RESEARCH ARTICLE

Spatial risk assessment for critical network infrastructure using sensitivity analysis

Michael Möderl (✉), Wolfgang Rauch

Institute of Infrastructure, University of Innsbruck, Technikerstr. 13, Innsbruck 6020, Austria

Abstract The presented spatial risk assessment method allows for managing critical network infrastructure in urban areas under abnormal and future conditions caused e.g., by terrorist attacks, infrastructure deterioration or climate change. For the spatial risk assessment, vulnerability maps for critical network infrastructure are merged with hazard maps for an interfering process. Vulnerability maps are generated using a spatial sensitivity analysis of network transport models to evaluate performance decrease under investigated thread scenarios. Thereby parameters are varied according to the specific impact of a particular threat scenario. Hazard maps are generated with a geographical information system using raster data of the same threat scenario derived from structured interviews and cluster analysis of events in the past. The application of the spatial risk assessment is exemplified by means of a case study for a water supply system, but the principal concept is applicable likewise to other critical network infrastructure. The aim of the approach is to help decision makers in choosing zones for preventive measures.

Keywords critical infrastructure, hazard, vulnerability, risk

1 Introduction

The protection of critical network infrastructure (CNI) is crucial, not only from the point of view of maintaining the daily needs of the public, but also for social stability and national security, because several scenarios threaten the infrastructure. Terrorist attacks may damage single components, hacking into control system or contaminate potable water. Interruptions of the service are the

consequence (e.g. water Gleick, 2006). Pipe bursts caused by deterioration results in performance deficits and generate financial penalties (Jayaram and Srinivasan, 2008). Excavators potentially damage underground infrastructure during road reconstructions. If climate change results in an increase of rainfall intensities, urban flooding also increases. Further, land use change can potentially lead to significant variation in demand of water and energy. The infrastructure and its management have to be prepared for such abnormal and future scenarios. This is a matter of risk assessment. The presented spatial risk assessment method serves for managing CNI such as pipeline, transportation, communication and energy transmission systems in urban areas under abnormal and future conditions.

1.1 Defining risk

Generally, risk is defined as product of consequence and probability. In this paper a different definition is used. Here, the risk of a system is assessed based on the information on vulnerability and potential hazards, respectively. The novelty of the spatial risk assessment method is the merging of vulnerability maps for CNI, calculated based on network transport models (in our case hydraulic simulations) and hazard maps of inferring processes based on Geographical Information System (GIS) analysis following the definition of risk published by the United Nations (UN DHA, 1992, Fig. 1). Using the presented method, the vulnerabilities of infrastructure are identified and (if necessary) eliminated by increasing the redundancy of the infrastructure. Further, hazard zones can be located to construct protection measures at proper sites. The presented spatial risk assessment is only tested on a water supply system, but is applicable to all other CNI. The case study focuses on a frequently realized hazard in China, namely flooding, but it is able to take into account any other possible hazard.
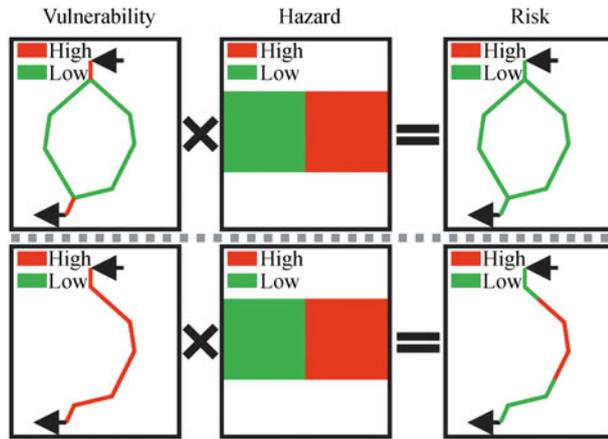
Fig. 1 Definition of terms for spatial risk assessment

1.2 Potential hazard zones

Hazard zones for e.g. avalanches (Gruber and Bartelt, 2007), earthquakes (Liu et al., 2010), landslides (Mansouri Daneshvar and Bagherzadeh, 2011) and land use changes (Chen et al., 2009) express the probability of hazards being realized. The frequency of interfering processes in China depends on regional and seasonal variation. In China 5 major threats, namely, flood, drought, earthquake, typhoon and landslide, account for 80%–90% of the total losses (Qu et al., 2007). Influences of typhoon activities on droughts and flood are analyzed (e.g. Zhang et al., 2011a), but also hazard due to debris flow (Zhang et al., 2011b) is investigated in literature. The hazard of land use change occurs not that spontaneous (Jiang et al., 2011), but is of interested taking into account future threat scenarios. If components of a CNI are located in hazardous zones, the probability of a system failure caused by an interfering process is high. However, hazard maps evaluate only the potential occurrence of an interfering process, but neither the probability of a subsequent component failure nor the consequences for CNI. To understand the true relevance of a threat scenario, an investigation of the vulnerability of CNI is additionally necessary. For instance a land slide could damage a water supply system component, but additional information is required to assess the resulting deficits in water supply under this abnormal and future condition.

1.3 Vulnerability of CNI

For the analysis of the vulnerability of CNI taking into account threat scenarios, it is a common undertaking to map the characteristics and the individual vulnerability of the components of the CNI. However, this neglects that failures and functional changes of individual components in the system have a very distinct influence on the performance of the entire system and the failure of a component causes not automatically a relevant

performance decrease. For instance, a failure of a main combined sewer overflow facility is more harmful to the entire system than a conduit blockage located in an upper section of the sewer system. Likewise failures in high voltage power lines are more critical than in low voltage lines. The term vulnerability is used to describe this fact. Derived from Ezell (2007), where different definitions are collected, vulnerability is defined as "*the identification of weaknesses in a system, focusing on defined threats that could compromise its ability to provide a service.*"

An example for a system-wide vulnerability assessment approach is shown in Ezell (2007). Therein a value model was used to measure the vulnerability of infrastructure systems (Infrastructure Vulnerability Assessment Model, I-VAM), but no network transport model was applied to assess vulnerability. Available vulnerability assessment tools used in the water security sector (e.g. RAMCAP (Risk Analysis and Management for Critical Asset Protection), RAM-W (Risk Assessment Methodology for Water) and VSAT (Vulnerability Self Assessment Tool) for more details see Brashear and Stenzler (2007)) aid in describing critical facilities and assets to protect by identifying system vulnerabilities and determining the level of protection to which the security system should be designed. None of these tools utilize network transport simulations. In Nilsson et al. (2005) intrusions into water supply systems are simulated. In Vreeburg et al. (1994) a quantitative method to determine the reliability of water distribution systems is introduced. Similarly to Mark et al. (1998) the assessment is based on hydraulic simulations. These papers apply the approach of transport vulnerability, but do not exploit the results spatially by using GIS. In Khanal et al. (2006) the influence of contamination events on water distribution system performance is investigated. Therein a vulnerability map was constructed by super-imposing the set of population exposure values onto their respective nodes. Following the principal idea of Khanal et al. (2006) the aim of the presented method is to improve the risk assessment procedure by generating vulnerability maps using network transport models and spatial sensitivity analysis. For instance an analysis of avalanche, debris flow and land slide hazard for water and waste water infrastructure is presented in (Möderl and Pauch., 2011).

2 Materials and methods

First, the spatial risk assessment method is described. Second, an example for a hazard assessment is shown. Last, performance indicators for CNI are defined as the basis for the vulnerability assessment using a spatial sensitivity analysis.

2.1 Spatial risk assessment

According to UN DHA (1992) risk is a merger of hazard

and vulnerability. Not only a risk map, but also a risk matrix can be generated. Here, the values in the matrix are the number of cells (125 m×125 m resolution) of related hazard and vulnerability groups.

2.2 Hazard assessment

Hazard zones can be assessed quantitatively based on existing data or using hazard models and if not available based on a GIS analysis. For the latter different geo-data sets can be used, such as a digital elevation model and land-use data. For qualitative assessment, experts can be interviewed about occurrence of hazards taking also into account the location. It is suggested to categorize hazards according to the probability of being realized in the subsets low, moderate and high.

As an example for a hazard analysis, the impact of flooding is described, which is a relevant threat scenario in China, but the method is applicable to all other potential hazards. Flood zones can be assessed with one-dimensional (e.g. HEC-RAS), two-dimensional and three-dimensional (OpenFOAM) hydraulic models. It is also possible to use orthophotos or expert knowledge of flood events in the past. Further a terrain analysis can highlight exposed areas. Here, a study to determine the potential flood zones in Austria (Merz et al. 2008) is used. In this study automatic methods, manual assessments as well as various sources of information including flood peak samples, rainfall data, runoff coefficients and historical flood data are combined to provide flood zones with a return period of 30, 100 and 200 years.

2.3 Vulnerability assessment

In the presented method the vulnerability of CNI is assessed taking into account transport deficits under abnormal and future condition. Economical consequences like cost for repair and compensation are not considered. The transport performance of a CNI is calculated using performance indicators (PI). Such PI can be used to evaluate the vulnerability by applying it under abnormal and future conditions according to threat scenarios. It is suggested that PIs are defined so that high values indicate low vulnerability or in other words a redundant system. In addition, the used network transport model should be able to simulate the relevant values, which are required for the calculation of the PI.

In the following, a specific PI for water supply is used, that was introduced by Möderl et al. (2007), but can easily be replaced for other studies. This PI (%) refers to water supply pressure calculated with Epanet2 (Rossman, 2000). The system is assumed to operate sufficiently as long as the pressure is within a predefined range. The actual pressure requirements are defined by setting a lower (p_l) and an upper (p_u) limit. Thus, the PI is defined with the following equation as the sum of the delivered demand at each junction (j) with accurate pressures $Q_{del}(p)$ divided by the sum of water required (Q_{req}) at each node:

$$\mathrm{PI} = \frac{\sum_{j=1}^{J} Q_{\mathrm{del},j}(p)}{\sum_{j=1}^{J} Q_{\mathrm{req},j}} \times 100\%, \quad Q_{\mathrm{del}}(p): p \in (p_l, p_u). \quad (1)$$

In this way, further PIs can be defined similarly for water supply and other CNI. The change in the transport performance of e.g. an urban drainage system can be assessed by PIs for surcharging and flooding (Möderl et al., 2009) using SWMM (Rossman, 2004).

Hazards have the potential to damage pumps, break pipes, contaminate potable water and block transport links among other system changes. In terms of simulation, the impact of such interfering processes is assessed by a spatial sensitivity analysis. Thereby, a parameter of each component is varied according to the impact of a threat scenario. After that, the performance of the entire system is evaluated and a PI is spatially joined to the location of the related component. These sensitivity maps are regarded as vulnerability maps as the parameters are varied according to a specific threat scenario. For instance, blockage is modeled by setting the transport capacity of each spatially distributed component to zero.

2.4 Case study

The application of the spatial risk assessment in the field of water supply is described by means of five water distribution systems which are located close to each other in the Tyrolean Alps, Austria. The total population supplied amounts to 21200. Each water distribution system is an independent network. A more detailed description of the study area is given in Vanham et al. (2008).

Data of infrastructure assets and water resources are collected. The demand is computed as annual average by a principal residence raster with a resolution of 150 m ×150 m based on a census of population. In the region tourism is by far the largest industry. Thus, water demand of tourism is considered as equivalent of overnight stays. No daily demand pattern was applied. The tanks are modeled as fixed pressure points, but the method can also be applied to a network model including tanks with dynamic water level simulation. The processes of model construction and calibration are not in the focus of this paper, but have received sufficient attention in order to ensure the quality of the result. Table 1 outlines characteristics of the water distribution systems.

3   Results and discussion

Results are structured into three sections. First, a hazard map for flooding is analyzed. Second, a vulnerability map

Table 1 Network characteristics of water distribution systems

Municipal	Reservoirs	Tanks	Junctions	Pumps	Pipes	Components
Oberndorf	4	0	144	3	157	308
St. Johann	2	2	253	1	281	539
Jochberg	1	3	84	1	93	182
Kitzbühel	6	3	132	6	156	303
Aurach	3	2	100	1	102	208
Total	16	10	713	12	789	1540

for a water supply system is discussed. Last, the spatial risk assessment is presented.

3.1 Hazard map

Flood zones impact CNI by potentially generating short circuits in power supply. Such power supply interruptions can subsequently lead to cascading effects e.g. disabling booster stations and other power supplied facilities. For the case of water supply, flood zones impact the system, when the pressure outside is higher than inside of a component. This situation can occur at water intakes (e.g. springs, wells) and tanks, but also at leaky pipes under pressure deficit conditions (e.g. caused by fire fighting). Figure 2 shows flood hazard zones. The zones are grouped in low, moderate and high hazard according to the return period (200, 100 and 30 years, respectively). In the background, the river network and the digital terrain model is mapped for better understanding of the flood processes. It is obviously that the probability of flood zone is high close to rivers and in depression areas. Several zones in the municipality in the north, namely St. Johann, are hazardous. Dykes can be constructed to protect CNI.

3.2 Vulnerability map

The innovative feature of the presented spatial risk assessment method is the spatial information on the vulnerability of components evaluated based on spatial sensitivity analysis and GIS. As vulnerability is expressed in terms of PI values, desired service levels for vulnerability groups have to be chosen. Green colors constitute low vulnerability (high performance under critical conditions) while red colors indicate high vulnerability (low performance under critical conditions).

Three of the water distribution systems (Fig. 3) reveal for most of the components low vulnerability. Two of the systems are moderately vulnerable. The calculation of the PI, using spatial sensitivity analysis, constitutes that 50% of the components exhibit values for PI that are higher than 97%. Vulnerable components in the systems are: 1) two wells in the valley floor and 2) two springs on the hillside including the corresponding main trunks. In addition, 3) two pipes that connect separated supply zones are highly
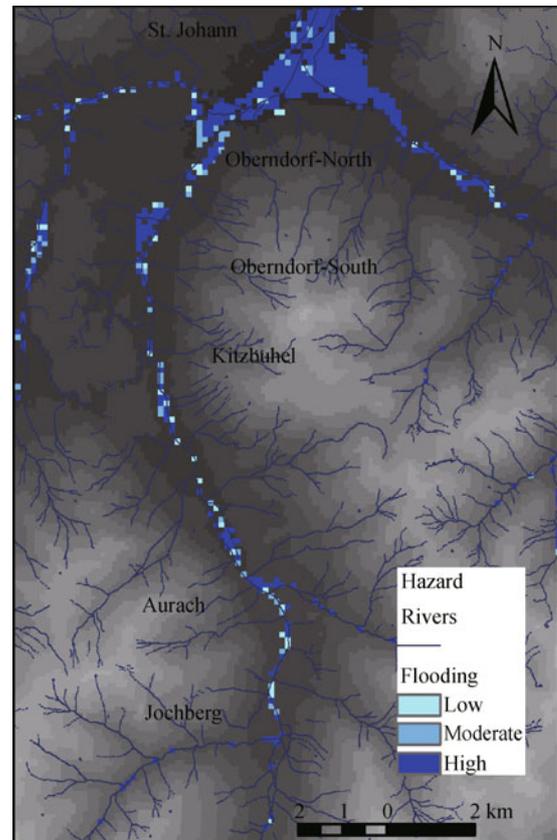
Fig. 2 Hazard map for flooding

vulnerable. These components are indicated with orange and red colors. A failure of these components would leave a significant part of the consumers without water. To improve the supply security these components should be constructed redundantly.

3.3 Risk map

In Fig. 4 the risk map for the five water distribution systems is shown. Along the main river a few narrow risk zones occur. A large zone in St. Johann is at low risk, because of large hazard zones. Moreover, the ground water well of St. Johann is at high risk. In Oberndorf-South a further zone is risky. This site is highlighted in Fig. 5 and
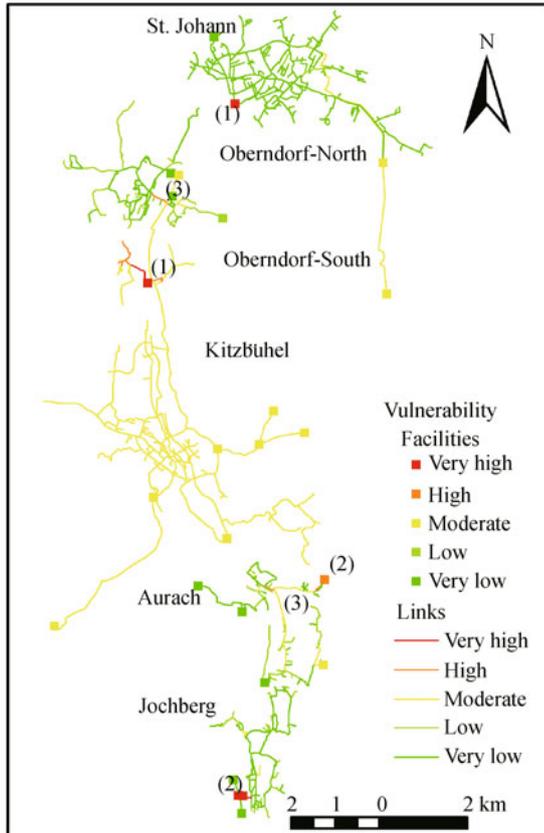
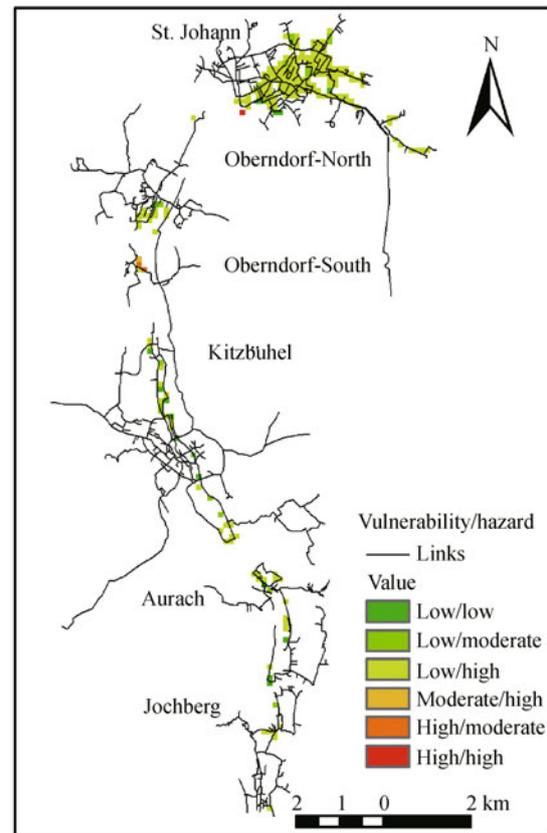**Fig. 3**   Vulnerability map for a water supply system

Fig. 4   Risk map for flooding and a water supply system

analyzed in detail in the following. Figure 5 shows hazard zones and the vulnerability maps separately. Because the system is only supplied by one ground water well, indicated with 1), this well and the pipes connected to the well are highly vulnerable. These pipes cross the river and a high hazard zone along the river. There are only pipes and no facilities in the zone. As long as these pipes do not leak, flooding cannot impact the system. Thus, as preventive measure, it is suggested to inspect these pipes more often.

In Table 2, the numbers of cells with corresponding hazard and vulnerability groups for flooding hazard and for all five water distribution systems are listed. In the majority of cases the raster cells are rated as low vulnerable. Based on the matrix, only 4 cells (9 ha) out of total of 1368 cells (approximately 3000 ha) are categorized as zones with moderate and high vulnerability or hazard (marked gray in Table 2). These risk zones, are recommended for an in-depth analysis and if required for preventive measures as discussed above. A risk assessment for other CNI can be worked out in a similar manner.

4   Conclusions

For the analysis of the vulnerability of CNI taking into

account threat scenarios, it is a common undertaking to map the characteristics and the individual vulnerability of the components of the CNI. However, this neglects that failures and functional changes of individual components in the system have a very distinct influence on the performance of the entire system. In this paper a method is presented where the effect of functional changes of a component are computed by means of a network transport models and expressed in terms of PI values. When this is done for each individual component of the entire system using spatial sensitivity analysis, spatial information on the vulnerability of the CNI is generated.

A water supply system including five water distribution systems is chosen to test the spatial risk assessment method and to evaluate the public drinking water supply security. Zones with high risk are identified, on a regional basis by merging a vulnerability map for a water supply system and a hazard map for flooding. The method is tested in the field of water supply, but can be easily used for other types of CNI. It was demonstrated that the spatial information of the vulnerability offers significant information on critical sites and indicates also how the risk can be reduced. For example vulnerabilities occur if different demand areas (e.g. separated by a river) are not properly connected. By strengthening these connections, the vulnerability can be eliminated. In addition, flooding hazard zones are located.
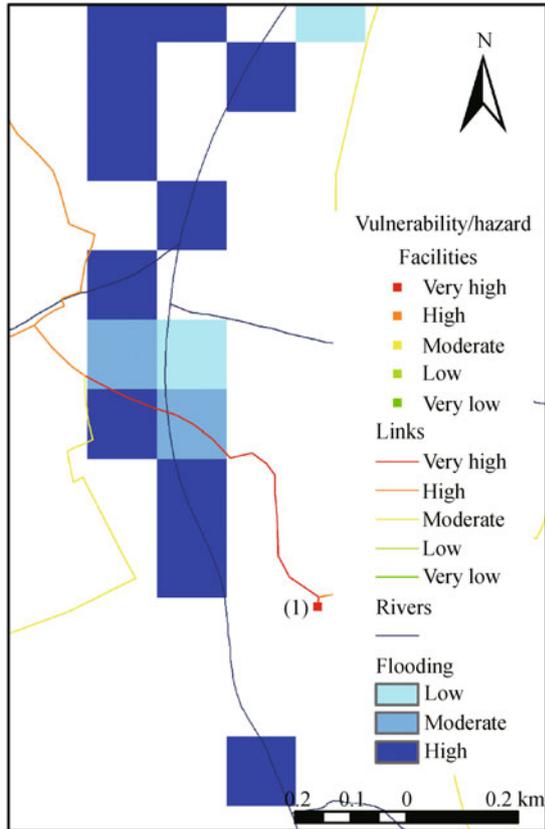
Fig. 5 Detail map of a risky site

Table 2 Risk matrix for flooding and a water supply system (elements indicate number of cells with corresponding hazard and vulnerability group)

Risk matrix	Low hazard	Moderate hazard	High hazard	Sum
Low vulnerability	16	17	183	216
Moderate vulnerability	0	0	1	1
High vulnerability	0	2	1	3
Sum	16	19	185	220

By constructing protection measures, the probability of the hazard being realized can be reduced. Thus, risk can be managed. The application of the spatial risk assessment method is seen as a valuable tool for directors of utilities to improve the security of their CNI, because it aids to choose sites of the CNI for implementing preventive measures. Further, system vulnerability can be considered in maintenance and rehabilitation planning.

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