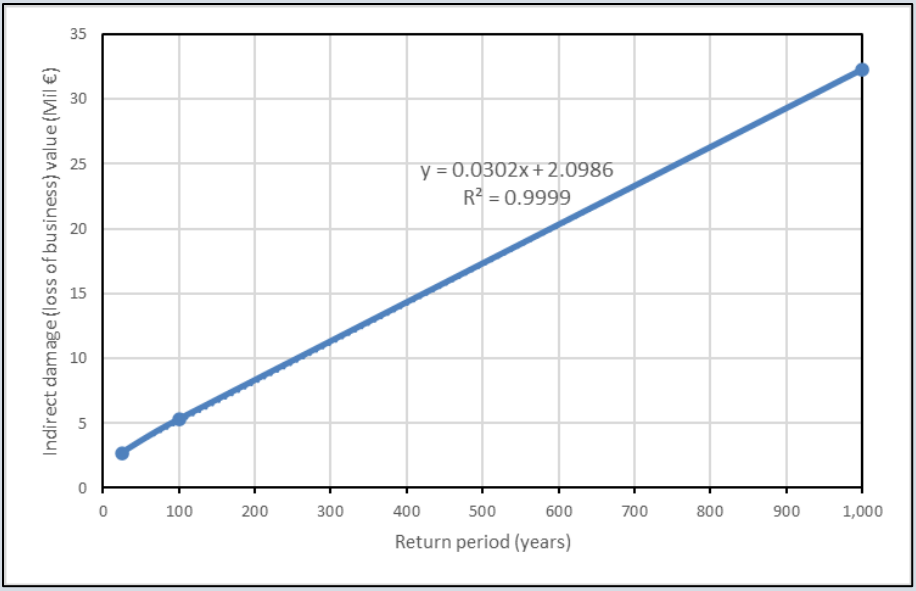
Risk tool layers for Infrastructure Managers

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

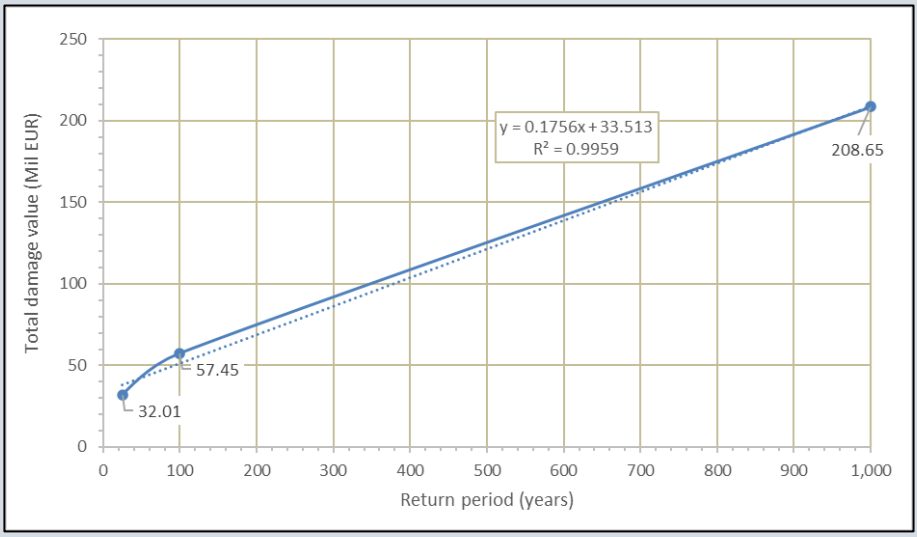
- Direct impacts to transport infrastructure, quantified in monetary terms
- Direct impacts to industrial and residential buildings, businesses, infrastructure and land per type, quantified in monetary terms
- Indirect impacts – Loss of business, disrupted due to the flood event.



Graphical representation of material damage to transport road infrastructure for three different return periods of floods



Graphical representation of indirect material damage for loss due to business interruption dependent on the return periods of floods



Graphical representation of total economic damage (€) for three different return periods of flood for the city of Karlovac area

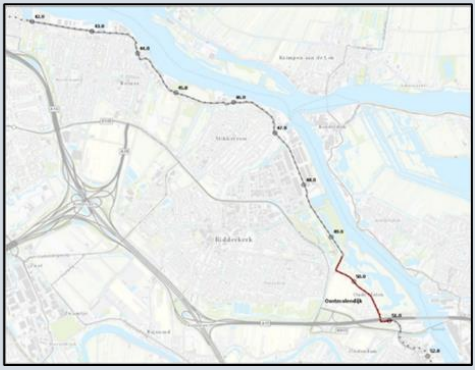
The flood risk assessment methodology is based on the intersection of flood hazard scenario for certain return period with the affected area, for which vulnerability or damage functions are developed. Results of the vulnerability analysis are combined with possible consequences of a flood in the developed GIS-based risk forecasting tool. 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. Both CPAs and IMs highlighted the need for structured and credible information's that can help and improve decision making processes prior and during a hazardous event such as floods.

Calculation of direct damage to transport infrastructure, buildings and land type is summed for three different flood scenarios. The total damage costs obtained through the model developed within oVERFLOw project are comparable to the estimated overall consequences over the last several years, both estimated to the similar amount, namely direct and indirect costs of an average of 40 million EUR per year, for the events of high probability. Based on the performed analysis it can be concluded that the total damage costs are increasing with an increase of the return period, or the extent of the flood event. These results support Infrastructure Managers decision making regarding investments into flood protection systems and other infrastructure based on the insight into areas with the highest risk.

CPAs are provided with the information on safe evacuation routes (flooded roads, safe and available bridges and embankments), location and number of most vulnerable population regarding type of buildings (low rise buildings-no dry floors). GIS layer with critical structure such as hospitals, schools, kindergartens, shelters etc. enables CPAs to prioritize evacuation and also have the information where it is possible to take the evacuated population.

Case study area - Netherlands

The case study area Oostmolendijk is located between the towns of Ridderkerk and Hendrik-Ido-Ambacht, along the river Noord in the Zuid-Holland province of the Netherlands, see the Figure below. The embankment is a small section of a greater embankment ring IJssel-monde also known as Dike Ring 17., the majority of which is considered stable. The section immediately beyond the study area however has had stability problems in the recent past, with a failure occurring during remediation works requiring large scale replacement. Oostmolendijk itself has developed large local shearing planes which is observed through cracks in the asphalt and landside slope showing that the body of the embankment is in motion. These problems can be explained by the presence of thick peat layers in the subsoil, which has low strength and stiffness values.

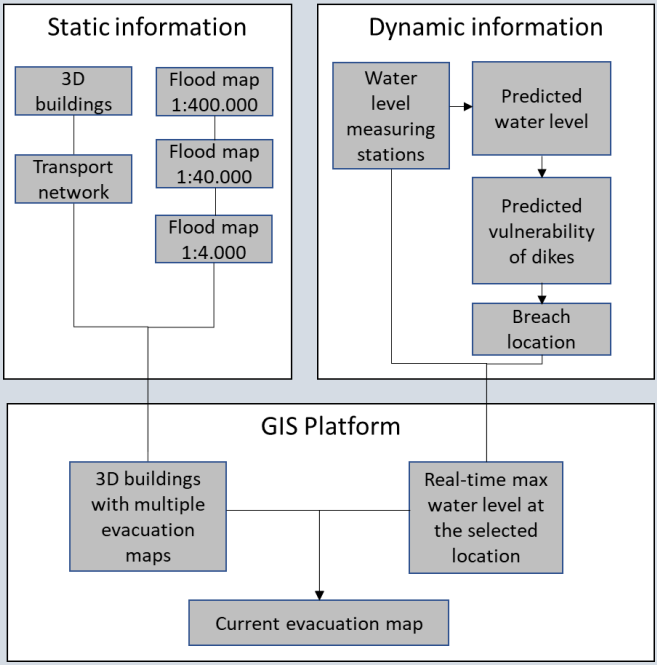


Case study site (left); Embankment Section 17-3, Oostmolendijk (in red) (right)[2]

Although the Dutch flooding emergency response system is very advanced, the country also deals with unique problems due to its geography. As the built environment in many areas is lower than the surrounding rivers, the country is more prone to flooding consequences: once an embankment has been breached, it's difficult to get the water out of the area. Even with lower water levels and a breach due to external circumstances, there will almost certainly be floods. However, the severity of the consequences is highly dependent on these water levels. For a better data-driven approach to flooding response, a real-time system for prediction of most vulnerable locations and highly risk areas which should be firstly evacuated has been developed. The aim of the proposed methodology is to integrate probabilistic vulnerability

[2] https://www.rijkswaterstaat.nl/

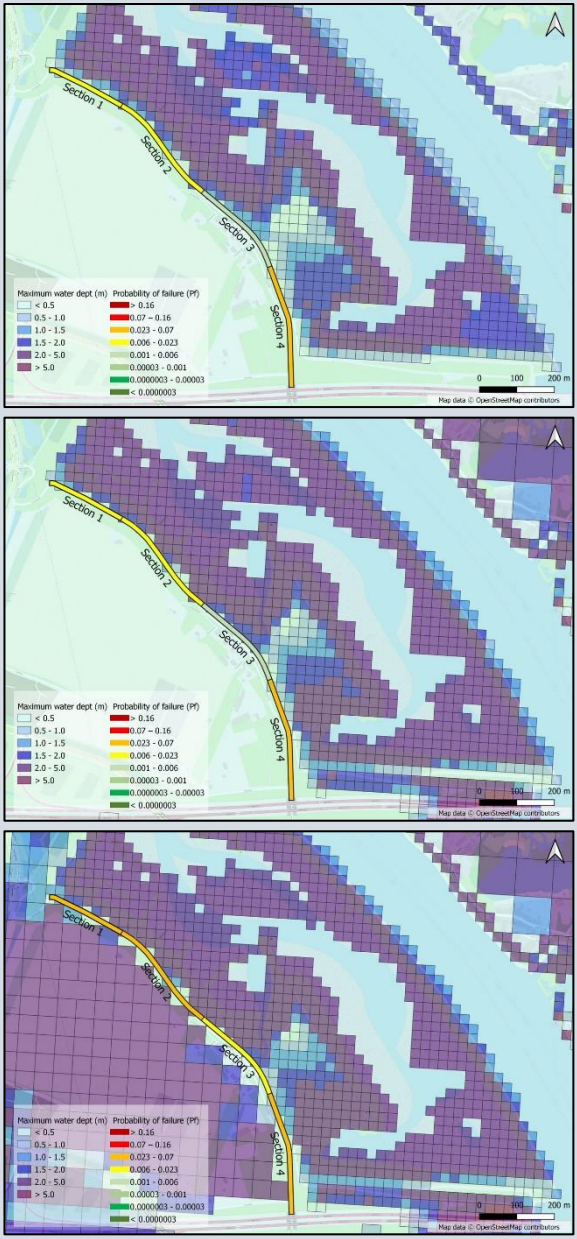
assessment of flood protection system and the prediction of the areas which need to be evacuated into the existing GIS platform and support decision making at the CPA.



Framework of the novel methodology for the improved response and preparedness planning for different flood hazard scenarios

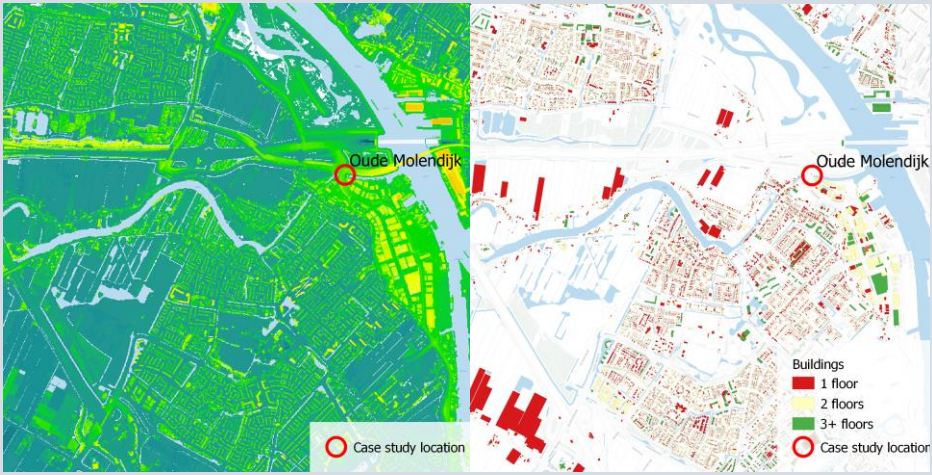
The flooding scenarios were downloaded from the LIWO site as raster formats[3]. The dyke sections are labelled from 1 to 4. These sections have been analysed and used to produce fragility curves that describe the probability of embankment failure (considering macro instability, piping, overtopping and rapid drawdown) should a flood event occur. A system probability of failure curve is used to combine the different failure mechanisms into one fragility curve, for each of the sections 1-4. The probabilities failure for different flood return periods (100/1.000/100.000 years) are shown on the following maps.

[3] https://basisinformatie-overstromingen.nl/#/viewer/1?center=51.82094,4.60141&zoom=7

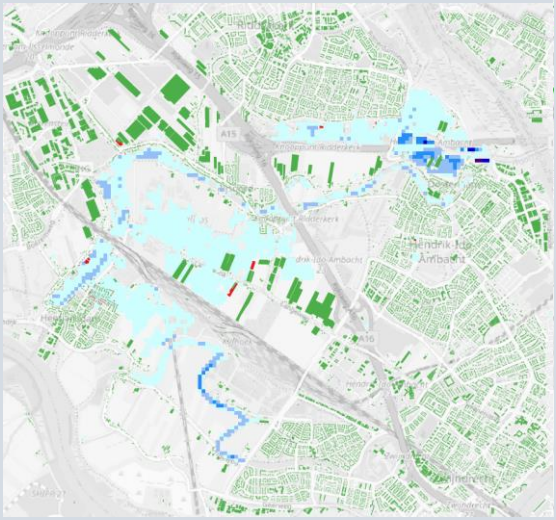


Embankment vulnerability Oostmolendijk divided in Sections 1 to 4 at for flood return period of 100,1.000,100.000 years

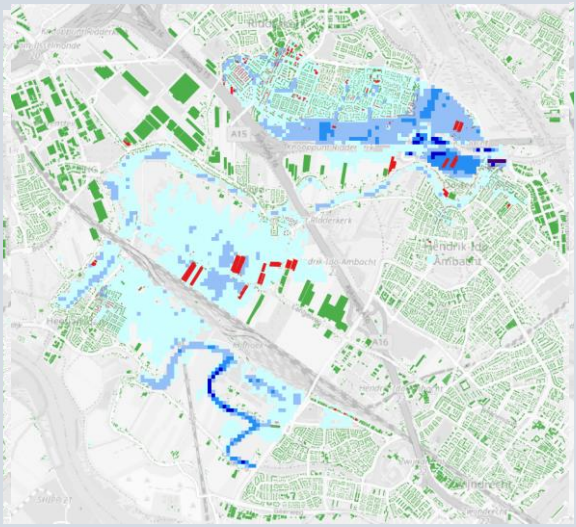
For development of evacuation plans information about the number of floors is established. In the flood-risk area, there are 32,965 building objects, of which an estimated 2,044 (6.2%) only have a ground floor. It is estimated that 4,030 (12.2%) have two and 26,891 (81.6%) have three or more floors.



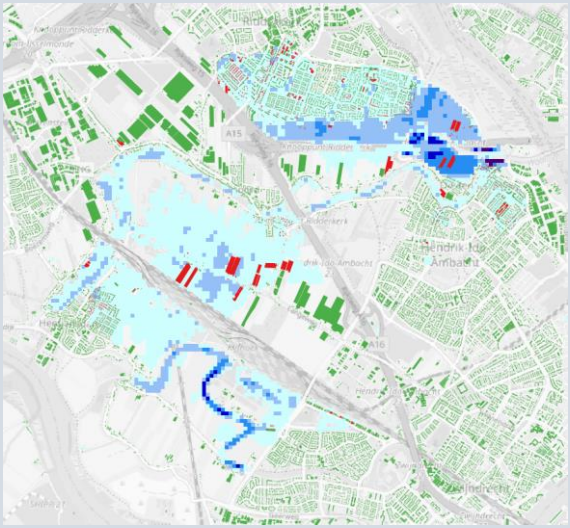
Digital Surface Model of the case study area (left) and the number of estimated floors of each building (right)



Flood scenario high probability of occurrence - Green buildings do not have to be evacuated, red buildings do



Flood scenario medium probability of occurrence - Green buildings do not have to be evacuated, red buildings do



Flood scenario low probability of occurrence - Green buildings do not have to be evacuated, red buildings do

The aim of the case study in the Netherlands was to improve the vulnerability assessment methodology and to integrate it into the current flood risk assessment methodology, focusing on the response and preparedness activities performed by CPA. Currently only the worst-case flooding scenario is developed into an evacuation plan. Moreover, this evacuation plan integrates all possible flooding scenarios of dyke breaches.

This research tried to develop an evacuation plan that integrates multiple possible scenarios of one embankment breach location. It aimed to assist in better informed decision making for first responders, if such a situation should happen. Predicted water levels, that are validated with real-time sensor data, have been combined with the 3D building registry and three flooding maps with varying return periods.

	oVERFLOw methodology -Real-time water level evacuation prediction	Current practice - LIWO model
Buildings - Evacuation	439	3,806
Buildings - No evacuation	32,527	29,160
Buildings - Total	32,966	32,966

Comparison of real-time evacuation predictions with the current LIWO dataset

It has been found that, in the case of an embankment breach at the lowest scenario probability 439 buildings need to be evacuated, which represent only 11% comparing to the current evacuation map, where 3,806 buildings need to be evacuated. All-in-all, decision making in case of evacuation is improved by a better prediction of the flooding depth, due to the inclusion of water level. It is also improved by a more granular approach to embankment breaches, by not aggregating all breaches into one. This method greatly reduces stress for the civil protection agencies and enables them to prioritize evacuation while large number of residents can stay in the relative comfort of their own home.

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Funded by European Union Civil Protection
Grant Agreement Number 874421