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An Overarching Risk Assessment Process to Evaluate the Risks Associated with Infrastructure Networks due to Natural Hazards

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Abstract: In Europe, extreme natural hazard events are not frequent but due to the complex interdependency of the infrastructure systems these events can have a devastating impact in any part of Europe. Protection against the impacts of natural hazards must be guaranteed for people to work and live in a secure and resilient environment. People who manage infrastructure have to handle these risks. The proposed overarching risk assessment process is constructed in a way so that computational support can be constructed in modules. Therefore, each module interacts with other modules by receiving and delivering information. The content of the modules depends on the established context of the risk assessment process. The use of the overarching risk assessment process is demonstrated by using it to evaluate infrastructure related risk due to natural hazards for an example region in Switzerland.

Keywords: *Infrastructure, natural hazard, risk assessment,*

1. Introduction

Infrastructure networks are the backbone of modern society. If they do not work as intended, which can happen due to natural hazards, there is a high probability that there will be significant consequences [1]. This can be predominantly attributed to system effects both during the event and following the event, and depends greatly on how all of the objects within the affected infrastructure networks behave, and how fast and how they will be restored so that they once again provide an adequate level of service. People who manage infrastructure, herein referred to as infrastructure managers, have to handle these risks. Each infrastructure manager relies on his own risk management processes. These processes are systematic, timely and structured processes that when followed will provide the infrastructure manager with a better understanding of what may go wrong with the system in which the infrastructure is embedded, the probability of this happening and the associated consequences. This risk assessment process is particularly challenging for managers of infrastructure networks, due to the large number of scenarios that need to be analyzed in order to assess the risks appropriately, the spatial and temporal correlations between these events [2], and the correlation between event occurrences, or so called cascading events [3].

In addition to the challenges in the physical world, the process is made even more complex because the risk assessment process requires that persons work together from many different disciplines who each have their own discipline based approaches to risk assessment that are not always harmonious with those in other disciplines. This makes it so that independent risk assessments from different persons are not always easy to aggregate to a level that is useful for the infrastructure manager.

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The overarching process presented in this paper is meant to be helpful to infrastructure managers who want to assess the infrastructure related risks due to natural hazards. It is to be used to help bring together people from many different disciplines so that they can provide information in a way that will be useful to an infrastructure manager. It has been specifically developed to deal with road and rail infrastructure networks but it is believed to be generally applicable to all types of infrastructure networks. The proposed overarching process is meant to fit within the risk management process of any infrastructure owner. This process is developed so that it can be coupled with detailed sub-processes to achieve varying levels of detail in risk assessment. This flexibility ensures that the overarching process is applicable for different types of infrastructure, different types of hazards, different levels of detail in the assessment, different sizes of regions, different types of regions and different levels of abstraction. It is also developed to ensure that the temporal and spatial correlation of events can be considered. More detailed information can be found in the report Adey *et al*.[4] which was submitted as a deliverable in the INFRARISK project. The work builds on that done for the Swiss Federal Roads Authority in 2005 [5,6].

2. Overarching Risk Assessment Process

The overarching risk assessment process is based on the ISO 31000 [7], including different principle activities: communicating and consulting, establishing the context, and identifying, analyzing, evaluating, treating, monitoring and reviewing risk. Beside the basic concepts of the ISO 31000, the proposed framework has been extended to allow explicit consideration of the spatial and temporal correlation between hazards as well as the modelling of the functional interdependencies between multiple objects in the infrastructure networks, including physical dependencies, cybernetic dependencies, geographical dependencies and the modelling of impacts. The process is described using generic definitions of sources, hazards, objects of the network and the network itself, which eases the application to different decision-making situations.

It is constructed keeping in mind that for many decision-making situations it will be desired to have the process be computer supported, for example to model specific parts of the system. It has also been constructed keeping in mind that different decision situations will require the use of different types of models and models that will provide different levels of detail.

In the following, a brief overview of the different subprocesses of the overarching risk assessment is given.

2.1 Problem Identification

The first step is to identify the question to be answered. This step includes the generation of preliminary thoughts on the area to be investigated. It is only once this question is identified that a meaningful risk assessment can be conducted. It will affect the system definition, the requirements of the assessment in terms of both input, *e.g.*, man-power, and output, *e.g.*, the accuracy of the results or the number and types of scenarios to be investigated. It will also affect the scope of the assessment and the level of detail.

2.2 System Definition

The system representation is a model of the relevant part of reality used for the evaluation and consists of all relevant realizations of stochastic processes within the investigated time period. It includes sufficiently good representations of the hazards, infrastructure, and consequences, as well as the interaction between them so that it can be reasonably certain that there is an appropriate understanding of the system and that the risks and the effectiveness of the strategies can be determined.

The system to be modelled includes all things required to assess risk, including the natural environment, *e.g.,* amount of rain, amount of water in rivers, the physical infrastructure, *e.g.,* the behaviour of a bridge when subjected to high water levels, and human behaviour, *e.g.,* traffic patterns when a road bridge is no longer functioning. As it is necessary to model the system over time, it is necessary to also model the spatial and temporal correlation between events and activities within the investigated time period. This includes the consideration of assumptions, agreements as to how the system will react in specific situations, and drawing fixed system boundaries where it is clear that the things outside the considered system are not being modelled. It also includes the consideration of cascading events.

2.2.1 Boundaries

By establishing spatial boundaries, the part of the natural and man-made environment to be specifically modeled is determined. In addition to the definition of the geographical space, this includes specification of where the objects are located, where the events and hazards can occur and where the consequences could take place. It is usually easy to specify the possible locations of the events, hazards and objects. It is more difficult to, however, determine how they are related, *e.g.,* heavy rain causes a flood hazard. This becomes even more difficult when the location of possible consequences is to be specified. Consequences can be far away from the location of the events, hazards, and infrastructure, and may be outside the direct area of responsibility of the infrastructure manager (*e.g.,* the collapse of a highway bridge on a trans-European highway network can have consequences on the free flow of goods in many countries).

By establishing temporal boundaries, the time period over which risk is to be assessed is fixed, as well as how this time period is to be subdivided for analysis purposes. With respect to time, the system representation can be made either: static or dynamic. In the case of a dynamic representation, the model evolves over time whereas in the case of a static representation time is not explicitly modelled.

2.2.2 Elements

It is proposed to group the system elements from initiating events to the events that are considered to be quantifiable and no further analysis is required. It is considered that the element types can be further grouped as either elements to which no value can be directly assigned or elements to which a value can be assigned. In the assessment of risk related to infrastructure due to natural hazards, one can label these further as “hazard elements” and “consequence elements”. Although the number of element types to be considered vary depending on the type of problem and the desired level of detail.

Each element type is considered to correspond with events, which can be considered to have a probability of occurrence. Five basic element types, or event types, that should be regularly considered are:

Source events, or initiating events, are events, which occur regularly (rainfall, tectonic plates movements, ground movement *etc.*). The occurrence of such an event does not necessarily mean that a hazard will be triggered.

Hazard events, or loading events, are events related to any earlier event or that may lead to consequences. A hazard always has a source event. It may also trigger another one (*e.g.,* earthquake triggers landslide). Most hazards evolve through space and time and interact with their environment. The time frame can vary from a few seconds (*e.g.,* earthquake) to over a few days (*e.g.*, flood) to several months (*e.g.*, drought). The area that is affected can range from very local, to global. In defining the hazards to be considered it is important to define the intensities of the hazards to be considered. This should include consideration of the return period of the hazards to be used, *e.g.*, 1/500 year flood or earthquake, and the loads to which the infrastructure will be subjected, *e.g.*, the amount of water in the river during a flood, the magnitude of ground motions during an earthquake, the amount of displaced soil during a landslide.

Infrastructure events include all the objects and the condition states of these objects to be considered, *e.g.*, a bridge collapse is an infrastructure event. How the infrastructure networks to be modelled are subdivided into infrastructure objects depends on the specific problem and the level of detail desired in the risk assessment. For example, a 10 km road link may be modelled as one element, although it consists of 3 bridges, 4 road sections and a tunnel, or it may be subdivided to explicitly consist of all eight of these objects. If more detail is required then each object could be subdivided. For example, one of the bridges could be seen as being composed of columns, bearings, decks, *etc.* In the development of the system representation it is important to consider which infrastructure objects are affected by which hazard and how the states of these objects may change over time. This is a difficult task as in many cases many objects could be affected but the effect might range from very small, *e.g.*, yielding of a reinforcement bar in a bridge during an earthquake, to very large, *e.g.*, collapse of the bridge. An example of a value that could be assigned to this element type may be the cost of reconstruction of the infrastructure object if damaged. This value depends on the level of damage that might happen and how the infrastructure manager plans to intervene on the object if it is damaged. Sometimes these are referred to as direct consequences, although this terminology is not used consistently. For more in-depth analysis, one might decide to not assign values directly to infrastructure elements and to model the human activities involved in restoring the infrastructure, which would allow a substantially higher level of detail in terms of the costs related to multiple objects in a network being affected simultaneously.

Network use events include the states of use of the infrastructure network that might occur. For example, due to a tunnel collapse the freight corridor between Rotterdam and Genoa is closed and no vehicles can travel on it. The probabilities of these events occurring are particularly difficult to estimate as their occurrence depends on spatial and temporal correlation, and physical relationships between initiating events, hazards and infrastructure events. The latter can lead to cascading events. An example of a value that can be assigned to this element type is the cost of deviating traffic around a closed road. For more in-depth analysis, one might decide to not assign values directly to network elements and to model the human activities involved in redirecting traffic, which would allow a substantially higher level of detail. Another example is the value of lost travel time due to the closed link. Of course the value assigned is highly dependent on the flow of traffic if the road is closed which in turn depends on the decisions of many persons in society.

Societal events include the actions of persons or groups of persons. For example, due the freight corridor between Rotterdam and Genoa being closed 50% of goods is put onto trucks, 40% of goods is diverted over other train routes and 10% is not delivered. In order to model the actions of persons or groups of persons it is often beneficial to group them into categories based on their general behavior, which in turn is coupled with how their behavior is to be modelled. Societal events may lead to other societal events. If they, however, do not then a value needs to be assigned to the event. This value then enters the risk assessment as a consequence.

As the events form the initiating event to the event upon which a value is placed forms a causal chain it is convenient to think of them in the form of an event tree, where each chain of events is represented by a path in the event tree. To build the tree it is necessary to determine the intensity measures to be used to define the events to be investigated, *e.g.*, the water height above which a flood event is considered to have occurred. At each branch in the event tree a decision is required to determine the value of the intensity measures, which allow classification of the event. The number of intensity measures used to describe the events depends on the problem being investigated and the level of detail required in the analysis. A very simple example is given in Figure 1.

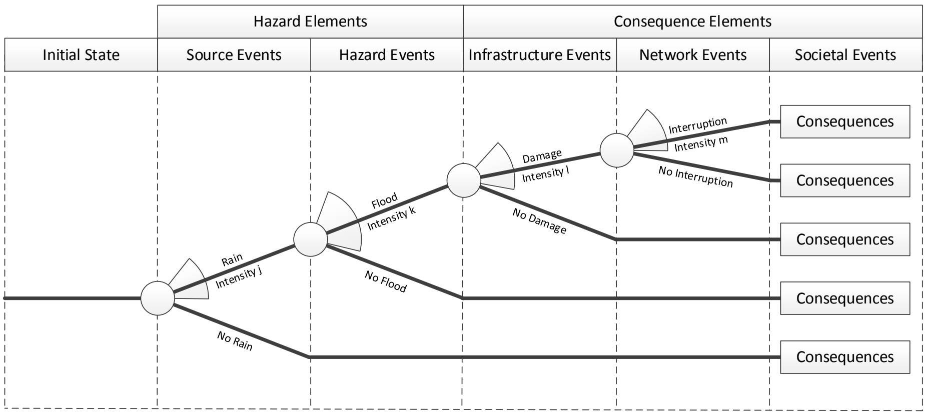

Figure 1: Example of a Simple Event Tree for the Risk Assessment of Infrastructure Networks

As can be seen from this simple example, there are an infinite number of ways to represent reality. Due to this, particular care needs to be used in the development of an appropriate system representation. The necessary detail to be used depends on the specific problem and the level of detail desired. If events at any level or complete ranges of the values of intensity measures are excluded, it should be explicitly explained and documented why, because in the following risk assessment, the risk coming from those hazards cannot be taken into account.

2.2.3 Relationships

In order to estimate the likelihood of each subsequent event in the causal chain of events appropriate models of the relationship between them are to be developed. For example, in order to determine the amount of water coming in contact with a bridge during a flood, it is necessary to model how the water which falls as rain reaches the river, taking into consideration, for example, the amount of water that seeps into the ground or evaporates, or is held in temporary retention ponds.

The amount of effort to be invested in this depends on the exact problem and the level of detail desired. For example, in some cases it may be sufficient to use one dimensional vulnerability curves based on expert opinion to estimate the amount of damage that a single building might incur during an earthquake. In other cases, it may be desirable to use multidimensional vulnerability curves based on detailed finite element models to estimate the amount of damage a large dam might incur during an earthquake. In general, extra effort should be spent to achieve more detail when it is suspected that the results will add additional clarity for decision-making. If additional clarity is not provided the extra effort is not worth it.

Although specific examples are given here, the general thoughts apply to all system elements, *i.e.,* initiating events, hazard events, infrastructure events, network events and societal events. If possible the availability of data to be used to model the relationships should be taken into consideration in determining the level of detail to be used.

2.3 Risk Identification

In the previous step emphasis is made on identifying the correct system elements to be used in the risk assessment and how to model the relationships between these. In its most extensive form the definition of these elements and relationships will provide all possible scenarios, or risks. As it is unrealistic to attempt to quantify all of these it is necessary to identify the specific scenarios that are to be part of the risk assessment. Each branch in Figure 1 is a scenario which has an associated risk.

The identification of the scenarios should be done in this step without an explicit estimation of their probability of occurrence or putting a value on the consequences. The starting point for the development of this set of scenarios is all combinations of the system elements in the system representation. It is useful in the identification of scenarios to first determine for who the risk assessment is to be done, and then to:

- start with the initiating events and think through how the infrastructure will be affected and then how humans will react to this,
- to start with the consequences and think through how the infrastructure would have to behave to something to cause these consequences, and
- to start with infrastructure behaviour and think in the other two directions.

Comprehensive identification of relevant scenarios is critical, because scenarios excluded in this step will not be included in further analysis and may result in an underestimation of risk. To minimize the possibility of this happening it is important that experts in each area are involved.

2.4 Risk Analysis

The analysis of risk has to do with estimating the probability of occurrence of the scenarios and the value of the consequences of the scenario if it occurs. It is only through doing this that an infrastructure manager can decide if action needs to be taken and if multiple options are available, which one is the best. It can be done using a qualitative or a quantitative approach. In both cases, however, the goal is to gain a better understanding of the probability of occurrence of a scenario and the consequence of that scenario.

Risk analysis, as with risk identification, can be undertaken with varying degrees of detail, depending on the specific problem, the information, data and resources available. Analysis can be qualitative, semi-quantitative or quantitative, or a combination of these, depending on the circumstances. The certainty with which both the probabilities of occurrence of each of the scenarios and the consequences can be estimated, as well as the sensitivity of these values to the modelling assumptions, need to be given appropriate consideration in interpreting the results. Indicators of the sensitivity of these values are the divergence of opinion among experts, the availability of information, the quality of information, the level of knowledge of the persons conducting the risk analysis, and the limitation of the models used.

2.5 Risk Evaluation

Risk evaluation has to do with verifying the meaning of the estimated risk to persons that may be affected, *i.e.,* stakeholders. This is true regardless if a qualitative or a quantitative approach is used. A large part of this evaluation is the consideration of how people perceive risks and the consideration of this over- or under-valuation with respect to the analyst's point of view used in the risk analysis step of the risk assessment. Through the risk evaluation there is the possibility to bring into the risk assessment aspects that have not been explicitly modelled in the risk analysis step. The risk evaluation steps help to bring decision makers closer to finding a solution that is more acceptable to all stakeholders.

One possible result of this step is that the risk analysis needs to be redone with more detailed system representations, improved models and different values. Another possible result is that it is decided that the risks are acceptable and no exploration of possible interventions are required [7].

3. Modules

The proposed risk assessment process is constructed in a way so that computational support can be constructed in modules. Providing a platform in which the necessary modules can be integrated does this. A module is a self-contained set of (computational) instructions with unambiguously defined input and output interfaces. Inputs are either provided via external input (*e.g.*, user input) or via internal input (*i.e.*, by using outputs of other modules generating compatible datasets). Therefore, each module interacts with other modules by receiving and delivering information. The type of information to be exchanged between modules is to be constant. Modules can perform a function itself or can be composed of sub-modules that each performs functions. The modular construction was chosen to allow continual updating of models as new information becomes available or better or detailed models are developed. The content of the modules depends on the established context of the risk management process. Thereby, modules can be described in terms of the functions they perform (*e.g.*, a specific quantitative model) and the data they exchange.

In order to provide an efficient and accurate risk analysis the structure of the models and the framework in which they are embedded have to be adapted for their specific needs. For example, a damage calculation module that evaluates damage curves for streets based on inundation values may only take one inundation file for execution. Therefore, this module needs to be executed for each time step separately. Other modules may in contrast need a time series as input and therefore only need to be executed once. Relationships between modules are defined through the order of execution (module 2 can only be executed after the data of module 1 is present) as well as the data to be exchanged. For example, a damage calculation module needs inundation depths stored in a file of type "GeoTIFF". This "GeoTIFF" is provided by a flood calculation module which produces this kind of data.

Additionally, there might be implicit assumptions for certain datasets. For example, when analyzing geodata, typically it is adopted that the datasets use the same Coordinate Reference System and lie within a similar extent. Infrastructure managers do not necessarily create modules themselves since it can be assumed that certain tasks, existing tools can be reused and assembled. Also, one module may be reused within several configurations.

The different modules need different information for the risk assessment. The type of input and output of each module has to be specified. In some cases this is done through the problem identification and the system definition steps of the process.

An information exchange structure has to be constructed together with the experts, stakeholders and infrastructure managers. For instance, for each module things such as the area of application, the type of model, or the kind of intensity measurement, have to be specified. Data compatibility between modules is ensured through the concepts of syntactic and semantic interoperability. According to IEEE [8], interoperability is defined as "the ability of two or more systems or components to exchange data and use information". In the context of the overarching methodology, these systems or components are represented in the form of modules.

Once, the modules and data are assembled appropriately, the infrastructure manager may perform simulations based on this framework. Running a simulation when specific external inputs are provided does this. These inputs may be defined by the infrastructure manager or potentially automatically when performing multiple runs (*e.g.,* by sampling a certain distribution using the Monte Carlo Method).

4. Example

In this section, the use of the overarching risk assessment process is demonstrated by using it to evaluate infrastructure related risk due to natural hazards for an example region. For the sake of simplicity, the example is presented in a sequential manner, although the process itself is highly iterative. The results of this example should be treated with care since only very simple physical models are used to evaluate the risk.

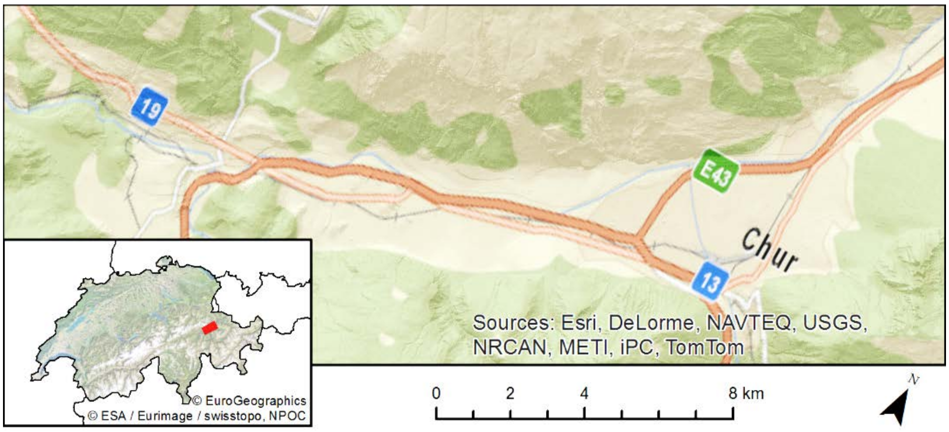

Figure 2: Overview of the Area of Interest.

4.1 Problem Identification

The target area is located around the city of Chur, the local capital of the easternmost Canton of Switzerland, Graubünden. The region is home to companies of different sectors such as finance, engineering and chemistry (*e.g.,* EMS-Chemie AG, Hamilton AG) and its road network is part of one of two major transports links for goods from Italy to Northern Switzerland. Also, the main station of Chur is an important railway junction to other regions of Graubünden. Most of these objects are located in a valley between several mountains (*e.g.,* Calanda, Montalin) with many watercourses draining into the main river Rhine.

The addressee of this risk assessment is the city administration (city planners) being interested in damage, cost and other consequences resulting from a low probability/high impact natural hazard scenario in the Chur region consisting of a coupled flood and landslide event.

4.2 System Definition

4.2.1 Boundaries

The spatial boundary of the system has been selected to be that shown in Figure 2. The system is spatially bordered by a bounding polygon which is aligned to the main valley of the region of interest and covers an area of approximately 150 km^2 in the Swiss coordinate reference system CH1903/LV03. Since the focus lies on the main watercourses, only those watercourses are taken into account. If a more detailed study is attempted, it is suggested that a thorough examination is undertaken to identify watercourses relevant for the target area.

The risk assessment is done for a flood hazard with a return period of 500 years. The occurrence of this hazard takes 3 days, *i.e.,* water rises slowly and inundated the surrounding areas, and finally the flood water goes down. In order to model the temporal evolvement of the flood hazard, the period of 3 days is subdivided into 72 time steps of one hour. To compare the risk with other cities and regions, the losses resulting from this analysis are converted into an average annualized loss.

4.2.2 Elements

Source event precipitation: The model of precipitation was constructed using the precipitation data from a historical event which occurred from 07.08.2007 to 09.08.2007 and is scaled in such a way that it corresponds to a precipitation event resulting in a flood with a return period of 500 years.

Hazard event flood: The model of the amount of water on each land surface area and in the rivers was developed using a set of interrelated tools. These are the Hydrological Modelling System (HMS) and the River Analysis System (RAS), both being maintained by the Hydrologic Engineering Center (HEC), as well as their interface applications GeoHMS and GeoRAS for the Geographic Information System ArcGIS.

Hazard event landslide: In this scenario, the increase in soil saturation due to precipitation triggers one of the pre-modelled debris flows from the SilvaProtect project [9] affecting the small town of Haldenstein. These potential debris flows are modelled using the software packages MGSIM and dfwalk.

Infrastructure event residential and industrial buildings: Information on buildings on the footprint level are taken from the swissBUILDINGS3D dataset (swisstopo). The buildings are represented by polygons and are additionally enriched with information on their type of use (*e.g.,* residential, industrial, agriculture).

Infrastructure event hospitals: In the area of interest, only one institution is present for ambulant care, the hospital of the Canton of Graubünden. This hospital consists of three separate buildings of which each is converted to point geometry to be used as a source for network analyses.

Infrastructure event road segments: Since road geometries for the target area can have lengths up to several hundred metres, these are partitioned in such a way that a spatial analysis can be undertaken on a feasible resolution. For this application, a segmentation interval of 4m was considered to give a reasonable trade-off between computational effort and accuracy. For reasons of performance, the segmentation process was limited to those regions which are affected by a hazard at any time step during the scenario. For flooding, it was considered that all roads affected by the flooding during the scenario can be selected by intersecting them with the flood plain with the greatest extent. A similar approach can be followed to consider the landslide geometry

Network events: The road network for the target area is extracted from the VECTOR25 dataset. Each road is represented by a linear geometry with assigned attributes on their type (swisstopo). Roads of subordinated types (agricultural, forest or bicycle way) are removed, because they are considered to be unsuitable for most motorized vehicles.

Societal events: Societal events are how the traffic behaves on the network when it is not fully operational. It is estimated using traffic simulations to estimate how much additional time is required to travel from anywhere in the hospital catchment area to the hospital.

4.2.3 Relationships

The interactions between infrastructure networks, elements and components of elements at the one hand side and between hazards, infrastructure and consequences on the other side, should be represented completely. This is necessary to determine dependencies in failure scenarios and evaluate common influencing factors.

Source-Hazard-Interaction: For reasons of simplicity and efficiency only a simple hydrological model for the runoff calculation is used. In the simple model, the precipitation can fall on the watershed's vegetation, land surface, and water bodies (streams and lakes). The runoff volume is computed by the volume of water that is intercepted, infiltrated, stored, evaporated, or transpired and subtracting it from the precipitation. Interception and surface storage are intended to represent the surface storage of water by trees or grass, local depressions in the ground surface, *etc*. Infiltration represents the movement of water to areas beneath the land surface. The ModClark model [10] is used to estimate the discharge during the precipitation event. This model accounts for retention by using a Linear Reservoir Model (LRM) and translation by taking account a grid-based travel-time model.

Hazard-Infrastructure-Interaction: To estimate damage resulting from inundation, simple damage curves are used. These take into account the inundation depth d, in the range of 0 to 5 m, associated with the infrastructure object and return a dimensionless damage factor $\alpha \in [0,1]$ where 0 represents no damage and 1 represents complete failure. The damage functions associated with the different categories are listed in Deckers, *et al*. [11]. For infrastructure affected by the landslide the damage is assumed to be 1 for both, roads and buildings independent of their type.

Infrastructure-Society-Interaction: It is assumed that if infrastructure is damaged that it would be restored to the condition it had prior to being damaged. These costs are estimated by multiplying the area of the affected object with the unit cost of constructing the object from scratch. For buildings, the area is directly derived from the geometry of the polygon. For roads, the area is calculated by multiplying the length of the linestring with the width associated with the corresponding road type. The unit values used are taken from Kutschera [12].

Infrastructure-Network-Interaction: Since this connectivity changes during the scenario due to node failure, for each time step a distinct network needs to be created. Impassable road segments due to natural hazards are excluded from the network, *e.g.,* by deleting segments with assigned inundation depths ≥ 0.3 m.

Network-Society-Interaction: The quantification of consequences related to travelling across the network resulting from the failure of infrastructure network nodes was undertaken in terms of the following non-exhaustive list of examples: travel time costs (*e.g.,* man hours of work time lost), vehicle operating costs (*e.g.,* increase of fuel needed), accident costs (*e.g.,* number and type of injuries/deaths), environmental costs (amount of additional nose/pollution) [13]. These predominately depend on the amount of additional travel time that will be incurred on the network when the network is in less than a fully operational state. In this example, this additional time was estimated by determining the shortest paths to be used when the network was in a failed state. For road networks, this measure typically is represented by the length of a road segment (shortest path) or, if additional information such as speed limits are available, by the time needed to pass a segment (fastest path). While this approach assumes an idealized behaviour of a virtual car driver, it should be sufficient to coarsely estimate the true route through the target area. After their computation, the shortest path lengths were decomposed by road class. Not only the total length of the shortest path is increasing with more and more streets becoming inaccessible, but also that the driver needs to use alternative roads of lower capacity.

4.3 Risk Identification

The target area has been historically prone to the mentioned natural hazards flooding and landslides. Information on past events are stored in the database "Unwetterschadens-Datenbank" [14] for the period ranging from 1975 to 2007. The database holds 43 natural hazard events located within the region of interest, including inundation, mudflow and mass movement events. In addition, two more recent projects, AquaProtect and SilvaProtect [9] provide model based information on regions vulnerable to floods and landslides.

Based on the problem identification, the risk assessment was conducted on a medium scale area where buildings are taken into account on the footprint level and streets are represented by connected linear geometries.

For the sake of simplicity, only one scenario is considered. This scenario is comprised of the following events: Source event is rainfall, the hazard events are a flood, defined as being more severe as the largest volume of water expected in the main river expected in 500 years, and a landslide. The infrastructure events are derived from the buildings, road sections and hospitals being in specified damage states. The network events are derived from the different combinations of damage states of the different infrastructure objects. The societal events are derived from modelling the traffic flow results from the different network condition states.

4.4 Risk Analysis

For the risk analysis of the considered scenario a quantitative approach is used. This approach is based on historical information, expert knowledge as well as physical and mathematical models. Most of the analysis is performed within a GIS framework. For example, the identification of buildings and roads at risk is undertaken using standard GIS functionality by spatially relating the geometries of the hazards to those of buildings and roads. Depending on the characteristics of the objects in question different approaches are used. For the infrastructure network analyses based on graph theory is performed, *e.g.*, to estimate the increased travel time required to reach the Chur hospital when the infrastructure network is not fully operational.

In order to aggregate risk that has been estimated based on the specific scenario, it is necessary to ensure that they are directly comparable and that they are not double counted. There is an especially high chance of this happening when cascading events are part of the scenarios.

The value associated directly to the condition of the infrastructure objects, *i.e.*, the infrastructure events assuming that the objects will be restored to a like new condition at a later point in time, are added. It is assumed that the maximum damage predicted throughout the three-day period is the amount of damage that needs to be repaired. No consideration was made as to how the repair work would be executed or whether or not there would be reduction in costs because multiple objects would be repaired at the same time. It is considered that the costs required to restore the objects from damaged condition states to fully operational due to either floods and landslides are additive. Based on the cost associated with the single objects for each time step, the development of the total losses for the whole region of interest can be calculated.

The costs related to the disruption of traffic on the road network are estimated by counting the number of additional hours of travel time that is required on the network while the network is not fully operational. These costs are added for each time step in the three-day period. In this case study it is assumed that all road sections are restored to normal immediately following the three-day period. For those that could not travel no extra costs where estimated as it was assumed that they could postpone their trips. The estimation would be significantly more complicated if these assumptions are not made and instead the time until actual repair of the infrastructure is estimated and the travel on the network is modelled for this entire duration, as well as the effects of not being able to travel.

Figure 3 exemplarily illustrates the results of this process. Here, for each event a pair of maps illustrates one stage of the overarching process in top-to-bottom order. To illustrate the change of the system, the left maps represent the state of the system for time step 20 and the right maps for time step 38. The simplified legends should suffice to conceive the relevant information.

The *source* maps show heavy rainfall over the region of interest, which decreases towards the end of the simulation period. The *hazard* maps show the maximum inundation depths of the resulting flood for each surface area until the respective time step. It becomes apparent that the maximum inundation depths increase with time, which therefore leads to increasing damages of affected infrastructure objects such as buildings and street segments. This causes rising reconstruction costs, which is shown in the *element* maps for the Haldenstein region. As indicated by the red rectangle in the *hazard* maps, this region is located in the northern part of the area of interest and is affected by flood as well as by the landslide. Because of the damage induced by these hazards, the road networks functionality is reduced as shown in the *network* maps. Here, red road segments indicate that they are isolated from the green main network. Impassable road segments are not shown. This reduced network state results for some regions, in particular in the northern and south-western parts, to be cut off from important infrastructure objects. For example, it is impossible for people in these areas to get to the hospital in Chur as indicated by the *society* maps.

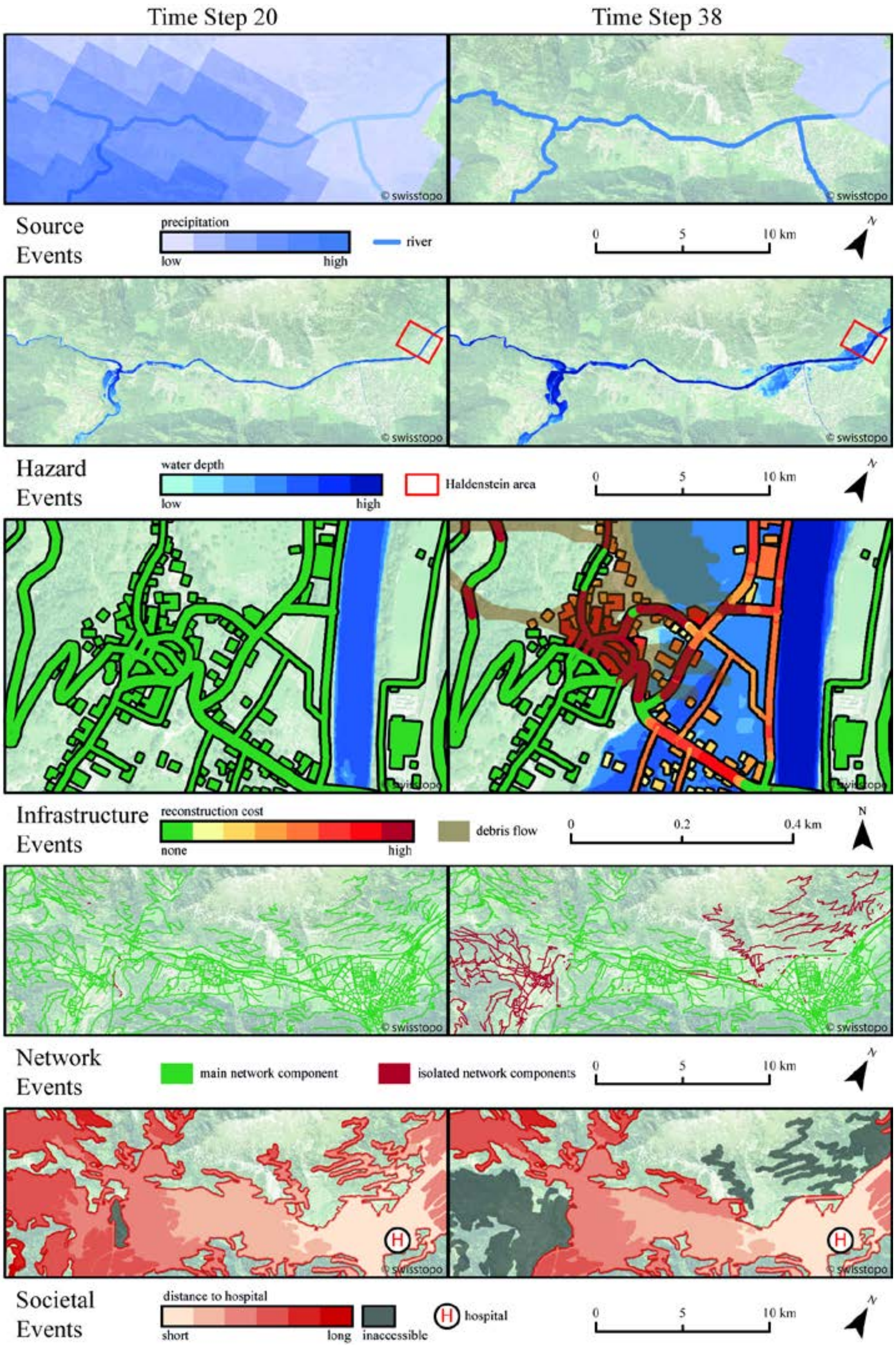

Figure 3: Example Results of the Main Processes of the Overarching Methodology for the Time Steps 20 and 38 for the Area under Investigation.

4.5 Risk Evaluation

In this paper, risk evaluation is not performed. If a complete risk management process is being conducted this work would need to be done in conjunction with the city administration of Chur. The results coming from the risk analysis would support this task in order to plan further analyses, safety measures or risk treatments.

5. Discussion

The example demonstrates that the proposed overarching risk assessment process is useful to assess infrastructure related risk due to natural hazards. Computer systems can highly accelerate its distinct steps so that the results can be delivered to infrastructure managers in a timely manner. However, in order to refine the results, the methodology needs to be applied to a greater number of scenarios.

The process can be used for a wide range of different problems at different levels of detail. In addition, the changes over time and interactions between different events can be modeled as shown in the example.

Although the proposed overarching risk assessment process can be used conceptionally for all kinds of different problems, its usefulness depends on the quality of available models and data. Often the physical models do not take into account interaction with their environment. For example, if a bridge collapses, the cross-section of the river will be changed, too.

In the presented example a deterministic point of view was chosen. In order to take the numerous uncertainties into account a probabilistic approach seems more suitable, especially when dealing with natural hazards. If one associates a probability of occurrence with the occurrence of the particular precipitation then one could quantify the risk. A more sophisticated example will require the consideration of the not only the probability of occurrence of different rain patterns, but also given the rain fall patterns, the probability of different water run-off events, different levels of water in different parts of the rivers, different behavior of the infrastructure objects in the network, and different behavior of the vehicles on the network. It would also require consideration of larger periods of time, in which multiple rain events occur and perhaps even different types of source events that may result in consequences.

In the expansion of the example to do this there are substantial hurdles with respect to the infinite number of scenarios possible, the uncertainties associated with many different models to be used to make approximations and the temporal changes in the probabilities of event occurrences.

6. Conclusions

This paper describes a generic overarching risk assessment process as well as an example of how it can be used and how it can be implemented using a GIS framework. Even in its current form it is believed that this process would be useful to infrastructure managers in the assessment of their infrastructure related risks due to natural hazards. It is applicable for different types of infrastructure, different types of hazards and different types of consequences and can take into consideration both simple and complex system representations.

The overarching risk assessment process will be further improved by taking into account multiple scenarios, including multiple initiating events, multiple hazards, multiple infrastructure events, multiple network events and multiple societal events. It will also be expanded to deal properly with the spatial and temporal consideration in the estimation of the probability of occurrence of scenarios and the establishment of the scenarios. More work is required to emphasis the human interaction in conducting the risk assessment.

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