

Caribbean Handbook on Risk Information Management



GFDRR
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5.5 Methods for risk assessment

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Introduction

Risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions (UN-ISDR, 2009, EC, 2011). Risk can be presented conceptually with the following basic equation indicated in Figure 1

Risk = probability of losses =

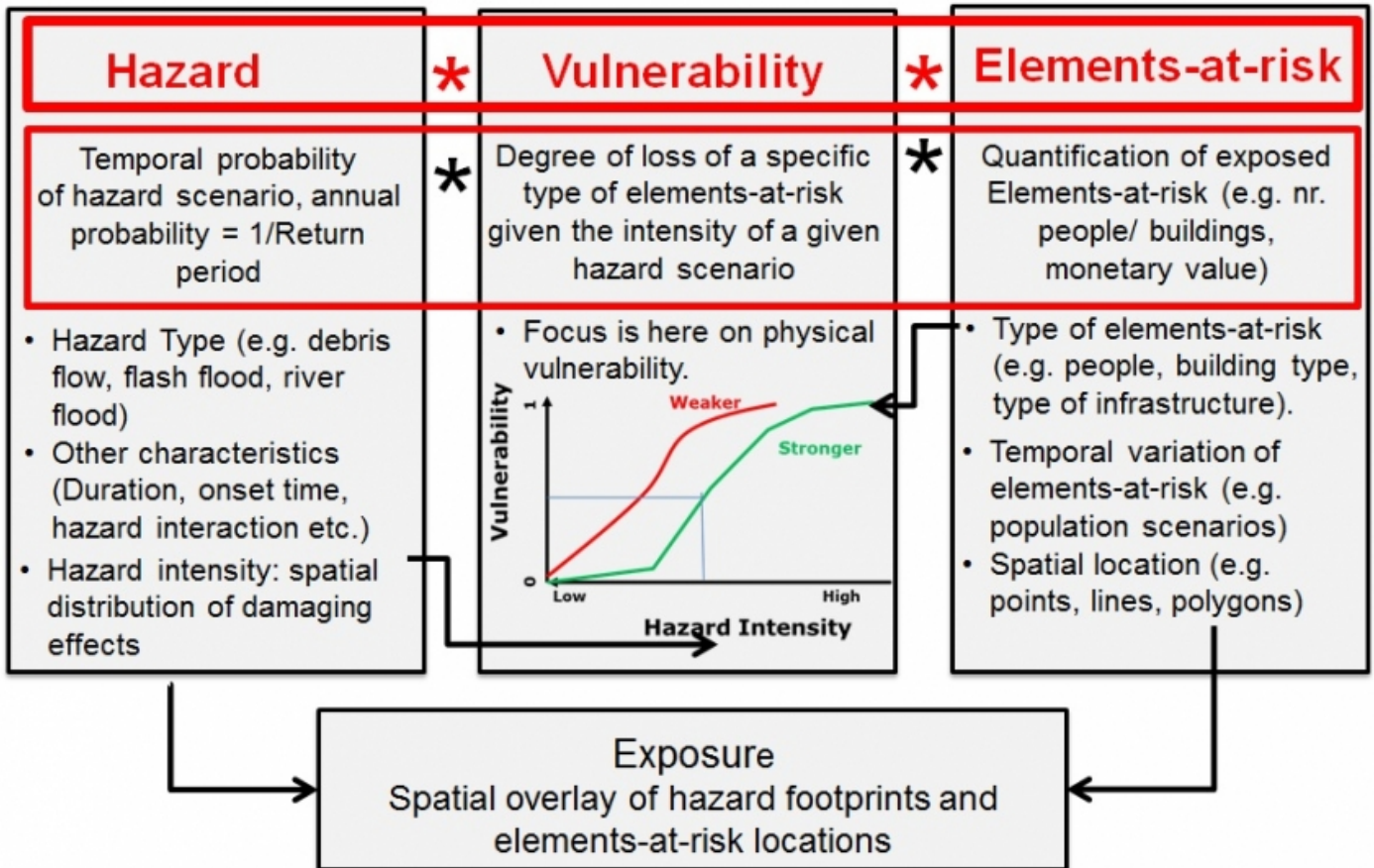


Figure 1: Schematic representation of risk as the multiplication of hazard, vulnerability and quantification of the exposed elements-at-risk. The various aspects of hazards, vulnerability and elements-at-risk and their interactions are also indicated. This framework focuses on the analysis of physical losses, using physical vulnerability data.

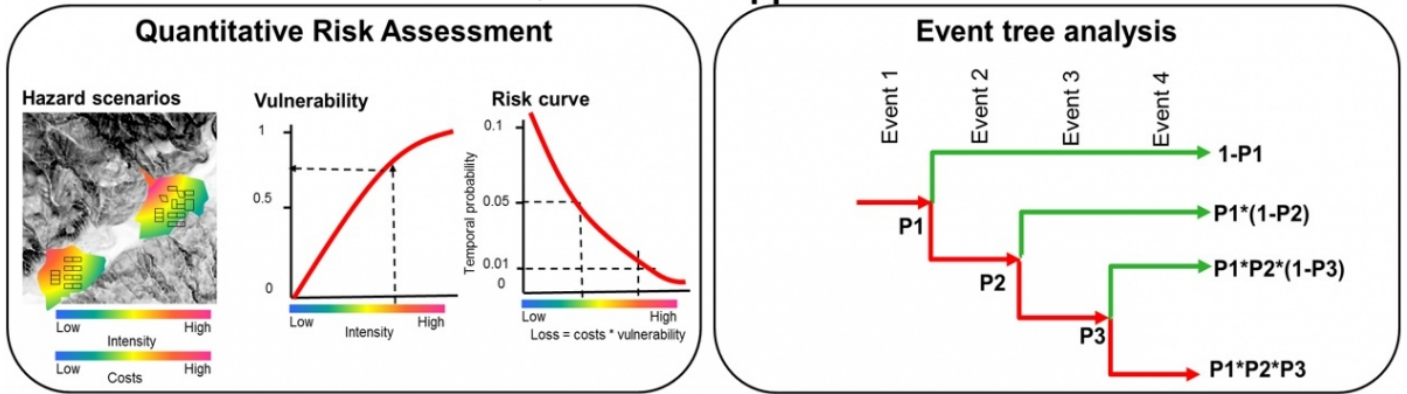
Risk assessment is a process to determine the probability of losses by analyzing potential hazards and evaluating existing conditions of vulnerability that could pose a threat or harm to property, people, livelihoods and the environment on which they depend (UN-ISDR, 2009). ISO 31000 (2009) defines risk assessment as a process made up of three processes: risk identification, risk analysis, and risk evaluation. Risk identification is the process that is used to find, recognize, and describe the risks that could affect the achievement of objectives. Risk analysis is the process that is used to understand the nature, sources, and causes of the risks that have been identified and to estimate the level of risk. It is also used to study impacts and consequences and to examine the controls that currently exist. Risk evaluation is the process that is used to compare risk analysis results with risk criteria in order to determine whether or not a specified level of risk is acceptable or tolerable.

Risk mapping for natural hazard risk can be carried out at a number of scales and for different purposes. Table 1 gives a summary. In the following sections four methods of risk mapping will be discussed: Quantitative risk assessment (QRA), Event-Tree Analysis (ETA), Risk matrix approach (RMA) and Indicator-based approach (IBA).

Table 1: Indication of scales of analysis with associated objectives and data characteristics (approaches: QRA = Quantitative risk assessment, EVA = Event-Tree Analysis, RMA = Risk matrix approach, IBA = Indicator-based approach)

Scale of analysis	Scale	Possible objectives	Possible approaches
International, Global	< 1 : 1 million	Prioritization of countries/regions; Early warning	Simplified RMA & IBA
Small: provincial to national scale	< 1:100,000	Prioritization of regions; Analysis of triggering events; Implementation of national programs; Strategic environmental assessment; Insurance	Simplified EVA, RMA & IBA
Medium: municipality to provincial level	1:100000 to 1:25000	Analyzing the effect of changes; Analysis of triggering events; Regional development plans	RMA / IBA
Local: community to municipality	1:25000 to 1:5000	Land use zoning; Analyzing the effect of changes; Environmental Impact Assessments; Design of risk reduction measures	QRA / EVA / RMA IBA
Site-specific	1:5000 or larger	Design of risk reduction measures; Early warning systems; detailed land use zoning	QRA / EVA / RMA

Quantitative approaches



Qualitative approaches

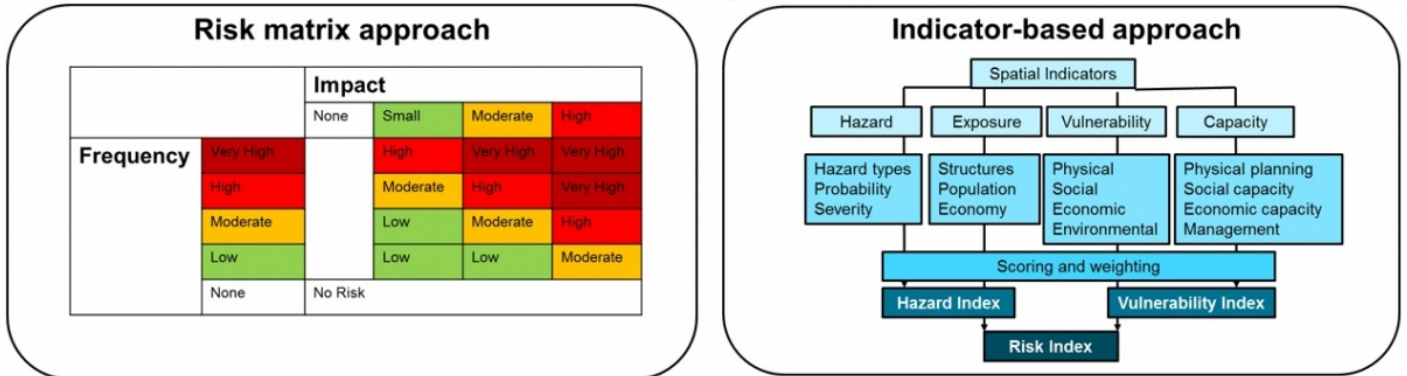


Figure 2: Components relevant for risk assessment, and the four major types of risk mapping that are presented in this section.

Quantitative Risk Assessment

If the various components of the risk equation can be spatially quantified for a given set of hazard scenarios and elements-at-risk, the risk can be analyzed using the following equation:

$$\text{Risk} = \sum_{\text{All hazards}} \left(\int_{P_T=0}^{P_T=1} P_{(T|HS)} * \left(\sum_{\text{All EaR}} (P_{(S|HS)} * (A_{(ER|HS)} * V_{(ER|HS)})) \right) \right)$$

In which:

$P_{(T|HS)}$ = the temporal probability of a certain hazard scenario (HS). A hazard scenario is a hazard event of a certain type (e.g. flooding) with a certain magnitude and frequency;

$P_{(S|HS)}$ = the spatial probability that a particular location is affected given a certain hazard scenario;

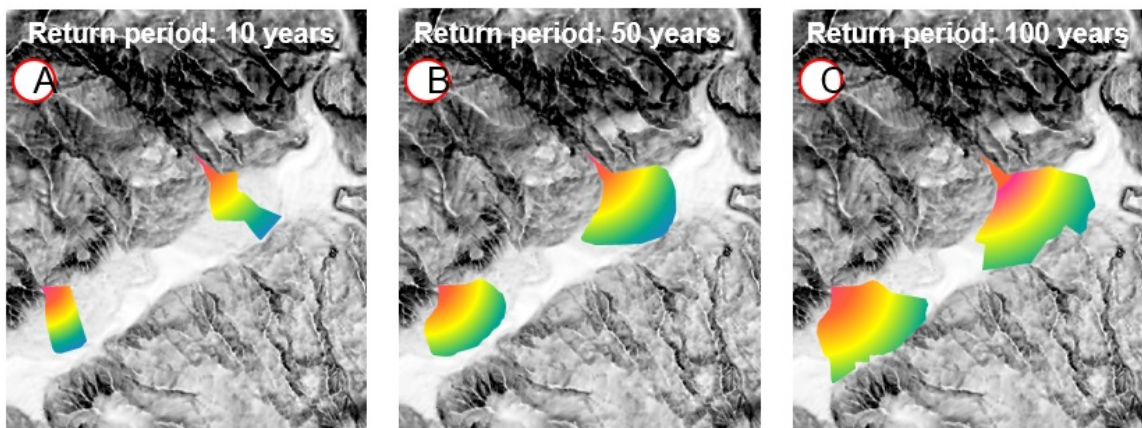
$A_{(ER|HS)}$ = the quantification of the amount of exposed elements-at-risk, given a certain hazard scenario (e.g. number of people, number of buildings, monetary values, hectares of land) and

$V_{(ER|HS)}$ = the vulnerability of elements at risk given the hazard intensity under the specific hazard scenario (as a value between 0 and 1).

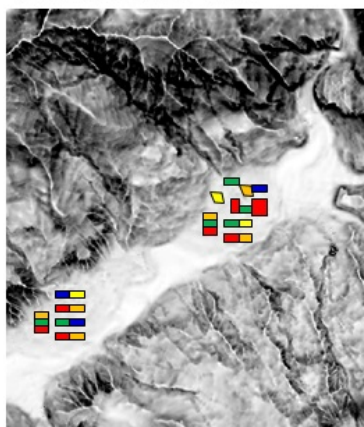
The method is schematically indicated in Figure 3. GIS operations are used to analyze the exposure as the intersection

between the elements-at-risk and the hazard footprint area for each hazard scenario. For each element-at-risk also the level of intensity is recorded through a GIS-overlay operation. These intensity values are used in combination with the element-at-risk type to find the corresponding vulnerability curve, which is then used as a lookup table to find the vulnerability value. The way in which the amount of elements-at-risk are characterized (e.g. as number of buildings, number of people, economic value) also defines the way in which the risk is calculated. The multiplication of exposed amounts and vulnerability should be done for all elements-at-risk for the same hazard scenario. The results are multiplied with the spatial probability that the hazard footprint actually intersects with the element-at-risk for the given hazard scenario $P(S \cap HS)$ to account for uncertainties in the hazard modelling. The resulting value represents the losses, which are plotted against the temporal probability of occurrence for the same hazard scenario in a so-called *risk curve*. This is repeated for all available hazard scenarios. At least three individual scenarios should be used, although it is preferred to use at least 6 events with different return periods (FEMA, 2004) to better represent the risk curve. The area under the curve is then calculated by integrating all losses with their respective annual probabilities. It is possible to create risk curves for the entire study area, or for different spatial units, such as administrative units, census tracks, road or railway sections etc. Risk can be presented in a number of different ways, depending on the objectives of the risk assessment (Birkmann, 2007). Risk can be expressed in absolute or relative terms. Absolute population risk can be expressed as individual risk (the annual probability of a single exposed person to be killed) or as societal risk (the relation between the annual probability and the number of people that could be killed). Absolute economic risk can be expressed in terms of Average Annual Loss, Maximum Probable Loss, or other indices that are calculated from a series of loss scenarios, each with a relation between frequency and expected monetary losses (Jonkman, van Gelder and Vrijling, 2002)

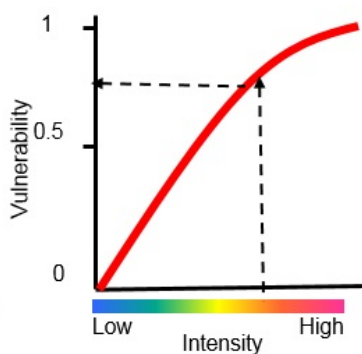
Hazard scenarios



Elements-at-risk



Vulnerability



Risk curve

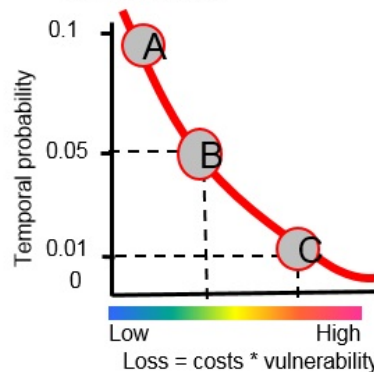


Figure 3: Schematic representation of Quantitative Risk Assessment. [Click to enlarge.](#)

The components that are involved in risk assessment have a high degree of uncertainty. Aleatory uncertainty is associated with the variation of the input data used in the risk assessment. For example the variations in soil characteristics used to model landslide probability, surface characteristics, building characteristics etc. These are normally incorporated in probabilistic risk analysis (Bedford and Cook, 2001) which calculates thousands of hazard and risk scenarios taking the variations of the input factors and calculating exceedance probabilities using techniques such as Monte Carlo simulation. Epistemic uncertainty refers to uncertainty associated with incomplete or imperfect knowledge

about the processes involved, and lack of sufficient data. This is often a serious problem as there may not be enough data available to determine individual hazard scenarios, or there are no vulnerability curves for the types of elements-at-risk within the study area. Probabilistic risk assessment takes into account all possible hazard scenarios and the uncertainty of the input factors, by running thousands of loss scenarios, and calculate eventually the loss exceedance curve. For a number of hazards, such as landslides or flooding, it is very complicated to develop a large number of hazard scenarios due to the large epistemic uncertainty caused by lack of data. In such cases uncertainty can be taken into account using the method illustrated in Figure 4. In this method data are used showing the range of possible values for the temporal probability, spatial probability, intensity of the hazard, value of the elements-at-risk and vulnerability. The uncertainty range in the temporal probability of the hazard scenario is reflected by a range of possible values on the Y-axis of the risk curve. The uncertainty in the hazard intensity (e.g. water height for flooding, impact pressure for landslides) combined with the uncertainty in the vulnerability curve will result in larger uncertainty ranges in vulnerability, which are then multiplied with the uncertainty range of the quantification of elements-at-risk (e.g. building costs). This then gives a range of values for the expected losses. So instead of a single point in the risk curve, each hazard scenario will result in a rectangle, defined by the variation in probability and losses. The upper right corners of the rectangle are connected to provide the most pessimistic risk curve, and the lower right corners are connected to provide the most optimistic risk curve. When calculating the area under the curves it is then possible to show the range in annual expected losses.

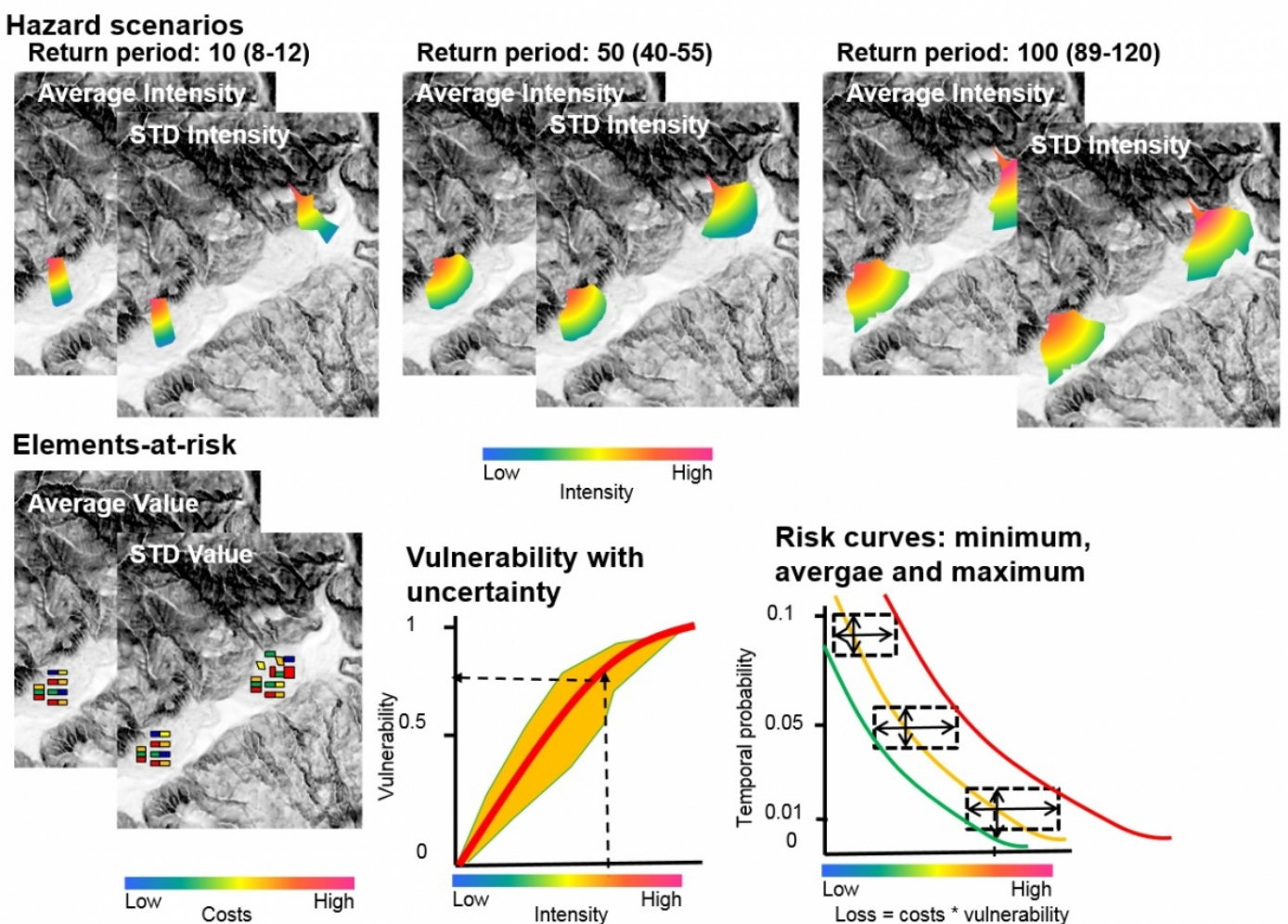


Figure 4: Method for including uncertainty in Quantitative Risk Analysis in cases where it is not possible to define many hazard scenarios. Click to enlarge.

The animation below gives an example of a quantitative risk assessment for buildings that are threatened to flooding with three different scenarios, each with a different probability of occurrence (2 years, 10 years and 50 years). In this simple example there are 3 elements at risk only (buildings) that are of two types. Type-1 buildings are weaker in construction than type-2 buildings. Based on past occurrences of flooding a relation has been made between the water depth and the degree of damage using vulnerability curves (explained in chapter 5, Section 5.3). This means that with the same water depth type-1 buildings will suffer more damage than type-2 buildings. The vulnerability curves presented in animation are hypothetical ones, but are the crucial component in the risk assessment. The three hazard scenarios will affect the three buildings in a different way. The small table in the animation indicates the water depth that can be expected for the three

houses related to the three scenarios

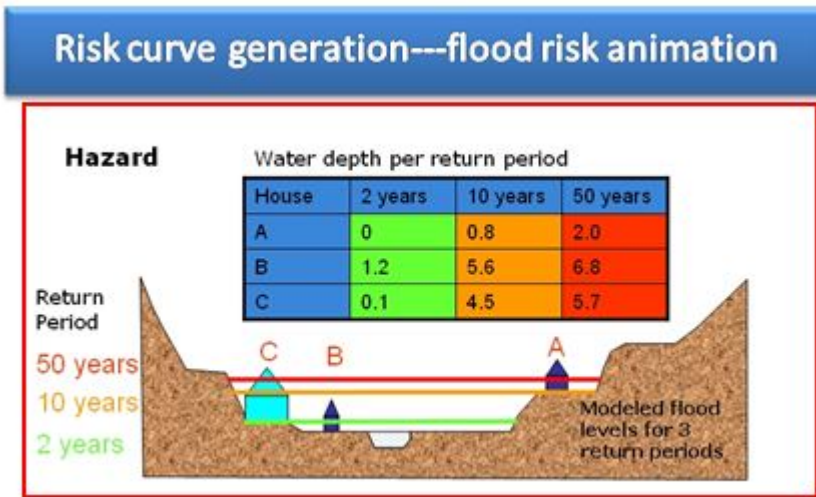


Figure 5: Step-by-step animation of risk assessment illustrated for flooding. Click to start the animation in a new window

Event-tree approaches

A number of hazard may occur in chains: one hazard causes the next. These are also called domino effects, or concatenated hazards. These are the most problematic types to analyze in a multi-hazard risk assessment. The best approach for analyzing such hazard chains is to use so-called event-trees. An event tree is a system which is applied to analyze all the combinations (and the associated probability of occurrence) of the parameters that affect the system under analysis. All the analyzed events are linked to each other by means of nodes (See Figure 6) all possible states of the system are considered at each node and each state (branch of the event tree) is characterized by a defined value of probability of occurrence.

Event tree analysis

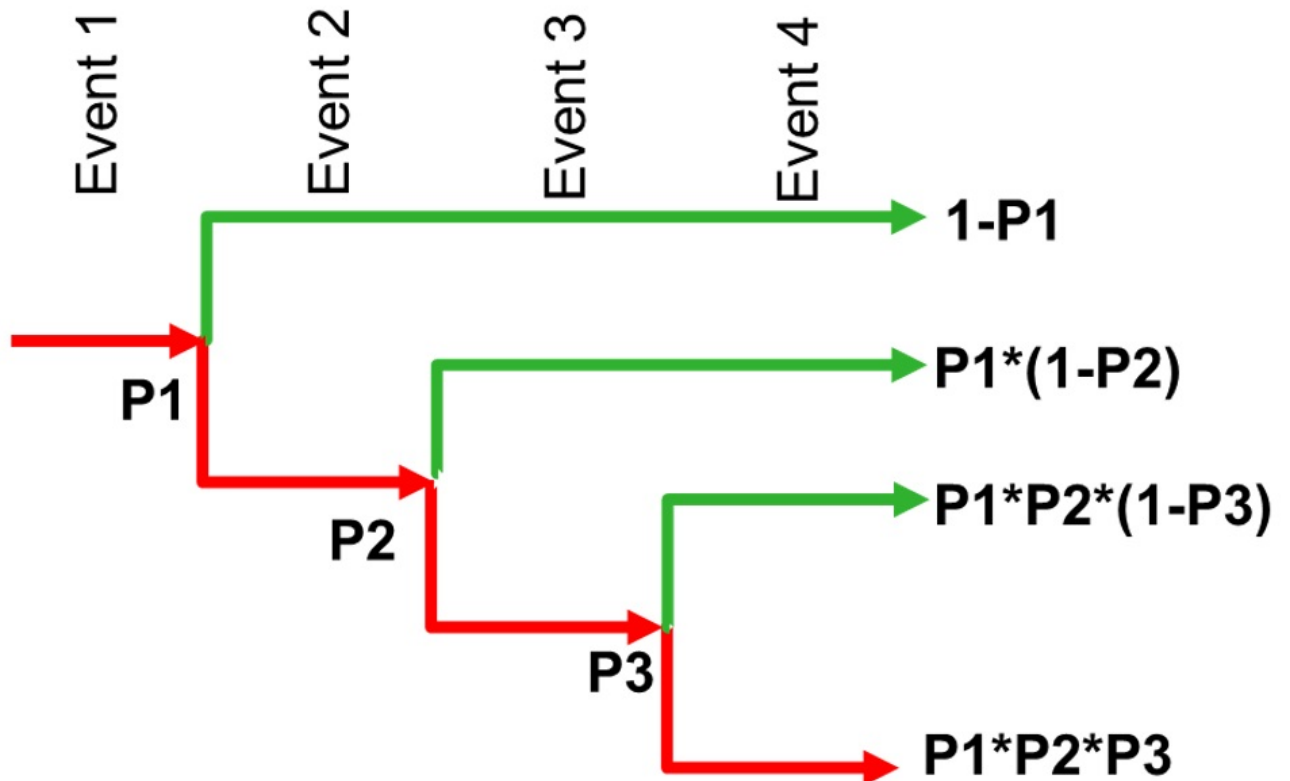


Figure 6: Schematic representation of an event-tree analysis.

The figure below gives an examples of an event tree for a situation where a rockfall in a lake may trigger a flood wave that would impact a village (from Lacasse et al., 2008)

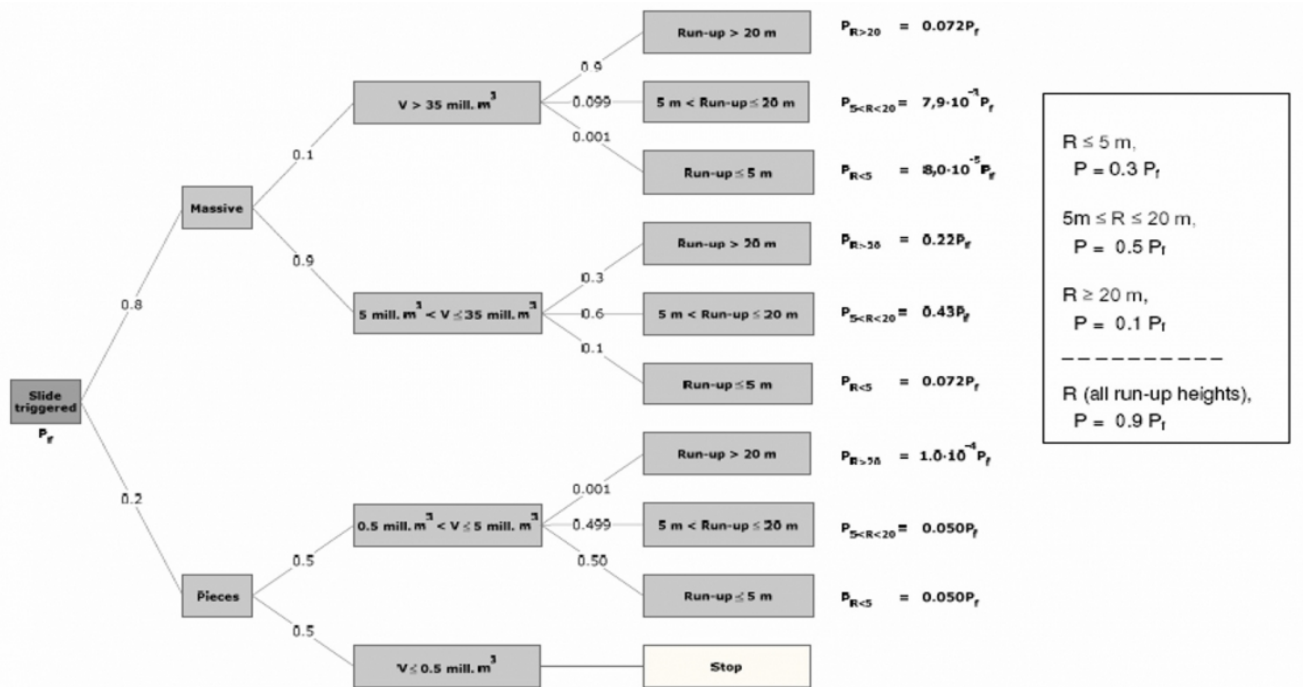


Figure 7: Bayesian Event tree for tsunami propagation, given that rock slide in Aknes has occurred (V = rockslide volume, R =run-up height). From Lacasse et al., 2008) Click to enlarge.

Risk matrix approach

Risk assessments are often complex and do not allow to develop a full numerical approach, since many aspects are not fully quantifiable or have a very large degree of uncertainty. This may be related to the difficulty to define hazard scenarios, map and characterize the elements-at-risk, or define the vulnerability using vulnerability curves. In order to overcome these problems the risk is often assessed using so-called risk matrices or consequences-frequency matrices (CFM), which are diagrams with consequence and frequency classes on the axes (See Figure 8). They permit to classify risks based on expert knowledge with limited quantitative data (Haimés, 2008; Jaboyedoff et al., 2014). The risk matrix is made of classes of frequency of the hazardous events on one axis, and the consequences (or expected losses) on the other axis. Instead of using fixed values, the use of classes allows for more flexibility and incorporation of expert opinion. Such methods have been applied extensively in natural hazard risk assessment, e.g. in Switzerland (Jaboyedoff et al., 2014). This approach also permits to visualize the effects and consequences of risk reduction measures and to give a framework to understand risk assessment. The system depends on the quality of the group of experts that are formed to identify the hazard scenarios, and that carry out the hazard filtering and ranking in several sub-stages characterized by frequency (probability) and impact classes and their corresponding limits (Haimés, 2008).

Risk matrix approach

		Impact			
		None	Small	Moderate	High
Frequency	Very High		High	Very High	Very High
	High		Moderate	High	Very High
	Moderate		Low	Moderate	High
	Low		Low	Low	Moderate
	None	No Risk			

Figure 8: Example of the risk matrix approach, which consists of a matrix with classes of frequency (of the hazardous event) and the consequences.

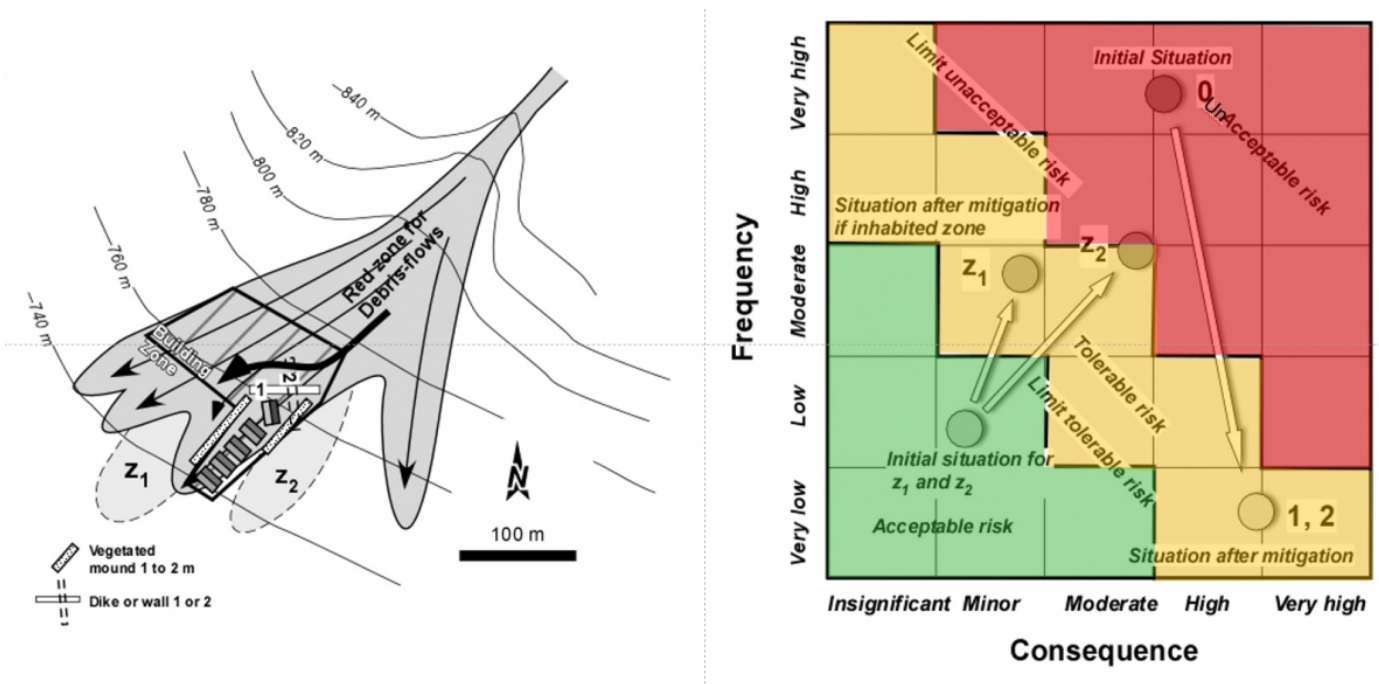


Figure 9: Example of potential building area in a high hazard area and illustration of the proposed solutions. The risk matrix is used to represent the degree of risk. The scope of tolerable risk (yellow) is between the limits of tolerance and of acceptability. The initial situation 0 is a combination of very high frequency of debris flows with a high impact. After construction of a deflection dike or wall the frequency doesn't change but the impact decreases considerably. The areas Z1 and Z2 on the other hand will get a higher frequency of occurrence and higher consequence as a result of the mitigation works (Jaboyedoff et al., 2014). Click to enlarge.

Indicator-based Approach

There are many situations where the (semi)-quantitative methods for risk mapping are not appropriate. This could be because the data are lacking to be able to quantify the components, such as hazard frequency, intensity, and physical

vulnerability. For instance when the risk assessment is carried out over large areas, or in areas with limited data. Another reason is that one would like to take into account a number of different components of vulnerability that are not incorporated in (semi-) quantitative methods, such as social vulnerability, environmental vulnerability and capacity. In those cases it is common to follow an indicator-based approach to measure risk and vulnerability through selected comparative indicators in a quantitative way in order to be able to compare different areas or communities. The process of disaster risk assessment is divided into a number of components, such as hazard, exposure, vulnerability and capacity (See Figure 10), through a so-called criteria tree, which list the subdivision into objectives, sub-objectives and indicators. Data for each of these indicators are collected at a particular spatial level, for instance by administrative units. These indicators are then standardized (e.g. by reclassifying them between 0 and 1), weighted internally within a sub-objective and then the various sub-objectives are also weighted amongst themselves. Although the individual indicators normally consist of quantitative data (e.g. population statistics), the resulting vulnerability, hazard and risk results are scaled between 0 and 1. These relative data allows to compare the indicators for the various administrative units. These methods can be carried out at different levels, ranging from local communities (e.g. Bollin and Hidajat, 2006) cities (Greiving et al, 2006) to countries (Van Westen et al., 2012).

Indicator-based approach

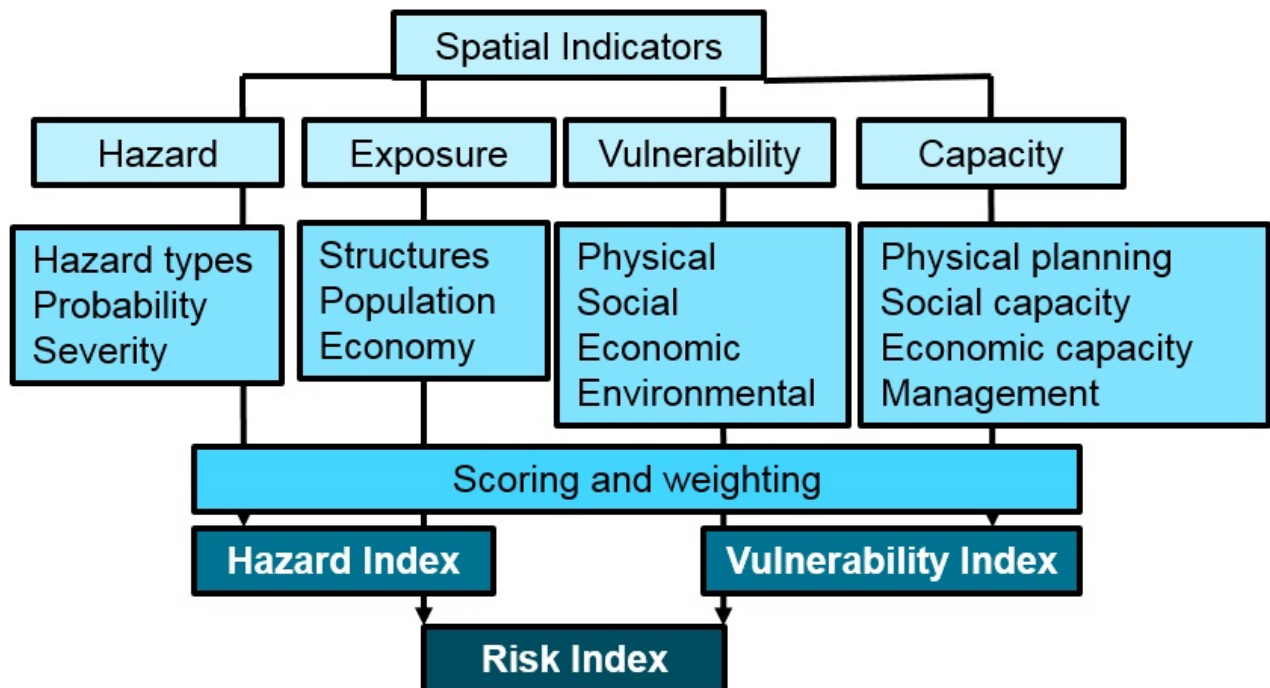


Figure 10: Risk Indicator based approach.

The approaches are mostly based on the development of so-called risk indices, and on the use of spatial multi criteria evaluation. One of the first attempts to develop global risk indicators was done through the Hotspots project (Dilley et al. 2005). In a report for the Inter-American Development Bank, Cardona (2005) proposed different sets of complex indicators for benchmarking countries in different periods and to make cross-national comparisons. Four components or composite indicators reflect the principal elements that represent vulnerability and show the advances of different countries in risk management: Disaster Deficit Index, Local Disaster Index, Prevalent Vulnerability Index and Risk Management Index. Each index has a number of variables that are associated with it and empirically measured. The DDI can be considered as an indicator of a country's economic vulnerability to disaster. Information on using the Disaster Risk Index for Belize can be found here: <https://www.imf.org/external/np/seminars/eng/2013/caribbean/pdf/be>. Peduzzi et al. (2005; 2009) have developed global indicators, not on the basis of administrative units, but based on gridded maps. The Disaster Risk Index (UN-ISDR, 2005b) combines both the total number and the percentage of killed people per country in large- and medium-scale disasters associated with droughts, floods, cyclones and earthquakes. In the DRI, countries are indexed for each hazard type according to their degree of physical exposure, their degree of relative vulnerability, and their degree of risk. Also at local scale risk indices are used, often in combination with spatial multi criteria evaluation (SMCE). Castellanos and Van Westen (2007) present an example of the use of SMCE for the generation of a landslide risk index for the country of Cuba, generated by combining a hazard index and a vulnerability index. The hazard index is made using indicator maps related to triggering factors (earthquakes and rainfall) and environmental factors. The vulnerability index was made using five key indicators: housing condition and transportation (physical vulnerability indicators), population

(social vulnerability indicator), production (economic vulnerability indicator) and protected areas (environmental vulnerability indicator). The indicators were based on polygons related to political-administrative areas, which are mostly at municipal level. Each indicator was processed, analysed and standardized according to its contribution to hazard and vulnerability. The indicators were weighted using direct, pair wise comparison and rank ordering weighting methods and weights were combined to obtain the final landslide risk index map. The results were analysed per physiographic region and administrative units at provincial and municipal levels. Another example at the local level is presented by Villagrán de León (2006) which incorporates 3 dimensions of vulnerability, the scale or geographical level (from human being to national level), the various sectors of society, and 6 components of vulnerability. The method uses matrices to calculate a vulnerability index, which was grouped in qualitative classes (high, medium and low).

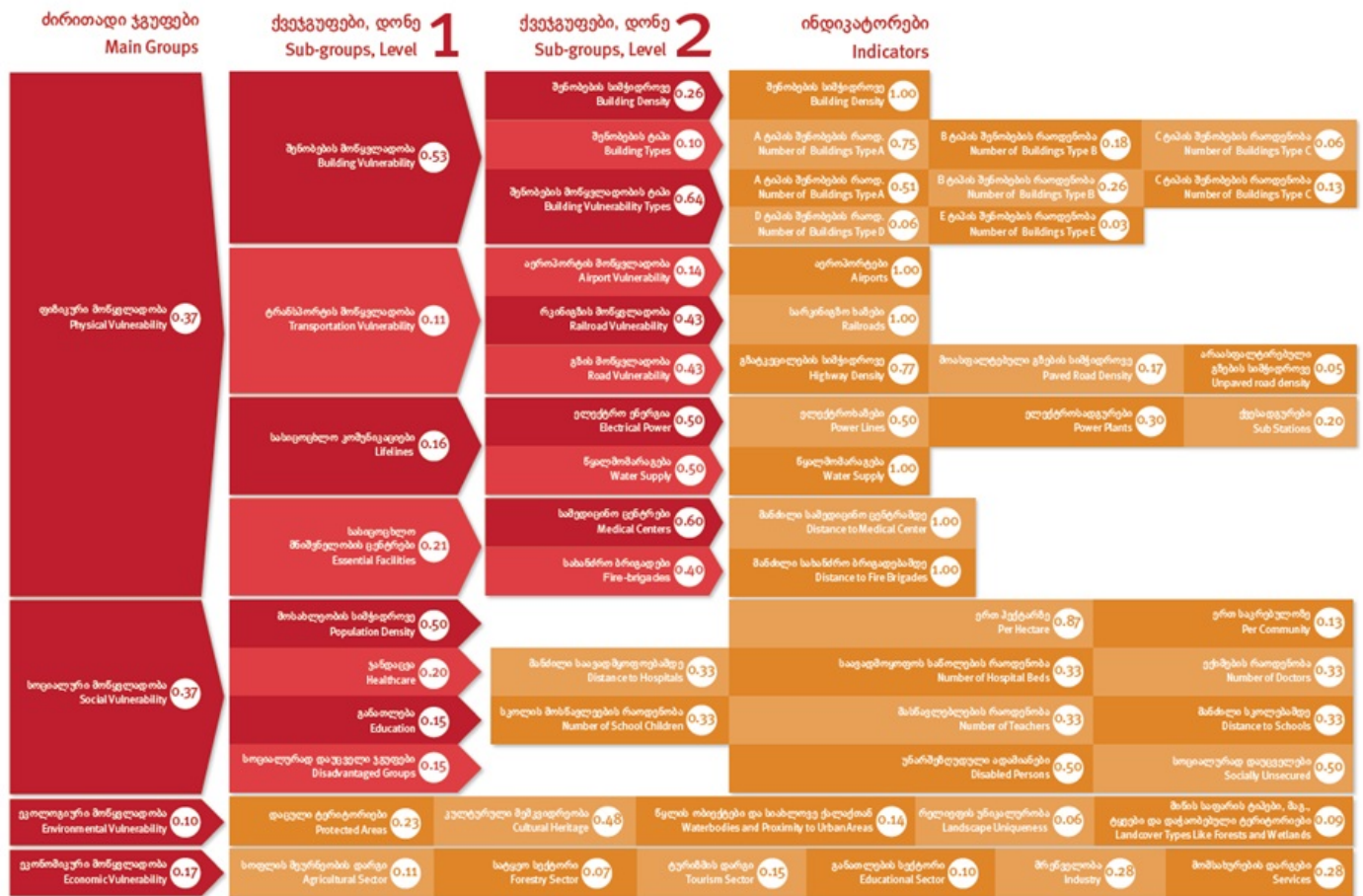


Figure 11: Example of the use of indicators in a Spatial Multicriteria Evaluation for the country of Georgia (Van Westen et al., 2012) Click to enlarge.

Conclusions

The four methods for risk assessment that were treated in this chapter all have certain advantages and disadvantages, which are summarized in Table 3. The Quantitative Risk Assessment method is the best for evaluating several alternatives for risk reduction, through a comparative analysis of the risk before and after the implementation followed by a cost-benefit analysis. The event-tree analysis is the best approach for analyzing complex chains of events and the associated probabilities. Qualitative methods for risk assessment are useful as an initial screening process to identify hazards and risks. They are also used when the assumed level of risk does not justify the time and effort of collecting the vast amount of data needed for a quantitative risk assessment, and where the possibility of obtaining numerical data is limited. The risk matrix approach is often the most practical approach as basis for spatial planning, where the effect of risk reduction methods can be seen as changes in the classes within the risk matrix. The indicator-based approach, finally, is the best when there is not enough data to carry out a quantitative analysis, but also as a follow-up of a quantitative analysis as it allows to take into account other aspects than just physical damage.

Table 2: Advantages and disadvantages of the four risk assessment methods discussed.

Method	Advantages	Disadvantages
Quantitative risk assessment (QRA)	Provides quantitative risk information that can be used in Cost-benefit analysis of risk reduction measures.	Very data demanding. Difficult to quantify temporal probability, hazard intensity and vulnerability.
Event-tree analysis	Allow modelling of a sequence of events, and works well for domino effects	The probabilities for the different events are difficult to assess, and spatial implementation is very difficult due to lack of data.
Risk matrix approach	Allows to express risk using classes instead of exact values, and is a good basis for discussing risk reduction measures.	The method doesn't give quantitative values that can be used in cost-benefit analysis of risk reduction measures. Assessment of impacts and frequencies is difficult, and one area might have different combinations of impacts and frequencies.
Indicator-based approach	Only method that allows to carry out a holistic risk assessment, including social, economic and environmental vulnerability and capacity.	The resulting risk is relative and does not provide information on actual expected losses.

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