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TOWARDS A DECISION SUPPORT SYSTEM FOR CONSEQUENCE ANALYSIS OF FLOODING ON CRITICAL INFRASTRUCTURE

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Critical infrastructures such as electricity networks, drinking water provision and transport infrastructures play an essential role in the functioning of our society. Flood events may, however, have significant impacts on critical infrastructure leading to adverse consequences for the society also far beyond the flooded regions. In order to better support the preparedness and response of responsible authorities, the Critical Infrastructure Preparedness and Resilience Research Network (CIPRNet) aims at developing a decision support system for critical infrastructure operators and authorities. This paper points out the importance of critical infrastructure using the example of flood events and shows the first steps of CIPRNet towards a decision support system for consequence analysis of critical infrastructure disruptions.

IMPORTANCE OF CRITICAL INFRASTRUCTURE IN FLOOD EVENTS

Critical infrastructure (CI) can be defined as "an asset, system or part thereof […] which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact […] as a result of the failure to maintain those functions" [1].

Thus, CI such as electricity or communication networks, drinking water provision or transport infrastructure, play an essential role in the proper functioning of our society and the economy. Flood events, however, may have significant impacts on CI, possibly leading to adverse consequences for society and economy also far beyond the flooded regions.

The European flooding of the Danube and Elbe rivers in summer 2013 caused direct economic damages in the order of 16 billion US$ in central Europe [2]. Moreover, CI such as electricity networks, railways lines, highways and communication networks have been considerably affected by flooding, leading to significant adverse impacts for the society and the economy in Central Europe. For example, the damage of a single bridge of a high-speed railway line in Germany led to major delays and cancellations within the Trans-European high-speed rail network for more than six months.

The course of the flood event and related emergency response actions exposed flaws in preparedness and the understanding of emergency responders of the need to protect CI. For instance, water level gauges failed, flood models flawed for the extreme amounts of water, emergency call numbers became timely unreachable, while in some areas first responders could not communicate due to failure of radio networks. As a consequence, protection and evacuation measures could not be carried out properly.

This paper will point out the importance of CI and related direct/indirect consequences with respect to flood events. A fictitious cross-boundary flooding scenario at the German-Dutch border along the River Rhine will be used to illustrate possible cascading effects caused by the failure of CI. The goals of Critical Infrastructure Preparedness and Resilience Research Network (CIPRNet) will be presented, and the first steps within the CIPRNet towards a decision support system for consequences analysis of critical infrastructure will be explained.

GOALS OF CIPRNET

CIPRNet is a Network of Excellence in Critical Infrastructure Protection (CIP) for research and development for a wide range of stakeholders including (multi)national emergency authorities, CI operators, policy makers, and the society. It is expected that CIPRNet will enhance the resilience of CI in Europe by improving the knowledge and understanding, preparation and mitigation of CI disruptions and their consequences.

As part of the joint research, a decision support system (DSS) is being developed for (multi)national emergency management authorities and CI owners. The DSS capabilities provide timely, actionable, risk-informed CIP analyses and strategies that support the preparation for, response to, and recovery from possible CI disruptions. For further information about CIPRNet it is referred to the project website www.ciprnet.eu.

Figure 1 shows the overall workflow and the different architectural components of the CIPRNet DSS. Hereby, CI simulators are linked with simulators of so-called external threats. It can be seen that different threats, such as floods, earthquakes or landslides, will be considered by analyzing historical data, forecasts and real time information.

TOWARDS A DECISION SUPPORT TOOL

The main objective of the CIPRNet DSS is to analyze possible critical scenarios from the prediction of the initial events (such as rainfall and related flooding) to the assessment of the impacts on CI networks and the consequences of the reduction or loss of CI networks Quality of Service (QoS) on the population, economy and industrial sectors. The structured workflow implemented by the DSS is composed of five functional blocks (Figure 1):

- B1. Monitoring of natural phenomena
- B2. Prediction of natural disasters and events detection
- B3. Prediction of physical damage scenarios
- B4. Estimation of impacts and consequences
- B5. Design of efficient strategies to cope with crisis scenarios

The general workflow will be customized in order to reflect the needs of the different European state members and state members’ CI. Consequently, the DSS workflow and reports need to be interlinked with the existing crisis management chain of command for decision making.

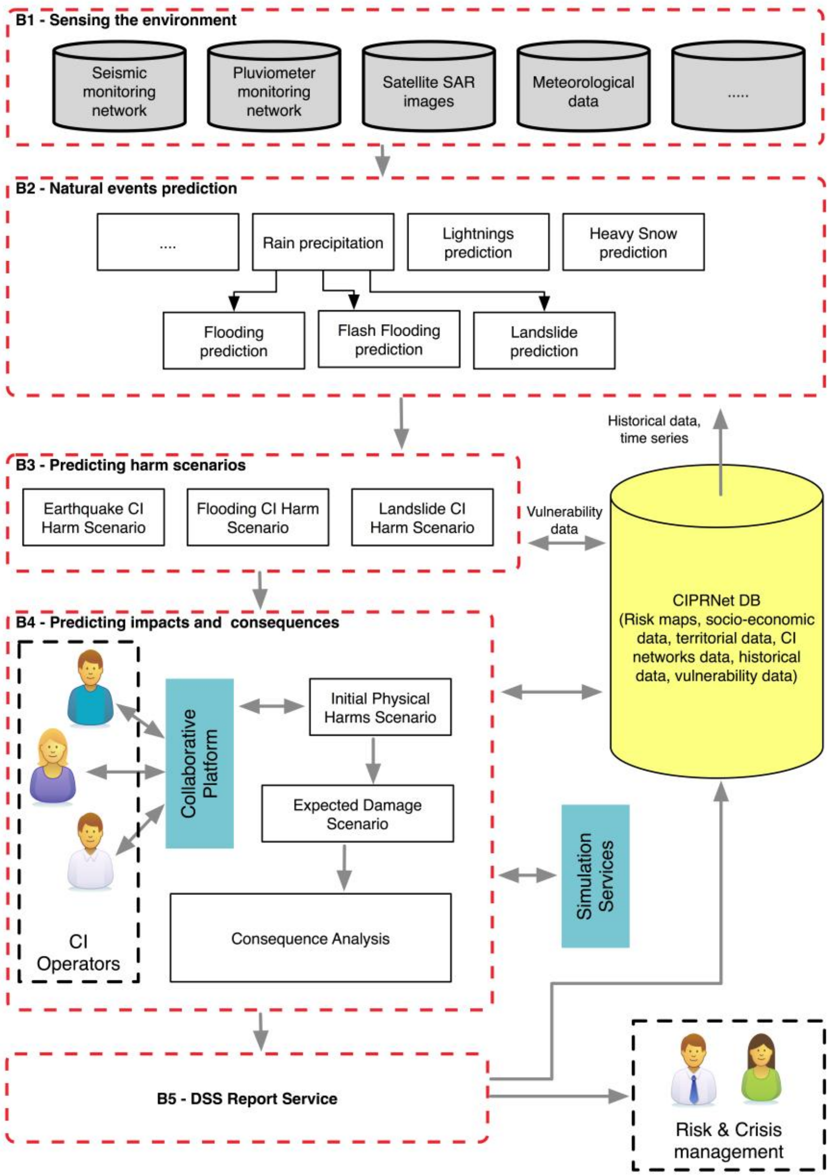

Figure 1. Overall CIPRNet workflow for the development of the DSS capability [3]

Risk Assessment Loop

The functional blocks B1-B5 form the Risk Assessment Loop (RAL) that aims to link quantitatively and qualitatively the risk $R(T_i, CI_j^x)$, expressed by the probability of a given threat to the consequences that its manifestations might have on CI elements. The theoretical framework of the RAL can be expressed as the risk associated to the lost (or the functionality reduction) of the element CI_j^x (x^{th} element of the j^{th} infrastructure) due to a natural threat [4]:

$$R(T_i, CI_j^x) = \Pr(T_i) V(CI_j^x, T_i) I(CI_j^x) \,, \tag{1}$$

where:

- $Pr(T_i)$ is the probability of occurrence of the threat T_i,
- $V(CI_j^x,T_i)$ is the vulnerability of the j^{th} component of the x^{th} CI with respect to the threat T_i,
- $I(CI_j^x)$ is the sum of the impacts that the absence of the j^{th} CI component produces upon failure in its network and in the other CI networks which are functionally related to it.

The RAL workflow can be summarized using the following algorithmic steps:

1. Compute the *Initial Physical Harms Scenario*: the DSS, using models to predict extreme natural events and CIPRNet vulnerability data, computes the CI components that may be considered in failure in the next hours.
2. Compute the *Expected Damage Scenario*: the DSS communicates the Initial Physical Harms Scenario to the involved CI operators using the Collaborative Platform of Figure 1. The DSS waits the reply of CI operators consisting of the expected reduction of QoS of their network. The DSS runs an Interdependency Simulator to evaluate possible failure cascading effects of the CI networks reduction of QoS.
3. Evaluate the consequences: the DSS runs the consequence analysis models to evaluate the consequence on population, environment, economic and industrial sectors of the Expected Damage Scenario. The consequences analysis models will rely on previous CIPRNet partners experiences as for example the work [5] for environmental consequences and [6] for consequences on society. Other models will be developed within the CIPRNet projects.
4. Write and send DSS reports: The DSS reports may contain information about multiple expected CI crisis scenarios as for example risk assessment and consequence analysis of the most probable CI crisis scenario and the worst CI crisis scenario.

The DSS outputs are structured reports containing risk assessment information and consequence analysis results. At the same time, the crisis management decision makers will be supported by a graphical user interface showing the same information contained in the DSS report. The display of the DSS is based on geographical maps, as different geo-referenced layers will allow the decision makers to have an instantaneous overall picture of the expected crisis scenario and its consequences.

CROSS-BOUNDARY FLOODING SCENARIO

In the following sections a possible flood event along the German-Dutch border is briefly described. The storyline will serve as a basis for the what-if analysis in CIPRNet and later on for the development of the DSS.

In order to demonstrate possible impacts from flooding on CI, the focus is set on the temporal development and specific properties of the threat. In case of a flood situation along the River Rhine, emergency managers have different options to manage the flood, for instance one dike ring can be flooded to prevent dike breaches further downstream. Hereby it is important to emphasize that most of the actions and decisions taken by responsible authorities are strongly dependent on the water levels observed or predicted along the main rivers.

The goal of the flood scenario is to find out the direct impacts of a flood and the indirect effects are through so-called cascading effects. These cascading effects are not always known beforehand. However, from other research projects such as FloodProBE [7] it was concluded that the electricity network and its nodes is the most important one of all the CI-networks, as most other CI are dependent on the electricity network and as it is vulnerable to many threats. The Dutch Quick-Scan analysis on CI [8], however, placed the water management CI (e.g. dikes, pumps, locks) at the top, followed by electrical power at number two.

Thus, different models, data and analyses are assimilated to show these cascading effects and their influence within the flooded area and beyond.

Storyline

A storyline scenario has been worked out for the areas along the River Rhine at the Dutch-German border area. The residential areas are protected from flooding by large dike rings (cf. Figure 3). In this scenario, due to a long period of rainfall in the Rhine basin and consequently high water levels along the rivers, the situation is critical along parts of the river banks. Water levels that occur every 1000 years are expected, which would be higher than ever measured.

Possible impacts on CI are analyzed by means of flood scenarios, which have been generated for different dike breach locations by responsible water boards. As part of the scenario, a possible dike breach along the Rhine near the Dutch-German border is assumed. In case of an actual failure this would lead to a large-scale flood with water levels up to 7.5 m in some areas (cf. Figure 3), resulting in about 750 victims without evacuation and approximately 8.8 billion Euro of economic losses.

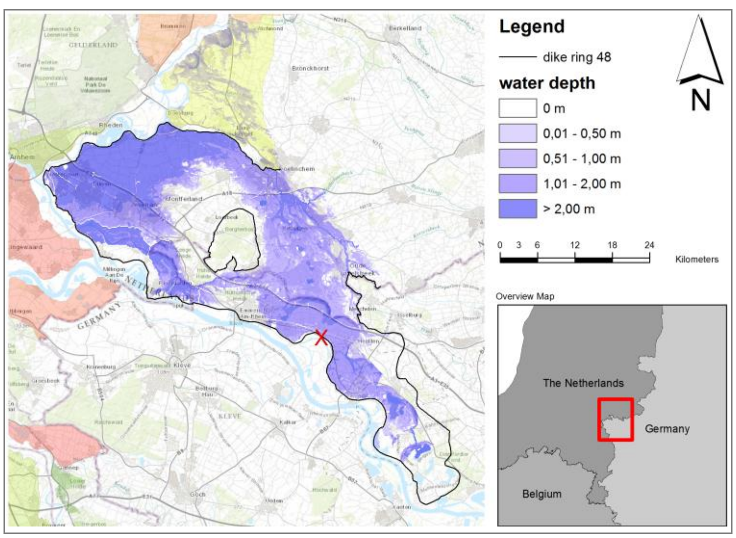

Figure 3. Possible flooding of dike ring 48 in case of a dike breach near the Dutch-German border, based on data from the water boards and ArcGIS (background map)

Within the storyline, possible cascading effects due to potential flood events for power grids, telecommunications and drinking water infrastructure, logistics and transport are analyzed. It is assumed that preparations are taken for large-scale evacuations.

The high water situation will further progress through the Rhine from Dutch-German border. The storyline indicates five possible ‘first’ events that could trigger cascading effects to other CI networks:

- Day 1: A small dike breach in Germany will cause problems around the city of Emmerich, leading to an increased alertness of the emergency authorities.
- Day 2: Caused by the saturation of a combined embankment (rail, road), a landslide will damage electricity cables and drinking water pipelines.
- Day 3: An incident around one of a traffic tunnel causes the disruption of both road and train connections between The Netherlands and Germany.
- Day 4: A dike breach near Rees will cause major floods in dike ring 48.
- Day 5: One of the main bridges downstream the River Rhine is considered to be instable and is therefore forced to shut down. This will lead to complicated evacuation and rescue operations.

As a first step of the what-if analysis based on the storyline, available information on CI in the study area has been collected. The focus has been set on spatial information (GIS data) and detailed information about the CI networks in the study area.

A quick scan of the GIS data has shown that such a flood event and related “first” events as described in the storyline could have major impact in CI. Beside the interruption of nearly all major roads and railways, the flood would also significantly affect the power network (cf. Figure 4) as eight power distribution stations in the flooded area are located in the flood extent. Their cut-off would not only mean the loss of energy distribution services within the dike ring, but potentially also outside the flooded area. Thus, in the subsequent analysis of CIPRNet a detailed analysis and modeling of CI networks has to be carried out.

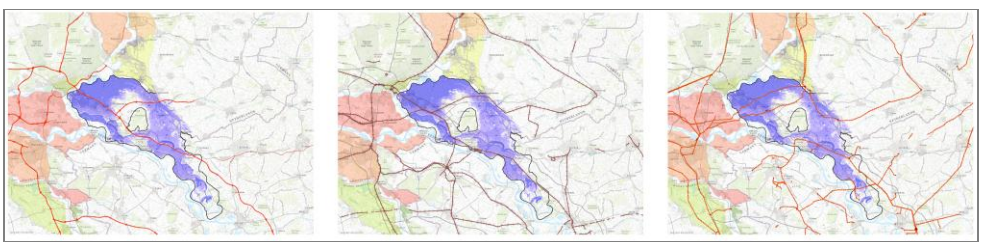

Figure 4. Identified CI networks to be affected in the storyline flood scenario: international highways (left), railway network (center) and power network (right), based on data from the water boards, OpenStreetMap and ArcGIS (background map)

Possible Implementation of the DSS

In the cross-boundary flood scenario, the DSS external sources of data (B1) may be represented by the water level sensor monitoring network maintained by a Dutch Water Boards and the meteorological forecast data. If possible, these data will be stored within the CIPRNet database to build historical data series that can be used to perform post events analysis and to develop realistic scenario for what-if analysis. The DSS RAL workflow may operate in different states:

1. Cold phase or normal condition (in the next future no CI failures are predicted).
2. Alert state (in the next future CI failures are predicted with high confidence level and the impacts and consequences are not negligible).
3. Hot phase (the DSS workflow is activated in order to evaluate the impacts and consequences of CI failures).

In the following a possible scenario is described to better understand the DSS sequence of operations and actions that can be performed in the cross-boundary flooding scenario for different operational states:

Cold phase (2 days before the event): As no CI failure has been predicted, the DSS executes the normal workflow: B1a) get meteorological data at a prefixed schedule time and extrapolate rain precipitation forecast data B1b) get pluviometric sensor data and, B1c) get dike water levels; B2a) get forecast data, B2b) run landslide forecast models and B2c) run other natural hazards forecast models. The output of B2, for each CI components of the area considered by the DSS, is represented by the so called Threat Strength Matrix where the rows refer to the type of threat's manifestation. The columns will indicate the severity of the threats. For each threat, its severity or intensity will be expressed using a grade scale [1-5]. After the computation of the Threat Strength matrix, the DSS proceeds with B3a. The vulnerability data are stored within the CIPRNet DB as a Vulnerability Matrix whose entries will be related to the maximum extent (strength) the element can stand without being structurally (and thus functionally) perturbed. Using the Threat Strength Matrix and the Vulnerability Matrix data, the DSS is able to compute the predicted Initial Physical Harms Scenario.

Alert state (1 day before the event): The output of B3 indicates that there are different CI components that will be affected by a natural event (i.e. a flooding event). In this case, the RAL workflow proceeds with steps B4 and B5 to communicate to the decision makers the expected CI damage scenario and its impacts and consequences. If the confidence level of the prediction is high and the impacts and consequences are significant, the DSS RAL workflow will enter in an alert state. Then, the RAL workflow may be triggered on an hourly basis, while the DSS will try to acquire detailed data as much as possible during B1 (e.g. radar now-casting data and satellite data acquisition) in order to increase the accuracy of the prediction.

Hot phase: The DSS Risk Assessment Loop may be triggered also on demand during an emergency hot phase. For instance, on day 2 the DSS operators may start the Risk Assessment Loop in order to evaluate the impacts and the consequences of one or more CI component reduction or loss of QoS. The DSS will give as output to the emergency decision maker visual and textual information in order to support the planning of risk mitigation strategies.

SUMMARY AND DISCUSSION

This paper highlights the importance of a DSS for large-scale flood events. Hereby, the cross-boundary represents a first step towards a decision support system for consequence analysis of flooding on CI.

CI plays an essential role for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people. It has been shown that natural threats such as large-scale floods may have significant impact on CI either directly or by means of cascading effects. However, due to the high complexity of and interdependencies between different CI domains, the effects of natural threats on CI are not yet well known. Previous events have shown that responsible authorities have difficulties with respect to the preparedness and understanding as well as response in case of CI failure.

Thus, the main objective of the CIPRNet DSS is to analyze possible critical scenarios from the prediction of the initial events to the assessment of the impacts on CI networks and related consequences or substantial reduction of the services of CI components impacted by a threat.

As a first step, a storyline scenario has been worked out for the Dutch-German border area. Within the storyline, possible cascading effects due to potential flood events on different CI networks have been described. On this basis, a what-if analysis will be carried out to analyze possible cascading effects due to selected "first" events. The what-if functionality will be used further used for the training of decision makers.

In a later phase, a DSS will be implemented to support decision makers in case of natural threats. The DSS will be fed with data coming from external sources and CIPRNet data. The most important outputs of the DSS are structured reports containing risk assessment information and consequence analysis results.

It is expected that CIPRNet will significantly contribute to the preparedness and understanding of emergency responders of the need to protect critical infrastructure. On a long term, the CIPRNet initiative will build a substantial and tangible basis towards the long-lasting European Infrastructures Simulation and Analysis Centre (EISAC).

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