Towards Cartographic Support for Risk Assessments of Civil Infrastructures

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Abstract. The impact of natural hazards on civil infrastructure systems can cause hardly predictable negative consequences for the society. To better understand these consequences, experts conduct complex risk assessments that incorporate a multitude of different models from several scientific disciplines and which result in vast amounts of heterogeneous datasets. Visualization methods from cartography and related disciplines can help to make sense of these results and can therefore facilitate finding and implementing suitable treatment strategies. In this paper, three cartographic concepts that may be beneficial for understanding these outcomes are described. First, the application of cartographic principles to adequately convey the effects on the modeled systems and consequences, second the use of navigation concepts that allow to explore the different possible outcomes in an efficient manner and third the use of comparative visualization methods in order to understand the change in the systems behavior for different model inputs. These approaches are illustrated by applying them to risk assessment data for the region of Chur, Switzerland.

Keywords: Risk Assessment, Natural Hazards, Civil Infrastructure

1. Introduction

Recent developments in civil engineering aim at incorporating dynamic models into risk assessment processes in order to simulate the consequences that arise from the impact of natural hazards on infrastructures. The results of these assessments help infrastructure managers to reduce risk by helping them determine and implement suitable treatment strategies.

In this paper, the risk assessment methodology described in Hackl et al. (2015) is used to demonstrate the potential of several cartographic techniques that may help in the decision-making processes based on such risk assessments. This methodology is based on ISO 31000 and was applied to a case study for the region of Chur, Switzerland. Although the data resulting from this process are used to illustrate the proposed cartographic methods, it is assumed that they can be applied to similar risk assessment methodologies as well.

The methodology recommends to computationally simulate the behaviour of four interrelated systems in order to perform the risk assessment: A natural system that may initiate a specific natural hazard, the hazard system itself, the infrastructure system (consisting of infrastructure elements as well as the networks they are part of) that is affected by the hazard, and the society, which relies on the infrastructure system. After performing the simulation, the results are analysed in order to quantify the consequences for the society associated with the simulated event.

For the case study, the four systems are 1) a precipitation-runoff system to simulate rainfall patterns and to compute associated discharge values, 2) a hydrogeomorphology system simulating a flood and potentially triggered landslides, 3) an infrastructure system that simulates the behaviour of infrastructure elements as well as the road network when affected by hazards, and 4) the society that uses the infrastructure network to reach important locations such as hospitals.

Cartographic visualization allows to comprehend how the effect of a certain natural event propagates through these systems and in which way it influences the final outcome of the risk assessment. Not only allow maps to understand risk on the level of spatially distributed elements or in spatially aggregated form but also to detect spatial clusters and patterns that may be important for decision-makers to implement location-dependent intervention measures.

The types of data produced during these assessments are described in *Section 2* along with possible visualization techniques. *Section 3* describes that novel navigation methods are needed to efficiently explore the data originating from such processes, whereas the use of comparative visualization methods can prove useful in order to understand different system states. *Section 4* gives a conclusion.

2. Cartographic Visualizations of Risk Assessment Data

In order to efficiently interpret risk assessment data, their specific characteristics need to be taken into account in order to create appropriate cartographic visualizations. In particular, three distinct types of data can be identified: Simulation data, aggregation data and auxiliary data. Cartographic considerations on these data types are given in the following subsections.

2.1. Simulation Data

Simulation data are generated as a result of the simulation of several interacting systems and therefore represent system states for particular points in time and visualizing these data can particularly help in answering questions such as: “What leads to which consequences related to a certain hazard for a given area?” Examples for datasets produced during such simulations are given in *Table 1*. Here, “system name” represents the system they belong to in respect to the Chur case study, “associated dataset” is the name of the actual dataset, “spatial data type” represents the actual GIS format and “time dependency” gives information on which properties of the dataset may change for each time step. In addition to the listed data, data that are not produced during a simulation may play a role as input datasets, such as digital elevation models for the precipitation-runoff and the hydrogeomorphology system.

However, creating appropriate maps for these data bears several challenges. First, the vast number of datasets cannot be displayed within one map representation alone so that splitting them up according to the systems they belong to is a straightforward consideration (see *Figure 1*). In addition, depending on the concrete system state to be visualized, other datasets may need to be removed from the map or changed to a more restrained representation. For example, concerning the infrastructure system, element state as well as the network topology may be of interest. However, the former is only conceivable at a large scale, while the latter is only sufficiently comprehensible on a smaller scale and when buildings are removed to avoid visual clutter. In addition, it may be useful to include elements of other systems as well, such as the flood extent in the infrastructure system since this directly allows to understand how water depths at infrastructure element locations induces damage and costs.

System Name	Associated Dataset	Spatial Data Type	Time-Dependency
Precipitation-Run-off	Precipitation	Raster	Cell Value
	Discharge	Vector	Attribute Value
Hydrogeomor-phology	Water Depth	Raster	Cell Value
	Velocity	Raster	Cell Value
	Shear Stress	Raster	Cell Value
	Debris Flow	Vector	Geometry
Infrastructure	Element Damage	Vector	Attribute Value
	Element Cost	Vector	Attribute Value
	Road Network Topology	Vector	Geometry
Society	Hospital Catchment Areas	Vector	Geometry

Table 1. Examples of data produced during the Chur risk assessment.

Second, the temporal nature of these datasets needs to be taken into account. Preferably, animated maps that include interactivity along with information visualization techniques would be highly beneficial. However, most mapping software packages are limited in this respect since even the rendering of one time step may take several seconds and prevents the user from any interaction. A mapping library that allows high-performance rendering while preserving cartographic quality and interaction would therefore be highly useful.

Third, probabilistic models are increasingly used in such processes. Rather than a single deterministic result, these produce outcomes with associated uncertainties. For example, a bridge affected by a flood may have a probability of 50% to be slightly damaged, 30% to be moderately damaged or 20% to be extensively damaged. Such information needs to be represented in an appropriate way by making use of uncertainty visualization concepts.

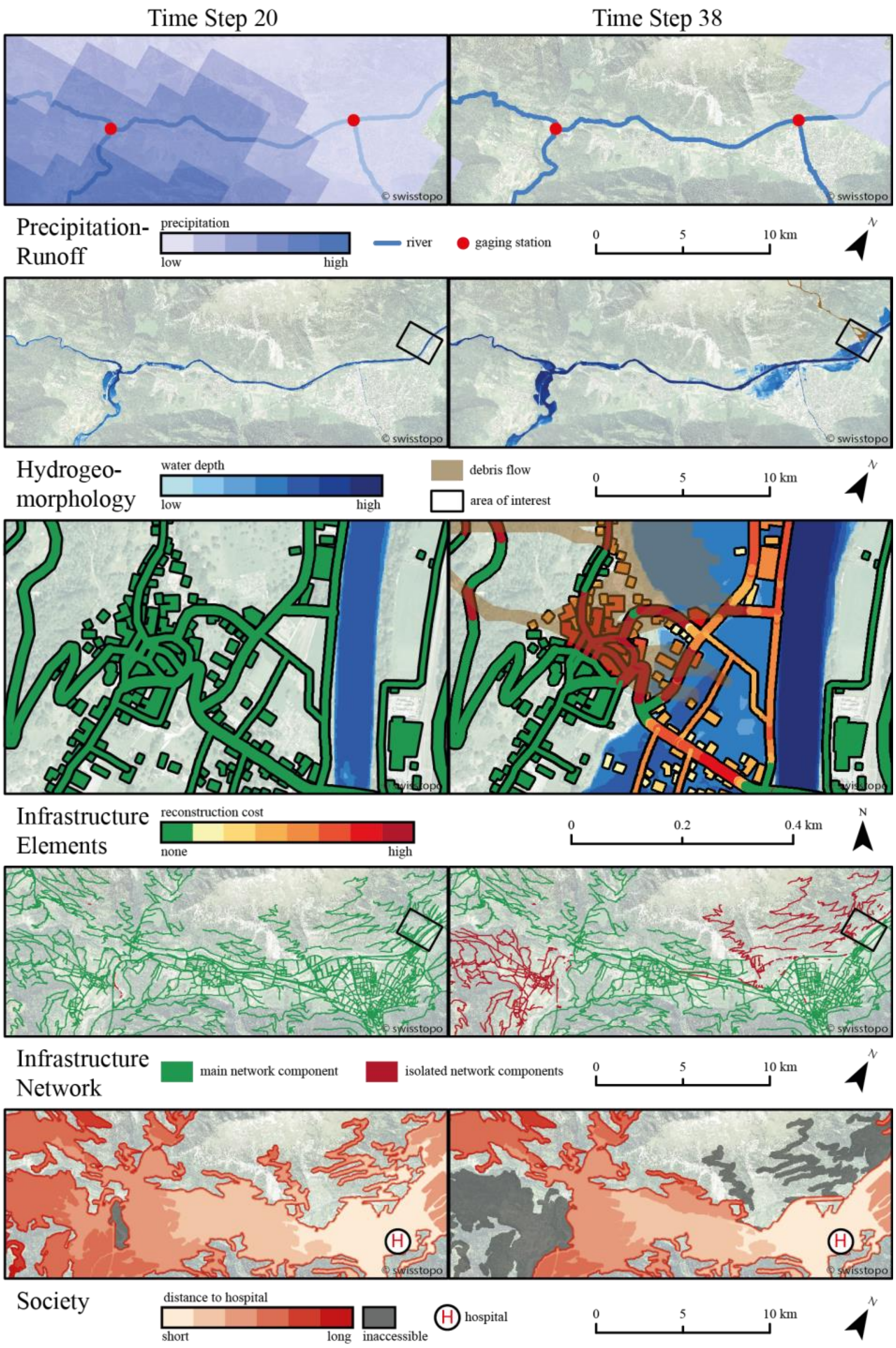

Figure 1. The states of the considered spatio-temporal systems for two time steps. The data were produced during a simulation run for a 500 year flood scenario (adapted from Hackl et al. 2015).

2.2. Aggregation Data

While simulation data alone can give information on the behavior of systems during certain scenarios, typically more condensed risk indicators are needed. These are produced by aggregating simulation data in order to give answers to questions such as “How high are the consequences associated for a certain natural hazard event?” and “How high are the risks in respect to a certain natural hazard?”. The following paragraphs describe different types of aggregation steps and the measures they produce.

Temporal aggregation: Temporal aggregation considers all datasets relevant for a certain consequence of interest of a particular scenario or set of scenarios and combines them to a single consequence measure. For example, one aggregation step could involve integrating the computed detour-related vehicle costs over all time steps to gain the overall detour-costs. Another example would be finding the maximum water depth at a buildings location to compute the corresponding damage and reconstruction cost following the event.

Spatial aggregation: Consequences are typically associated with a certain feature such as reconstruction costs for buildings or detour costs for a properly delineated road network. However, often it is necessary to estimate these measures for a greater region, which makes it necessary to accumulate these consequences spatially. For example, it would be of interest how high the overall reconstruction cost for buildings for the entire city of Chur are.

Scenario aggregation: In order to compute an actual risk measure, such as expected annual losses, aggregation of the consequences of several scenarios with different return periods needs to be performed. For example, *Equation 1* can be used for this purpose (Deckers et al., 2010).

Equation 1:

$$R_a = \sum_{i=1}^{n} \frac{1}{i} (C_i - C_{i-1})$$

In this equation, R_a is the averaged annualized risk and C the consequences related to a scenario with a return period of i years. This way, a risk measure considering the estimated reconstruction costs related to several scenarios, such as a 100 year flood, a 300 year flood and a

500 year flood can be combined to compute expected annual reconstruction costs. Examples for risk maps on different aggregation levels are shown in *Figure 2*.

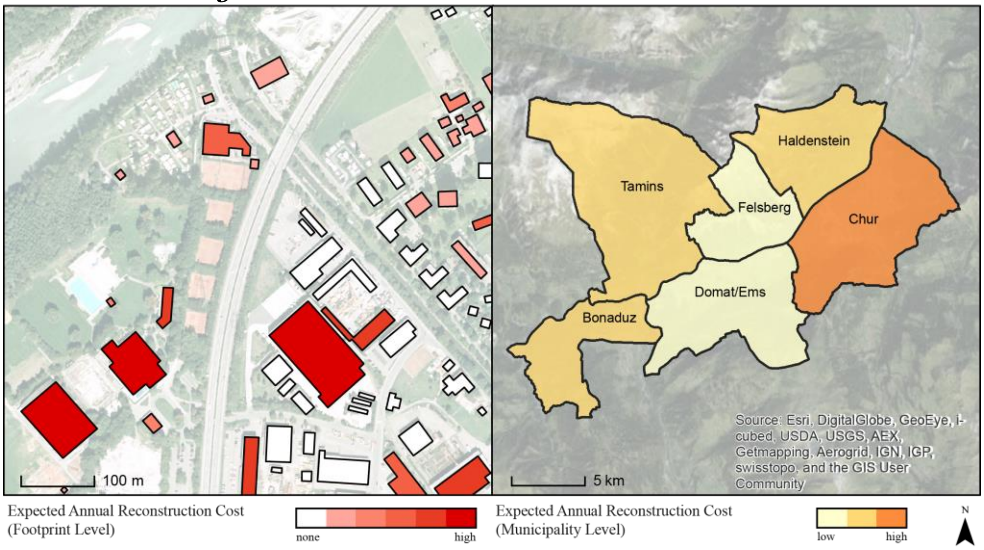

Figure 2. Risk encoded in color on the footprint level of buildings (left) and aggregated on the municipality level (right).

2.3. Auxiliary Data

Auxiliary data is independent of the actual risk assessment process and should be integrated in risk-related cartographic representations for orientation purposes. This should be done with care in order to avoid distraction from the more important simulation or aggregation data of interest.

3. Cartographic Navigation and Comparative Visualization Techniques

In order to understand the behaviour of the infrastructure system and the relationship between the subsystems, for example to retrace the chain of events that lead to specific consequences, cartographic navigation techniques need to be provided. These should allow to select the scenario, system and time step of interest or the corresponding aggregation results of a complex risk assessment.

In addition, interventions, such as placing mobile barriers during a flood event to protect important buildings, may cause a change in the course of a simulation run. In other words, there would be alternative developments of the systems included in the scenario from the point in time on this change was introduced (Waser et al. 2010). Such alternative timelines yield additional challenges for navigation. Inspiration of how to address this task can be gained from related disciplines, such as visual analytics where domain-specific simulation environments are provided. Examples are tools that allow to influence the simulation of epidemic outbreaks (Afzal et al. 2011), the behaviour of power grids due to loading events (Mittelstädt et al. 2013), or the simulation of single flood scenarios (Waser et al. 2010 & Konev et al. 2014). We adapted these techniques to represent the states of multiple systems (see *Figure 3*). Here, the evolution of each system is represented by a sequence of coloured rectangles. At time step eight, two different precipitation datasets are introduced for the precipitation-runoff system, each leading to a flood corresponding to the minimum and maximum boundaries of the 95% confidence interval for the expected maximum discharge value of a 300 year flood. Sample maps for the highlighted time step of interest are depicted in *Figure 4*.

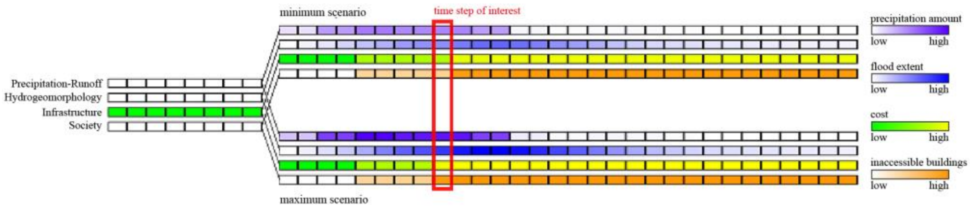

Figure 3: Visualization method representing the states of multiple systems and allowing to navigate through different simulation branches.

Closely related to the need to integrate different simulation inputs is the ability to understand which changes in the system state these induce. This is particularly important in risk assessments where the consequences related to a certain natural hazard scenario need to be analysed. Two cases where comparison is considered particularly useful are described below.

Comparison of Intervention Abilities: An important aspect in risk management is the implementation of strategies to reduce negative consequences related to natural hazards. The selection of the interventions to be included in strategies to reduce risks can involve modifications to infrastructure networks (e.g. increasing the robustness of a bridge or adding more scour protection). An estimation of the benefits of including such an intervention, therefore, requires a comparison of the performance of the network with and without the intervention.

Comparison of Natural Hazard Scenarios: Allowing to compare different natural hazard scenarios helps to understand which consequences a specific scenario causes in respect to those of comparable ones. This case is shown in *Figure 4*. By using the inter-scenario navigation technique, it is possible to select the time step of interest and display maps that depict the different states of the system either by providing multiple aligned maps (*Figure 4* left, middle) or by computing the difference of these realizations (*Figure 4* right).

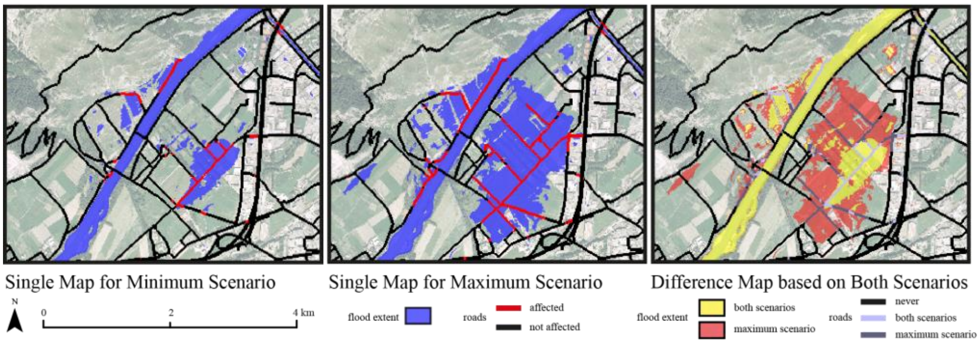

Figure 4: Possibilities to depict change for multiple scenarios using multiple aligned maps (left, middle) as well as difference maps (right).

However, with the number of scenarios to be compared is rising, the computation of such differences for the resulting large amount of possible combinations is a considerable challenge, because of the high demand in respect to computational power and storage capabilities. Therefore, techniques need to be developed that allow the generation of such maps in an efficient way.

4. Conclusion

Risk assessments to analyze the risks that arise from failing infrastructure due to natural hazards are complex tasks that produce huge amounts of heterogeneous datasets. These datasets need to be visualized efficiently so that decision-makers can easily use them to implement suitable strategies for risk reduction. For this purpose, visualization experts need to develop appropriate cartographic representations to depict system states as well as provide efficient comparison techniques, such as difference maps. These can aid in better understanding the changes in consequences of comparable hazards on the infrastructure and the society or in assessing the ability of interventions in reducing risks. Finally, techniques for the navigation through multiple simulation branches need to be provided. Addressing these issues may significantly increase the ability of cartographic techniques in helping decision-makers in understanding geospatial systems and ultimately reducing risks related to natural hazards.

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