FP7 2013 Cooperation Work Programme
Theme 6: Environment (Including Climate Change)

Novel indicators for identifying critical *INFRA*structure at *RISK* from Natural Hazards

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Preliminary Model, Methodology and Information Exchange

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Executive Summary

This report contains the preliminary version of the proposed risk assessment process, an explanation of how it can be supported from the IT point of view and an example of how it can be used. The point of preparing this preliminary version, with all of its rough edges, is to transfer this knowledge to the participants of the INFRARISK project, in an effort to focus, or harmonise, the work of all involved.

The overarching process presented in this report 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.

In addition, it is aimed at providing information on the general tasks a decision support system should perform in order to assist the user, i.e. the infrastructure manager, during the distinct steps of the risk assessment process by taking into account the proposed methodology.

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1 INTRODUCTION

1.1 Background

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 (World Bank 2005). Normal design of infrastructure objects ensures that the infrastructure related risk due to natural hazards that can occur with a high to medium probability is relatively low. This is in a large part because system[1] effects can be ignored, i.e. there is a high level of certainty that there will not be cascading events, such as an earthquake that causes landslides or the rerouting of traffic that causes the overloading of a bridge, and that if one infrastructure object is adversely affected other infrastructure objects within the networks will provide adequate levels of service. It does not, however, ensure that the risk related to natural hazards that occur with a low to very low probability is low. Such rare events, e.g. the Italian earthquake in 2009 and the flood in Germany in 2013, can result in significant consequences. 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, must manage 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. By following such processes an infrastructure manager will be better equipped to make decisions of how to improve his infrastructure network. Risk management processes are seen as an integral part of how an infrastructure management organisation functions, and should be used to complement many other processes, including strategic planning and change management processes (ISO 31000 2009). Due to the fact that things can go wrong in many different ways, there is a vast amount of literature from all disciplines.

The overarching risk management process can be seen as described in the ISO 31000, including different principle activities; communicating and consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk. A schematic illustration based on ISO 31000 is shown in **Error! Reference source not found.**.1. Risk identification, risk analysis and risk evaluation are often seen together as the risk assessment process.

[1] The system referred to here includes all things that need to be modelled in order to evaluate risk, it includs the natural environment, infrastructure and human behaviour.

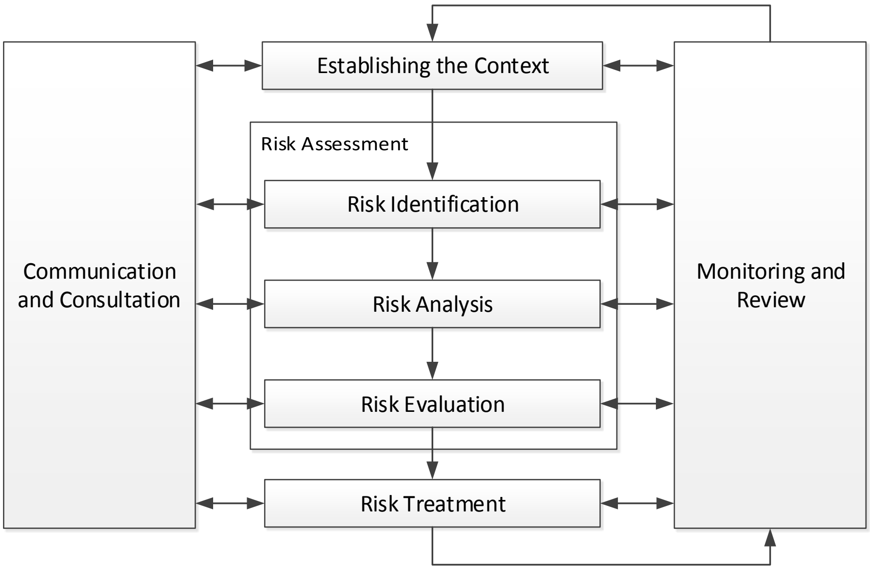


Figure 1.1 Risk Management Process (ISO 31000 2009)

The risk assessment process is particularly challenging for owners of infrastructure networks who are attempting to assess infrastructure related risk due to natural hazards, due to

- the large number of scenarios that need to be analysed in order to assess the risks appropriately, due to the large number of initiating events to be considered, (e.g. heavy rainfall, tectonic plates movements), which can result in natural hazards (e.g., floods, landslides, earthquakes), which in turn can affect the infrastructure objects and, therefore the infrastructure networks, which in turn affect how humans react to this and, therefore, consequences.
- the spatial and temporal correlations between these events, or system elements, e.g. it is highly likely that two objects near each other will experience their maximum earthquake loads simultaneously, but it is highly unlikely that two objects far apart from each other will experience their maximum earthquake loads simultaneously. The spatial and temporal extent of the hazard delimitates the exposure of a system. Depending on the regions social, economic and environmental dimensions and its capacity to react, this area will be more or less vulnerable to the hazard (MOVE 2011).
- the correlation between event occurrence, or so called cascading events. Each alone can have a significant effect on the infrastructure. They, however, can also trigger others (cascading events) (Garcia-Aristizabal and Marzocchi 2011). The consideration of single-hazards is difficult, but the consideration of multiple hazards is even more so Nadim and Liu (2013).

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.

The overarching process presented in this report 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 includes the three sub-processes risk identification, risk analysis and risk evaluation. The definitions of each of these are given in the Appendix 0.

1.2 Scope

This report presents the preliminary version of the proposed overarching process to be used to assess the infrastructure related risks due to natural hazards. It can be used independent of the considered natural hazard or region. 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.

The proposed overarching 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.

The proposed overarching process can be used by infrastructure managers to bring different disciplines together to allow for appropriate identification and assessment in a region of infrastructure related risk due to natural hazards.

The overarching process presented in this report is considered to be the preliminary version. It will be tested through its use as a procedural guide for the participants of the INFRARISK project in conducting the case studies. Upon completion of the INFRARISK project, when it is refined on a more detailed level, it will be able to be used by decision makers to assess the risk related to infrastructure caused by natural hazards in practice.

1.3 Structure of report

In Chapter 2 the proposed overarching risk assessment process is explained in the context of a larger risk management process. In Chapter 2 the required IT support to ensure the overarching risk assessment process can be conducted is explained. Chapter 2 includes an example of how the overarching process with the appropriate IT support, explained in Chapter 5, can be used to assess the infrastructure related risks due to natural hazards in a region. The conclusions and recommendations are given in Chapter 6 and the references are given in Chapter 7. The report also contains numerous appendices. These are used to lighten the text, and are referred to where appropriate in the document.

2 RISK ASSESSMENT PROCESS

The proposed risk assessment process is one that allows explicit consideration of the spatial and temporal correlation between hazards and 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 events, hazards, objects of the network and the network itself, which increases its ease of use in multiple 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. This has been done so that it is easy to integrate both simple and complex models, and has the additional benefit that old models can be easily replaced with better models once they become available. For ease of understanding, the proposed risk assessment process is explained within the context of a risk management process,Figure 2.1.

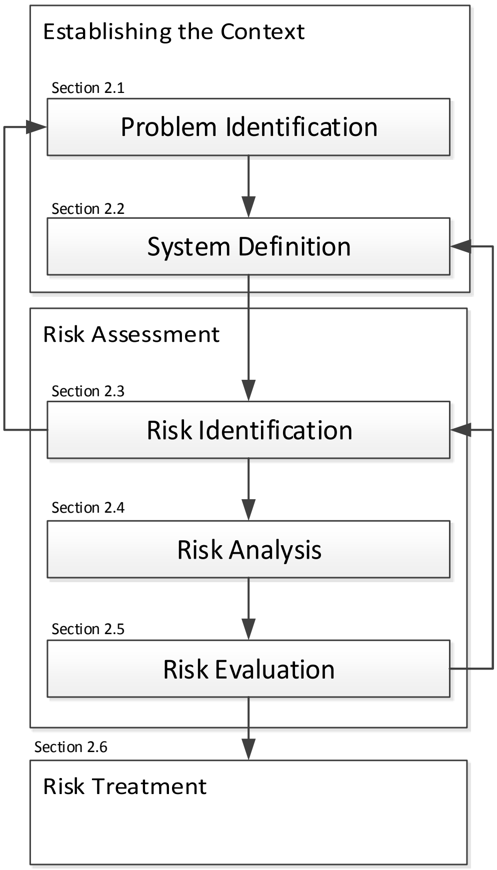


Figure 2.1. General risk management process

The risk management process includes different sub-processes. The problem identification process, the system definition processes, the risk identification process, the risk analysis process and the risk evaluation process. The problem identification process and the system definition process are seen as precursors to the subsequent three.

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, e.g. the type of hazard that might occur, e.g. flooding, why additional information is required, e.g. there is a sneaking suspicion that the collapse of one bridge in the network during an extreme flood would results in much higher consequences than would be acceptable?

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. Some important things to keep in mind when formulating the question are:

- the objective of conducting the risk assessment, including consideration of how the results of the assessment will be used in the risk management process.
- the different interests of the multiple stakeholders and what each of them would like to have out of the risk assessment process, and
- the thresholds to be used to define if a risk is acceptable or if action is to be taken, including consideration of any externally imposed constraints, for example due to legal, regulatory, and professional requirements, such as the policies, objectives and the strategies that are in place to achieve the goals.

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 system being modelled are not being modelled. It also includes the consideration of cascading events.

2.2.1 Define system boundaries

Two types of system boundaries to be established when assessing infrastructure related risk due to natural hazards are spatial boundaries and temporal boundaries. These boundaries depend on the specific problem.

2.2.1.1 Define spatial 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).

In the case of flooding, the spatial boundaries might be, for example, the land on which rain will fall and over which the water will run, the rivers over which bridges cross, the infrastructure that may be affected by floods and over which traffic is flowing, as well as area in which human activities will be affected, through which consequences are to be estimated. The spatial boundaries do not need to be constant throughout an investigated time period.

2.2.1.2 Define temporal boundaries

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: where the temporal aspects are built into the system representation, e.g. a bridge can collapse due to a flood in year one, or in year two.
- dynamic: where the temporal aspects are not built into the system representation, and are considered using the system representation with appropriate values of input parameters, e.g. degree of corrosion of reinforcement, to estimate the risk related to the collapse of the bridge in year one and then again in year two.

The selection of the time period to be analysed, the number and size of intervals into which this period should be divided, and whether or not a static or dynamic system representation is used depends on the specific problem.

2.2.2 Define system 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 varies depending on the type of problem and the desired level of detail, a good starting point is the five following element types where the first two can be seen as “hazard elements” and the remaining three can be seen as “consequence elements”. Each element type is considered to correspond with an event, which can be considered to have a probability of occurrence. Five basic element types, or event types, that should be regularly considered are:

1. 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.

2. Hazard events, or loading events, are events related to any earlier event or that may lead to consequences. A hazard always has an initiating 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.

3. 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 kilometre 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 though must be given to which infrastructure object is affected by which hazard and the likely condition states that the object may have if subjected to a hazard. 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.

4. Network 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, which 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. Such costs are also sometimes referred

to as direct consequences. 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. It may be decided to model these directly in the system representation. These consequences are sometimes referred to as indirect consequences, but this terminology is not used consistently.

5. 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 behaviour, which in turn is coupled with how their behaviour is to be modelled. Societal events may lead to other societal events. If they, however, do not than a value needs to be assigned to the event. This value then enters the risk assessment as a consequence.

In determining the specific system elements for each type appropriate consideration should be given to how the system is affected changes throughout the investigated time period. For example, immediately after a road is closed someone will drive along a long detour in order to arrive on time for a meeting, but two months after the road is closed the person will plan to go by train for a similar meeting.

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 2.2.

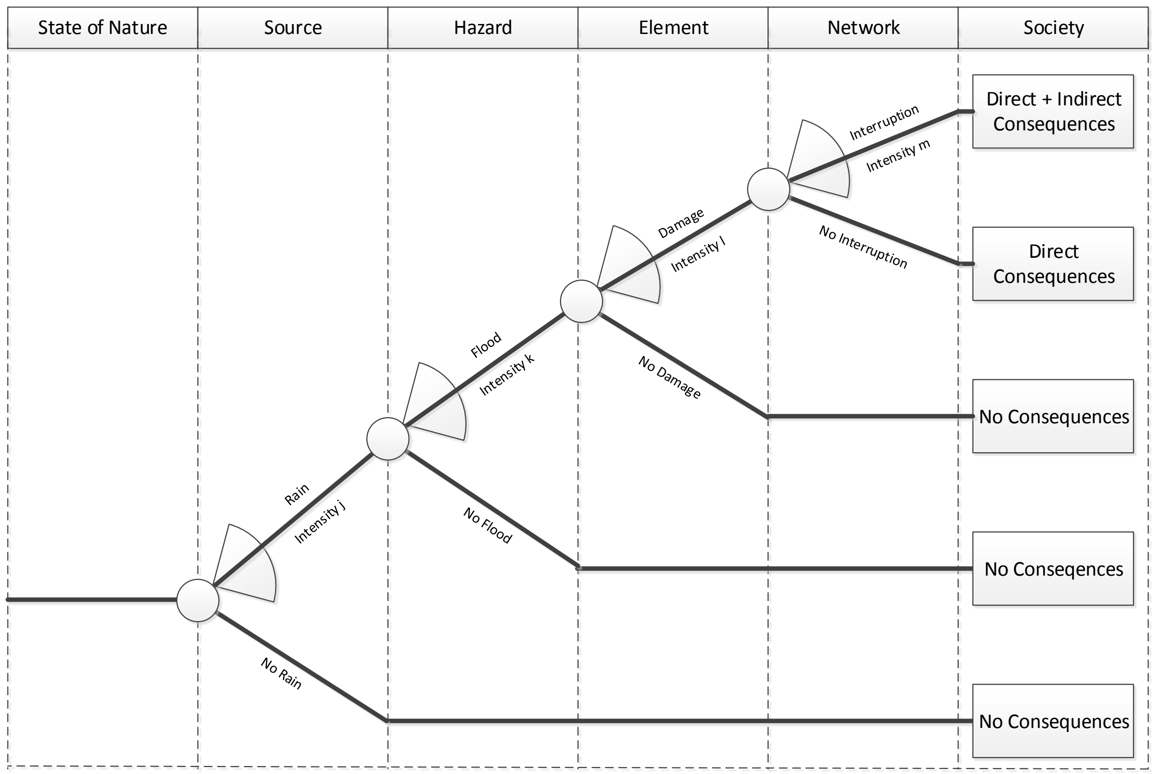


Figure 2.2 Example of a simple event tree for the risk assessment of infrastructure networks

In Figure 2.2, the source event is rain. It may be considered that this event occurs if it rains with intensity j (e.g. the precipitation in [mm/h]) for a specified period of time within the investigated time period, otherwise it may considered that this event does not occur. If this rain event occurs, however, it is not certain that there will be a flood. This may happen only if, for example, the soil moisture is above a specified level and the amount of water in the river is above a certain value before it starts raining. If a flood occurs, it is then also not certain if the bridge will be damaged. This depends on the exact values for example, of the water depth in the vicinity of the bridge and the length of time over which this depth of water is sustained. If the bridge is damaged it is not certain how damaged it may be. If damage is measured as the plastification of at least one reinforcement bar in the bridge than a yielding of the reinforcement would mean no damage has occurred. If the bridge is damaged it is then not certain how the traffic will be disrupted. Will all vehicles make the planned detour? Will 10 % simply not travel?

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. Unless documented, they would become “black swans”.

The first effort made in defining the system elements will in most cases be based on the logical assumptions of experts. The system elements may be expanded or reduced depending on the results of more in depth thought or through the use of more detailed models. In general the more detailed the system representation the more likely it will be able to capture cascading events that are not initially obvious. For example, if one first sets out to investigate how a road link is affected by flooding one may concentrate directly on how much rain makes its way across the land surface and into the river. If, however, one starts to model this in more detail and sets up models that include the water saturation content and how the soil behaves when it is saturated it may become obvious that a hazard including heavy rainfall on steep slopes with saturated soil may also trigger landslides which may end up hitting the road link being investigated. Such discoveries are by no means mistakes and once they are made the system representation should be adapted to take them into consideration.

If possible the availability of data to be used to model the relationships between system elements should be taken into consideration in determining the system representation to be used. Early consideration will help reduced the number of iterations to be made on the system representation.

2.2.3 Define relationships between system elements

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. Early consideration of will help reduced the number of iterations to be made on the system representation.

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 2.2 is a scenario, or in other words a 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.

2.3.1 Events to which no value is to be placed

Events to which no value is to be placed, are ones that are by themselves neither good nor bad, e.g. rainfall. In the identification of the scenarios to be considered it is necessary to think through the different events that have to be modelled so that risk can be evaluated, e.g. the amount of rain and the amount of water in the river that will come in contact with the bridge. It is necessary in this step to think through how the events will be modelled both spatially and temporally, and how these events will affect the events to which values can be assigned, e.g. the how high water levels affect a bridge.

2.3.2 Events to which a value is to be placed

Events to which a value is to be placed are those considered to be bad or good and require at least in some respects no further analysis to state what value this is. For example, a value can be assigned to the collapse of a bridge if it is assumed that this bridge will be rebuilt to provide exactly the same level of service as it provided before collapse and it can be assumed that this will cost x monetary units. If this assumption cannot be made than an infrastructure event, e.g. bridge collapse may be used as an event to which no value is placed. It may also be both.

Although perhaps already clear, the assessment of infrastructure related risks due to natural hazards is only meaningful through the estimation and the evaluation of how humans are affected by different events. For example, the cost to rebuild a bridge once it has collapsed, or the amount of additional travel time incurred by the users of road network while a bridge is out of service.

The values placed on this behaviour must always be made with respect to a default scenario. In the assessment of infrastructure related risk due to natural hazards this is normally the behaviour that would be expected if no hazard occurs. A possible classification of quantifiable human behaviour for road networks is given in Adey et al. (2012).

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:

$$R = p * C \qquad (1)$$

where p is the probability that a scenario occurs and C is the consequences related to this 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.

2.4.1 Qualitative approach

A qualitative approach is one where relatively exact estimates of the probability of occurrence of a scenario or relatively exact estimates of the consequences are not required. It allows a first impression of the risks. This approach is based exclusively on the experience of the experts and the risks, as well as the probability of occurrence and their consequences are categorized in general terms, e.g. “very high”, “high”, “moderate”, “low” and “very low”.

A qualitative approach is a good start for risk assessment in many cases. It offers a quick overview of the risk associated with each scenario. It is fast and relatively inexpensive.

A qualitative risk assessment may be sufficient for the risk assessment, i.e. once it is completed an infrastructure manager has all the information he needs. If not the infrastructure manager will be in a much better position to say where effort needs to be focused when he embarks on a more detailed, and quantifiable, risk assessment.

Even though a qualitative approach does not use numbers, effort is made to assign ratings, such as “high” and “low” in a sensible and comparative way. Using qualitative analysis it is common to develop risk matrices as shown in Figure 2.3, and then assessing where each scenario falls in the matrix.

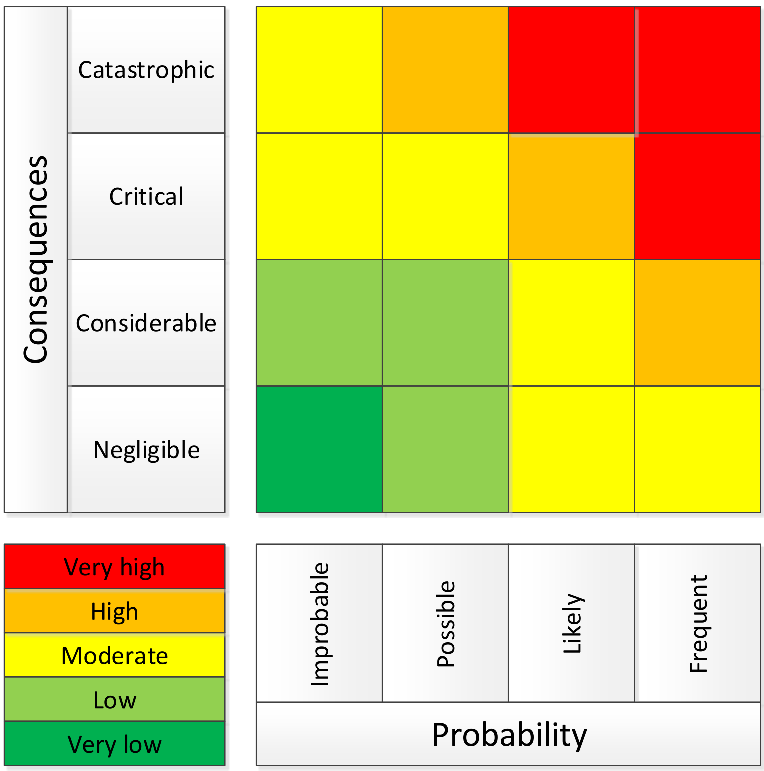


Figure 2.3: Risk matrix

The number categories used to describe the probabilities and the consequences depends on the specific problem and the amount of detailed desired, as well as the ability of experts to say in which category a scenario would fall.

When conducting a qualitative risk analysis it is important that all participants have roughly the same understanding of the words used to describe each class, i.e. all experts should provide roughly the same answer to the questions such as “what are low consequences?”, “what is an improbable probability of occurrence?”.

2.4.2 Quantitative approach

A quantitative approach is one where relatively exact estimates of the probability of occurrence of a scenario and relatively exact estimates of the consequences are required. With such an approach the risk analysis is based on information in form of data, expert knowledge, physical and mathematical models, etc. The result of a quantitative risk analysis is an exact number (Equation 1), that indicates the risks associated with each scenarios and an exact number to indicate the risk associated with all relevant scenarios considered together, even if it is acknowledged that there is uncertainty with respect to these numbers.

The estimation of the probability of occurrence (or occurrence rate) of the scenario requires estimation of the conditional probabilities of occurrence of each intermediary event in the causal chain from initiating event to quantifiable consequences. This in turn requires the development of models to establish the basic relationship between events, e.g. a rainfall of x means a water depth of y in the river, and the estimation of the probabilistic distributions to be used to model the uncertainty related to each of the key parameters.

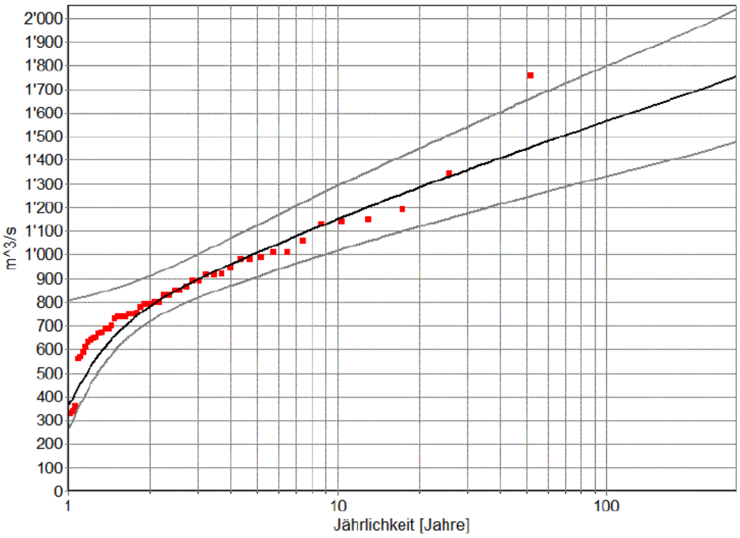
A number of approaches can be undertaken for the risk analysis, depending on the type of infrastructure, the objective of the analysis and the available information. Some of the instruments and methods for the quantitative risk analysis are described in the following sections.

2.4.2.1 Statistical analysis

The extensive growth of IT systems to capture data about hazards, infrastructure and human behaviour, such as the database of earthquake-induced ground failures in Italy (Martino, Prestininzi and Romeo 2014), and the Swiss flood and landslide damage database (Hilker, Badoux and Hegg 2009), provide rich data sets which can be used when conducting a risk analysis. Statistical models of different complexity have been developed to estimate the risk related to the failure of an individual infrastructure objects, with respect to both the probability of occurrence of a hazard and the probability of failure of the infrastructure object (Debon, et al. 2010).

Even with a rich data set, however, statistical analysis on its own will fall short of providing a detailed estimate of the risks related to infrastructure, since detailed information on, for example how often or how an infrastructure object fails due to specific loads is not available. It is not available simply because it is not collected, but instead because infrastructure very rarely fails and if it does it is reconstructed in a way that it will no longer fail if subject to the same loads again. (Kröger und Zio 2011).

Statistical analysis can, however, be used to estimated the probability of occurrence of numerous events within the risk scenarios. An example of the results of a statistical analysis of the occurrence of high water levels based on a series of past observations is shown in Figure 2.4).



Verteilung: Pearson-III
Vertrauensintervall: 95%

Jährlichkeit [Jahre]	Abfluss [m3/s]
2	782
5	1010
10	1153
30	1358
50	1448
100	1567
300	1753

Figure 2.4: Uncertainty in estimating floods by frequency analysis (BAFU 2014)

Even here though there is some uncertainty introduced in the estimates through the fact that the data samples are of rather limited size from the statistical point of view, meaning that the parameters of the probability distributions that are estimated from at a particular site may not be "true" parameters of distribution of flood population at that site.

2.4.2.2 Probabilistic modeling

This approach comprised a variety of methods used for the risk analysis, such as Event trees, fault trees, Markov chains, Bayesian networks, and Monte Carlo simulations. (Kröger und Zio 2011).

2.4.2.2.1 Event trees

Event trees, are used to analyse and display different discrete scenarios, their corresponding probability of occurrence and the resulting consequences, as used in Figure 2.2 and Figure 2.5. They are built from a starting event and branch at each subsequent event based on the values of key parameters (in Figure 2.2) these key parameters were intensity measures. When the event tree is complete it is a logical and visual representation of the set of scenarios that can occur.

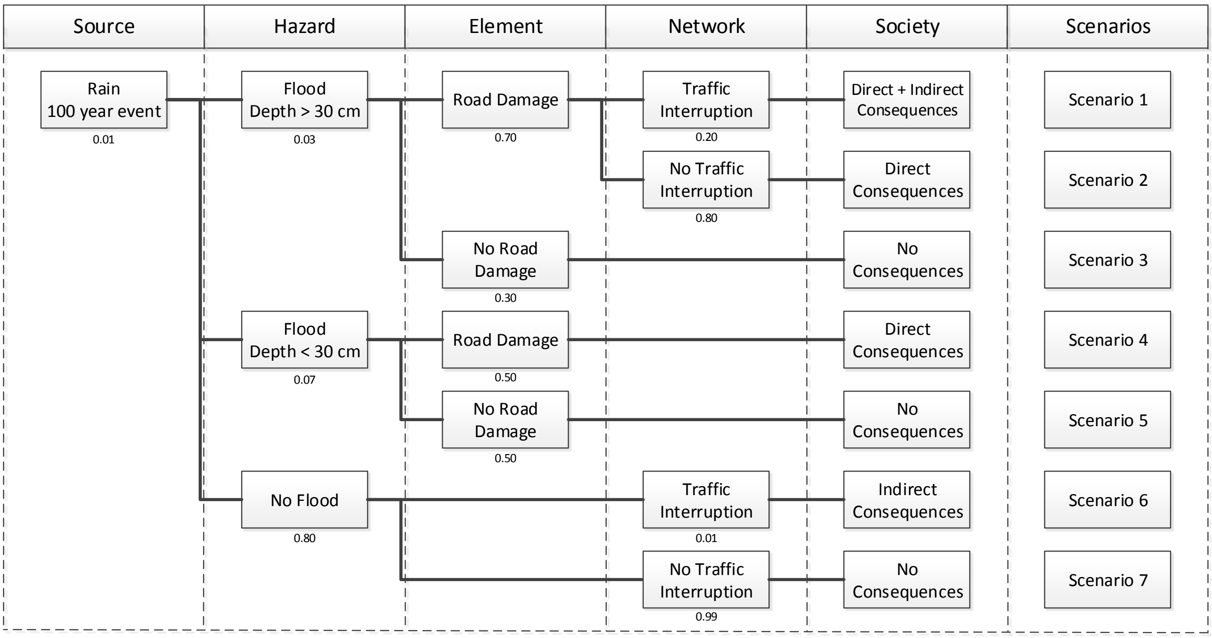


Figure 2.5: Simplified event tree for a flood risk analysis

In Figure 2.5, the initiating event is a 100 year precipitation, which can cause a flood hazard or not. In this example, the flood can lead to different damage states related to an infrastructure element, which can result in a network interruption. Also the heavy rain itself can cause an interruption. Each path defines a possible scenario, which has to be considered in the risk assessment.

2.4.2.2.2 Fault tree

Fault trees are used when it is desired to focus on the particular ways a system can fail. It is particularly well suited to determine the probability of a specific event happening when this event can happen due to different precursor events. Fault trees are often used in the evaluation of large safety-critical systems (Henley and Kumamoto 1981).

A fault tree is generally constructed with one undesired event as the top event, for example, the collapse of a bridge. The fault tree may then be constructed to consist of all combinations of bridge elements that need to fail in order for the bridge to collapse. The construction of the fault tree normally begins with the top event and then proceeds to so-called base events. The development of fault trees is based on the following assumptions (Bobbio, et al. 2001):

1. Events are binary events e.g. failure or no failure
2. Events are statistically independent
3. Relationships between events and causes are represented by means of logical AND and OR gates.

In the development of a fault tree one normally starts by developing a definition of a top event and then developing logical expressions of sub-events that may lead to the occurrence of the top event. The last events in the tree are base events. Once a fault tree is constructed and the probability of occurrence of the base events are estimated the probability of occurrence of the top event can be estimated. Figure 2.6 contains a fault tree developed for the analysis of floods caused by failure of sea dikes, and it includes 30 different failure mechanisms (Kortenhaus, et al. 2002).

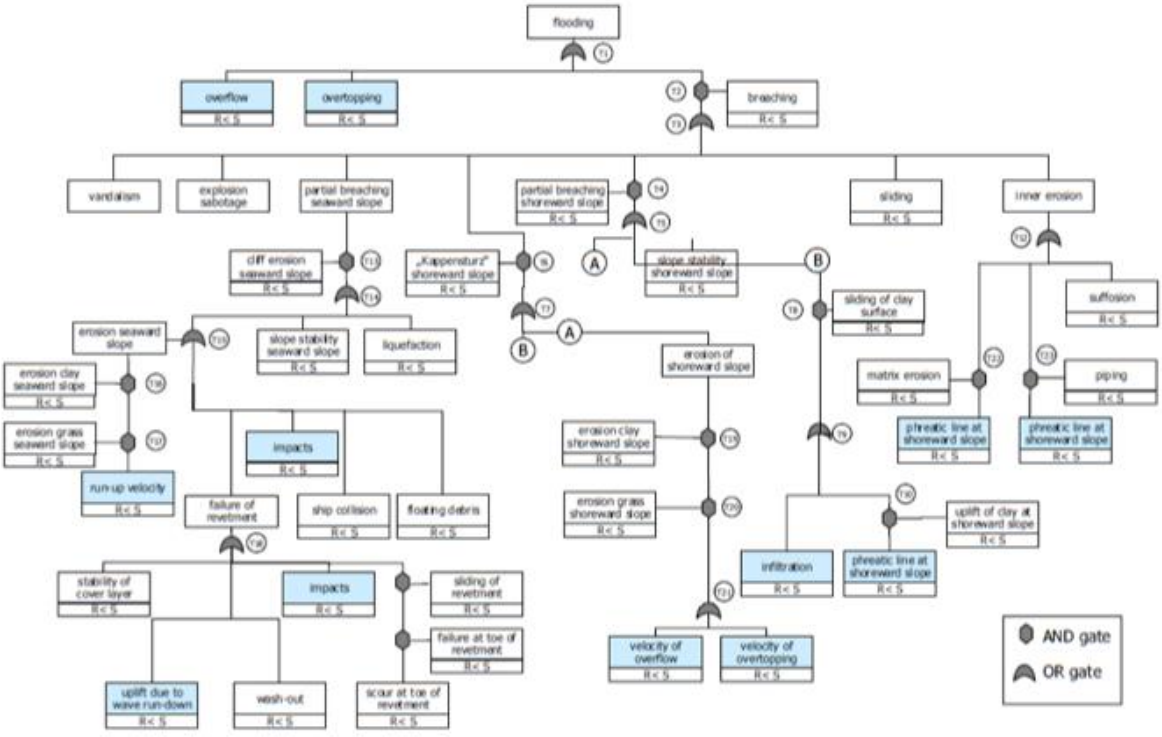


Figure 2.6: Fault tree for sea and estuary dikes based on detailed failure analysis (Kortenhaus, et al. 2002)

Fault trees can also be used to assess the infrastructure related risk due to natural hazards. Their focus, however, is more on a specific type of consequence, which may happen due to hazard of different types, e.g. a bridge may collapse due to a flood or an earthquake.

2.4.2.2.3 Bayesian networks

Bayesian networks are used to predict the behaviour of a system, in a way similar to that event trees but are much more robust in the number of possible scenarios that can be encompassed, and much more flexible in their ability to be able to use existing information, or evidence, in the estimation of likely consequences. The use of Bayesian networks allows the consideration of both expert opinion and observations of occurrence of stochastic events. Once the relationships between the system elements are included in the Bayesian network the weights put on these connections are determined to give the best fit between the value of the inputs and the values of the outputs, according to Bayes' theorem.

The relationship between all types of events, whether they are hazard events, or consequence events, and all types of relationships, e.g. linear or circular, can be modelled in Bayesian networks (Nadim and Liu 2013).

Bayesian networks have been used to make estimates in many different disciplines, ranging from terrorist risks (Hudson, et al. 2002), the nuclear risks (Kim and Seong 2006), dam risks (Smith 2006), environmental risks (Aguilera, et al. 2011), earthquake risks (Bayraktarli, et al. 2005) (Bensi, Der Kiureghian and Straub 2011) and landslide risks (Stassopoulou, Petrou and Kittler 1998) (Straub 2005). An example is shown in Figure 2.7.

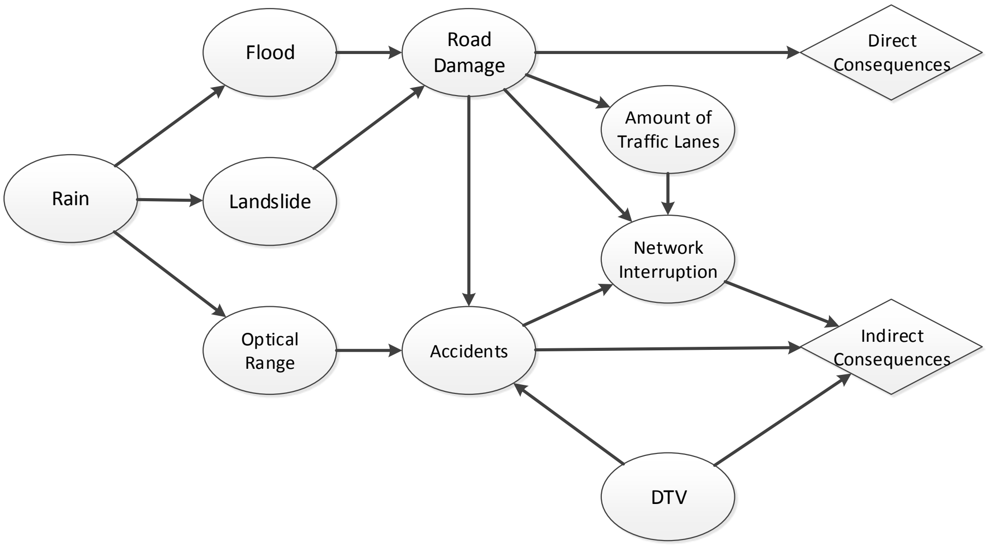


Figure 2.7: Simple Bayesian network

2.4.2.2.4 Monte Carlo simulation

Monte Carlo simulation is often used when the models of the system required to estimate risk are complex, nonlinear, or involves several uncertain parameters. It involves the repeated deterministic computation of user-defined transformation models using random values as input (i.e., random values drawn from user-generated sampling distributions). The number of evaluations/repetitions necessary to establish the probability distributions of the output parameters will depend on the number of input parameters, their probability distributions, the complexity of the propagation model, and the accuracy requirements of the output (Nadim and Liu 2013).

2.4.3 Hazard models

In order to analyse risk, especially using a quantitative approach, it is necessary to develop models that describe how the occurrence of on event affects the occurrence of other events in mathematical terms. A few examples are given in the following sections, for the flood hazard, the earthquake hazard and the landslide hazard.

2.4.3.1 Flood hazard

Floods can be generated by various combinations of meteorological and hydrological processes and include pluvial floods, riverine floods, coastal floods, and rising groundwater (Garcia-Aristizabal and Marzocchi 2012). They are normally characterized by a flood return period, i.e. the expected frequency with which a flood of specific magnitude. The parameters used to describe magnitude vary. Common intensity indicators include inundation depth, flow velocity or water contamination.

They need to be selected taking into consideration the specific problem and the level of detail desired.

Volume of water in a river is often used for river floods when the focus of investigations is the design of flood protection infrastructure. However, for the estimation of the amount of damage that occurs during a river flood it is useful to know the spatial patterns of inundations and flood intensity indicators are required. These are typically computed with the 1D and/or 2D modelling approaches, which range in their complexity from the simple linear and planar surface interpolation to the fully-dynamic shallow water models with or without consideration of failures of flood protection structures. One may additionally distinguish between steady-state and unsteady inundation simulations. Steady-state modelling produces time-invariant estimates of inundation area and depths, usually based on the peak flow boundary condition. Although very fast, the approach inherently disregards any dynamic effects such as, e.g., flood water storage and subsequent attenuation of peak flow along the river reach, whereas, the unsteady models do account for the river channel-floodplain interaction and hydrograph transformation (MATRIX D2.1).

The hydraulic models, in many cases, run deterministically with a specified set of parameters to produce inundation characteristics associated with specific flood return periods. There has, however, been a substantial amount of work recently to use these models together with probabilistic approaches, for example, Sayers, et al. (2002); Hall, et al. (2003); Apel, et al. (2004); (2006); van Mierlo, et al. (2009); (Di Baldassarre, et al. (2009); Vorogushyn, et al. (2010).

Another often used tool in the assessment of flood risk, is the probabilistic flood hazard maps, which indicate the values of the inundation intensity indicators and their associated probability of occurrence with reference to the specified gauge station. The uncertainty ranges of flood intensity indicators are given as percentile maps, which display the flood characteristics corresponding to a certain percentile as computed in a Monte Carlo framework. Uncertainties derived in this way can be further propagated to obtain the probabilistic flood risk estimates (MATRIX D2.1). The maps, however, do not yet take into consideration the spatial correlation between flooded areas.

Flood risk assessments at a local scale are undertaken at the micro- or meso-scale (Apel, Aronica, et al. 2009). A micro-scale assessment is based on single elements at risk, i.e., damages are calculated for each affected object (building, infrastructure object, etc.). A meso-scale assessment is based on spatial aggregations, typically land use units, e.g., residential and industrial areas. Damage functions or models are rarely developed for individual objects.

The spatial scale of the analysis, the availability of input data and the required accuracy of the damage assessment influence the level of detail considered. While micro-scale assessments, for instance, base their estimations on the construction costs of different building types (Blong 2003), studies on the macro-scale use the gross capital stock of fixed assets in the exposed area. Exposed asset values can vary in space and time.

2.4.3.2 Landslide hazard

A landslide is the movement of a mass of rock, debris, or earth down a slope under the influence of gravity (Cruden and Varnes 1996). Landslide susceptibility is influenced by different factors (including geological, morphological, physical and human). The main landslide triggering factors are:

1. Rainfall: Landslides can be triggered by short duration, intense rainfall events, such as the rainfall associated with thunderstorms, or long duration rainfall events with lower intensity, or a combination of both. The reduction of effective material strength by percolating water is generally considered to be the primary cause of rainfall induced landslides.

2. Earthquakes: The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to the inertial forces during the ground shaking itself or the rapid increase in pore water pressure induced by the cyclic stresses and subsequent reduction of the soil shear strength. Strong earthquakes may cause widespread landsliding and other ground failure (i.e., liquefaction) and cause large damages.
3. Human-induced landslides may result from changes in a slope, by changes in the strength or effective stresses in the ground, changes in geometry and boundary conditions, and modifications or changes in the material behaviour.

Methods used for landslide hazard assessment include the following: (i) Heuristic methods, where expert opinion is used to assess the hazard. These methods combine the mapping of the landslides and their geomorphologic setting as the main input factors for assessing the hazard. (ii) Knowledge based analysis or heuristic data mining' is the science of computer modelling of a learning process, (iii) Statistical or probabilistic approach, based on the observed relationships between each factor and the past distribution of landslides. Methods include multivariate analysis (Carrara, et al. 1995), logistic regression (Ayalew und Yamagishi 2005), and Bayesian methods and neural networks (Lee, et al. 2006). (iv) Deterministic methods applying classical slope stability principles such as infinite slope, limit equilibrium and finite element techniques and some with GIS-integration (Baum, et al. 2005).

The calculation of the probability of occurrence of landslides includes the spatial and temporal probability of landsliding. Spatial probability is meant as the likelihood of the occurrence of landslides in a given location or terrain unit (i.e., Chung and Fabbri (1999); Gorsevski, et al. (2006)). The temporal landslide probability is also an important element in quantitative risk analysis.

The probability of occurrence of landslides is often shown in the form of hazard maps. These usually do not, however, capture the spatial and temporal correlation of the landslides.

2.4.3.3 Earthquake hazard

Most earthquakes have a tectonic origin and their sources are spatially associated with seismic faults. In the earthquake catalogues, single seismic events are characterized by the location of the source (geographical coordinates and focal depth) and the earthquake`s magnitude.

Earthquake hazards may include: ground shaking, surface faulting and ground failure (e.g., liquefaction, subsidence, slope effects). Each of those phenomena may cause different mechanisms of damage to the elements of built environment. The occurrence and severity of possible seismic effects depends on the complex combination of the earthquake's magnitude, the distance from the source, and the local geological and geomorphological conditions (Garcia-Aristizabal and Marzocchi 2012).

The two main approaches to seismic risk analyses are probabilistic and deterministic approaches:

- The probabilistic approach is normally used for design purposes and investigate all possible earthquakes in a specific area. Attention is not normally focused on the spatial correlation of the ground acceleration that are likely to occur.
- The deterministic approach is normally used when the effects from a single seismic event with preselected values of key parameters is of interest. Parameters of the earthquake are typically selected on the basis of so-called worst-case scenarios (for the insurance industry and disaster preparedness) or design scenarios (for the purpose of earthquake-resistant

construction).

A detailed comparison of probabilistic and deterministic approaches is given in McGuire (2001), who conclude that the methods should be complementary, where on the one hand, probabilistic analysis may guide the choice of deterministic events, while on the other, deterministic events may guide the refinement of the probabilistic analysis (Garcia-Aristizabal and Marzocchi 2011).

Probable ground motions are often shown in the form of hazard maps. These maps do not, however, take into consideration the spatial correlation of the peak ground accelerations.

2.4.4 GIS analysis

Because of the spatio-temporal properties of natural hazards and related phenomena, geospatial analyses can be performed in order to derive further information, i.e. to explore the consequences of these hazards on the infrastructure. An overview on geospatial analysis capabilities is given by Huisman and de By (2009) where a distinction is made between:

- Functions considering only one geospatial data layer (e.g. classification, retrieval, measurement)
- Functions considering several geospatial data layers (overlay analysis)
- Functions considering the neighbourhood of geospatial features (e.g. buffering, interpolation)
- Functions considering the connectivity in geospatial networks (e.g. shortest path)

These methods play an important role when geospatially coupling different models related to natural hazards and infrastructure objects. For example, by overlaying a field of peak ground acceleration values resulting from an earthquake with a data layer of bridges, the distribution of these values could then be derived for discretized locations for the local coordinate system of the single bridge objects. This information could then be further passed to models in order to evaluate their behaviour when exposed to such loading.

An example for a temporal analysis might be to find the maximum value for an inundation cell over the whole period.

It should be noted that there is a smooth transition between models and analysis. For example, depending on the point of view, a method to compute a shortest path can either be seen as a kind of network analysis (in the context of GIS) or model.

2.4.5 Infrastructure models

2.4.5.1 Resistance to flood

The parameters usually used to assess the resistance of infrastructure to floods, include size, type and structure of the object, as well as details related to flood mitigation measures, such as water proofing of buildings or adapted use, flood experience and early warning (ABI (2003); Kreibich, et al. (2010); Parker, et al. (2007); Olfert and Schanze (2008)). A comprehensive overview of damage influencing factors that have been considered in flood damage modelling is provided by Merz, et al. (2010).

2.4.5.2 Resistance to landslides

The resistance of infrastructure to landslides is usually determined by estimating whether or not a landslide reaches the infrastructure. This is often done by intersecting the expected spatial extent of the mass movement with spatially distributed inventories of the infrastructure considered to be at risk (MATRIX D2.1).

The vulnerability of infrastructure to landslides has many different aspects (Birkmann 2006), and there are some variations in the approaches used to investigate different types of objects, e.g. Leone, et al. (1996); Faella and Nigro (2003); Roberds (2005). In order to determine landslide risk zoning, it is necessary to develop specific vulnerability indicators for every object at risk, using the concept of probabilistic fragility functions and appropriate definitions of relevant damage states (Pitilakis 2006).

2.4.5.3 Resistance to earthquakes

The resistance of infrastructure to earthquakes is generally understood as its susceptibility to structural damage by a certain level of ground shaking (MATRIX D2.1). For example, fragility functions relate an intensity measure (e.g. spectral acceleration) to a probable physical damage grade of a damage classification (EMS-98). They are specific to a building typology which can be found in a given location. Analysis of seismic vulnerability and probable seismic damage can be done following engineering-based or intensity-based approaches (e.g., FEMA (1999); Crowley, et al. (2004); Schwarz, et al. (2004); Tyagunov, et al. (2006)). An extended list of references showing the development of seismic vulnerability assessment methodologies over the past three decades can be found in Calvi, et al. (2006).

2.4.5.4 Agent based modeling

Agent-based modelling can be used to describe the dynamic system operational behaviour, with close adherence to the reality of coupled processes involved (D'Inverno and Luck 2004). A major advantage of this approach is the possibility to include physical laws into the simulation and to emulate the behaviour of the infrastructure as it emerges from the behaviours of the individual agent and their interactions (Schläpfer, Kessler und Kröger 2008).

2.4.6 Network models

2.4.6.1 Deterministic models

In a risk assessment it is being attempted to put a value on the human behaviour related to a series of events. This behaviour can be predicted using a myriad of models. When dealing with transportation infrastructure many of the models will be related to the movement of vehicles. They are, however, required to estimate things such as, the number of accidents, the increased travel time, the amount of pollution and the amount of effort spent on repairing infrastructure.

2.4.6.2 Network or graph theory

Topological analysis based on classical graph theory can be used to discover relevant properties of the structure of an infrastructure network. This approach represents the network by a graph, in which physical components are mapped into nodes connected by unweighted edges, representing the links of physical connections among them (Kröger und Zio 2011).

2.4.6.3 Agent based modeling

Agent-based modelling can be used, equally as well to model the behaviour of humans as they react to failed infrastructure. An example of results from a traffic modelling tool that uses is agent-based modelling is shown in Figure 2.8.

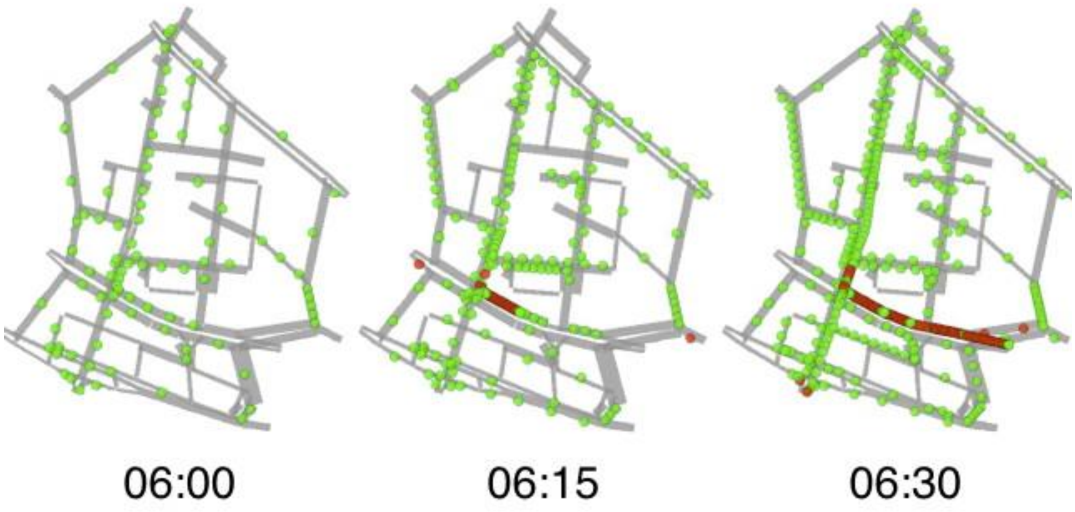


Figure 2.8: Agent-based traffic modeling (MATSim 2014)

2.4.7 Value of human behavior

The estimation of the value of the consequences, e.g. a unit of time lost in travel or the value of a lost life, requires the use of many different models and methods. Examples are given in Adey et al. (2012).

2.4.8 Aggregation of risk

Depending on how the scenarios have been defined the aggregation can be easy or difficult. If all scenarios are defined to the same level of detail and mutual exclusive then the risks can simply be added. If not attention (and work) will be required to aggregate risk. The risk can then be shown in different ways. For a number of different hazards the consequences are plotted against the annual probability of exceeding this amount for individual hazard risk and aggregated hazard risk in Figure 2.9. Through these points a curve is fitted, the so-called risk curve, and the area below the curve is representative of the total risk.

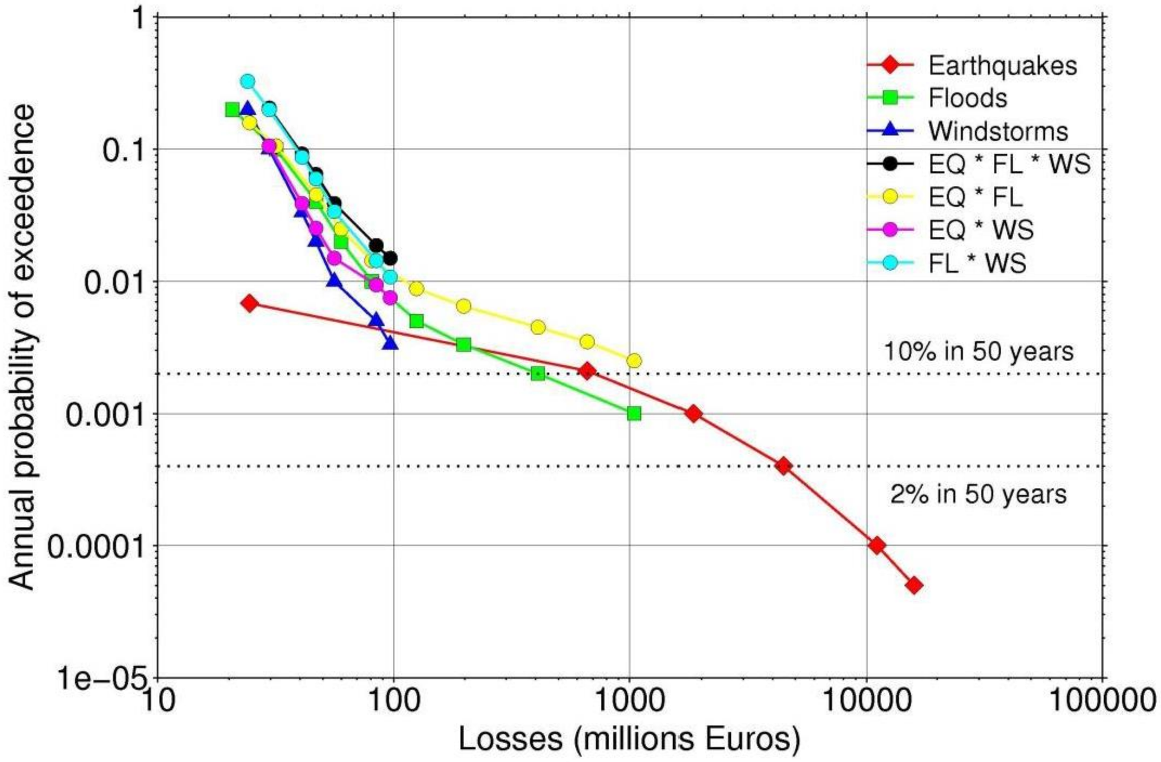


Figure 2.9: Individual risk curves for different hazards
(earthquakes – EQ, floods – FL, windstorms – WS) (MATRIX D8.4 2013)

In a multi-hazard risk assessment this procedure is carried out for all individual hazards, taking into consideration the interrelations between hazards (e.g. cascading effects, such as a landslide damming a river and causing a flood). If the risk is normalized into annual risk, it is then possible to evaluate the multi-hazard risk (van Westen, et al. 2011). Care must, however, be taken to deal with length of time it takes restore infrastructure once it has failed.

The annual risk is then estimated taking into consideration the consequences caused by an event with a 1-year period, plus half of the damage difference between the maximum event in a 2-year period and a 1-year period, … and so on (Deckers, et al. 2010):

$$R_a = \sum_{i=1}^{n} \frac{1}{i} (C_i - C_{i-1}) \qquad (2)$$

Where R_a is the averaged annualized risk, C the consequences related to a scenario with a return period of i years.

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 helps 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 (ISO 31000).

2.6 Risk treatment

Risk treatment involves the selection of the best way to modify the system being analysed, i.e. interventions, and to implement it. The best way to modify the system may be comprised of one or more interventions. These interventions can include physical changes to the infrastructure, alteration of the natural environment or activities to alter the human behaviour during or following a hazard event. This also includes the monitoring of the system.

The selection of the best way to modify the system involves balancing of the costs and effort of implementation against the benefits derived, taking into consideration constraints such as legal, regulatory, and other requirements such as social responsibility and the protection of the natural environment. Costs here are not exclusively economic costs but all negative impacts associated with the execution of interventions, and benefits are not exclusively economic benefits but are all positive impacts that can be achieved if interventions are executed.

The values and perceptions of stakeholders and the most appropriate ways to communicate with them, are to be given appropriate weight in the selection. Where risk treatment options can impact on risk elsewhere in the system or outside the system, the affected stakeholders should be involved in the decision-making process as far as possible. Although the risk treatment option that results in the most net benefit to all stakeholders taking into consideration constraints, it must be realised that the optimal solution will not be optimal for each stakeholder.

It should also be kept in mind that risk treatment itself can introduce risks, for example that the implemented measure is ineffective. To reduce such risks it is adviseable that monitoring of the system be an integral part of all risk treatment options (ISO 31000).

3 IT SUPPORT OF RISK ASSESSMENT PROCESS

In this section, it is aimed at providing information on the general tasks a decision support system (DSS) should perform in order to assist the user, i.e. the infrastructure manager, during the distinct steps of the risk assessment process by taking into account the methodology described in the previous section. This tool to be developed is named INFRARISK Decision Support Tool (IDST) and mainly consists of the Process Workflow Engine (PWE) as described in Task 7.3 and the Graphical User Interface (GUI) as described in Task 7.4 of the INFRARISK project.

Setting up computational support for the risk assessment process tailored to the needs of a specific user community is a complex task which incorporates a vast amount of expert knowledge of different disciplines and often computationally challenging processes (e.g. for quantitative risk assessment and in particular for probabilistic modelling).

The IDST should be usable so that it can be configured to be used for different case studies each having distinct requirements in terms of models, analysis functionality, data and how these components are driven to yield useful results.

Since the IDST should enable the end-users (in the following termed **“users”**) to conduct risk assessment, it first needs to be clarified which parts of the risk assessment process can be supported by the IT system. In this case, the users are assumed to be road managers being aware of the fact that infrastructure elements (e.g. roads, bridges) managed by their organisation might be prone to natural hazards. Therefore, they already undertook the first step “Problem Identification” (see Section 2.1).

Afterwards, the steps “System Definition”, “Risk Identification” and “Risk Analysis” follow where IT support is considered possible. However, these steps cannot be directly mapped to unique IT components if a system of high usability for the user should be created, because the conduction of these steps involves detailed expert knowledge of different domains. Therefore, a hybrid approach for user-friendly risk assessment is suggested that consists of two stages.

First, the IDST should be configured in terms of the “System Definition”, “Risk Identification” and “Risk Analysis”. This includes gathering relevant modules (e.g. analysis tools, models) and associated data (e.g. needed river geometries, asset values) as well as the definition of allowed user inputs to the system (e.g. definable in the GUI) and how these modules are connected.

This configuration step needs to be performed by an expert group who’s members are considered to be **“authors”** having in-depth knowledge in various relevant disciplines enabling them to perform this complex task. After configuring the IDST appropriately, it is released so that the user may run simulations based on this configuration, e.g. via a user interface.

Second, the user is enabled to perform the steps “Risk Identification” and “Risk Analysis” of the risk assessment process in a manageable fashion. This is ensured by providing a limited set of configuration possibilities within the user interface and displaying the results in a clear and easy way. For “Risk Identification”, examples are the specification of the types of hazards to be considered (e.g. landslides and floods), or the type of a flood (e.g. 100 year, 300 year, 500 year). For “Risk Analysis”, a specific approach may be selectable (e.g. using a Monte Carlo method or a Bayesian network).

The remaining step of the risk assessment process "Risk evaluation" and the final step in a typical risk management process "Risk treatment" are not directly supported, although results of the IDST may be incorporated into these steps.

An overview of how the IDST is to support the proposed risk assessment process is shown in Figure 3.1 including the relevant steps from the users and the authors' point of view. The blue boxes are the steps in the proposed process. The white boxes mainly explain how the user and author interact with the IDST to ensure that the steps in the risk assessment process are conducted appropriately. These are elaborated in more detail in the corresponding sections of the report.

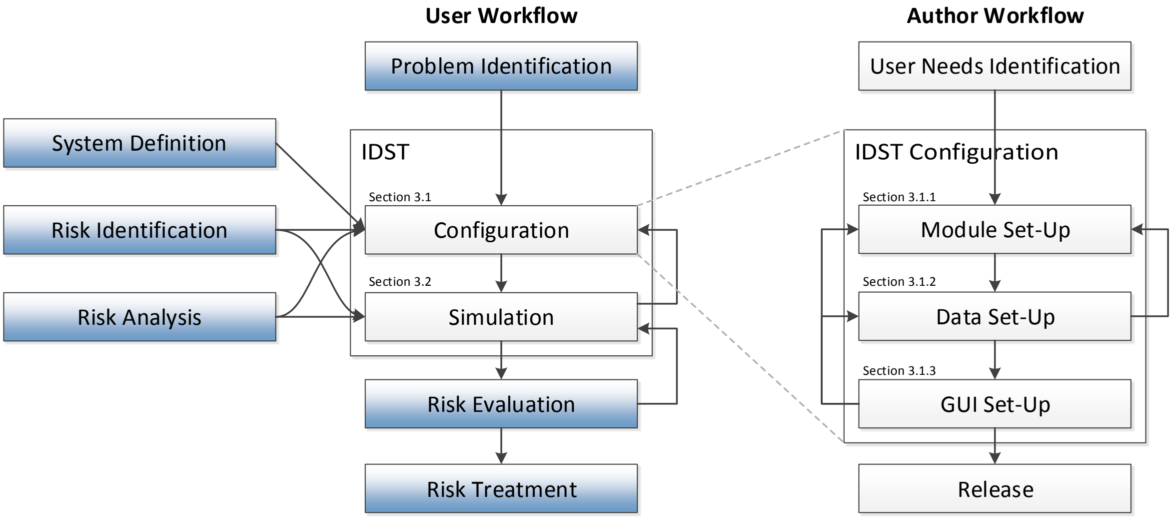


Figure 3.1: Possible user and author workflows for the IDST

It is important to note that the considerations for the IT support in this section describe a preliminary concept and will very likely be subject to future modifications and enhancements.

3.1 Configuration

When defining a system for a case study, authors need to investigate thoroughly how each of the selected system elements, i.e. source events, hazard events, infrastructure events, network events and societal events can be represented and which relationships between them should be taken into account. This process involves many aspects, such as:

- The spatial resolution and delineation including the selection of an appropriate Coordinate Reference System (CRS)
- The temporal resolution and delineation
- The availability of suitable data
- The availability of suitable models
- The availability of suitable analysis tools
- The use of an appropriate strategy for risk analysis
- The tasks the user should be enabled to perform
- The tasks the user is able to perform

These aspects are often interdependent. For example, if data is only available for a low level of detail, models for a higher level of detail might not be useful. In addition, this model might not support fine adjustment of certain parameters being potentially interesting for the users so that again another model might be more suitable. One example for a minimalistic configuration for the IDST is shown in Figure 3.2. The terms depicted in this figure are described in the following sections.

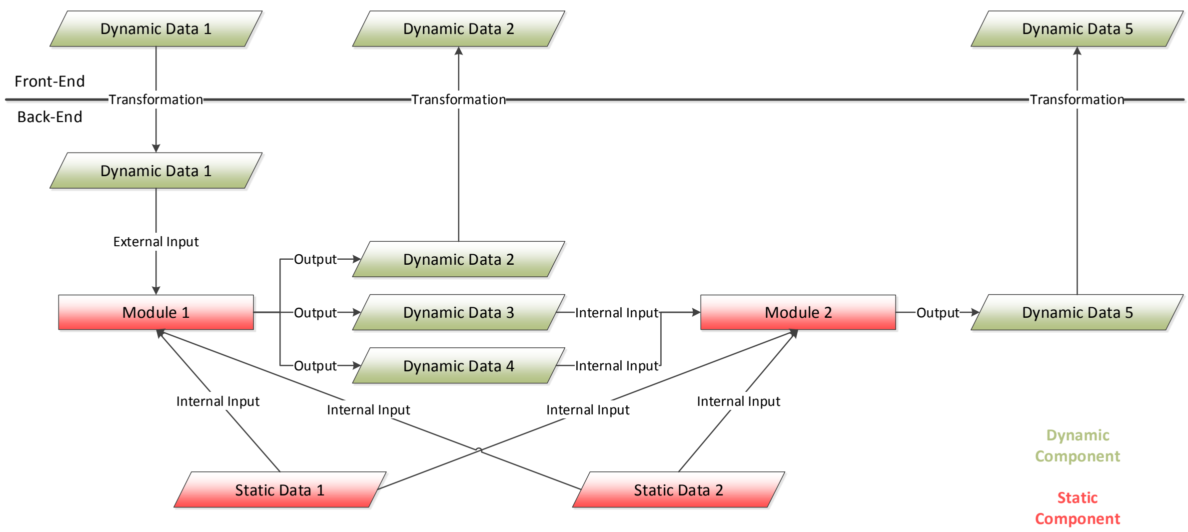


Figure 3.2: Simple example for a configuration of the IDST

3.1.1 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 analysing geodata, typically it is adopted that the datasets use the same CRS and lie within a similar extent.

Authors 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.

3.1.1.1 Information exchange

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.

For the INFRARISK project, such an information exchange structure has to be built up together with the experts, stakeholders and infrastructure managers. For instance, for each module information have to be specified about the area of application, the type of model, or the kind of intensity measurement, etc..

Data compatibility between modules is ensured through the concepts of syntactic and semantic interoperability. According to IEEE (1990), 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.

3.1.1.2 Standards and web-services

Many standards have been established as a means to guarantee interoperability between software systems. Their development is mainly driven by standardization organizations, such as the International Organization for Standardization (ISO), the World Wide Web Consortium (W3C), and, specifically for the geospatial domain, the Open Geospatial Consortium (OGC).

The W3C primarily focusses on the creation of standards for web technologies (W3C 2013), such as the Hypertext Transfer Protocol (HTTP) as a communication protocol, the Hypertext Markup Language (HTML), a language to describe web pages, or the eXtensible Markup Language (XML), a hierarchical data exchange format.

Based on such generic standards, more domain specific standards were developed. For the transfer of geodata, especially the Geographic Markup Language (GML), a dialect of XML is of particular importance (OGC 2007).

Web-Services may use such standards so that interoperability is guaranteed. Typical examples are the Web Map Service (WMS) (OGC 2006) to deliver maps using typical picture formats like PNG or JPEG, the Web Feature Service (WFS) (OGC 2005) to deliver geographical vector-based geodata and the Web Coverage Service (WCS) (OGC 2012) to deliver raster-based geodata rather for processing than for portraying.

3.1.1.3 Syntactic interoperability

In (van der Veer and Wiles 2006) syntactic interoperability is described as follows:

"Syntactic interoperability is usually associated with data formats. Certainly, the messages transferred by communication protocols need to have a well-defined syntax and encoding, even if it is only in the form of bit tables. However, many protocols carry data or content, and this can be represented using high-level transfer syntaxes such as HTML, XML or ASN.1."

Therefore, syntactic interoperability allows for a smooth data exchange between modules on a technical level. To allow for syntactic interoperability for spatial data, particular format descriptions such as standardized by the OGC can be used (e.g. Simple Feature Access).

3.1.1.4 Semantic interoperability

While syntactic interoperability assures that the input of one module can be read by another module, it must be additionally guaranteed that the values stored in the exchanged data represent the information needed for proper processing. This concept is known as semantic interoperability, which is described in IDABC (2004) as follows:

"Semantic interoperability is concerned with ensuring that the precise meaning of exchanged information is understandable by any other application that was not initially developed for this purpose. Semantic interoperability enables systems to combine received information with other information resources and to process it in a meaningful manner."

For example, using a raster file as input for a flooding module, the flooding module might inherently interpret the contents of the file as an elevation field. However, on a syntactic level, handing over a raster field representing values of a different measure (e.g. sea level pressure) would be a valid operation, yet leading to undefined behaviour of the module and consequently to useless results.

Semantic interoperability needs to be guaranteed by the author, as automated tests on semantic interoperability are difficult to undertake.

3.1.2 Data

Data used can come in any shape such as tabular data (e.g. comma separated value consisting of asset values for different street types), geodata or in form of any kind of proprietary data (potentially with weak interoperability capabilities). This data can be distinguished in terms of their type (e.g. specific geodata formats) and in terms of when they are generated.

Data that is generated during a simulation can be termed **dynamic data** (e.g. flood plains for the distinct time steps). During configuration of the system only their type is known.

The other type of data is **static data** where not only the type is known when configuring the system but also the content. An example would be surface elevation in shape of a digital terrain model. Such kind of data might additionally be pre-processed before being incorporated into the system.

3.1.2.1 Geodata

The focus on the approach lies in the incorporation of geospatial data, in particular of type vector and raster, which are common for geographic information systems.

To represent geospatial objects and phenomena such as natural hazards and infrastructure objects within a computational environment, typically two complementary concepts are used. First, the entity-based approach views space as to be populated by entities with clearly defined spatial boundaries and associated properties (e.g. the footprint of a building and its type of use). Second, the continuous field approach typically represents natural phenomena as a set of spatially varying values of some attribute such as precipitation, temperature or elevation (Burrough and McDonnel 1998).

There is a smooth transition between both concepts. For example, elevation information for distinct points in space and time typically is stored using the continuous field approach. However, this information can be directly used to derive drainage basins for watercourses, which then are rather represented as entities. On the other hand, precipitation values measured at meteorological gage stations, which are represented as entities can be used to compute a continuous field of precipitation values using interpolation methods.

Figure 3.3 depicts both concepts by giving concrete examples of their implementation in the form of rasters and triangulated irregular networks (TIN) for the continuous fields approach as well as in the shape of polygons and topological networks for the entity approach.

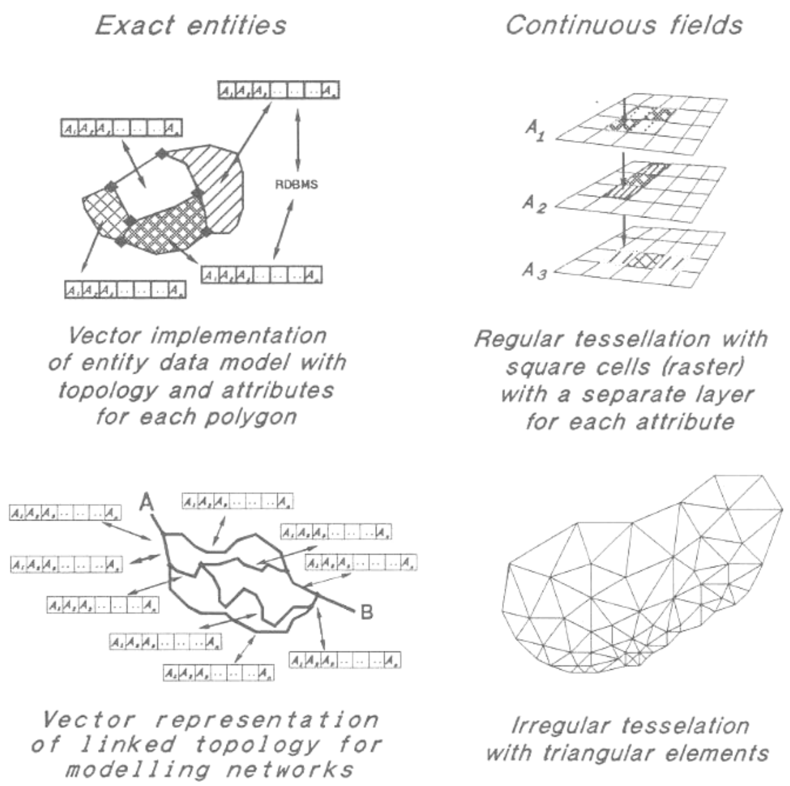


Figure 3.3: Different concepts to computationally represent spatial information (Burrough and McDonnel 1998)

3.1.2.2 Data Storage

During operation, in particular when used by several users, the system will likely produce high amounts of data. Therefore, efficient storage mechanisms will be needed to reduce storage load. For geodata, several possibilities exist depending on their type.

For example, for vector data a database solution should be considered: Static data (e.g. buildings with associated geometries and attributes such as type of use) can be stored in a database such as PostgreSQL with the PostGIS extension. Dynamic data (e.g. a table with values water depth and damage associated with each building) can then be stored in additional tables referencing the base data.

For raster data, efficient data formats such as NetCDF could be considered instead of the more common GeoTIFF format.

However, these approaches along with additional ones need to be investigated in detail. In addition, it is not clear yet which types of data will be exchanged between future modules and where data and modules may reside. Therefore, distributed computing architectures should be considered. Furthermore, data storages can be categorized by location and the type of access. For example, the location of data can be somewhere on the local file system, within the local network, or somewhere on the internet or in the cloud. In addition, accessing this data can come in different shapes. Data may be accessed by using an RDBMS (by accessing a table, view or retrieving data using a complex query), via certain specifications to retrieve data from within a file (e.g. by defining a time step, variable name, etc. for a NetCDF file) or by sending a request to a web-service.

3.1.3 Graphical User Interface

To ensure high accessibility and usability of the IDST, a flexible Graphical User Interface needs to be developed and adapted for each case study configuration. Its primary goal is to allow the user to define external inputs in order to run simulations and to evaluate the results. The external inputs to be chosen and the results to be shown to the user need to be carefully prepared by the authors by taking into account the background and knowledge of the user. Complex input forms should be avoided. Figure 3.4 and Figure 3.5 depict examples of how scenario definition and risk analysis may be conducted using a GUI. For example, as shown in Figure 3.4, defining the time step when a landslide is triggered can be conducted by selecting the corresponding option, which is present in the context menu when right clicking on the geometry. An external input for a flood can be selected using a combo box. Other means need to be investigated of how external inputs can be defined intuitively.

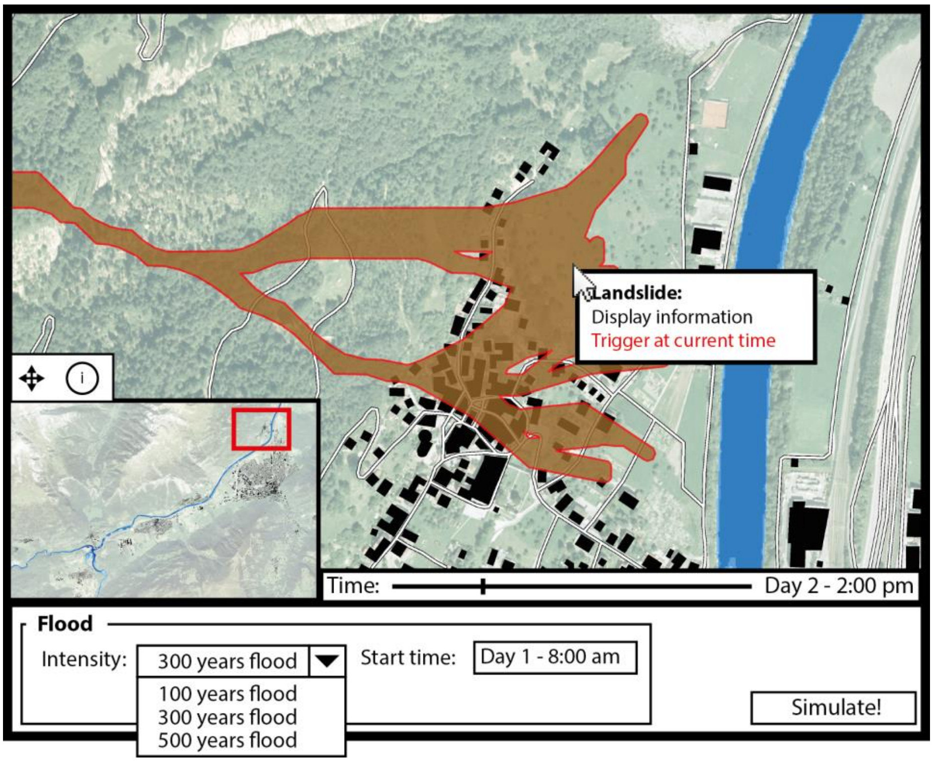


Figure 3.4: Simple example for the definition of external inputs

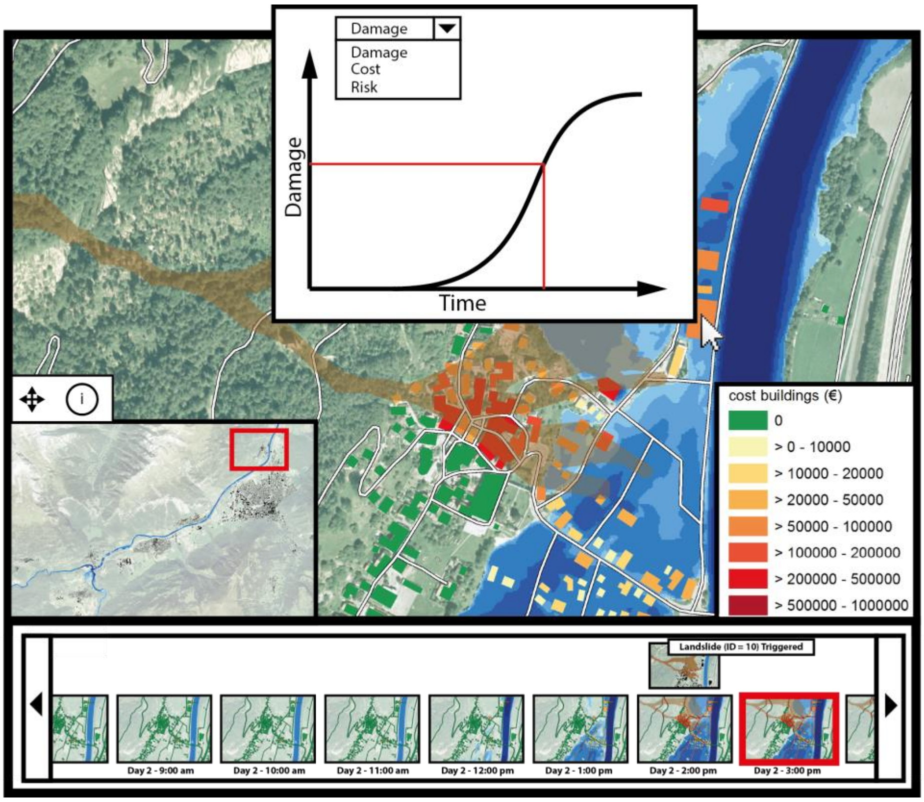


Figure 3.5: Simple example for the analysis of the results of a simulation

Figure 3.5 depicts possibilities to present the results of a risk analysis. For example, a specific measure (e.g. damage) associated with specific objects can be encoded in color or using other graphical variables. However, to get details on the course of a specific measure, the user can click on an object, which results in a graph to be displayed. Advanced methods to communicate the outcomes of the risk analysis process should be investigated, in particular in respect to probabilistic results and uncertainty.

It should also be considered to incorporate methods from the field of visual analytics (see e.g. Andrienko et al. (2008); Thomas and Cook (2005)) into the map-driven graphical user interface to facilitate analysis tasks.

3.2 Simulation

Once, the modules and data are assembled appropriately and the user interface is configured, the user may access the IDST to perform simulations. Running a simulation when specific external inputs are provided does this. These inputs may be defined by the user or potentially automatically when performing multiple runs (e.g. by sampling a certain distribution using the Monte Carlo Method). Examples for external inputs are:

- 500 year flood as input for a precipitation generation module
- Earthquake at position lat=10° lon=12° at time step 10 with magnitude 8 as input for a shakemap generation module
- Landslide with ID=5 at time step 30 as input for a road damage computation module

An external input can come in any transferable shape, for example in the form of a certain value (e.g. a single integer), a structure consisting of several values (e.g. a list of integers) or a complete file (e.g.

a shapefile). Commanding the system to perform a simulation will result in the execution of the modules in the order and fashion defined by the author. Examples for the results of a simulation are:

- Flood plain at time step 1, at time step 2, etc.
- Discharge value at time step 1, at time step 2, etc.
- Probability that landslide with ID=10 is triggered at time step 1, at time step 2, etc.

3.3 Architecture

One possible architecture for the IDST is depicted in Figure 3.6. Here a distinction is made between the IDST GUI, which is run on the client-side (e.g. using a web browser), and the server where data storage and module execution is performed. Data exchange between client and server may take place using different formats such as XML, JSON, PNG, and others be it for representing external inputs (e.g. by constructing a suitable XML file) or presentation of results (e.g. providing map-based visualization through OGC web-services such as WMS, WFS, and WCS). In this example, the IDST Process Workflow Engine is implemented in the form of a management system where data and modules can be added to a registry so that their location, their interfaces, the data they produce and receive and other information is stored. Authors then can access this information to define relations between modules, which again are stored in the registry. During execution, the system decides where new data has to be stored and makes this data accessible to modules as well as to the user.

Since the IDST and the overarching risk assessment process should be usable in a generic way, defining modules, their interconnections, incorporating system data as well as declaring external inputs should be performed easily. Therefore, an authoring tool for case study configurations would be beneficial.

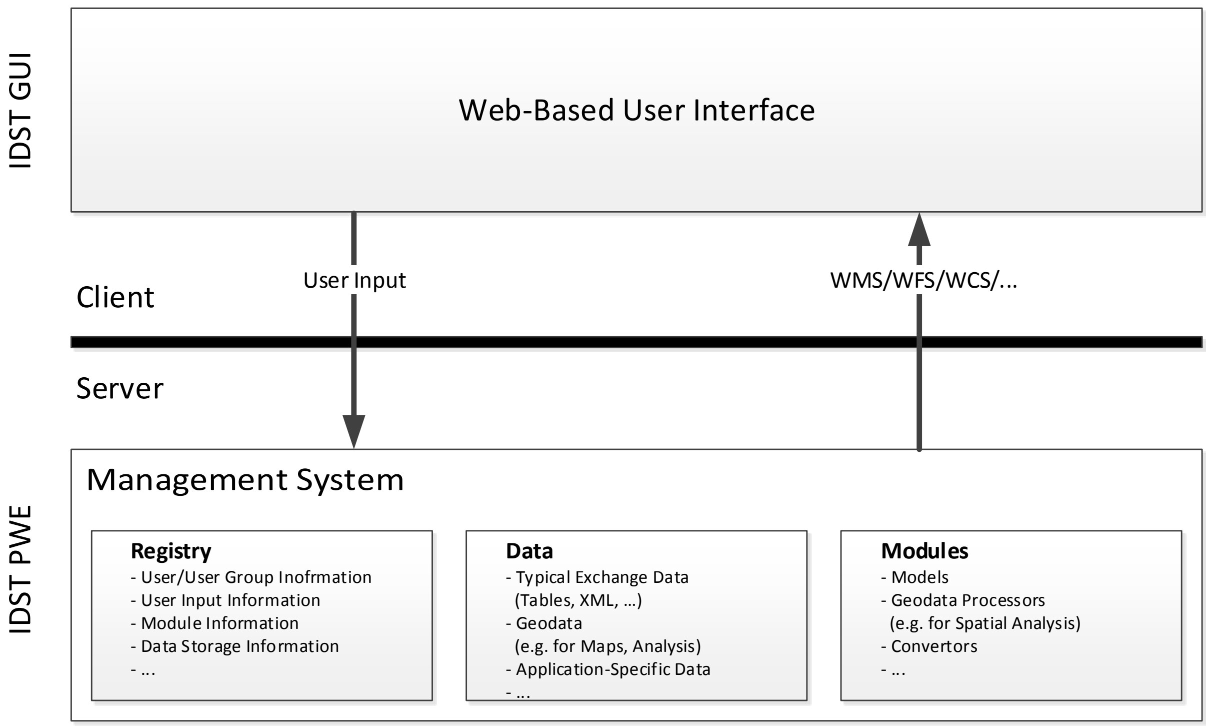


Figure 3.6. Example architecture for the IDST

Several workflow management application were identified which potentially may help with the process of defining and connecting different modules. Some of these are Taverna[2] (Wolstencroft, et al. 2013), OMS3[3], and jABC[4].

Special attention should be paid to OpenMI (Gregersen, Gijsbers and Westen 2007), an open standard to define model interfaces so that models can exchange information at runtime. The standard was already applied to different environmental models in particular from the hydrological domain and includes possibilities allowing models to query data from other models based on geospatial and temporal aspects.

Specifically for data conversion purposes, ETL applications provide suitable functionality. Examples for this kind of software are GeoKettle[5], Talend[6] and FME[7].

[2] http://www.taverna.org.uk
[3] http://www.javaforge.com/project/oms
[4] http://ls5-www.cs.tu-dortmund.de/projects/jabc/index.php
[5] http://www.spatialytics.org/projects/geokettle/
[6] https://www.talend.com/
[7] http://www.safe.com/fme/fme-technology/fme-desktop/overview/
(All accessed June 5, 2014)

4 EXAMPLE

In this section, the use of the overarching risk assessment process is demonstrated by using it to evaluation 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 as indicated in Figure 2.1.

The material provided via a WMS used to include basemap information to the maps in this section is copyrighted © by ESA / Eurimage / swisstopo, NPOC and free for use.

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 Rhein (see Figure 4.1).

4.1.1 Addressee

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.

4.1.2 Questions

Specifically the city administration would like to know their road related risk due to the occurrence of the 500 year flood and consideration of landslides. They would also like to know

- which buildings and objects are likely to be adversely affected by these hazards,
- the extent of this damage,
- the costs of restoring these objects so that they can once again provide an adequate level of service if they are adversely affected and
- how the damaged infrastructure will affect the ability of people to reach the hospital, and
- how the damaged infrastructure will affect travel time on the road network

4.2 System definition

The collection of all events, elements, consequences, assumptions, agreements and boundary conditions, which are necessary for the risk assessment, constitute the considered system. With this step all essential parts of the risk assessment are defined, this can only be reached in coordination with the city administration.

4.2.1 Define system boundaries

4.2.1.1 Define spatial boundaries

The spatial boundary of the system has been selected to be that shown in Figure 4.1. The system is spatially bordered by a bounding polygon which is aligned to the main valley of the region of interest[8] and covers an area of approximately 153km² in the Swiss coordinate reference system CH1903/LV03 (EPSG code:21781). All of the following geodata are defined for or transformed into this coordinate reference system. Many of these were extracted from the VECTOR25 dataset (swisstopo, VECTOR25 2014), the main source for topographic maps of Switzerland with a scale denominator of 25.000.

A digital terrain model of 6mx6m resolution based on the DTM-AV (swisstopo, Height Models 2014) is used to incorporate elevation information in this application. For more advanced modelling approaches, it is suggested to use a digital elevation model of higher resolution if possible. Also, it might be considered to use a digital surface model instead.

A military area is located in the periphery of the city of Chur being restricted for civil use. This region is created manually using official sources (VBS 2014) and has to be taken into account when modelling shortest routes and service areas.

Since the focus lies on the main watercourses, only those watercourses being labelled as “Fluss” (river) in the VECTOR25 database are taken into account. This classification is true for the watercourses Rhein and Hinterrhein and partly true for the watercourses Rabiusa and Plessur where the classification occasionally changes to “Bach” (stream). The whole geometry of the Plessur watercourse is used because it flows through the city of Chur and is therefore being considered particularly important. However, the watercourse Rabiusa is neglected, since it is only classified as “Fluss” in the very periphery of the target area. For future applications, it is suggested that a thorough examination is undertaken to identify watercourses relevant for the target area.

[8] SW Coordinates: 742670.0m/ 183390.0m, NE-Coordinates: 763360.0m/ 196900.0m

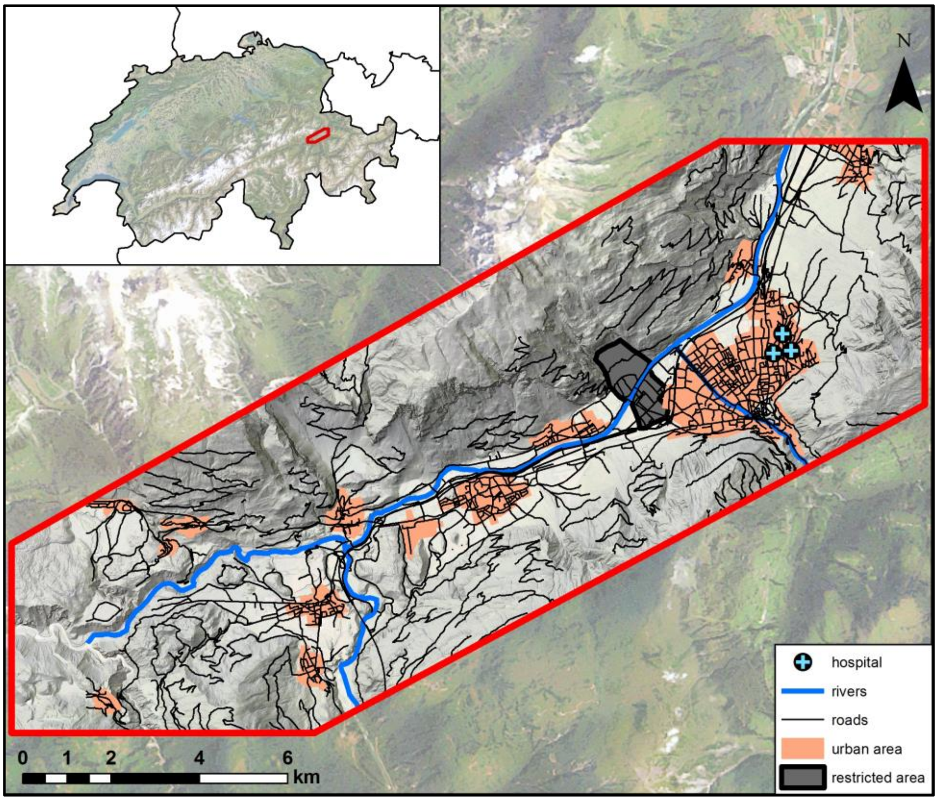


Figure 4.1: Application area. Note that buildings are aggregated to continuous areas in order to reduce visual clutter. For analysis purposes buildings on the footprint level were used

4.2.1.2 Define temporal boundaries

Since the answers to the questions given in Section 4.1.2 vary in time, they need to be given for different time steps during the scenario. 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 an 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 Define system elements

4.2.2.1 Source events

4.2.2.1.1 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. An example is shown in Figure 4.2. This data has grid cells with a spatial resolution of 1kmx1km and a temporal resolution of 1 hour. The original data is provided by MeteoSwiss.

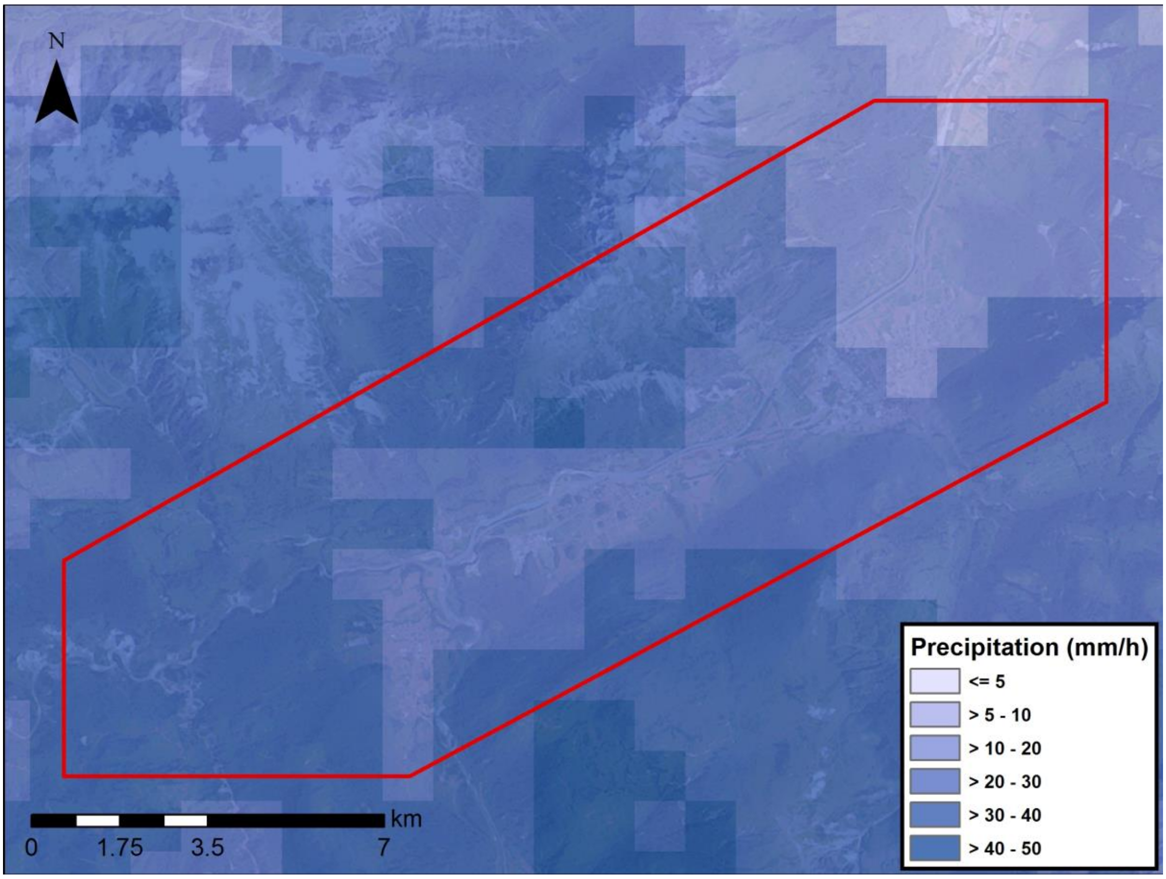


Figure 4.2: Radar Data for precipitation

4.2.2.2 Hazard events

4.2.2.2.1 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.

While the HMS tool is used to generate hydrographs the RAS tool is used to estimate the amount of water on each land surface area and in the rivers, using the HMS inputs. The process performed in this sample application is described in Section 5.3. It should be noted that these tools behave as black-box applications since only compiled files but not source code is available limiting its flexibility and extensibility.

To model the flow of water in the rivers, the RAS follows a simple one-dimensional, steady simulation approach for open channels. This method adopts a constant velocity and movement of the water along the flow path and is based on the continuity equation (conservation of mass), impulse-momentum equation, and Bernoulli’s equation (equation of energy conversation). For this, the tool needs hydrographs and the river network geometries. Additionally, dependent on the segment of the cross-section, different roughness coefficients based on Manning’s Values. The results of the model are comprised of a polygonal flood area as well as raster maps for inundation and flow velocity.

4.2.2.2.2 Landslide

In this scenario, the increase in soil saturation due to precipitation triggers one of the pre-modelled debris flows from the SilvaProtect project (Losey and Wehrli 2013) affecting the small town of Haldenstein at time step 38. These potential debris flows are modelled using the software packages MGSIM and dfwalk (geo7 2014) and need the following input data:

- To estimate potential source points of debris flows, a digital elevation model (e.g. to calculate slope, catchments) and geological data (e.g. lithology, permeability of the subsurface) have been taken into account.
- To model the range of the debris flow, a 2-parameter model has been used which takes into account slope, a sliding coefficient and the mass to drag ratio (Perla, Cheng and McClung 1980).
- Finally, to estimate the spreading of the debris flow, a random walk approach is followed where the probability of a subsequent cell to be chosen is based on its slope and the current flow direction.

4.2.2.3 Infrastructure events

4.2.2.3.1 Residential and Industrial Buildings

Information on buildings on the footprint level are taken from the swissBUILDINGS3D dataset (swisstopo, swissBUILDINGS3D 2014) and cover the following municipalities: Chur, Haldenstein, Felsberg, Tamins, Bonaduz. The buildings are represented by polygons and are additional enriched with information on their type of use (e.g. residential, industrial, agriculture) which are extracted from the dataset “Grundlagen Richtplanung Siedlung” provided by the Canton of Graubünden (geo.gr.ch 2014).

4.2.2.3.2 Hospitals

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

4.2.2.3.3 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 has been proven to be a reasonable trade-off between computational effort and accuracy. For reasons of performance, the segmentation process can be limited to those regions which are affected by a hazard at any time step during the scenario. For flooding, it is adopted that all roads affected by the flooding during the scenario can be selected by intersecting them with the flood plain with the greatest extent (time step 38). A similar approach can be followed to consider the landslide geometry. For buildings, such a segmentation is not needed since these geometries usually are of sufficient small size.

4.2.2.3.4 Road network

The road network for the target area is also extracted from the VECTOR25 dataset. Each road is represented by a linear geometry with assigned attributes on their type (swisstopo 2011). Roads of types “Fussweg” (footway) and “Feld-, Wald-, Veloweg” (agricultural, forest or bicycle way) are removed, because they are considered to be unsuitable for most motorized vehicles.

4.2.2.4 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 when the infrastructure network is not fully operational.

4.2.3 Define relationships between system elements

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.

4.2.3.1 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 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. The LRM treats a catchment area as a reservoir where inflow is stored in form of precipitation which is discharged with time lag. The grid-based travel-time model uses a grid with associated averaged travel lengths to the corresponding outlet in order to estimate the spatially varying duration needed for precipitation to reach the outlet. The used grid has a resolution of 2kmx2km and is intersected with the watersheds resulting in a set of cells and cell parts (see Figure 4.3).

These data generated using GeoHMS is then exported to HMS. As additional inputs, the precipitation data are imported as well as the monthly means of the rivers runoff rates. An example for a resulting hydrograph is depicted in Figure 4.4.

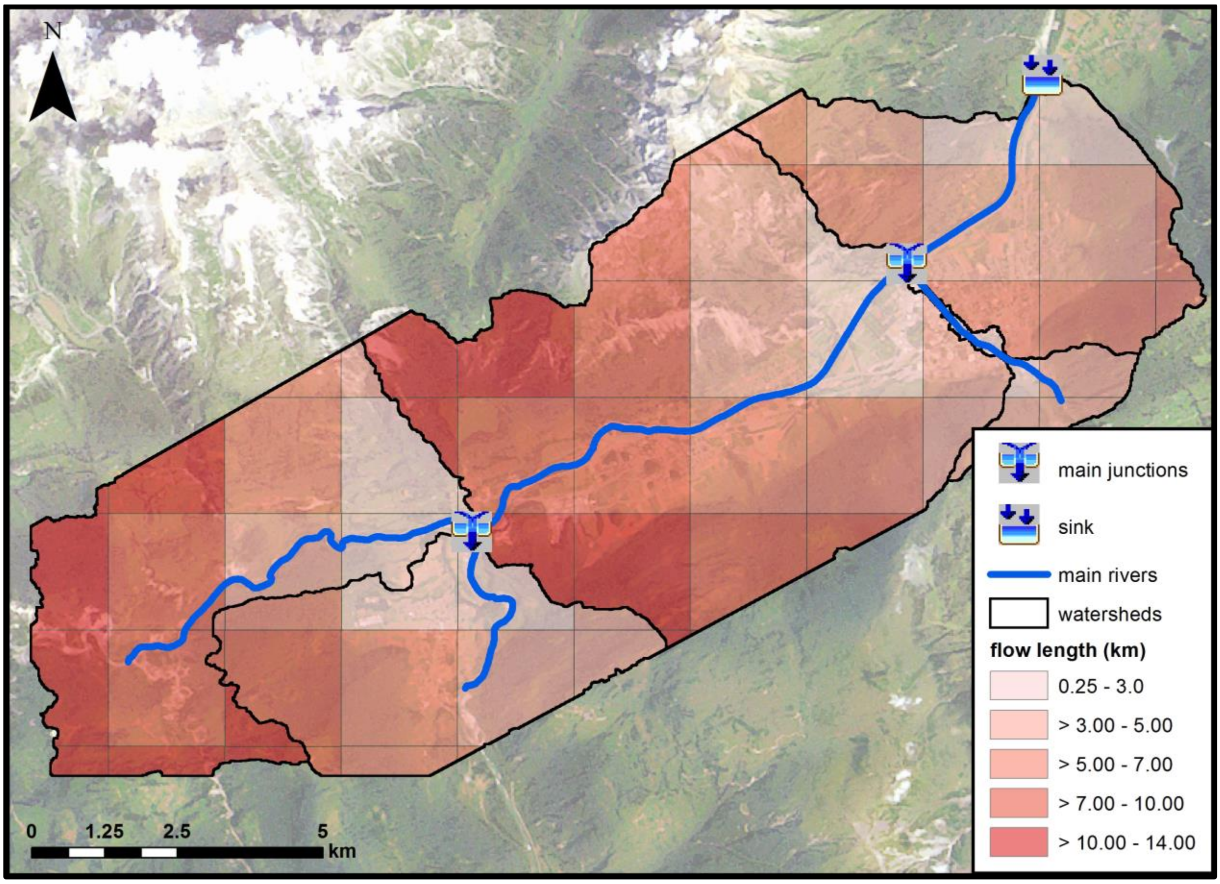


Figure 4.3: Grid-based travel-time

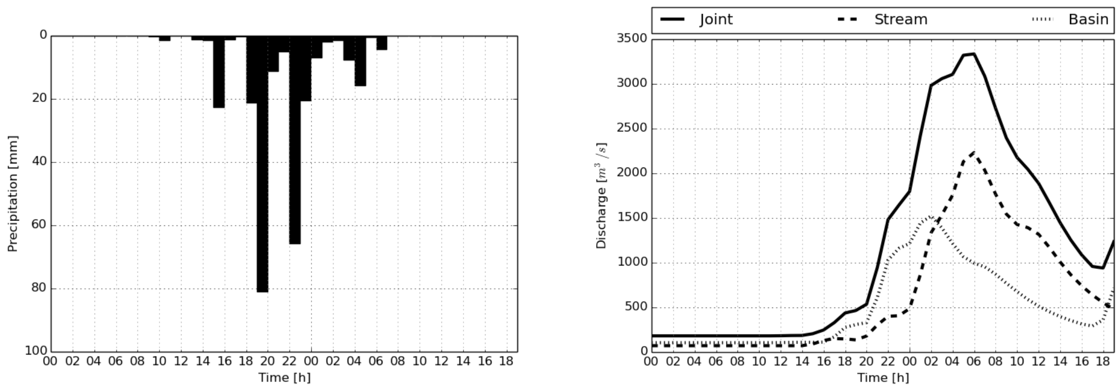


Figure 4.4: a) Hydrograph b) Discharge

4.2.3.2 Hazard-Infrastructure-Interaction

To estimate damage resulting from inundation, simple damage curves are used. These take into account the inundation value d $\epsilon\,[0,5]$ associated with the infrastructure object and return a dimensionless damage factor $\alpha\ \epsilon\,[0,1]$ where 0 represents no damage and 1 represents complete failure. The damage functions associated with the different categories are listed in Deckers, et al. (2010). For buildings affected by the landslide the damage is assumed to be 1 for both, roads and buildings independent of their type. An example is shown in Figure 4.5.

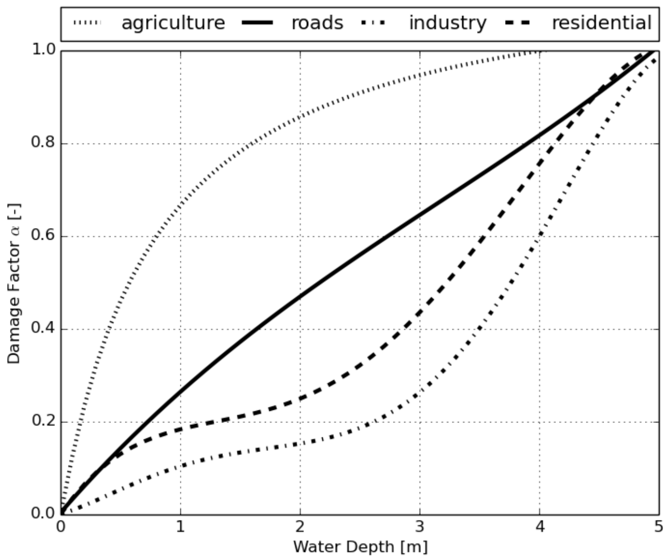


Figure 4.5: Damage functions

4.2.3.3 Infrastructure-Society-Interaction

It was assumed that if infrastructure was damaged that it would be restored to the condition it had prior to being damaged. These costs were estimated by multiplying the area of the affected object with the unit cost of constructing the object from scratch. For buildings, the area was directly derived from the geometry of the polygon. For roads, the area was calculated by multiplying the length of the linestring with the width associated with the corresponding road type. The unit values used were taken from Kutschera (2008) and are shown in Table 4.1.

Category	Value (€ / m²)
Residential	256.44
Industry	225.83
Mixed	431.98
Agriculture	2.27
Forestry	0.86
Water and Energy	254.82
Roads	92.08

Table 4.1: Unit cost of constructing each type of object

4.2.3.4 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. To refine this street model, roads crossing the restricted area are excluded from the dataset and only those roads are taken into account, which provide sufficient capacity. Also, impassable road segments due to natural hazards are excluded, e.g. by deleting segments with assigned inundation depths > 0.3m, resulting in a distinct road network for each time step. However, additional information such as one-way streets and turn restrictions are not taken into account. Also, errors might occur at bridge locations since these are by default treated as crossways. These limitations need to be kept in mind when performing network analyses and examining their results.

4.2.3.5 Network-Society-Interaction

The quantification of consequences related to travelling across the network resulting from the failure of infrastructure network nodes can be 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)

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 condition state.

In this example this additional time was estimated by determining the shortest paths to be used when the network was in a failed condition 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 (see Figure 4.6). 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.

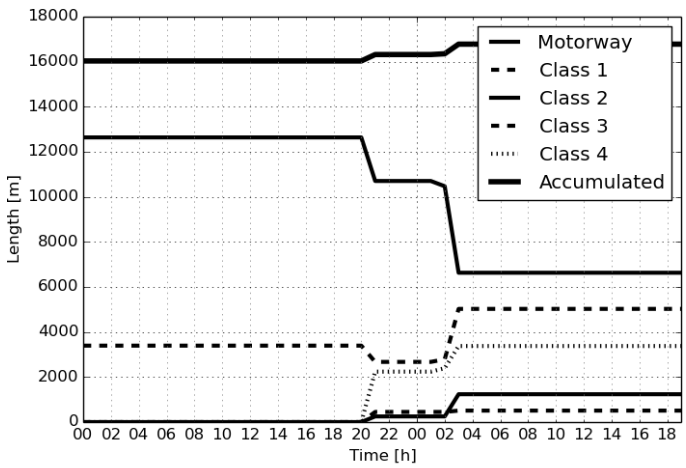


Figure 4.6: Composition of the shortest path by road category

4.3 Risk identification

4.3.1 Review of Historical Data

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"

(Hilker, Badoux and Hegg 2009) for the period ranging from 1975 to 2013 and in the database of the PLANAT (2014) project ranging back to several thousands of years.

4.3.1.1 Unwetterschadens-Datenbank

The database holds 43 natural hazard events located within the region of interest. From these, 27 fall into the category inundation/mudflow. The other 16 recorded events are either of type rockslide (5) or mass movement (11).

Some of these events damaged the infrastructure of the affected areas. Only 4 events have caused "high/catastrophic" damage from which each is of type "inundation/mudflow". Consequences include disruption of the railway system (11), of the road network (16) or bridges (17) and the power supply (1). Additionally, in 10 cases buildings were damaged. This underlines that examining the consequences of flooding and landslides on the infrastructure is of high relevance for the target area.

4.3.1.2 Planat

The planat database holds several entries on natural hazard events relevant to the target area. These include:

- Mudslide near Domat-Ems (21stApril 2013)
- Storm and Flood in Switzerland including the target area (21st/22ndAugust 2005)
- Mudslides near Schlans and Rueun (14th / 16thNovember 2002)
- Mudslide near Domat-Ems (24thJuly1981)
- Rockslide near Flims (~10'000 years ago)
- Earthquake with epicentre in Churwalden (3rdSeptember 1295)

4.3.1.3 Review of Previous Projects

In addition, two more recent projects, AquaProtect and SilvaProtect provide model based information on regions vulnerable to floods and landslides.

Information from the project AquaProtect consists of flood plains for the return periods of 50, 100, 250, and 500 years for the target area. The results from the project SilvaProject include geometries for (unconfined) debris flows, avalanches, stone falls and overbank sedimentation. Figure 4.7 illustrates this information for a subsection of the target area. It is obvious that buildings as well as the road network can be directly affected by these hazards.

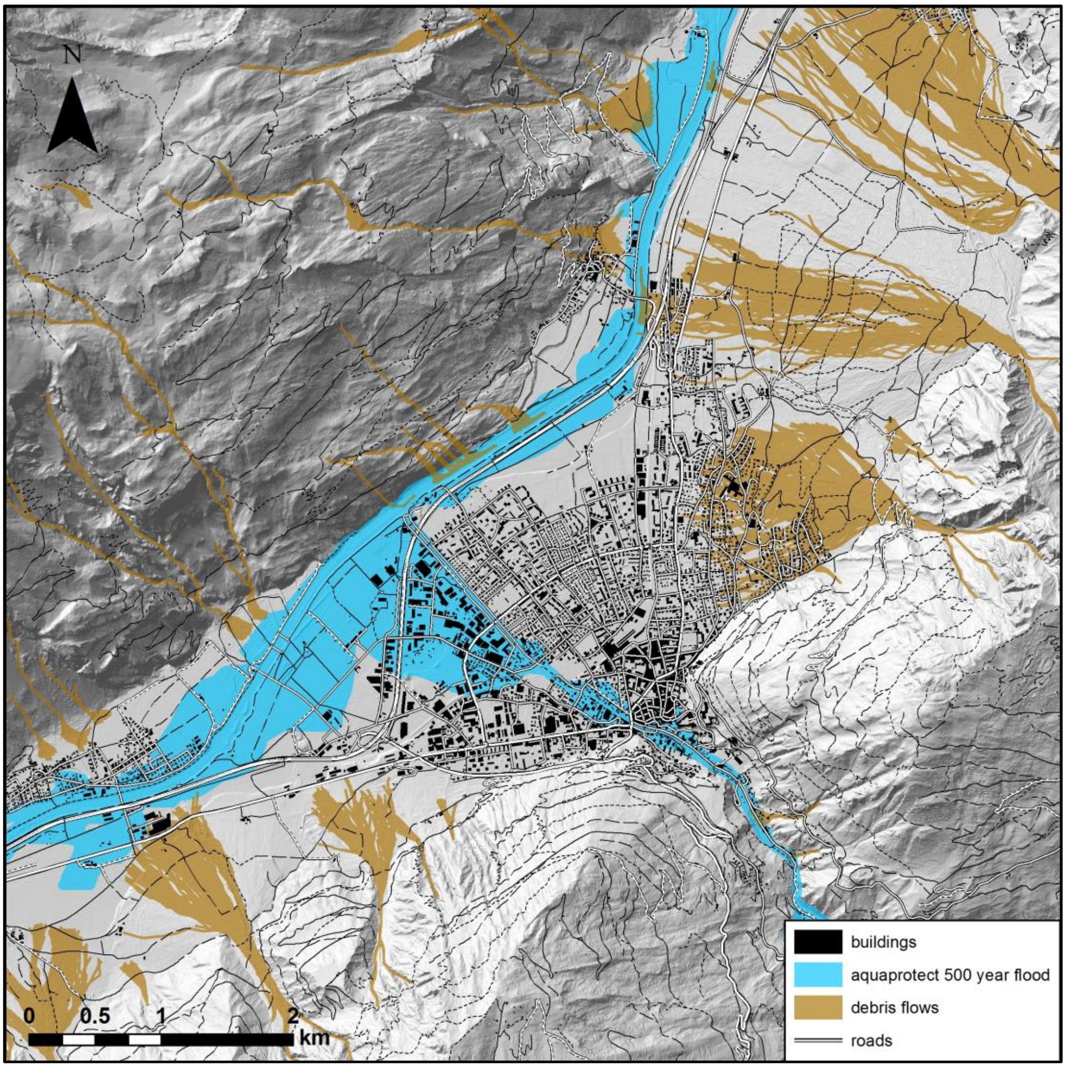


Figure 4.7: Subset of the results of the SilvaProtect project (brown: debris flows) and of the AquaProtect project (blue: 500 year flood inundation area). It clearly shows areas around the central town of Chur which are potentially affected by these hazards

4.3.2 Level of detail

Based on the initial questions, the risk assessment is conducted on a medium scale area where buildings are taken into account on the footprint level and streets are represented by connected linear geometries. Since the answers to these questions vary in time, they need to be given for different time steps during the scenario. For reasons of simplicity and efficiency only simple hydrological and hydromechanical models for flood modelling as well as pre-modelled geometries of landslides (Losey and Wehrli 2013) that might occur in the future of the target area are used. Also, basic damage and cost models are used. Cascading effects between natural hazards are not considered. In a post-processing step, the results of the assessment need to be prepared in such a way that they can be easily grasped using e.g. visualizations such as diagrams, maps and videos. These along with descriptive information should then be sufficient for the city administration to answer the questions mentioned above.

4.3.3 Scenarios

Only one scenario was considered. This scenario was comprised of the following events: Source event was rainfall, the hazard events were 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 were derived from the buildings, road sections and hospitals being in specified damage states. The network events were derived from the different combinations of damage states of the different infrastructure objects. The societal events were 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, physical and mathematical models. Event trees and GIS analyses are used.

4.4.1 Event tree

An event tree was developed to examine a chronological series of subsequent events and consequences. This allowed a logical evaluative process which works by tracing forwards through a causal chain to model risk. This approach was applied to the system early in the design process to identify potential issues that may arise rather than correcting the issues after they occur.

4.4.2 GIS analysis

Most of the analysis was performed using GIS software. 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 were used.

One example is the assignment of water depth to an infrastructure object, in order to calculate associated damage and cost. Here, for a building, all pixels that intersect with this building were investigated in order to find the highest inundation value. For roads, the water depth at the centroid of the segment was extracted. This process is illustrated in Figure 4.8.

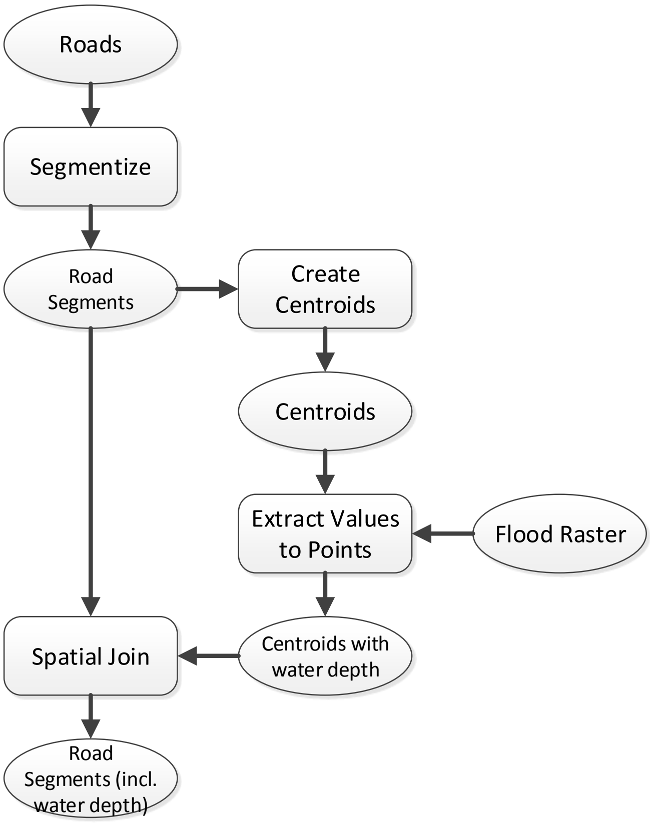


Figure 4.8: Sample GIS work flow: Assign water depth to street segments

4.4.3 Statistical analysis

In practice, the assumption about independent data is usually taken into account by selecting annual maximum values of the variable of interest (e.g. annual maximum discharge). In this way, an annual maximum series is established, which is the most common type of series used in flood frequency analysis.

The annual maximum series contains information only on the largest peak flows from every year, which are not necessarily all floods. It may happen that the second (or third, etc.) largest value from a wet year represents severe flood and is larger than annual maximum in a dry year; that kind of information on floods is lost in annual maximum series.

In spite of this shortcoming the annual maximum values for both precipitation and discharge were used to estimate the relationship between the return period and the intensity. Example curves are shown in Figure 4.9.

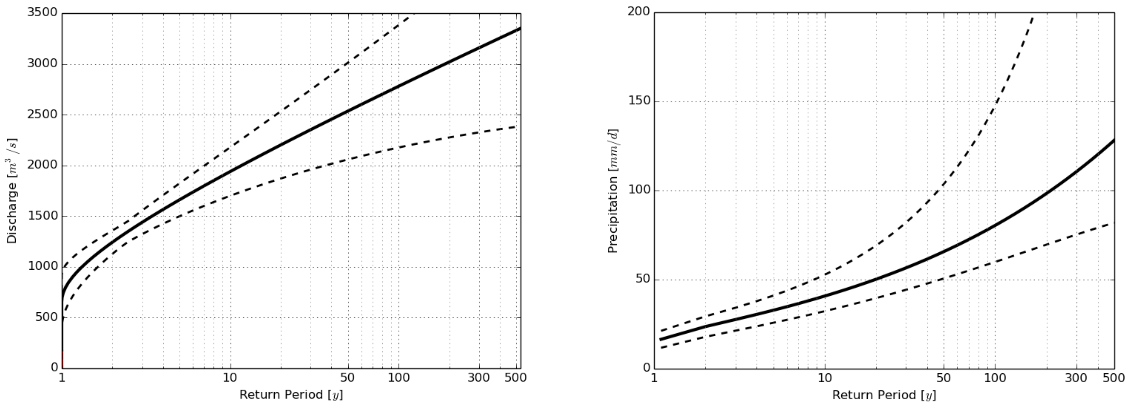


Figure 4.9: Statistical analysis of precipitations and discharges

4.4.4 Graph theory

For the infrastructure network analyses based on graph theory was performed, e.g. to estimate the increased travel time required to reach the Chur hospital when the infrastructure network was not fully operational. An example illustration of shortest route is shown in Figure 4.10.

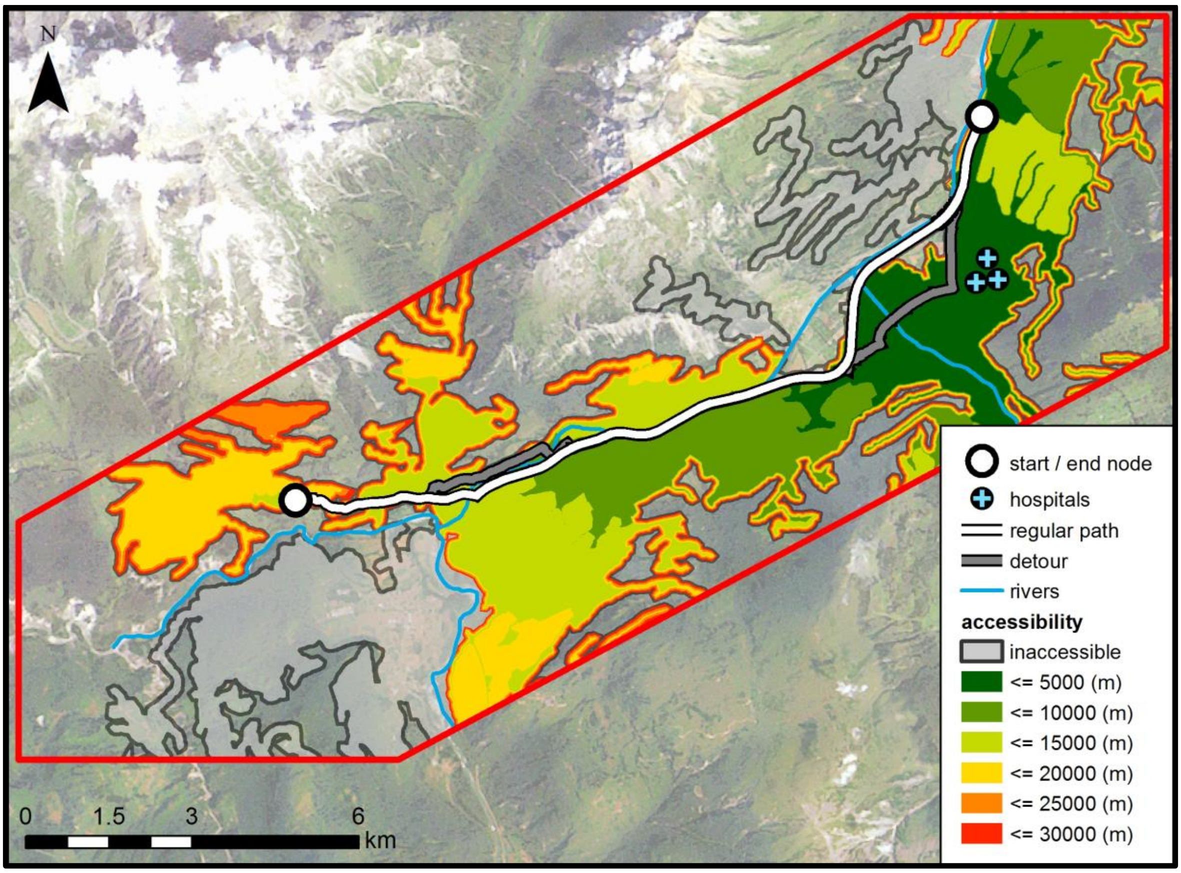


Figure 4.10: Consequences of inaccessible routes on the shortest route between two nodes and the accessibility of the hospitals

4.4.5 Aggregation of risk

As stated earlier, in order to aggregate risk that has been estimated based on different scenarios, 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. As the maximum damage is recorded for each infrastructure object over the three-day period, and there is only one maximum recorded over the three-day period the costs can be added. 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 (see

Figure 4.11).

It was considered that the costs required to restore the objects from damaged condition states to fully operational due to either floods and landslides were 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 amounting to a total value of approximately 11.8 Mio € (flood only: 8.0 Mio €) for buildings and 4.4 Mio € (flood only: 3.8 Mio €) for roads.

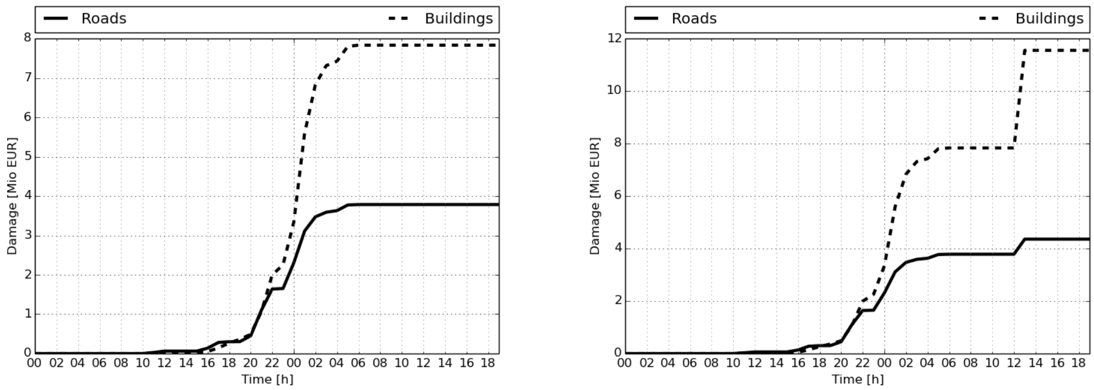


Figure 4.11: Development of total direct consequences for roads and buildings in the target area. a) flood only b) flood and landslide

The costs related to the disruption of traffic on the road network were estimated by counting the number of additional hours of travel time that was required on the network while the network was not operational (see Figure 4.12). These costs were added for each time step in the three-day period. In this case study it was assumed that all road sections were restored to normal immediately following the three-day period. The estimation would be significantly more complicated if this assumption was not made and instead it the time until actual repair of the infrastructure was estimated and the travel on the network was modelled for this entire duration.

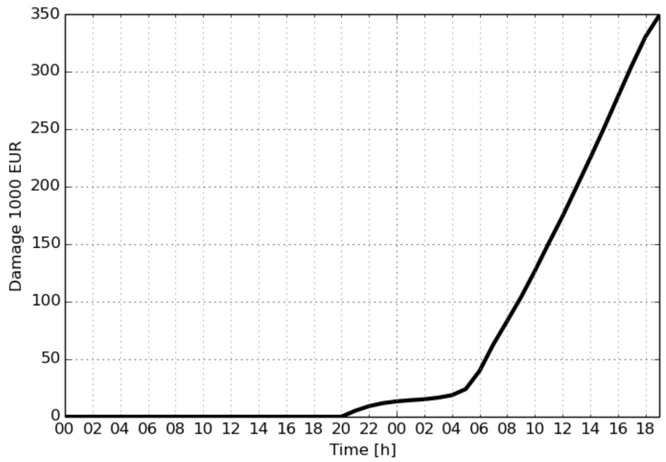


Figure 4.12: Indirect consequences due to detours

Based on this information, it was estimated that the costs due to additional travel time were 0.35 Mio €.

With 16.2 Mio. € consequences for rebuilding the infrastructure and 0.35 Mio € consequences for extra travel time for persons going to the hospital. The total consequences associated with the investigated scenario are 16.55 Mio. €.

As we are only interested in this example with the flood event that produces exactly the flood intensity associated with the 500 year flood and this flood has a return period of 1/500, the annual risk related to the 500 year flood is 0.033 Mio. €

4.5 Risk evaluation

The risk evaluation was not done as it falls outside of the risk assessment process. If a complete risk management process was being completed this work would need to be done in conjunction with the city administration of Chur. The results coming from the risk analysis (e.g. Figure 4.13) would support this task in order to plan further analyses, safety measures or risk treatments.

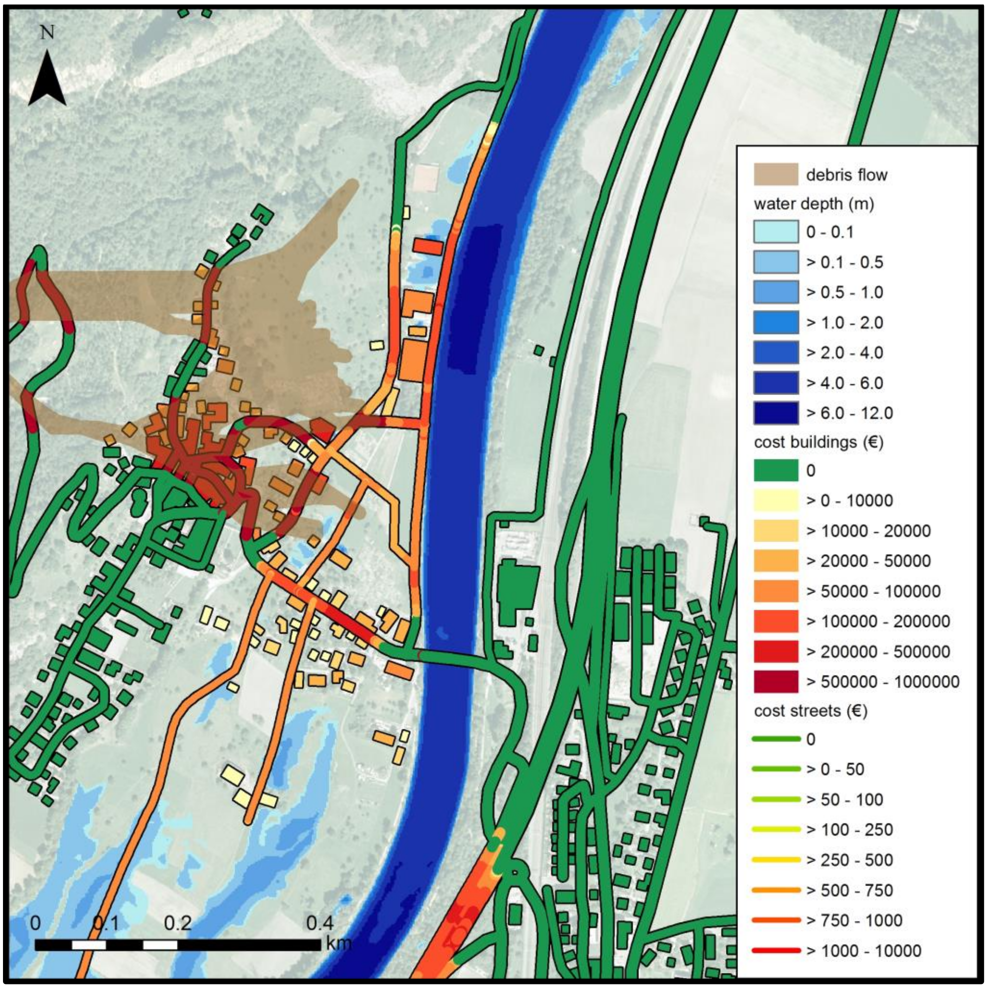


Figure 4.13: Hazards and infrastructure losses at Haldenstein

4.6 Summary

The example, although simple with respect to the number of scenarios investigated, demonstrates that the proposed overarching risk assessment process is useful in the assessment of infrastructure related risk due to natural hazards. It also shows that the methodology can be implemented in a way so that an infrastructure manager has computer support.

Next steps in the development of the example will be to consider multiple scenarios, comprised of more initiating events, more hazard events, more infrastructure events, more network events and more societal events. The example will also be extended to take into consideration the temporal and spatial uncertainty of the occurrence of these events. Optimistically the attempt to extend the example in this way will lead to new ideas as how to simplify the estimation processes so that the risk assessment processes does not become too computationally expensive.

5 EXAMPLE IT SUPPORT

In this section, the steps undertaken to support the risk assessment process in the example are described. This includes the description of the general workflow, the description of the distinct modules as well as the input and output data. Additionally, it is pointed out which data is considered dynamic data and static data using the terminology introduced in Chapter 3. Whether or not a dataset is considered dynamic or static varies depending on the analysis requirements. For example, start and end node for the shortest path may also be selectable by the user rather than being "hard coded" in the system. Additionally it is described which pre-processing steps need to be undertaken in order to create the static data. These pre-processing steps and corresponding data are depicted in yellow colour, in appropriate figures, to distinguish them from dynamic and static components.

The modules used mostly represent either stand-alone tools or self-made scripts that perform specific tasks by using the ArcGIS Python-API. Executing the stand-alone tool and scripts was mostly performed manually. The workflow is additionally categorized in distinct logical units to ease their description. The whole workflow is attached to this document in Appendix B. The datasets, along with their type and other characteristics, are explained in Appendix E.

5.1 Precipitation generation

The first step was to create precipitation data that can be used to simulate a flood of a certain intensity. This was assumed to be associated with a heavy rain fall event which was estimated by extrapolating existing rain fall data. More precisely, in this simple approach, this was done by linearly scaling existing precipitation data in the form of a NetCDF raster file (1kmx1km spatial resolution covering Switzerland, 1h temporal resolution covering 744h for the month August from which only 72h were used from 7.8.2007 to 9.8.2007) by the factor of 42.5 using the NetCDF Operators (NCO). This value was chosen heuristically to retrieve discharge values corresponding to a 500 year flood in the following flood computation module. This is illustrated in Figure 5.1.

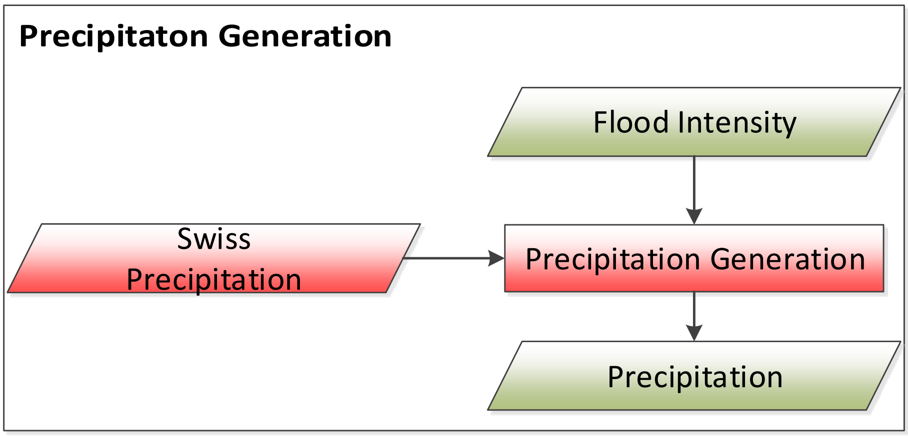


Figure 5.1: Steps to undertake to generate suitable precipitation data

5.2 Discharge modeling

The desktop-application HEC-HMS was used for discharge modelling. This software first had to be set up for the region of interest by providing information on the river network, river junctions and others (pre-processing). This data was incorporated in the basin model file, which was the primary input for HEC-HMS. Creating the basin model involved a variety of steps that need to be undertaken primarily using GeoHMS, a support software for use within ArcGIS. These steps are depicted in the following diagram and will not be described in this document. However, further information on HEC-HMS can be found in the manual (Hydrologic Modeling System HEC-HMS). The iterative workflow which is proposed when performing HEC-HMS simulations is attached in Appendix C. The pre-processing steps undertaken to create a basin model as input for HEC-HMS are shown in Figure 5.2.

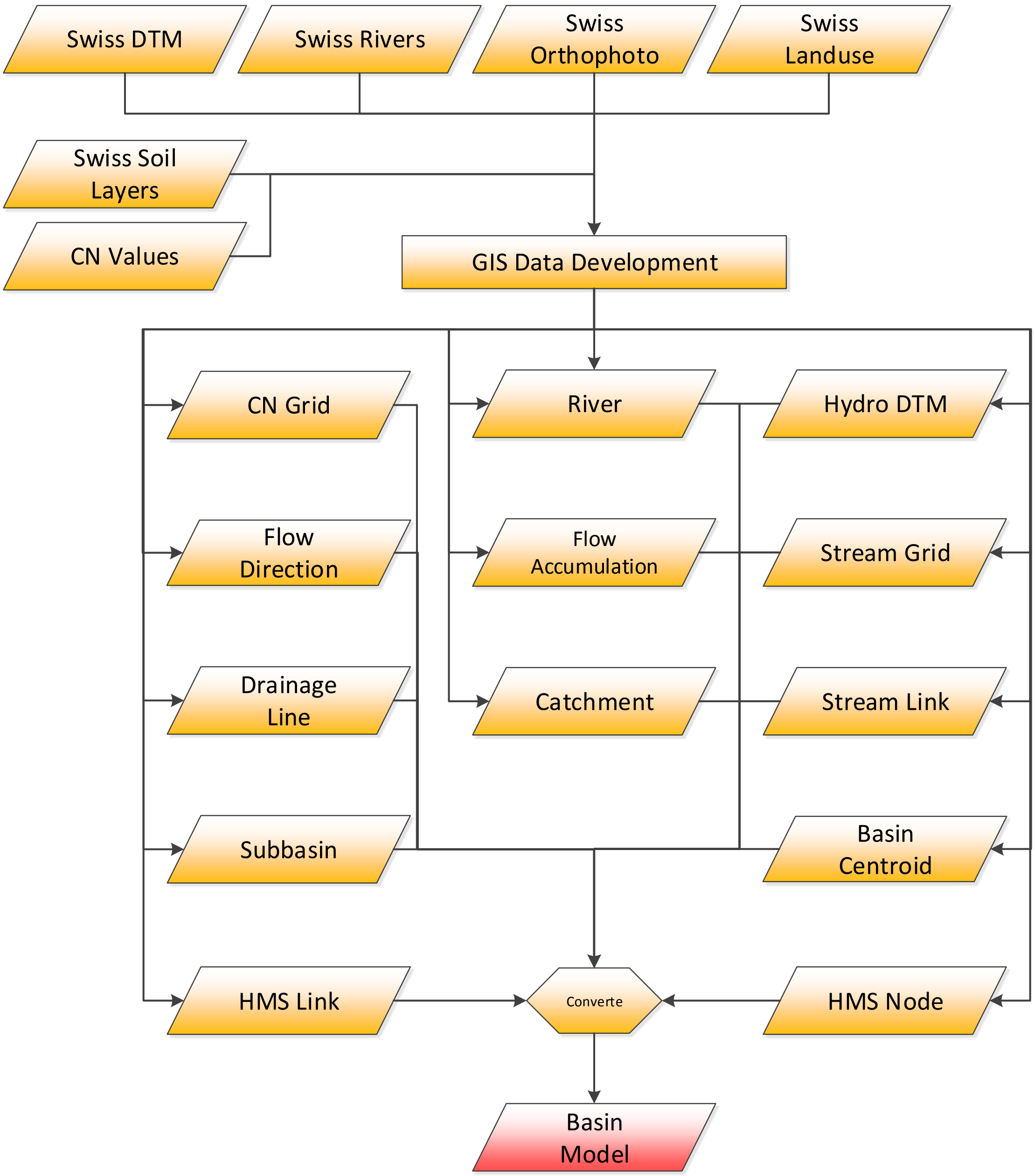


Figure 5.2: Preprocessing steps undertaken to create a basin model as input for HEC-HMS

After the HMS project was set up, precipitation data was imported into the HEC-HMS. As the software only reads DSS file formats, the NetCDF file was converted. This was done in two steps. First by converting the NetCDF file to a series of distinct ASCII-Grid files (one for each time step) using ArcGIS. Second, using the tool “asc2dssGrid.exe” coming with the HEC-GridUtil package to convert these ASCII-Grid files to the DSS format.

Boundary conditions were defined manually within the HEC-HMS. After running the HEC-HMS using these inputs, the software produced precipitation values for the local grid cells and a time series of discharge values for the distinct nodes of the river network.

The process is illustrated in Figure 5.3.

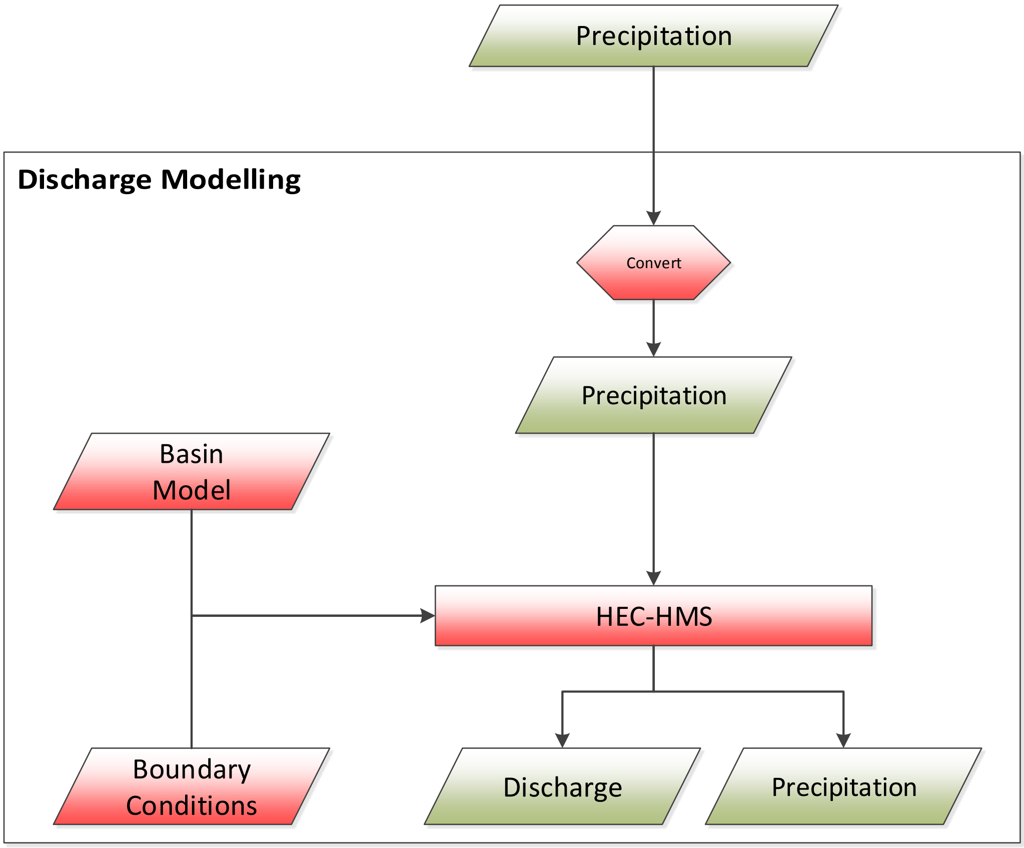


Figure 5.3: Process to generate discharge data using HEC-HMS

5.3 Flood modeling

Flood modelling was performed using HEC-RAS. This desktop-based software, like HEC-HMS, first needed to be set up for the region of interest by providing a RAS GIS import file. This again was created using an ArcGIS interface application called HEC-GeoRAS. The data involved to set up this import file are depicted in the following diagram. The pre-processing steps are shown in Figure 5.4.

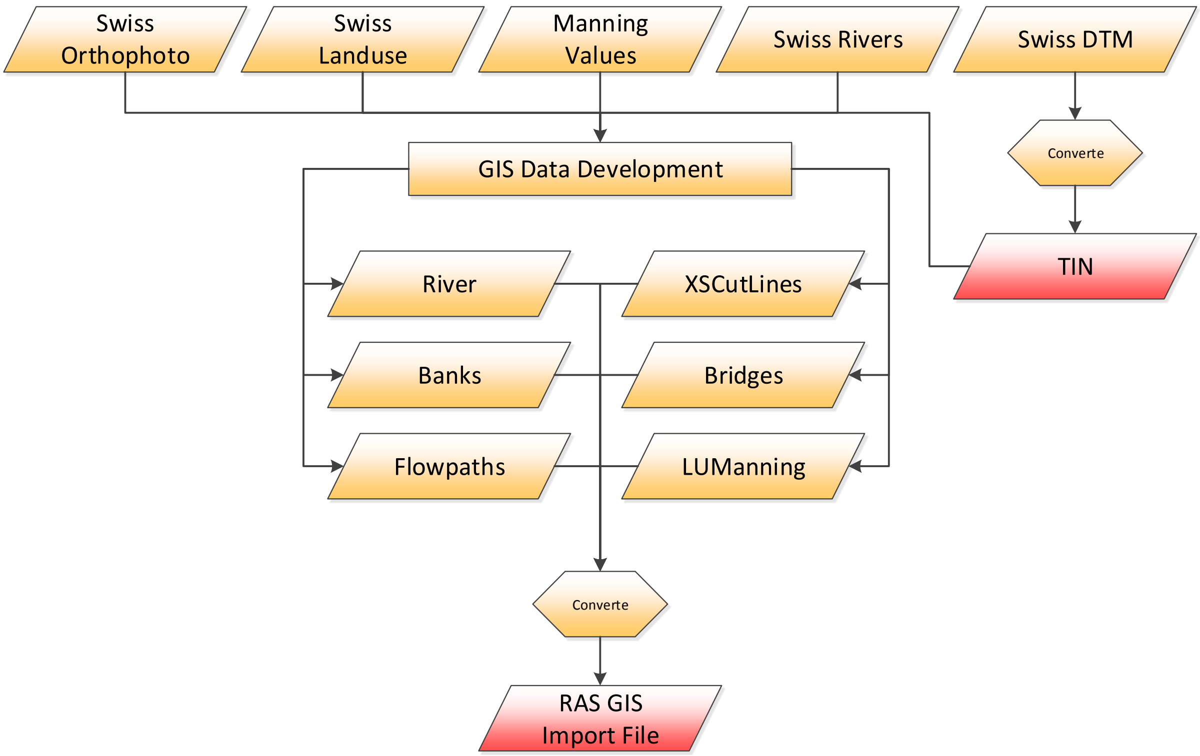


Figure 5.4: Preprocessing steps undertaken to create a RAS GIS import file using HEC-GeoRAS.

Afterwards, the discharge file computed by HEC-HMS was imported into the HEC-RAS as base data for flood modelling. The modelling results were created as a HEC-RAS specific database, which could not be directly read by GeoRAS and could, therefore, not be used within ArcGIS. Therefore, a conversion tool accessible from GeoRAS was used to generate a readable xml-based data format. This was then used to generate a set of typical geodata file formats. The generated files were one raster for each time step for the velocities and one raster for each time step for inundation depth. Each were encoded in the ESRI Grid file format. Additionally, the extent of the flood plain was created as a vector file in the shapefile format for each time step. The whole workflow is included in Appendix D. More information on HEC-RAS can be found in the user's manual (HEC-RAS 2010). This process is illustrated in Figure 5.5.

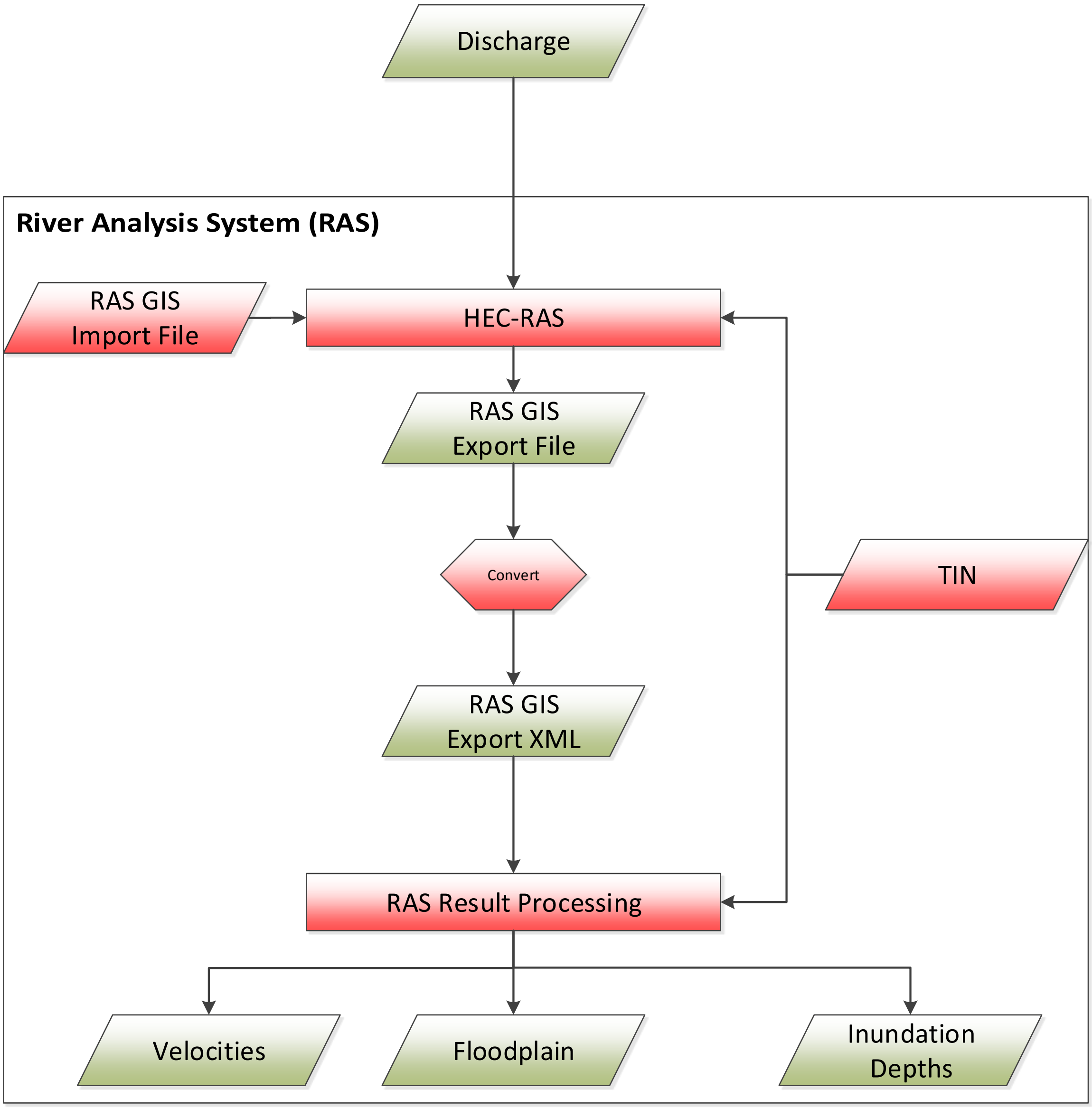


Figure 5.5: Process to generate flood data using HEC-HMS

5.4 Flood post-processing

Post-processing of flood data was done to more efficiently perform the next steps of the workflow. First, the flood plain with the greatest extent was determined and taken as a basis to select only those infrastructure objects, which would be affected by the flood. Determining this flood plain is done manually.

Second, for some computations inundation depths were presented in aggregated form in the sense that inundation depth values may only stagnate or increase in time. This ensured that the damage associated with buildings was not decreasing again when the flood ebbs away. This operation was performed using a Python script accessing the ArcGIS API. Although simplified, the process basically involved the following operation: For each time step the history of each cell was scanned to find the maximum value until this time step. These maximum values were then stored in a new file. These steps are illustrated in Figure 5.6.

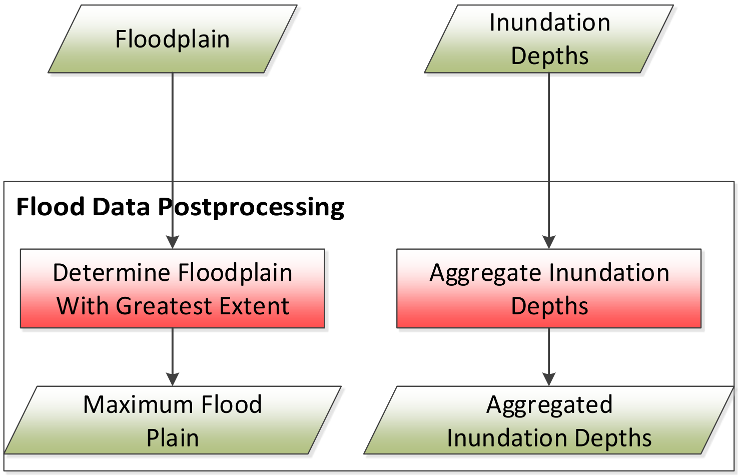


Figure 5.6: Postprocessing steps to be performed on flood related data

5.5 Landslide triggering

Triggering the landslide was performed heuristically. This involved the selection of a suitable landslide affecting buildings and roads, as well as, the selection of a suitable time step when the landslide should be triggered. The geometries used were from the SilvaProtect database. The data needed to select a landslide to be triggered is illustrated in Figure 5.7.

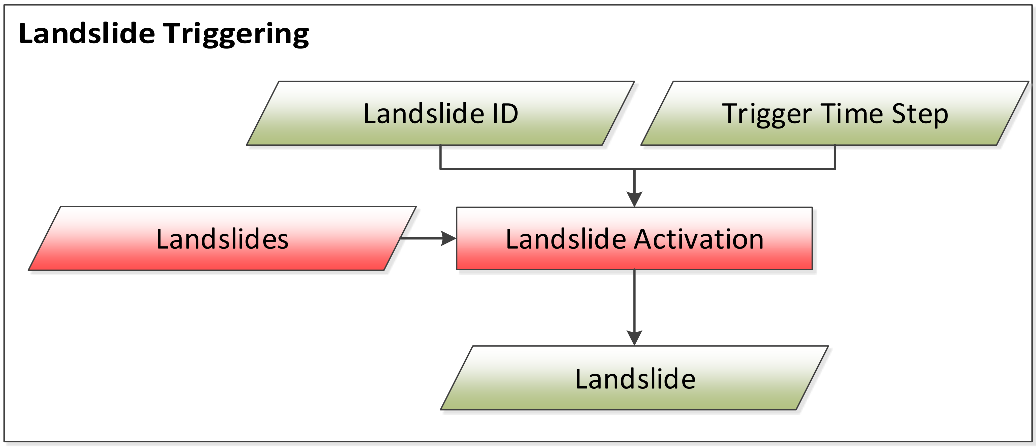


Figure 5.7: Data needed to select a landslide to be triggered

5.6 Damage and cost calculations

Damage and cost calculations were performed for both, buildings and roads, incorporating the relevant vulnerability curves for damage based on inundation depths and the landslide. However, both system element types had to be enriched with additional information during the pre-processing stage. For buildings, the land use type was added (e.g. residential area, industrial area) so that better estimations of damage and therefore costs could be made. The pre-processing steps for buildings are shown in Figure 5.8.

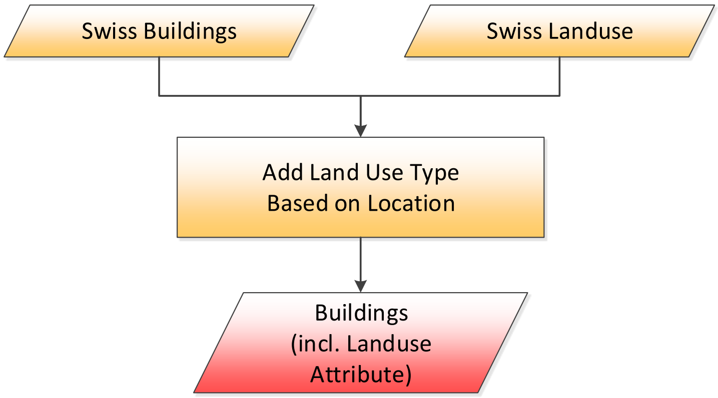


Figure 5.8: Preprocessing step for buildings

For roads, the road width was used to estimate the costs associated with the damage. Therefore, it was necessary to obtain the road widths for each class of road using a GIS and adding them to the attribute table. Additionally, roads with unsuitable road classes were deleted from the dataset. This process is illustrated in Figure 5.9.

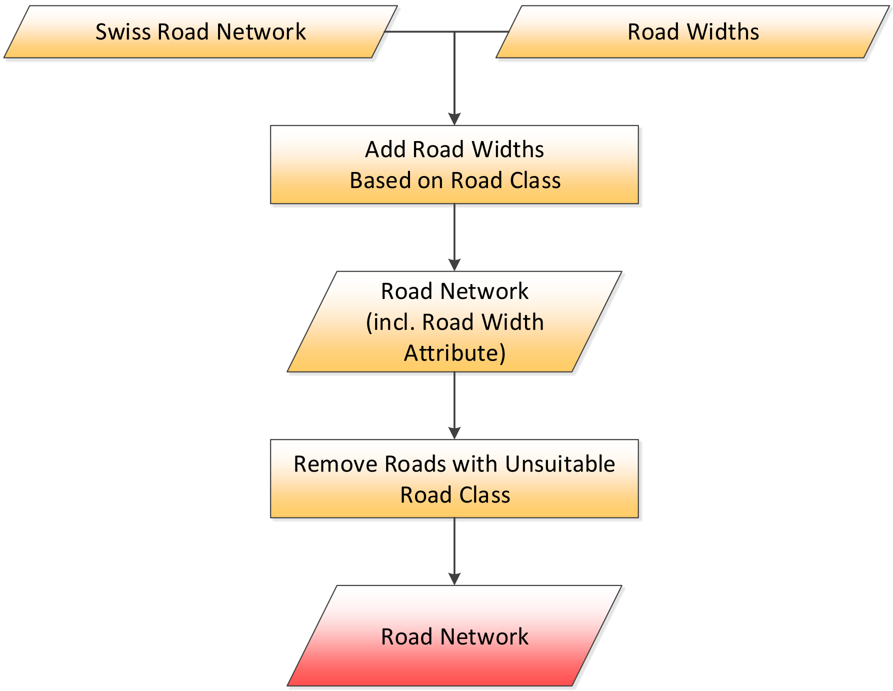


Figure 5.9: Preprocessing steps for the road network

Damage and cost calculation were performed in two steps. First, both measures were computed for the aggregated inundation depths for each time step. To reduce computational effort, the floodplain with greatest extent was used to determine which infrastructure objects might be affected by the flood.

For the road network, the affected geometries were additionally split by an interval of 4m to provide a feasible resolution to compute where the damage occurred. These functions were done using standard GIS functionality, namely overlays (e.g. intersect) and the field calculator of ArcGIS. Afterwards, it was checked if the landslide was already triggered for the current time step and if so, the damage is computed for all system elements hit by it. The damage for all affected elements is then set to maximum. These tasks again can be undertaken using standard GIS functionality. The process to perform damage and cost calculations is given in Figure 5.10.

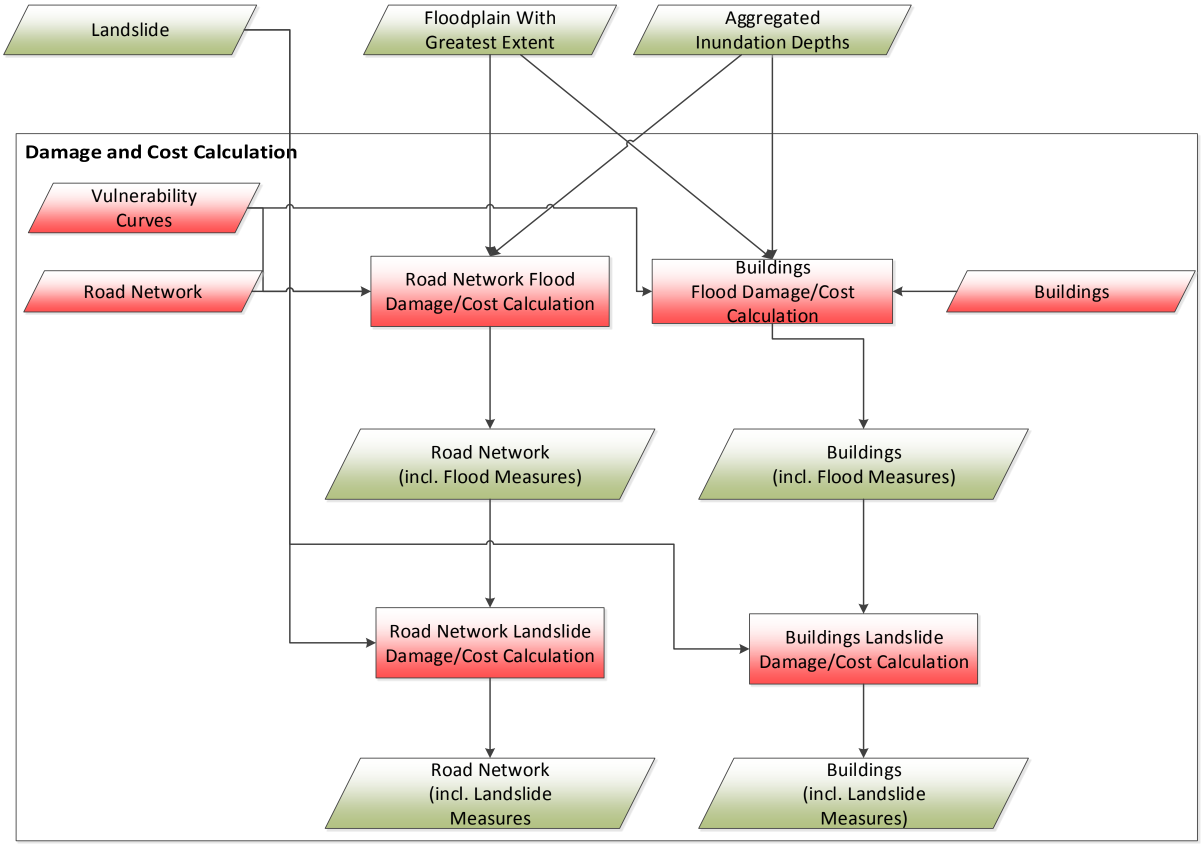


Figure 5.10: Process to perform damage and cost calculation based on flood and landslide data

5.7 Network Analysis

To compute the consequences of the load of network elements on the performance of the network, several steps need to be undertaken.

The first step was network preparation. Here, unpassable segments were identified and removed from the network so that routing over these segments could not occur. This was done by filtering all road segments where the inundation value was greater than 0.3m and subsequently removing them from the dataset. The second step was to transform the geometrical network into a topological network using ArcGIS Network Analyst so that it was possible to perform routing operations on it.

The catchment areas of the hospitals were then computed using the Service Area function of the Network Analyst. Therefore, hospital geometries in the form of point geometries were imported as source nodes into the Service Area Layer along with the distance values for the catchment areas (in this case 5000m, 10000m, 15000m, 20000m, 25000m, 30000m). The restricted military area was included by making the roads in this region impassable.

For shortest route computation, the start and end node of the route, as well as the impassable routes in the restricted area were again specified. The result was a linestring consisting of the geometries of the roads being part of the shortest route. In order to determine the length of the roads in each road class on the shortest route, an intersection with the underlying road network was done. This was done using the standard GIS functionality primarily using ArcGIS' "intersection" and "dissolve" function. The aggregated lengths for the road in each class were exported to a csv-file.

The processes to conduct the network analysis is given in Figure 5.11.

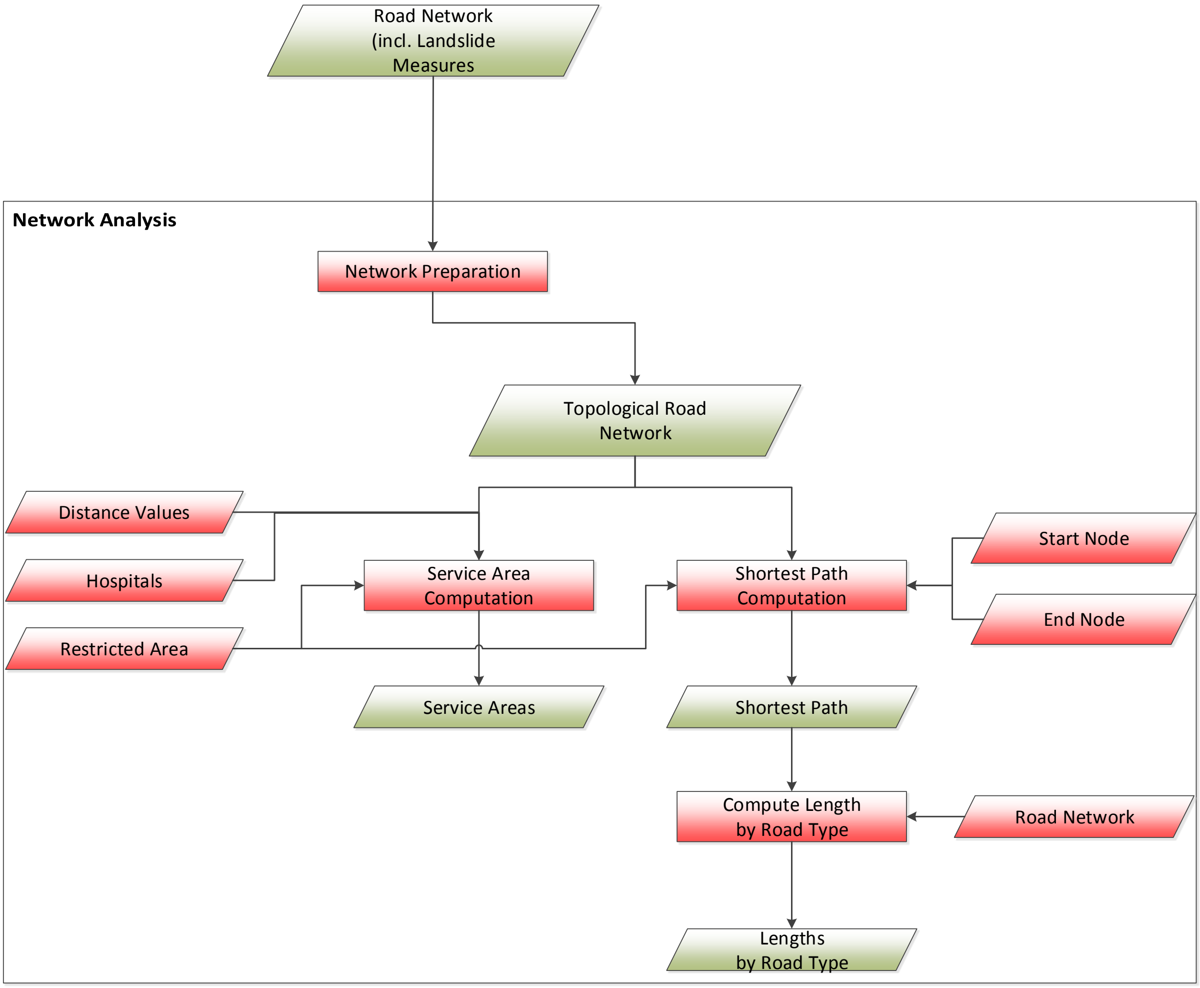


Figure 5.11: Processes to undertake network analyses based on a damaged road network

6 CONCLUSION

This report contains the preliminary version of the proposed risk assessment process, an explanation of how it can be supported from the IT point of view and an example of how it can be used.

The point of preparing this preliminary version, with all of its rough edges, is to transfer this knowledge to the participants of the INFRARISK project, in an effort to focus, or harmonise, the work of all involved.

Even in its current form it is believed that the proposed risk assessment process would be useful to infrastructure managers in the assessment of their infrastructure related risks due to natural hazards.

The risk assessment process is applicable for different types of infrastructure, different types of hazards and different types of consequences. It can take into consideration both simple and complex system representations and therefore an also incorporate non-cascading and cascading events.

This process will now be tested through its use by the participants in the assessment of risks in the case studies. It will most certainly be modified, based on the experiences of this endeavour, but the process that will emerge will be substantially more applicable by actual infrastructure managers in environments where they are to work with many multiple partners.

In addition to testing the proposed process more work will be made to expand the process to deal with 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.

On the IT support side further work will include the investigation of other software solutions to avoid being dependent on specific suppliers, i.e. in order to utilize the full potential of the proposed conceptual framework, it is suggested to use freely available and modifiable, i.e. open-source, components for implementation.

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APPENDIX A: TERMINOLOGY AND ABBREVIATIONS

Table A.1: Terminology (1/3)

Term	Definition
Acceptable risk	A level of risk, in which, society is not willing to execute interventions to reduce the risk. The acceptable level of risk depends on possible interventions and ability of society to execute an intervention. This is synonymous with tolerable risk.
Bayesian probability	The likelihood or degree of belief of an event occurring.
Black Swan	Option 1: An event for which no statistical distribution exists. It can be an event that occurred previously but never before occurred at an assumed low probability magnitude. Option 2: A hazard or hazard scenario that has not been modeled but if it occurs will result in higher consequences that anything else modeled.
Causal analysis	A process to describe and/or estimate the probability of the occurrence of precursor events, i.e. events that lead to other events or causes.
Consequence	The result of an event. It may be seen as positive or negative. It may or may not be directly monetisable.
Consequence analysis	A process to describe and/or estimate subsequent events and setting a value to these events.
Critical infrastructure	Infrastructure considered to be essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people.
Damage state	A state in which an object does not provide an adequate level of service.
Element at risk	An aspect of the system that plays a significant role in the determination of risk, e.g. if the variation of the number of persons living in an area has a large effect on the risk in the area, than this element of the system is considered to be an element at risk
Failure	The inability of an object to provide an adequate level of service, e.g. if an adequate level of service of a bridge includes having a safety margin of x and following an earthquake it has a safety margin of x -1 it has failed, or if an adequate level of service of a road section includes having no cracks and following a flood it has cracks, it has failed.
Fault	When an object does not work as intended it is said to have a fault, e.g. the bearing of bridge does not provide the lateral displacement it was intended to provide, or the steel of which a track is made does not have the specified yield stress. A fault does not mean that the object provides an inadequate level of service.
Frequentistic probability	The probability determined using theoretical arguments or adequate statistical data.
Hazard	Any event or a sequence of events that can lead to consequences. e.g. earthquake or earthquake which leads to ground accelerations which leads to physical damage of a bridge.
Hazard identification	A process to determine the hazards and hazard scenarios to be considered in an analysis.
Hazard scenario	A combination of multiple hazards that can lead to negative consequences, e.g. earthquake leads to ground accelerations and flood leads to high water levels, together they lead to physical damage of a bridge and a road section.

Table A.1: Terminology (2/3)

Term	Definition
Interested party	Person or group having an interest in the performance of an organization. Examples: Customers, owners, people in an organization, suppliers, bankers, unions, partners or society.
Intervention analysis	A process to identify possible interventions to change risk.
Mitigation	A process of selection and execution of interventions to reduce the consequences of a particular event.
Object	Something part of physical infrastructure that is generally thought of as one piece, e.g. a bridge, a road section, a tunnel.
Objective risk	An estimate of the risk obtained using theoretical arguments or adequate statistical data (for example the annual expected fatalities from car accidents) or from quantified risk analysis methods (QRA, PRA).
Reliability	The ability of an object to provide an adequate level of service, e.g. fulfill code requirements, over a given period of time (e.g. design life).
Residual risk	The risk remaining after an intervention has been executed to minimize risk or the decision has been made to execute no intervention to minimize risk.
Risk	The multiplication of the probability of occurrence of an event and its consequences for a given hazard, area and time period.
Risk acceptance	A process of determining that no intervention should be executed to minimize risk
Risk analysis	A process to estimate risk once it is known what scenario(s) is(are) being investigated. Risk analysis is synonymous with risk estimation.
Risk assessment	A process to identify and analyse risks
Risk avoidance	A process of not becoming involved in a situation, with which risk is associated.
Risk communication	The process of exchanging or sharing information about risk between the decision-maker and other stakeholders.
Risk control	A process to ensure that the level of risk is acceptable/tolerable.
Risk estimation	A process to estimate risk once it is known what scenario(s) is(are) being investigated. Risk estimation is synonymous with risk analysis.
Risk evaluation	A process to evaluate the risks estimated in risk analysis, and the significance of these risks to all involved stakeholders.
Risk identification	A process to determine the causal chain of events that could happen, i.e. the scenario that could happen
Risk financing	Financial resources secured to ensure that interventions to execute interventions to change risks.
Risk management	The process to evaluate and change risk.
Risk optimization	A process to minimize the negative risks.
Risk perception	Way in which a stakeholder views a risk, based on a set of values or concerns.
Risk reduction	A process of selection and execution of interventions to reduce risks.
Risk retention	The decision that no intervention should be executed to minimize risk.
Risk transfer	A process of shifting the risk associated with one situation from one stakeholder to another.
Risk treatment	A process to determine what needs to be done once the risk is estimated. A process of selection and execution of interventions to change risk

Table A.1: Terminology (3/3)

Term	Definition
Safety	The state of having a low probability of being hurt or killed.
Safety management	A process to ensure to that there is an adequate level of safety
Sensitivity analysis	A process to describe and/or calculate the effect of variations in the input data and underlying assumptions in general on the final result.
Stakeholder	An individual, group or organization that can affect, be affected by, or perceive itself to be affected by, a risk
System	A bounded group of interrelated, interdependent or interacting elements forming an entity that achieves a defined objective in its environment through interaction of its parts.
Tolerable risk	A level of risk, in which, society is not willing to execute interventions to reduce the risk. The acceptable level of risk depends on possible interventions and ability of society to execute an intervention. This is synonymous with acceptable risk.
Value at risk	The maximum consequences that can occur due to the occurrence of a hazard or hazard scenario, e.g. the maximum number of fatalities and the maximum number of building to be restored multiplied by the cost of restoring these.
Vulnerability	The risk related to a specific event or combination of events. It is seen as a subset of risk. For example, the vulnerability related to an earthquake occurring leading to a bridge collapsing is estimated assuming that an earthquake occurs and estimating the probability of the ground accelerations knowing that the earthquake has occurred and multiplying these probabilities with the probable consequences.

Table A.2: Abbreviations

Abbreviation	Meaning
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
ASN.1	Abstract Syntax Notation One
AV	Amtliche Vermessung (engl. official cadastral surveying)
CRS	Coordinate Reference System
CSV	Comma Separated Value
DSS (file format)	Data Storage System
DSS (information	Decision Support System
DTM	Digital Terrain Model
EPSG	European Petroleum Survey Group
ESRI	Environmental Systems Research Institute
TIFF	Tagged Image File Format
GIS	Geographic Information System
GML	Geographic Markup Language
GUI	Graphical User Interface
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IDST	INFRARISK Decision Support Tool
IT	Information Technology
JPEG	Joint Photographics Expert Group
JSON	JavaScript Object Notation
NCO	NetCDF Operators
NetCDF	Network Common Data Form
OGC	Open Geospatial Consortium
PNG	Portable Network Graphics
PWE	Process Workflow Engine
RAS	River Analysis System
RDBMS	Relational Database Management System
TIN	Triangulated Irregular Network
W3C	World Wide Web Consortium
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Map Service
XML	eXtensible Markup Language

APPENDIX B: GENERAL WORKFLOW

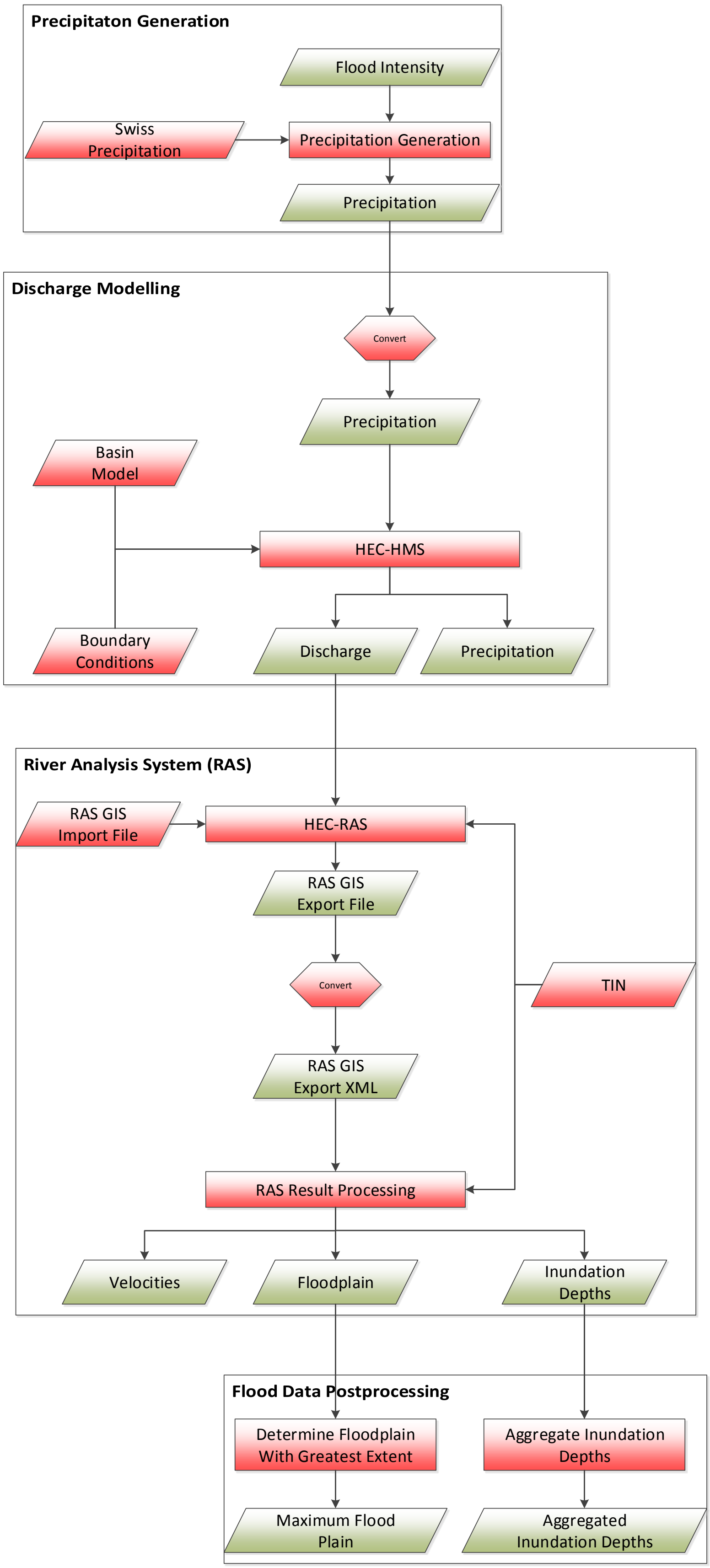

Figure B.1: General workflow part 1

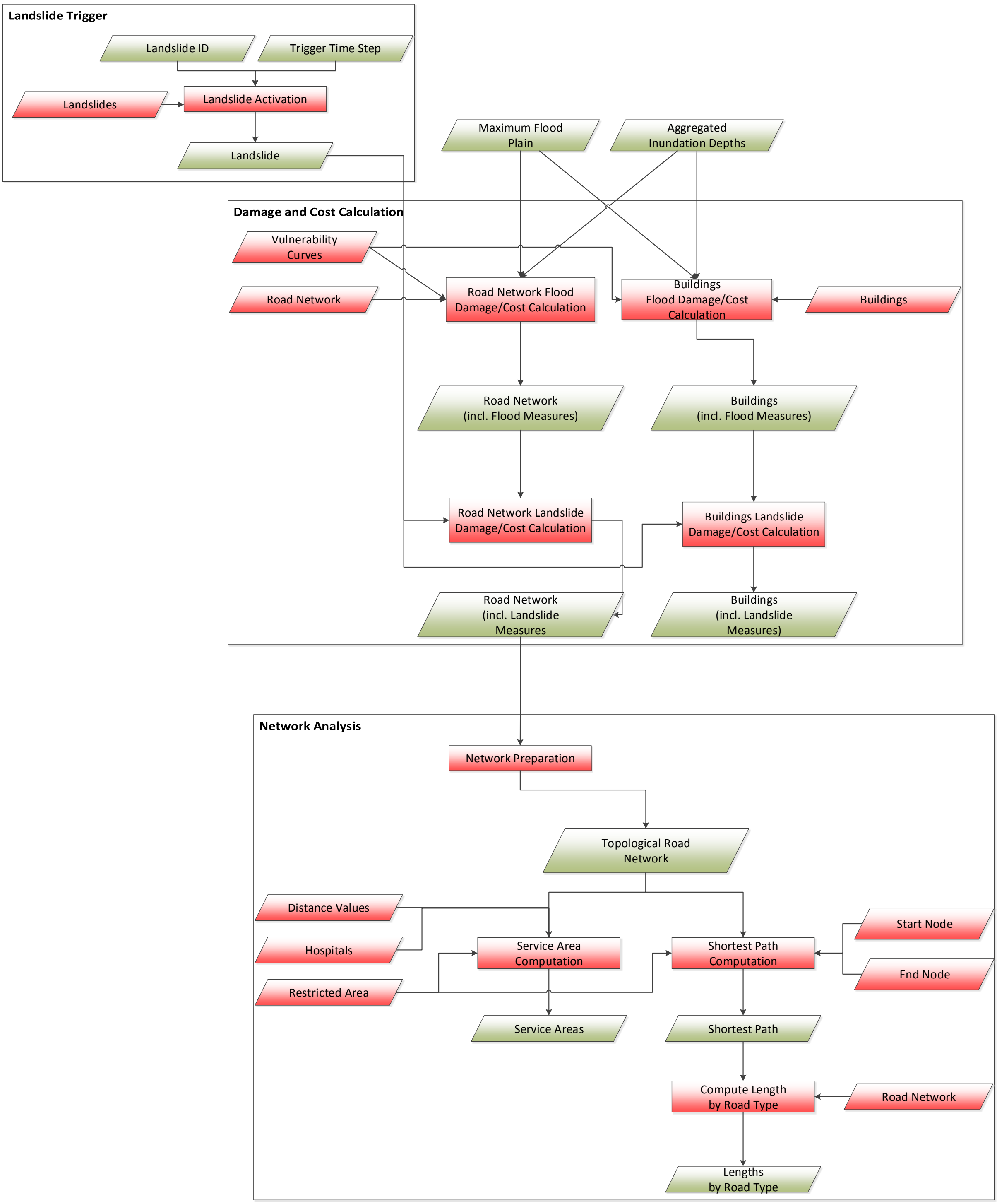

Figure B.2: General workflow part 2

APPENDIX C: HEC-HMS WORKFLOW

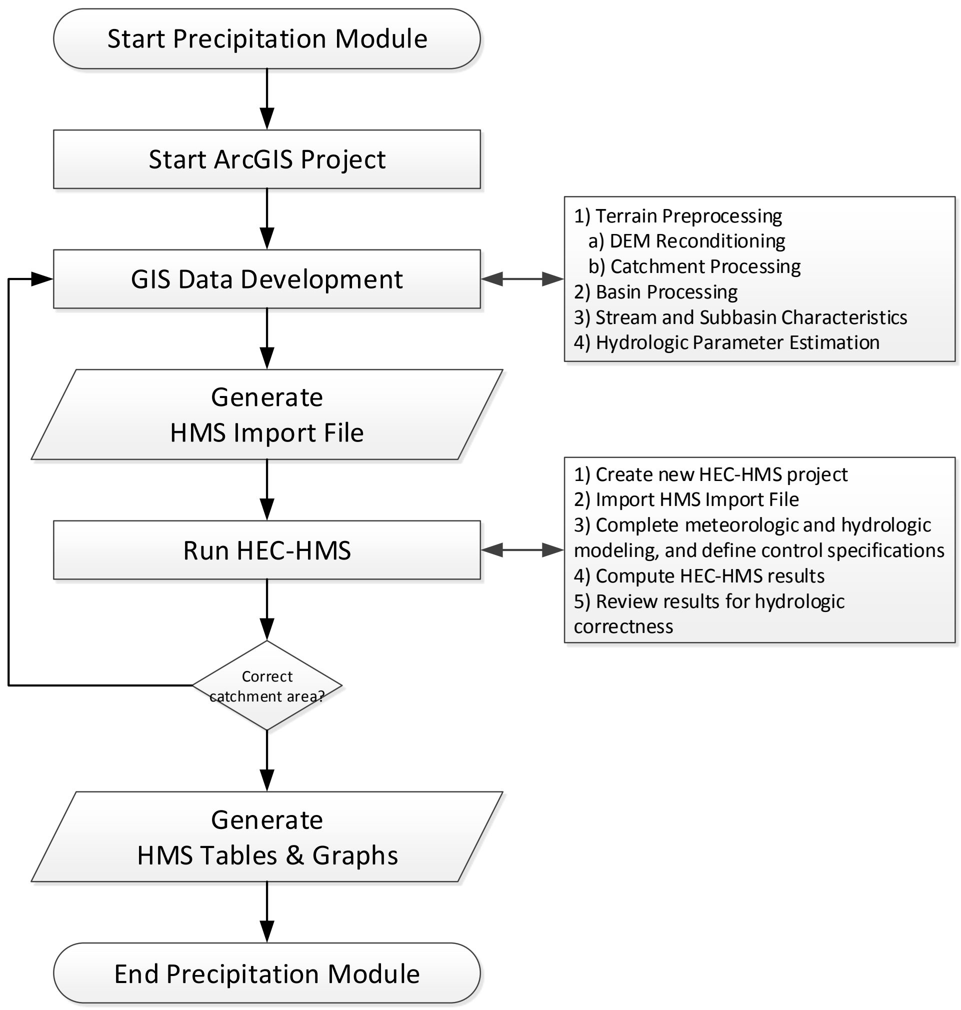

Figure C.1: HEC-HMS workflow

APPENDIX D: HEC-RAS WORKFLOW

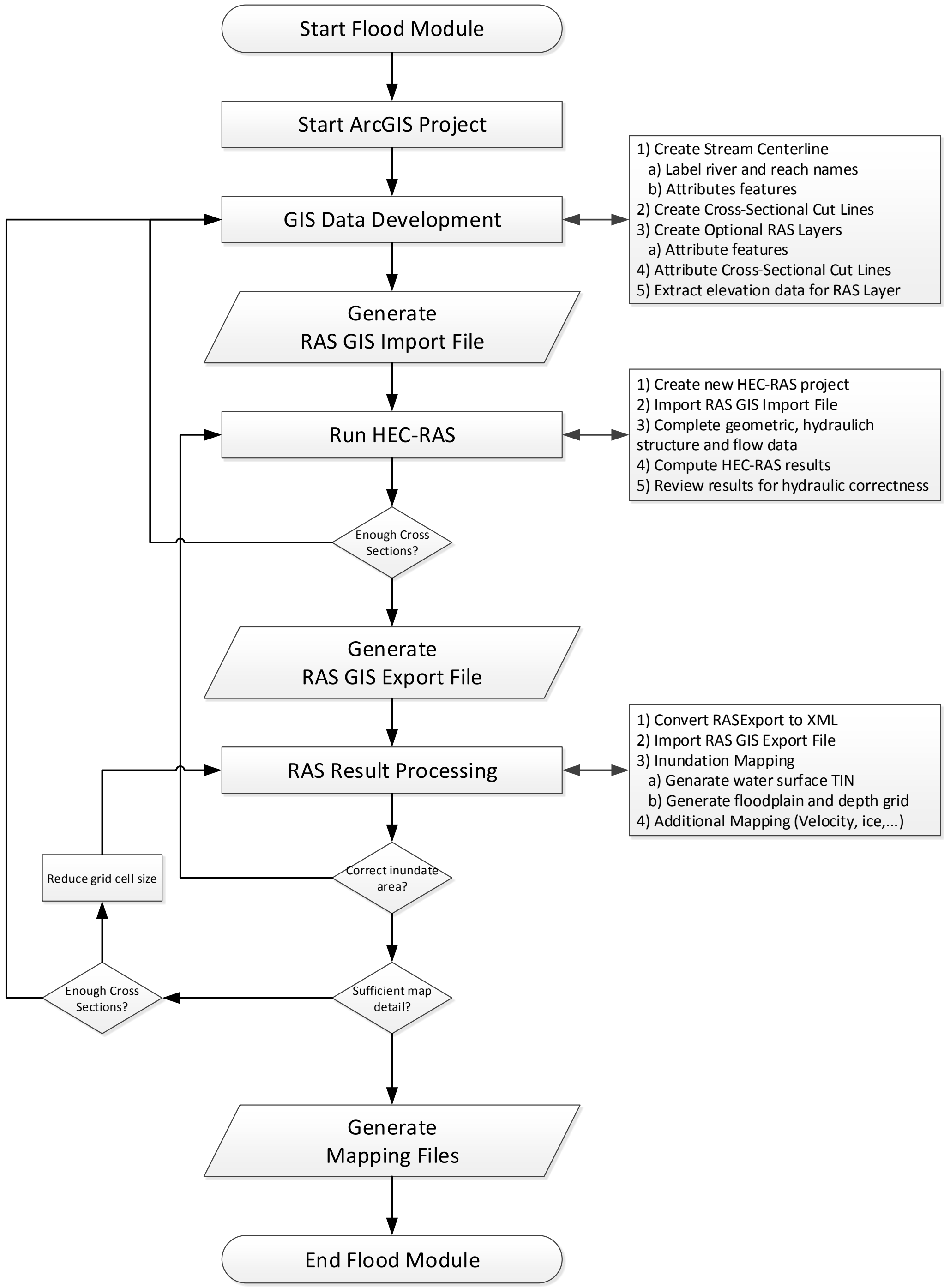

Figure D.1: HEC-RAS workflow

APPENDIX E: DATA OVERVIEW

The following table lists the data used within the example application. In square brackets, additional information is placed. The type column describes its type of representation. For geodata, vector types are entity-based and raster and TIN types are field-based. This destinction cannot be made for non-geodata types such as tables. The format column describes the actual format the data is stored in. This can either be a file, a single value or a group of single values which might been inserted manually. The stage column describes at which stage the dataset is generated or used. Preprocessing data is usually used to create static data and plays no role within the simulation (but maybe for visualization). Static data is used within a simulation as input for modules. Dynamic data is created during a simulation. The time column describes how time is incorporated for a specific data set. “Time Step” means that for each time step a single file is created (e.g. multiple raster files for inundation), “Sime Series” means that the whole time series is stored within a single file (e.g. precipitation within a NetCDF file). “Independent” means that the data is independent of the time (e.g. the terrain model is valid for all time steps, therefore only one file is needed).

Table E.1: Data (1/3)

Data	Type	Format	Stage	Time
Aggregated Inundation Depths	Raster	tiff	Dynamic	Time Step
Banks	Vector	shp	Preprocessing	Independent
Basin Centroid	Vector	shp	Preprocessing	Independent
Basin Model	Database	mod	Static	Independent
Boundary Conditions	Manual	Diverse	Static	Independent
Bridges	Vector	shp	Preprocessing	Independent
Buildings (incl. Flood Measures)	Vector	shp	Dynamic	Time Step
Buildings (incl. Landslide Measures)	Vector	shp	Dynamic	Time Step
Buildings (incl. Landuse Attribute)	Vector	shp	Preprocessing	Independent
Catchment	Vector	shp	Preprocessing	Independent
CN Grid	Vector	shp	Preprocessing	Independent
CN Values	Table	csv	Preprocessing	Independent
Discharge	Table	csv	Dynamic	Time Series
Distance Values	Manual	Integers	Dynamic	Independent
Drainage Line	Vector	shp	Preprocessing	Independent
End Node	Vector	shp	Static	Independent

Table E.1: Data (2/3)

Data	Type	Format	Stage	Time
Flood Intensity	Manual	Integer	Dynamic	Independent
Floodplain	Vector	shp	Dynamic	Time Step
Flow Acumulation	Vector	shp	Preprocessing	Independent
Flow Direction	Vector	shp	Preprocessing	Independent
Flowpaths	Vector	shp	Preprocessing	Independent
HMS Link	Vector	shp	Preprocessing	Independent
HMS Node	Vector	shp	Preprocessing	Independent
Hospitals	Vector	shp	Static	Independent
Hydro DTM	Raster	tiff	Preprocessing	Independent
Inundation depths	Raster	ESRI Grid	Dynamic	Time Step
Landslide	Vector	shp	Dynamic	Independent
Landslide ID	Manual	Integer	Dynamic	Independent
Landslides	Vector	shp	Static	Independent
Lengths by Road Type	Table	csv	Dynamic	Time Step
LUManning	Vector	shp	Preprocessing	Independent
Manning Values	Table	csv	Preprocessing	Independent
Maximum Floodplain	Vector	shp	Dynamic	Independent
MeteoSwiss Precipitation	Raster	NetCDF	Static	Time Series
Precipitation [HMS output]	Table	csv	Dynamic	Time Series
Precipitation [HMS input]	Database	dss	Dynamic	Time Series
RAS GIS Export File [GeoRAS output]	Database	xml	Dynamic	Time Series
RAS GIS Export File [RAS output]	Database	sdf	Dynamic	Time Series
RAS GIS Import File	Database	sdf	Static	Independent
Restricted Area	Vector	shp	Static	Independent
River	Vector	shp	Preprocessing	Independent
Road Network	Vector	shp	Preprocessing	Independent
Road Network (incl. Flood Measures)	Vector	shp	Dynamic	Time Step
Road Network (incl. Landslide Measures)	Vector	shp	Dynamic	Time Step
Road Network (incl. Road Width Attribute)	Vector	shp	Preprocessing	Independent

Table E.1: Data (3/3)

Data	Type	Format	Stage	Time
Service Areas	Vector	shp	Dynamic	Time Step
Shortest Path	Vector	shp	Dynamic	Time Step
Start Node	Vector	shp	Static	Independent
Stream Grid	Raster	tiff	Preprocessing	Independent
Stream Link	Vector	shp	Preprocessing	Independent
Subbasin	Vector	shp	Preprocessing	Independent
Swiss Buildings	Vector	shp	Preprocessing	Independent
Swiss DTM	Raster	tiff	Preprocessing	Independent
Swiss Landuse	Vector	shp	Preprocessing	Independent
Swiss Orthophoto	Raster	tiff	Preprocessing	Independent
Swiss Rivers	Vector	shp	Preprocessing	Independent
Swiss Road Network	Vector	shp	Preprocessing	Independent
Swiss Soillayer	Vector	shp	Preprocessing	Independent
TIN [Surface Elevation]	TIN	adf	Preprocessing	Independent
Topological Road Network	Vector (Topological)	ESRI Network Dataset	Dynamic	Time Step
Trigger Time Step	Manual	Integer	Dynamic	Independent
Velocities	Raster	ESRI Grid	Dynamic	Time Step
Vulnerability Curves	Code	Python	Static	Independent
XSCutLines	Vector	shp	Preprocessing	Independent

APPENDIX F: COMMON GEODATA FORMATS

Vector-Based Geometrical Representations

- 2D Geometries
- Additionally Elevation at Nodes ("2.5D")
- Mostly Simple Features (e.g. Shapefiles)
- Different possibilities to store "time" in data
    - Column-Based: One Column for each Time Step/Attribute combination
    - Row-Based: One Row for each Time Step/Feature combination

Raster-Based Geometrical Representations

- 2D Geometries
- Additional Elevation at Cells ("2.5D")
- Time typically stored as bands
- One Band for each TimeStep/Attribute Combination

Other Formats:

- Triangulated Irregular Network (TIN)
- Topological Data
- 3D-Vector Data (e.g. PostGIS)
- …

Most Geodata Processing Tools are tailored to Vector-Based and Raster-Based data (e.g. GDAL/OGR). 3D and Temporal aspects are mostly only insufficiently supported. However, some GIS tools and data support additional concepts, these include:

GRASS GIS

- 3D-Dimensional Raster Based
- Topological Representation of Vector Data
- Temporal Data (with Version 7 – to be released)
- Limited Interoperability with other GIS-Tools

NetCDF

- "Raster"-Format for high-dimensional data (e.g. 4D: Latitude, Longitude, Level, Time)
- Analysis Tools (CDO, NCO)
- Tailored WMS: ncWMS
- Tailored to Climate Data

APPENDIX G: SAMPLE GIS FUNCTIONALITY

Geometrical Conversion / Manipulation

- Line to Point (Centroid)
- Merge Linestrings
- Segmentize Network (e.g. every 4m)

Geospatial Queries

- Find Lines that Intersect Polygon
- Find Pixels Intersecting Polygon

Spatial Joins

- Assign Raster Value to Point Based on Location

Tabular Joins

- Assign Asset Values to Buildings

Field Calculation

- Calculate Damage Depending on Inundation Value Using Vulnerability Curve

Network Analysis

- Find Shortest Path between two Nodes
- Find All Nodes Within Distance to a Node

Construct Cross-Section

Perform Operations on Subselections

Perform Batch Processing

Calculate Statistics

Create New Geometries based on User Input

- Cut Lines for GeoRAS

Map Algebra