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Chapter 2

Multi-hazard risk assessment and decision making

Cees J. van Westen and Stefan Greiving

The earth is shaped by endogenic processes, caused by forces from within the earth, resulting in hazardous events like earthquakes or volcanic eruptions, and exogenic processes, caused by forces related to the earth's atmosphere, hydrosphere, geosphere, biosphere and cryosphere and their interactions. Anthropogenic activities have had a very important influence on a number of these processes, especially in the last two hundred years, for instance through the increase of greenhouse gasses, leading to global warming, but also through dramatic changes in the land cover and land use, and overexploitation of scarce resources. The above mentioned processes from endogenic, exogenic and anthropogenic nature may lead to potentially catastrophic events, even in locations that may be far away. For instance earthquakes might trigger landslides which may lead to landslide-dammed lakes that may break out and cause flooding downstream. Or the dams of large reservoirs in mountains, constructed for hydropower, irrigation or drinking water, may fail under an earthquake or extreme rainfall event and cause a similar flood wave.

These potentially harmful events are called hazards. They pose a level of threat to life, health, property, or environment. They may be classified in different ways, for instance according to the main origin of the hazard in geophysical, meteorological, hydrological, climatological, biological, extra-terrestrial and technological (See Table 2.1, from Guha-Sapir *et al.* 2016). Such classifications are always a bit arbitrary, and several hazard types could be grouped in different categories, e.g. landslides could be caused by earthquakes, extreme precipitation and human interventions.

Hazards have a number of characteristics that should be understood in order to be able to assess and subsequently reduce their potential damage. Hazards with certain magnitudes may occur with certain frequencies, as small events may occur often, and large events seldom. In order to be able to establish a magnitude-frequency

Table 2.1 Classification of hazard types as used by the International Disaster Database EM-DAT (Guha-Sapir *et al.* 2016), which is based on and adapted from the he IRDR Peril Classification and hazard Glossary (IRDR, 2014).

Main Group	Main Sub-group	Main Type	Sub-Type
Natural	Geophysical: A hazard originating from solid earth. This term is used interchangeably with the term geological hazard.	Earthquake	Ground shaking, tsunami
		Mass movement	
		Volcanic	Ash fall, lahar, pyroclastic flow, lava flow
	Meteorological: A hazard caused by short-lived, micro- to meso-scale extreme weather and atmospheric conditions that last from minutes to days.	Storm	Extra-tropical storm, tropical storm, convective storm
		Extreme temperature	Cold wave, heat wave, severe winter conditions
		Fog	
	Hydrological: A hazard caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.	Flood	Coastal flood, riverine flood, flash flood, ice jam flood.
		Landslide	Avalanche (snow, debris), mudflow, rockfall
		Wave action	Rogue wave, seiche
	Climatological: A hazard caused by long-lived, meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability.	Drought	
		Glacial Lake outburst	
		Wildfire	Forest Fire, land fire (bush, pasture)

	Biological: A hazard caused by the exposure to living organisms and their toxic substances or vector-borne diseases that they may carry. Examples are venomous wildlife and insects, poisonous plants, and mosquitoes carrying disease-causing agents such as parasites, bacteria, or viruses (e.g. malaria).	Epidemic	Viral , bacterial, parasitic, fungal, prion disease
		Insect infestation	Grasshopper, locust
		Animal accident	
	Extraterrestrial: A hazard caused by asteroids, meteoroids, and comets as they pass near-earth, enter the Earth's atmosphere, and/or strike the Earth, and by changes in interplanetary conditions that effect the Earth's magnetosphere, ionosphere, and thermosphere.	Impact	
		Space weather	Energetic particles, geomagnetic storm
Technological	Industrial accident		Chemical spills, collapse, explosion, fire, gas-leak, poisoning, radiation, other
	Transport accident		Air, road, rail, water
	Miscellaneous accident		Collapse, explosion, fire, other.

relationship for hazard events, it is generally necessary to collect historical data (e.g. from seismographs, meteo-stations, stream gauges, historical archives, remote sensing, field investigations etc.) and carry out statistical analysis (e.g. using extreme event analysis such as Gumbel analysis) (Van Westen *et al.* 2008). The magnitude of the hazard gives an indication of the size of the event, or the energy released, whereas the intensity of a hazard refers to the spatially varying effects. For example earthquake magnitude refers to the energy released by the ruptured fault (e.g. measured on the Richter scale) whereas the intensity refers to the amount of ground shaking which varies with the distance to the epicentre (e.g. measured on Modified Mercalli scale). The magnitude of floods may be measured as the discharge in the main channel at the outlet of a watershed before leaving the mountainous area, whereas the intensity may be measured as the water height or velocity which is spatially distributed, and depends on the local terrain. For some types of hazards there is no unique intensity scale defined, e.g. for landslides (Corominas *et al.* 2015).

These events may be potentially harmful to people, property, infrastructure, economy and activities, but also to the environment, which are all grouped together under the term Elements-at-risk or assets. Also the term exposure is used to indicate those elements-at-risk that are subject to potential losses. Important elements-at-risk that should be considered in analysing potential damage of hazards are population, building stock, essential facilities and critical infrastructure. Critical infrastructure consists of the primary physical structures, technical facilities and systems, which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency (UN-ISDR, 2009). Elements-at-risk have a certain level of vulnerability, which can be defined in a number of different ways. The general definition is that vulnerability describes the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UN-ISDR, 2009). There are many aspects of vulnerability, related to physical, social, economic, and environmental conditions (see for example Birkmann, 2006). When considering physical vulnerability only, it can be defined as the degree of damage to an object (e.g. building) exposed to a given level of hazard intensity (e.g. water height, ground shaking, and impact pressure).

2.1 RISK

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 presented conceptually with the following basic equation indicated in Figure 2.1. Risk can presented conceptually with the following basic equation:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Amount of elements-at-risk} \tag{2.1}$$

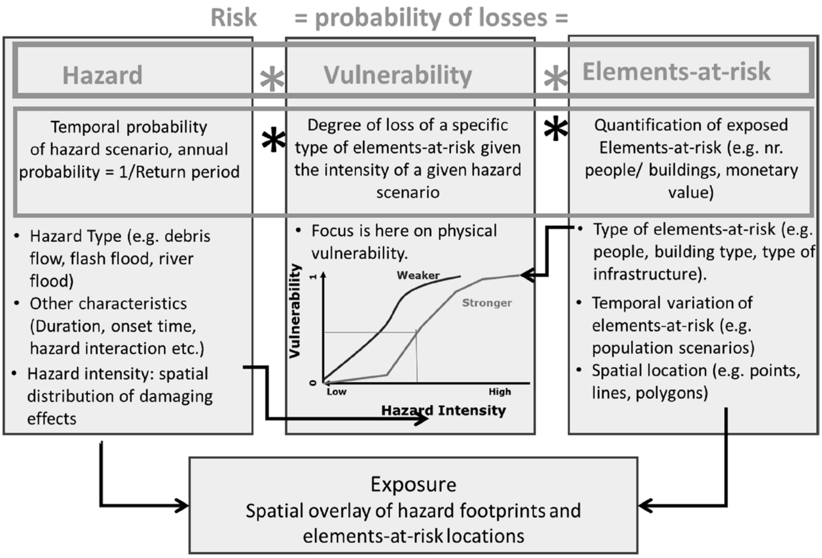


Figure 2.1 Schematic representation of risk as the multiplication of hazard, vulnerability and quantification of the exposed elements-at-risk. The various aspects of hazards, vulnerability and elements-at-risk and their interactions are also indicated. This framework focuses on the analysis of physical losses, using physical vulnerability data.

The equation given above is not only a conceptual one, but can also be actually calculated with spatial data in a GIS to quantify risk from geomorphological hazards. 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 presented. Table 2.2 gives a more in-depth explanation of the various components involved. In order to calculate the specific risk equation 2.1 can be modified in the following way:

$$R_S = P_{(T:\mathrm{Hs})} \times P_{(L:\mathrm{Hs})} \times V_{(\mathrm{Es|Hs})} \times A_{\mathrm{ES}} \tag{2.2}$$

in which:

$P_{(T:\mathrm{Hs})}$ is the temporal (e.g. annual) probability of occurrence of a specific hazard scenario (H_s) with a given return period in an area;

$P_{(L:\mathrm{Hs})}$ is the locational or spatial probability of occurrence of a specific hazard scenario with a given return period in an area impacting the elements-at-risk;

$V_{(\mathrm{Es|Hs})}$ is the physical vulnerability, specified as the degree of damage to a specific element-at-risk E_s given the local intensity caused due to the occurrence of hazard scenario H_S;

A_{Es} is the quantification of the specific type of element at risk evaluated (e.g. number of buildings).

Table 2.2 Components of risk with definitions, equations and explanations.

Term	Definition	Equations & Explanation
Natural hazard (H)	A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. This event has a probability of occurrence within a specified period of time and within a given area, and has a given intensity.	$P_{(T:HS)}$ is the temporal (e.g. annual) probability of occurrence of a specific hazard scenario (H_s) with a given return period in an area; $P_{(L:\mathbf{HS})}$ is the locational or spatial probability of occurrence of a specific hazard scenario with a given return period in an area impacting the elements-at-risk
Elements-at-risk (E)	Population, properties, economic activities, including public services, or any other defined values exposed to hazards in a given area". Also referred to as "assets".	E_s is a specific type of elements-at-risk (e.g. masonry buildings of 2 floors)
Vulnerability (V)	The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards. Can be subdivided in physical, social, economical, and environmental vulnerability.	$\mathrm{V}_{(Es\|Hs)}$ is the physical vulnerability, specified as the degrees of damage to E_S given the local intensity caused due to the occurrence of hazard scenario H_S It is expressed on a scale from 0 (no damage) to 1 (total loss)
Amount of elements-at-risk (A_E)	Quantification of the elements-at-risk either in numbers (of buildings, people etc), in monetary value (replacement costs etc), area or perception (importance of elements-at-risk).	A_{ES} is the quantification of the specific type of element at risk evaluated (e.g. number of buildings)
Consequence (C)	The expected losses (of which the quantification type is determined by A_E) in a given area as a result of a given hazard scenario.	C_S is the "specific consequence", or expected losses of the specific hazard scenario which is the multiplication of $V_S \times A_{ES}$

Table 2.2 Components of risk with definitions, equations and explanations (*Continued*).

Term	Definition	Equations & Explanation
Specific risk (R_S)	The expected losses in a given area and period of time (e.g. annual) for a specific set of elements-at-risk as a consequence of a specific hazard scenario with a specific return period.	$R_S = H_S \times V_S \times A_{ES}$ $R_S = H_S \times C_S$ $R_S = P_{(T:Hs)} \times P_{(L:Hs)} \times V_{(Es\|Hs)} \times A_{ES}$
Total risk (R_T)	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 in a given area and time period. It is calculated by first analyzing all specific risks. It is the integration of all specific consequences over all probabilities.	$R_T \approx \Sigma(R_T) = \Sigma(H_S \times V_S \times A_{ES})$ Or better: $R_T = \int(V_S \times A_{ES})$ – For all hazard types – For all return periods – For all types of elements-at-risk. It is normally obtained by plotting consequences against probabilities, and constructing a risk curve. The area below the curve is the total risk.

The term risk mapping is often used as being synonymous with risk analysis in the overall framework of risk management. Risk assessments (and associated risk mapping) include: a review of the technical characteristics of hazards such as their location, intensity, frequency and probability; the analysis of exposure and vulnerability including the physical social, health, economic and environmental dimensions; and the evaluation of the effectiveness of prevailing and alternative coping capacities in respect to likely risk scenarios (UN-ISDR, 2009; EC, 2011; ISO 31000). In the framework of natural hazards risk assessment, the term risk mapping also indicates the importance of the spatial aspects of risk assessment. All components of the risk equation (Figure 2.1) are spatially varying and the risk assessment is carried out in order to express the risk within certain areas. To be able to evaluate these components there is a need to have spatially distributed information. Computerized systems for the collection, management, analysis and dissemination of spatial information, so-called Geographic Information Systems (GIS) are used to generate the data on the various risk components, and to analyse the risk (OAS, 1991; Coppock, 1995; Cova, 1999; van Westen, 2013). Hazard data is generally the most difficult to generate. For each hazard type (e.g. flooding, debris flow, rock fall) so-called **hazard scenarios** should be defined, which are hazard events with a certain magnitude/intensity/frequency relationship (e.g. flood depth maps for 10, 50 and 100 year return periods). Different types of modelling approaches are required for the hazard scenario analysis, depending on the hazard type, scale of analysis, availability of input data, and availability of models. Generally speaking a separate analysis is required to determine the probability of occurrence for a given magnitude of events, followed by an analysis of the initiation of the hazard (e.g. hydrological modelling or landslide initiation modelling), and of the run-out or spreading of the hazard (e.g. hydrodynamic modelling or landslide run-out modelling). Overviews of hazard and risk assessment methods for landslides for example can be found in Corominas *et al.* (2014), and for floods in Prinos (2008). Elements-at-risk data are very often based on building footprint maps, which represent the location of buildings, with attributes related to their use, size, type and number of people during different periods of the year (e.g. daytime, night-time). Remote Sensing is often used to extract these building maps if existing cadastral maps are not available. For other elements-at-risk like transportation infrastructure and land cover maps also remote sensing data are used as important inputs. Vulnerability data is often collected in the form of vulnerability curves, fragility curves or vulnerability matrices, which indicate the relationship between the levels of damage to a particular type of element-at-risk (e.g. single storey masonry building) given intensity levels of a particular hazard type (e.g. debris flow impact pressure). Generation of vulnerability curves is a complicated issue, as they can be generated empirically from past damage event for which intensity and damage is available for many elements-at-risk, or through numerical modelling (Roberts *et al.* 2009). Table 2.2 gives an overview of the various components of risk.

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 *et al.* 2002). It is also possible to differentiate between direct risk (which is the risk directly resulting from the impact of the hazard) and indirect risk (which may occur later as a consequence of the direct impact). Some examples of direct risk are the destruction of physical objects (e.g. buildings, transportation infrastructure), and examples of indirect losses are loss of revenues and economic production, disruption of transportation networks leading to longer travel time etc. A significant component of the losses are intangible (difficult or impossible to quantify), for example the societal or psychological impact of disaster events.

2.2 MULTI-HAZARD RISK

One of the difficult issues in natural hazards risk assessment is how to analyse the risk for more than one hazard in the same area, and the way they interact. Figure 2.2 shows an illustration of how different sets- of triggering factors can cause a number of different hazards. There are many factors that contribute to the occurrence of hazardous phenomena, which are either related to the environmental setting (topography, geomorphology, geology, soils etc.) or to anthropogenic activities (e.g. deforestation, road construction, tourism). Although these factors contribute to the occurrence of the hazardous phenomena and therefore should be taken into account in the hazard and risk assessment, they are not directly triggering the events. For these, there is a need for triggering phenomena, which can be of meteorological or geophysical origin (earthquakes, or volcanic eruptions). A generally accepted definition of multi-hazard still does not exist. In practice, this term is often used to indicate all relevant hazards that are present in a specific area, while in the scientific context it frequently refers to "more than one hazard". Likewise, the terminology that is used to indicate the relations between hazards is unclear. Many authors speak of interactions (Tarvainen *et al.* 2006; de Pippo *et al.* 2008; Marzocchi *et al.* 2009; Zuccaro & Leone, 2011; European Comission, 2011), while others call them chains (Shi, 2002), cascades (Delmonaco *et al.* 2006a; Carpignano *et al.* 2009; Zuccaro & Leone, 2011; European Comission, 2011), domino effects (Luino, 2005; Delmonaco *et al.* 2006a; Perles & Cantarero, 2010; van Westen, 2010; European Comission, 2011), compound hazards (Alexander, 2001) or coupled events (Marzocchi *et al.* 2009).

Compared to single processes, standard approaches and methodological frameworks for multi-hazard risk assessment are less common in the literature (Kappes *et al.* 2012), which is related to the complex nature of the interaction between the hazards, and the difficulty to quantify these.

2.2.1 Independent events

The simplest approach is to consider that the hazards are independent and caused by different triggers. This means that the expected losses from one hazard type are independent from the losses expected from the other hazard type. If that is the case, the risk can be calculated by adding the average annual losses for the different types of hazard. This would be the case for example for earthquake hazard and flood hazard. They have different triggering mechanisms, which do not directly interact. Therefore, earthquake hazard is independent of flood hazard and may be analysed separately. Also the risk may be analysed separately and the resulting losses could be added. Other examples of independent hazard are for instance technological hazards and flood hazards. Many of the existing software tools for multi-hazard risk assessment (See section 2.9) deal with these hazard independently, and sum up the losses. However, when these apparent independences are examined in detail, the relation may be more complicated. For instance, an earthquake may trigger landslides that may block a river leading to flooding, which makes that the earthquake and flood risk cannot be considered entirely independent. Even flooding and technological hazards cannot be considered completely independent: during flood events there may be a higher risk of technological accidents.

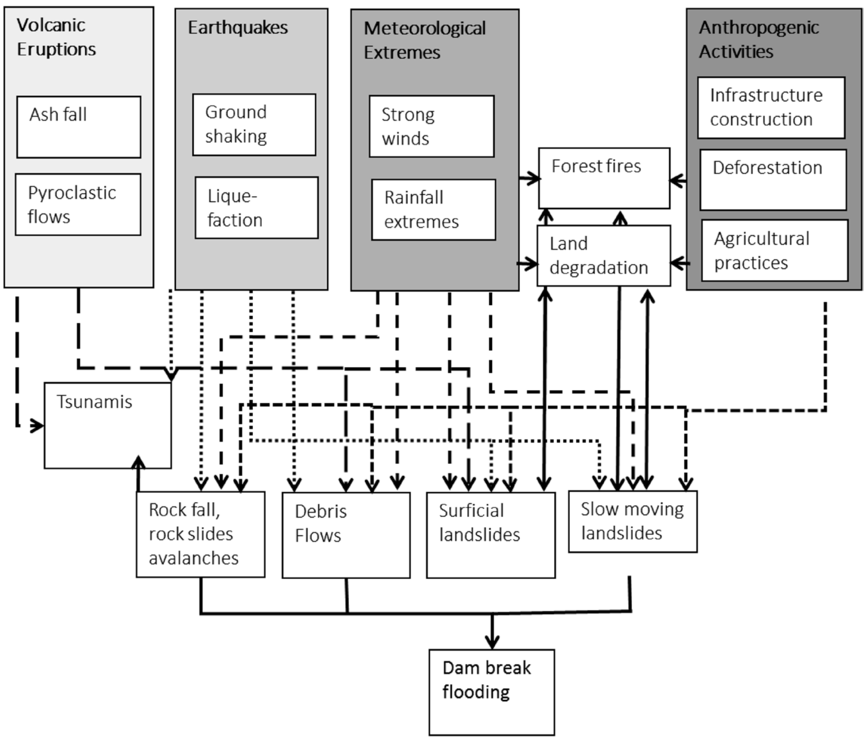


Figure 2.2 Schematic representation of multi-hazards interactions between the main triggering events (volcanic eruptions, Earthquakes, Meteorological extremes, and anthropogenic activities) and secondary hazards.

2.2.2 Coupled events

The second multi-hazard relationship is between different hazard types that are triggered by the same triggering event. These are what we would call **coupled**

events (Marzocchi *et al.* 2009). The temporal probability of occurrence of such coupled events is the same as it is linked to the probability of occurrence of the triggering mechanism. For analysing the spatial extent of the hazard, one should take into account that when such coupled events occur in the same area and the hazard footprints overlap, the processes will interact, and therefore the hazard modelling for these events should be done simultaneously, which is still very complicated. In order to assess the risk for these multi-hazards, the consequence modelling should therefore be done using the combined hazard footprint areas, but differentiating between the intensities of the various types of hazards and using different vulnerability-intensity relationships. When the hazard analyses are carried out separately, the consequences of the modelled scenarios cannot be simply added up, as the intensity of combined hazards may be higher than the sum of both or the same areas might be affected by both hazard types, leading to overrepresentation of the losses, and double counting. Examples of such types of coupled events is the effect of an earthquake on a snow-covered building (Lee & Rosowsky, 2006) and the triggering of landslides by earthquakes occurring simultaneously with ground shaking and liquefaction (Delmonaco *et al.* 2006b; Marzocchi *et al.* 2009). Within multi-hazard risk assessment the best way to treat coupled risk is to take the maximum of the risks that are coupled. For example, during the same tropical storm a village may be hit by flash floods or debris flows. Once it is hit by one type there is damage, and buildings cannot be destroyed twice during the same event.

2.2.3 One hazard changes conditions for the next

A third type of interrelations is the influence one hazard exerts on the **disposition** of a second hazard, though without triggering it (Kappes *et al.* 2010). An example is the "fire-flood cycle" (Cannon & De Graff, 2009): forest fires alter the susceptibility to debris flows and flash floods due to their effect on the vegetation and soil properties. This problem highlights the fact that the conditions that make certain areas more susceptible to hazards may change constantly. For instance, land cover and land use have a large effect on hydro-meteorological hazards, such as flooding and landslides. When these change as a result of other hazards (like forest fires), also the susceptibility to landslides, debris flows or floods increases. Many of the hazard relations are of this type. For instance, volcanic eruptions may lead to the deposition of volcanic ash, which will increase the susceptibility to landslides and flooding. Earthquakes may trigger landslides, and the landslide scars that are unvegetated may lead to increased erosion and debris flows. It is very difficult to take this type of relationship into account before one particular hazard has changed the conditions that make the terrain more susceptible to the second hazard. The practice is to update a multi-hazard risk assessment each time after the occurrence of a major hazard event (like a volcanic eruption, major earthquake or hurricane).

2.2.4 Domino or cascading hazards

The fourth type of hazard relationships consists of those that occur in **chains**: one hazard causes the next. These are also called **domino** effects, **concatenated**, or **cascading** hazards. These are the most problematic types to analyse in a multi-hazard risk assessment. Hazard may occur in sequence, where one hazard may trigger the next. These hazard chains or domino effects are extremely difficult to quantify over certain areas, although good results have been obtained at a local level (e.g. Peila & Guardini, 2008). The best approach for analysing such hazard chains is to use so-called event-trees (See section 2.3.2). However, it is often very difficult to apply such event-trees in a spatial manner, where in fact different parts of an area may require different event-trees. This is true for instance for the chain: earthquake-landslide-damming-dam break flood. Each part of the terrain has a different susceptibility to landslides. But also each earthquake, which a given depth and magnitude, may trigger different landslide patterns. If a landslide may be generated, the next step is to evaluate whether the size is large enough to dam a river. This also depends on the location of the landslide with respect to the river, the width of the river and the river discharge. Once the river is dammed it depends on the type of material in the dam and the strength of the river, whether the landslide dam is broken fast or whether there is a possibility for a lake to develop, which may cause more severe flooding when the dam breaks later. This sequence is described by Fan *et al.* (2012).

2.2.5 Example of multi-hazard chain: Layou Valley landslides in Dominica, Caribbean

The Layou-Carholm landslide, located on the Caribbean island of Dominica, represents an example of a multi-hazard situation that achieved climactic proportions in 1997 and 2011. The Layou River, with a length of 17 km is one of the largest watersheds in Dominica (70 km^2) and drains about 9% of the land (ACOE, 2004). The Layou Tuff forms vertical walls along the lower Matthieu and Layou Rivers through these reaches. This welded tuff resulted from ignimbrite eruptions in the Late Pleistocene (Roobol & Smith, 2004). Landslides were common in the area, with specific reports occurring between 1987 and 1997. There is an eyewitness account of a slide following Hurricane Hugo in 1989 and also following Hurricanes Iris, Luis and Marilyn in 1995. There was a major change to the pattern of small landslides. Dramatic slumping occurred between November 18 and 25, 1997. Two major slides blocked the river and created a natural dam. The dam was breached on November 21 with mudflows reaching the sea accompanied by extensive flooding of the lower river valley. The larger of the Layou flood events which happened on November 28, 1997, measured 1,325,000 m^3. A wall of material estimated at 50 feet high was washed downstream. The riverbed rose dramatically in its lower reaches. This elevation was estimated at 10 meters at the location of the bridge. The river had dried up between 18 and 20 November 1997 and then flooded on November 21. Further landslides occurred on November 25, 1997 and October 8 and 11, 1998 with subsequent dam breaks being significant events. End-of-the-year measurements show that the lake depth increased from 22 m in 1998 to nearly 40 m in 2008 (DeGraff *et al.* 2010). The maximum volume estimate is 3,611,985 m^3, assuming failure by overtopping and complete draining of the lake (Breheny, 2007). A major dam break event occurred on 28/06/2011. The road along the Layou River to Pont Casse was closed, due to flood hazard. R Also in later years the Layou valley was heavily affected by floods and landslides. In August 2015, during tropical storm Erika, severe flooding damaged the road in a number of places (Figure 2.3).

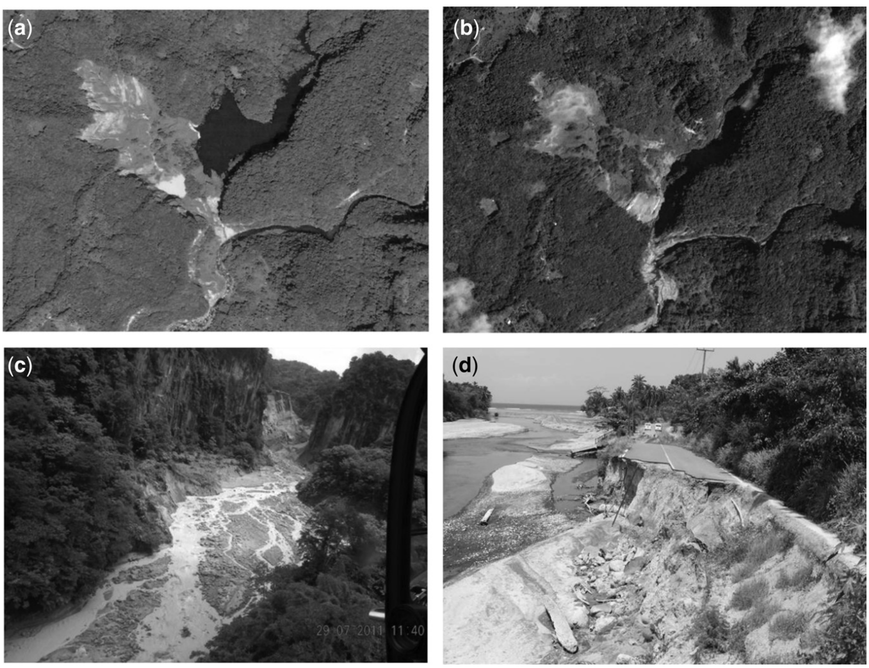


Figure 2.3 Mathieu landslide dam development. **(a)** Carholm landslide blocking the Mathieu River and forming a lake in 1997 (Satellite image from 3-8-2005), **(b)** Google Earth image from 21-12-2012 after the breaching of the landslide dam in 2011 **(c)** View of the river valley just below the breaching point. **(d)** Downstream part of the valley where the road was washed out by heavy flooding on 27 August 2015 during Tropical Storm Erika.

Table 2.3 shows the main multi-hazard relationships for a number of hazards occurring in the Caribbean countries.

Table 2.3 Main hazard types and their interactions. The relationship should be read starting from the left and reading horizontally (Source: www.charim.net).

	Earthquake	**Volcanic Eruption**	**Tsunami**	**Storm Surge**	**River Flooding**	**Landslides**	**Forest Fires**
Earthquake	–	Independent	Chain	Independent	Independent	Chain	Independent
Volcanic eruption	Independent	–	Chain	Independent	Disposition	Disposition	Chain
Tsunami	Caused by	Caused by	–	Independent	Independent	Chain along coast	Independent
Storm surge	Independent	Independent	Independent	–	Chain	Chain	Independent
River flooding	Independent	Independent	Independent	Coupled	–	Coupled	Independent
Landslides	Caused by	Independent	Independent	Coupled	Coupled	–	
Forest Fires	Independent	Coupled	Independent	Independent	Disposition	Disposition	–

2.3 RISK ANALYSIS APPROACHES

Risk assessment is a process to determine the probability of losses by analysing 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 2.4 and Figure 2.4 give 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 2.4 Indication of scales of analysis with associated objectives and data characteristics.

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

Approaches: QRA = Quantitative risk assessment, EVA = Event-Tree Analysis, RMA = Risk matrix approach, IBA = Indicator-based approach.

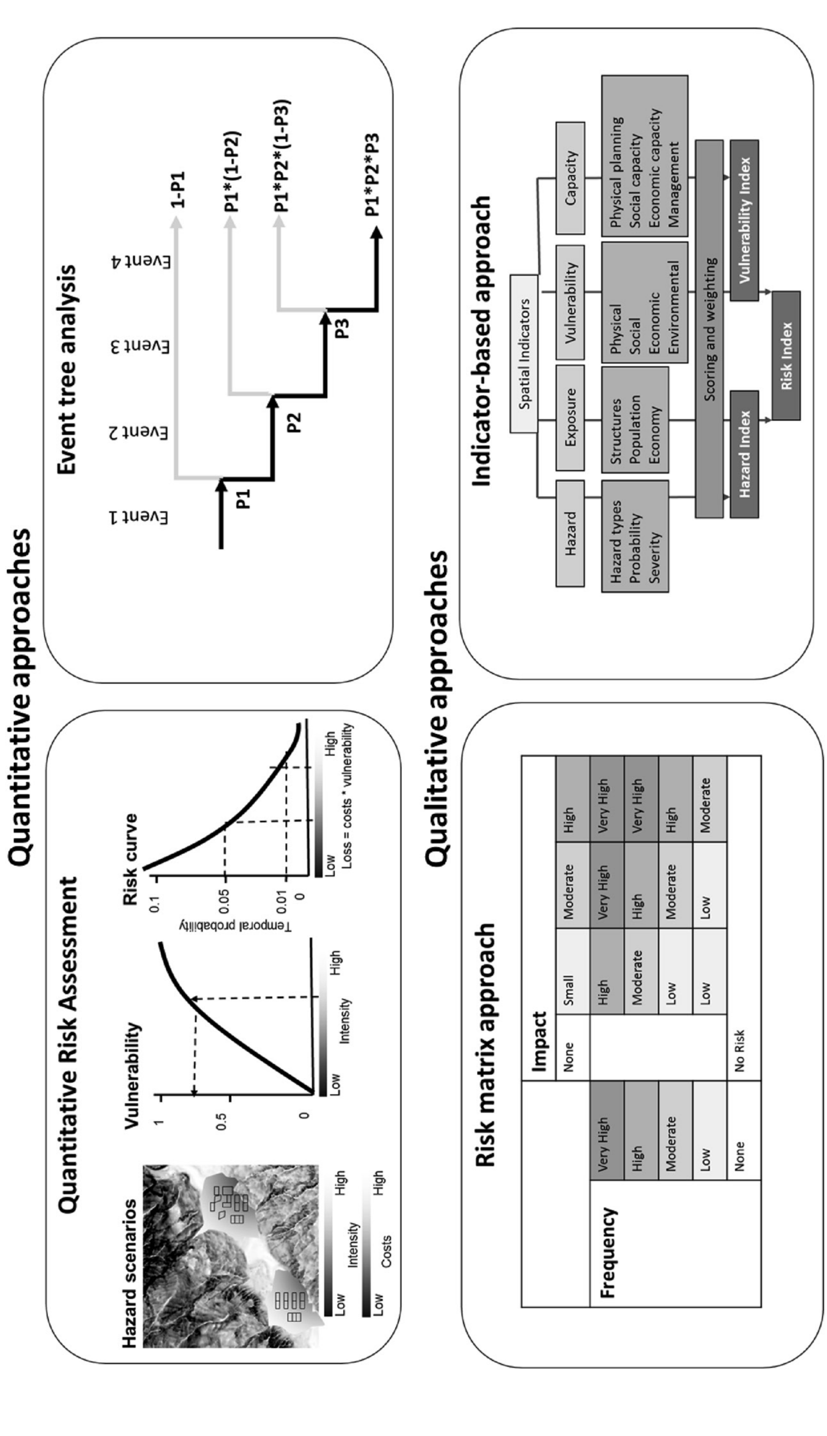


Figure 2.4 Components relevant for risk assessment, and the four major types of risk mapping that are presented in this section.

2.3.1 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 analysed using the following equation:

$$\text{Risk} = \sum_{\text{All hazards}} \left(\int_{P_T=0}^{P_T=1} P_{(T|\text{HS})} \times \left(\sum_{\text{All EaR}} \left(P_{(S|\text{HS})} \times \left(A_{(\text{ER}|\text{HS})} \times V_{(\text{ER}|\text{HS})} \right) \right) \right) \right) \tag{2.3}$$

In which:

$P_{(T|\text{HS})}$ = 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;
$P_{(S|\text{HS})}$ = the spatial probability that a particular location is affected given a certain hazard scenario;
$A_{(\text{ER}|\text{HS})}$ = 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
$V_{(\text{ER}|\text{HS})}$ = 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 2.5. GIS operations are used to analyse 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 $P_{(S|\text{HS})}$ 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.

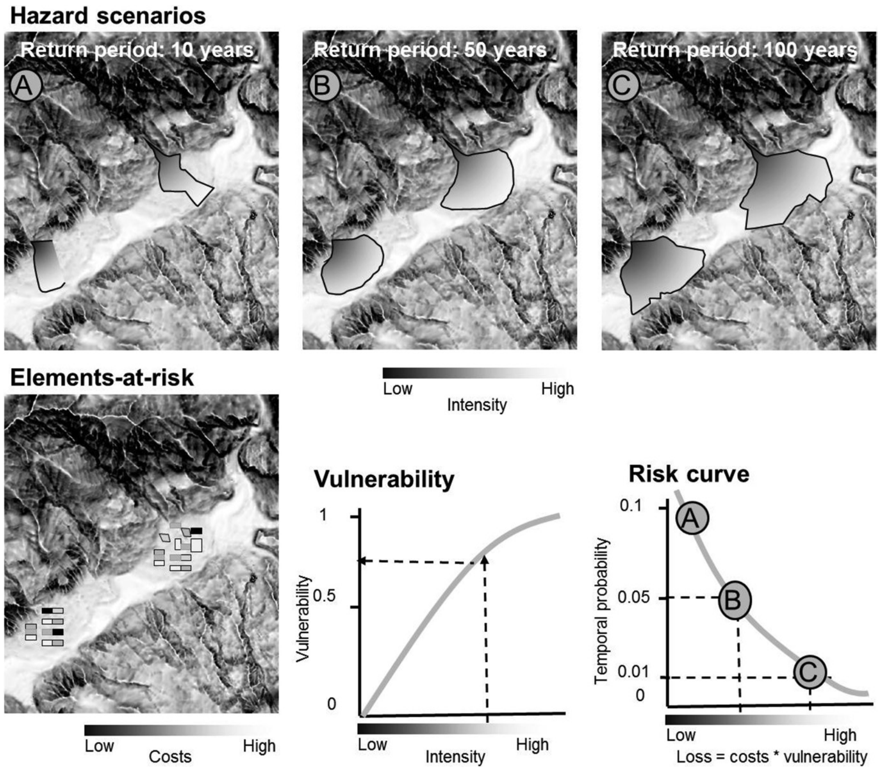


Figure 2.5 Schematic representation of Quantitative Risk Assessment.

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 & 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 2.6. 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 results 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. Thus, 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.

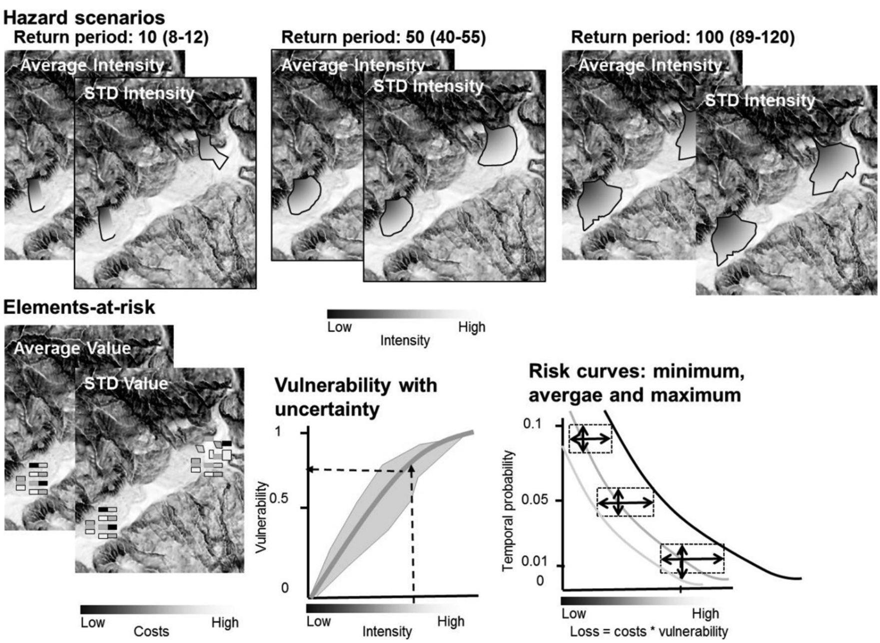
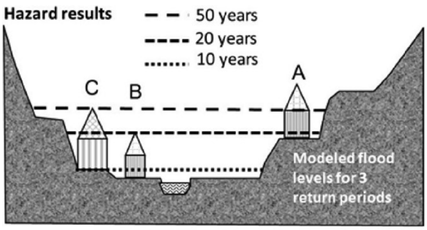


Figure 2.6 Method for including uncertainty in Quantitative Risk Analysis in cases where it is not possible to define many hazard scenarios.

Figure 2.7 gives an example of a quantitative risk assessment. In this simple example we are taking a flood situation. The figure shows a cross section through a flood plain. There are three hazard scenarios, which have been modelled using a flood model. They have different return periods (10 years, 20 years and 50 years). In this simple example there are 3 elements at risk only (buildings) that are of two types. Building A and building B are wooden and relatively weak buildings. They have also lower replacement values. They are located in different elevations. Building C is a concrete building, which is stronger. It is also located at a higher elevation than building B. It is also larger and more expensive. In the exposure analysis, there is overlaying the flood heights with the building heights and the water height is calculated for each hazard scenario and for each building. For the 10 years return period, building A is not flooded, and building C only 0.1 meter. For the 20 year return period, all buildings are flooded, but with different degrees. For the 50 year return period, all buildings are flooded, building B and C very much. For the vulnerability analysis, there is a need for vulnerability curves, which are related for each type of building the degree of loss to a building with a given water height. These curves are generated from past event damage assessment, by correlating the water height with damage. For example: building B has an exposed intensity of 5.6 for the scenario of 20 years return period. And it is a wooden building so we take the value of 5.6 on the X-axis of the vulnerability curve, representing the flood depth. Because it is a wooden building, the curve for the wooden buildings is looked up, and then the damage value on the y-axis is read. This is done for all buildings and for all return periods. The replacement values (amount) are filled in, and the replacement values (amount) are multiplied with the vulnerability to calculate losses. The losses for the buildings are summed up for the same hazard scenario (return period). The annual probability is calculated: 1 divided by the return period. The probability is plotted for each scenario against the losses, and fit a curve through the points, which links all probabilities with all losses. The area below the curve represents the Average Annual Losses. It is the integration of all losses over all probabilities.

2.3.2 Event-tree approaches

As mentioned in section 2.2.4 a number of hazards may occur in chains: these are also called domino effects, or concatenated hazards. These are the most problematic types to analyse in a multi-hazard risk assessment. The best approach for analysing such hazard chains is to use so-called event-trees. An event tree is a system, which is applied to analyse all the combinations (and the associated probability of occurrence) of the parameters that affect the system under analysis. All the analysed events are linked to each other by means of nodes (See Figure 2.4) 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. Figure 2.8 gives an example 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).



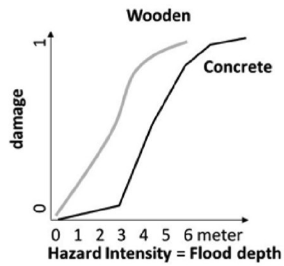
Exposure results

House	10 years	20 years	50 years
A (wood)	0	0.8	2.0
B (wood)	1.2	5.6	6.8
C (concrete)	0.1	4.5	5.7

Vulnerability results

	Return Period	Vulnerability
A	10	0
B	10	0.2
C	10	0.05
A	20	0.1
B	20	1
C	20	0.5
A	50	0.4
B	50	1
C	50	0.8

Vulnerability curves



Loss calculation results

	Return Period	Vulnerability	Amount	V*A (loss)	Aggregate loss	Probability
A	10	0	100000	0	20000	0.1
B	10	0.2	50000	10000		
C	10	0.05	200000	10000		
A	20	0.1	100000	10000	160000	0.05
B	20	1	50000	50000		
C	20	0.5	200000	100000		
A	50	0.4	100000	40000	250000	0.02
B	50	1	50000	50000		
C	50	0.8	200000	160000		

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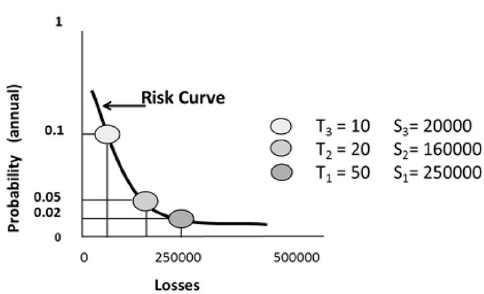
Risk curve

	Aggregate loss	Probability
A	20000	0.1
B		
C		
A	160000	0.05
B		
C		
A	250000	0.02
B		
C		



Average Annual Risk: Area under curve

$$\text{Average Annual Risk} = \frac{1}{T_1}\cdot S_1 + \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\cdot\frac{S_1 + S_2}{2} + \left(\frac{1}{T_3} - \frac{1}{T_2}\right)\cdot\frac{S_2 + S_3}{2}.$$

Figure 2.7 Schematic presentation of the steps involved in quantitative risk analysis. See text for explanation.

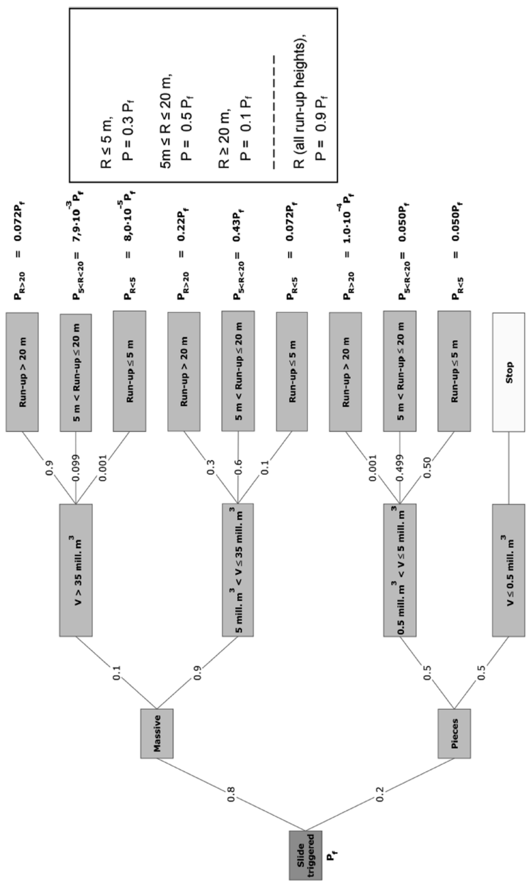


Figure 2.8 Bayesian Event tree for tsunami propagation, given that rock slide in Åknes has occurred (V = rockslide volume, R = run-up height). From Lacasse *et al.* (2008).

2.3.3 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 the so-called risk matrices or consequences-frequency matrices (CFM), which are diagrams with consequence and frequency classes on the axes (See Figure 2.4). They permit to classify risks based on expert knowledge with limited quantitative data (Haimes, 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 (Figure 2.9 from 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 (Haimes, 2008).

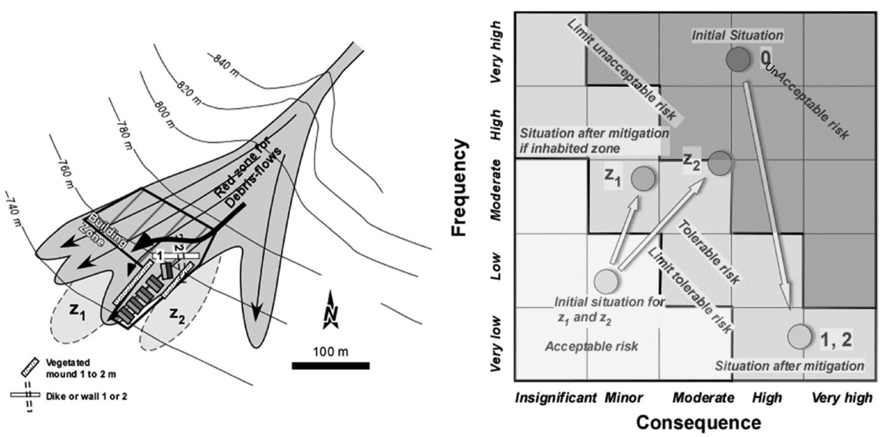


Figure 2.9 Example of potential building area in a high hazard area and illustration of the proposed solutions. The risk matrix is used to represent the degree of risk. The scope of tolerable risk (yellow) is between the limits of tolerance and of acceptability. The initial situation 0 is a combination 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).

2.3.4 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 2.4), through the so-called criteria tree, which list the subdivision into objectives, sub-objectives and indicators (Figure 2.11). 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 & Hidajat, 2006) cities (Greiving *et al.* 2006) to countries (Van Westen *et al.* 2012).

The approaches are mostly based on the development of the 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. 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. Van Westen *et al.* (2012) developed a similar approach for national scale vulnerability and risk assessment for the country of Georgia (Figure 2.10 and

Figure 2.11). 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).

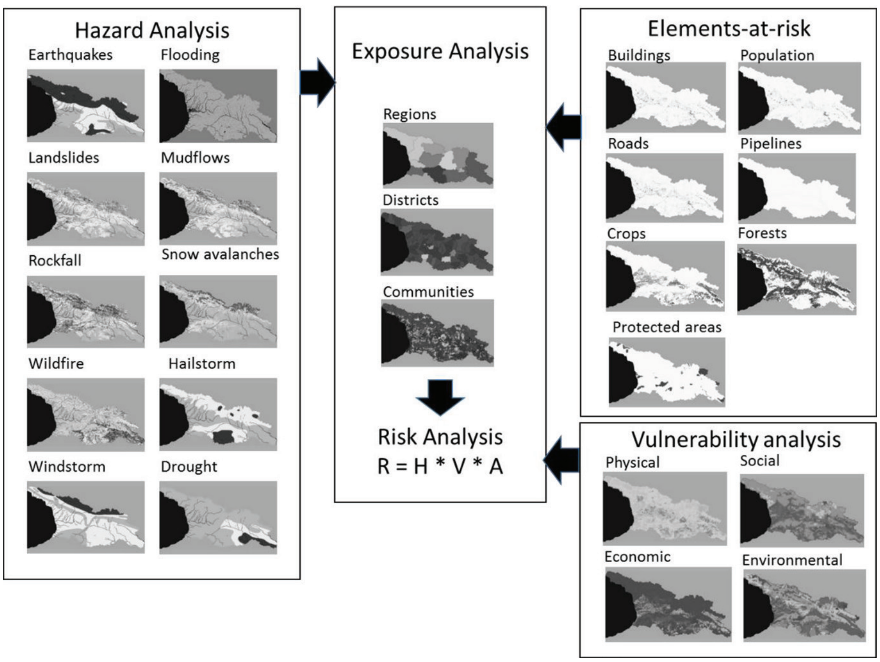


Figure 2.10 National scale multi-hazard risk assessment using an indicator-based approach for the country of Georgia (Caucasus). The method is developed in a web-based platform (http://drm.cenn.org/index.php/en/) and a risk atlas (https://issuu.com/grammallc/docs/atlas_of_risk?pageNumber=1&e=5243266/2932778).

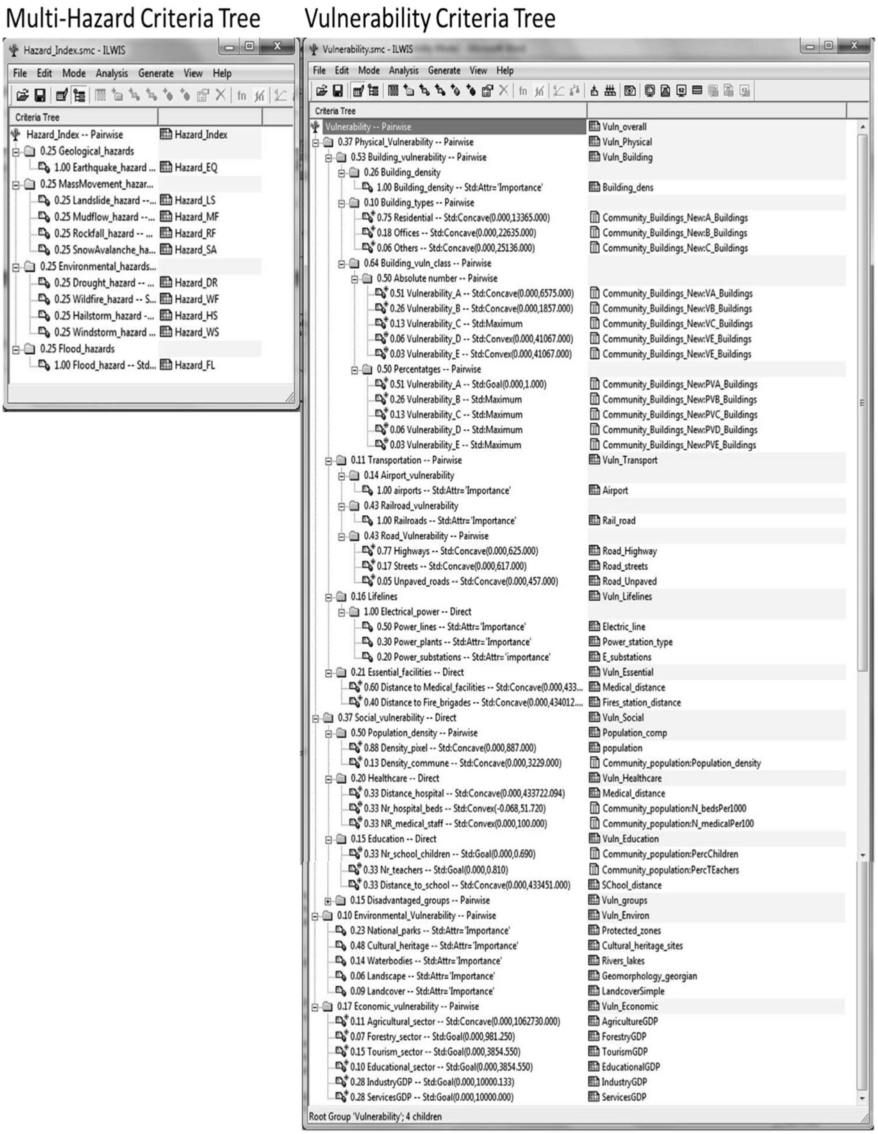


Figure 2.11 National scale multi-hazard risk assessment using an indicator-based approach for the country of Georgia (Caucasus). A multi-hazard map was generated using a hazard criteria tree, which was combined with a vulnerability criteria tree. The vulnerability criteria tree is composed of a number of main groups: physical vulnerability, social vulnerability, environmental vulnerability and economic vulnerability. These are subdivided into subgroups and eventually in a number of spatial indicators, which are standardized and weighted. (Van Westen *et al.* 2012).

2.4 RISK ANALYSIS AND DECISION MAKING: A CASE STUDY

After the introduction parts, the second half of this chapter deals with the application of risk analysis in decision making. This is done through illustrating the procedures with a hypothetical case study.

The overall aim of the second part of this chapter is to illustrate how to analyse possible changes in risk to multi-hazards. These changes may be related to possible risk reduction measures, but also to possible future scenarios related to land use change, population change, and climate change, and the effect of possible intervention alternatives on top of these possible future scenarios. This is illustrated in Figure 2.12, which has four possible workflows:

(A) **Analysing the current level of risk.** In this workflow the stakeholders (e.g. local authorities) are interested to know the current level of risk in their municipality. They request expert organizations to provide them with hazard maps, asset maps, and vulnerability information, and use this information in risk modelling. They use the results in order to carry out a risk evaluation.

(B) **Analysing the best alternatives for risk reduction.** In this workflow the stakeholders want to analyse the best risk reduction alternative, or combination of alternatives. They define the alternatives, and request the expert organizations to provide them with updated hazard maps, assets information and vulnerability information reflecting the consequences of these alternatives. Once these hazard and asset maps are available for the alternatives, the new risk level is analysed, and compared with the existing risk level to estimate the level of risk reduction. This is then evaluated against the costs (both in terms of finances as well as in terms of other constraints) and the best risk reduction scenario is selected.

(C) **The evaluation of the consequences of possible future scenarios.** Possible future scenarios can be formulated that project possible changes related to climate, land use change or population change due to global and regional changes, and which are only partially under the control of the local planning organizations. Stakeholders would like to evaluate the effect of these changes on the hazard and assets (again here the updated maps should be provided by expert organizations) and how these would translate into different risk levels.

(D) **The evaluation how different risk reduction alternatives will perform under different future scenarios.** (trends of climate change, land use change and population change). This is the most complicated workflow, as it requires to calculate the present risk level, the effect of different risk reduction alternatives, and the overprinting of these on the scenarios. For each of these combinations of alternatives & scenarios new hazard, assets and risk maps need to be made.

These four different workflows will be presented more in detail in the coming sections. First, the study area and case study data set will be presented.

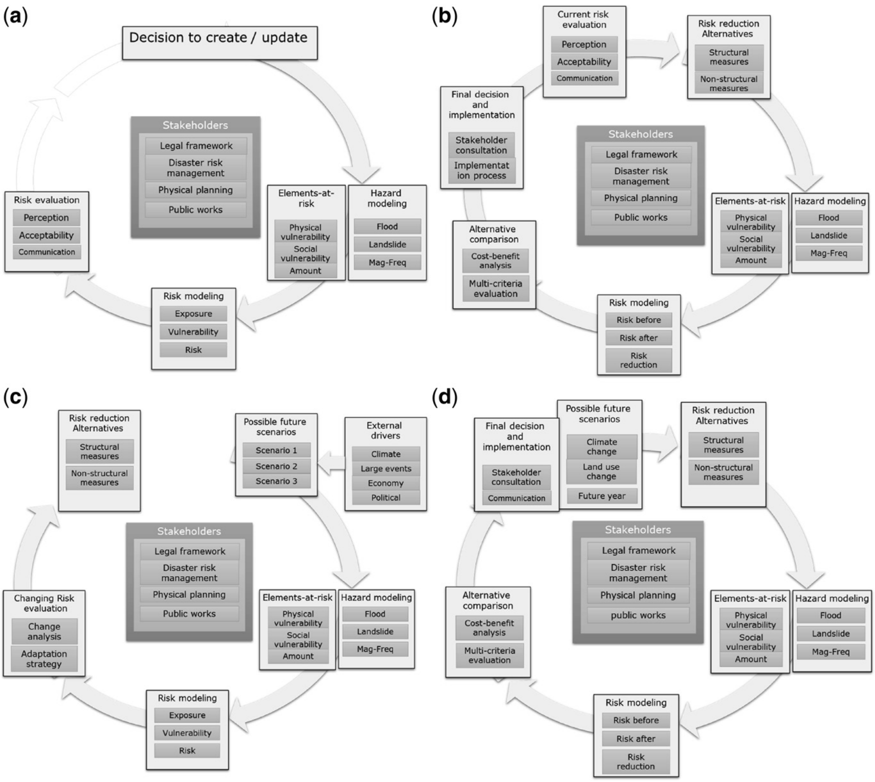


Figure 2.12 Four situations where risk assessment is used in decision making. (**a**) Analysing the current level of risk. (**b**) Analysing the best risk reduction alternative; (**c**) Analysing changing risk due to possible future scenarios. (**d**) Analysing the best "change-proof" alternative: the alternative that behaves best under possible future scenarios. See text for more explanation.

2.4.1 The case study data set

The case study data set was based on an original dataset from Nocera Inferiore, located between Naples and Salerno in Italy. This data set was prepared for the EU FP7 project SAFELAND (2011a, 2011b). The procedure and results for the hazard and risk assessment of the existing situation were reported by Ferlisi *et al.* (2016). The various risk reduction alternatives and the involvement of various stakeholders in the selection of the optimal measures was presented by Linnerooth-Bayer *et al.* (2016). Narasimhan *et al.* (2016) presented results on Cost-Benefit Analysis for some of the risk reduction measures. The Nocera dataset is used as a start, but it has modified the data and methods so that it allows to show the various procedures for multi-hazard risk assessment dealing with a hypothetical case study of a mountainous slope along the coast of a Caribbean island.

Therefore, the original hazard maps are modified to reflect the situation for the various alternatives, and scenarios, and additional tsunami hazard maps are added. Building attributes were modified by us, and all land parcel maps have been generated by ourselves based on available high resolution images. It was decided to choose a hypothetical case because of the difficulty in getting the right data for achieving all objectives in the same study area. This analysis requires local scale hazard intensity maps, detailed element-at-risk maps, vulnerability curves, risk reduction alternatives and future scenarios. Many of these data are still not available for a single area. Nevertheless, it is hoped that by following the examples in this chapter, readers get a better idea of the procedure and can eventually also apply it in their own situation, once data is available. There is also a series of GIS exercises, with descriptions, open source GIS software and a spatial dataset, available that follow the procedures step-by-step and downloaded from http://www.charim.net/use/41. The available maps are illustrated in Figure 2.13 and 2.14, respectively.

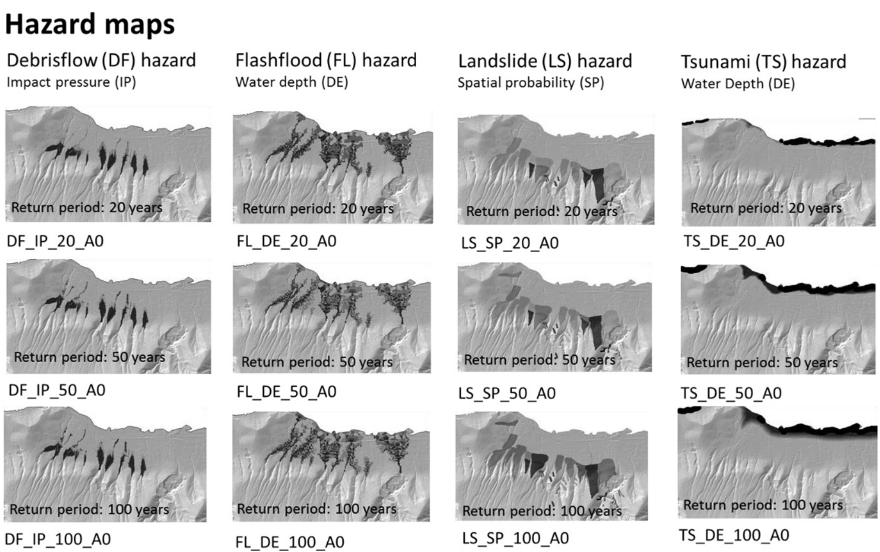


Figure 2.13 Hazard intensity maps for 4 hazard maps (debrisflows, floods, landslides and tsunami) and 3 return periods.

2.4.2 Hazard input data

The case study area is a mountainous area along the coast, with steep forested slopes in the south part, and a fault-related mountain front with triangular facets, from which landslides may be triggered. The steep slopes have a number of steep gulleys, and landslides may form in the upper parts that could lead to debris flows. During heavy rainfall also flash floods may occur in these gulleys, which may affect the flatter areas in the north. The flatter northern part of the area has agricultural, and residential areas. The area is affected by landslides, debris flows, flash floods and possibly also by tsunami. Frequency estimation of hazardous events was carried out based on the analysis of historical hazard data and rainfall data, and hazard assessment for landslides, floods and debris flows were carried out for different return periods using various models, such as OpenLISEM, SEEP/W, Slope/W, TRIGRS and FLO-2d (Ferlisi *et al.* 2016). The debris flow, flood and tsunami maps have intensity data (impact pressure for debris flows, and depth for flooding and tsunami). The landslide hazard maps do not have intensity maps, but only spatial probability maps indicating the chance that a particular area will be affected by a landslide.

The hazard maps have a specific code, which consist of the following components:

- **Hazard type:** the name of the hazard map start with two characters referring to the hazard type: LS = landslides, MF = mudflow, FL = Flood, DF = Debris flows, TS = Tsunami
- **Return Period:** this is the average frequency with which the events are expected to occur. This is based on the analysis of the magnitude and frequency of the triggering rainfall, or of the events themselves (e.g. flood discharge, or the number of landslides occurring in a particular period). The following return periods were used: 20, 50 and 100 years. For some specific situation also longer return periods (200 years) were used.
- **Intensity:** the intensity indicates the spatially distributed effect of the hazard event. This can be water depth (DE) for flooding or tsunami, or impact pressure (IP) for debris flows. These have been modelled using specific hazard modelling software. These models require quite a lot of input data and assumptions. In this chapter we will not deal with the methods how the hazard maps were created. For some types of hazards (e.g. landslides) it may also not be possible to generate intensity maps, as data or models are lacking.
- **Spatial probability:** the spatial probability indicates the chance that a particular location would actually be affected by the hazard. This could be the result of uncertainty in the flood modelling or runout modelling. Or it could also represent (in the absence of an intensity map) the likelihood that a particular area will be affected by landslides based on the area of the units, divided by the area of landslides that have occurred in the past. In this way, it can be used to reclassify the so-called landslide susceptibility maps into spatial probability maps.

2.4.3 Input data: elements-at-risk

It is possible to use four types of elements-at-risk maps: building footprints, land parcels (land use related units), line elements (e.g. transportation lines) and point elements (e.g. individual objects). In the case study, the work involves only building footprints and land parcels as elements-at-risk types (Figure 2.14). Each of them have information on:

- **Land use:** land use is one of the most important characteristics and it is used to model a number of other attributes (e.g. population).
- **Element-at-risk types:** for land parcels this would be the same as the land use type (e.g. forest, residential, commercial etc.) and for building footprints this would be the construction types. Different types of elements-at-risk can be affected differently by hazard events. For the risk analysis this is important as this provides the link to vulnerability curves, which will be explained later.
- **Value:** this is the replacement value of the elements-at-risk in monetary units (Euros, US dollars etc.). These are mostly estimated by multiplying unit costs (e.g. per m^2) with the area of land parcels or floor space for building footprints.
- **People:** the number of people that might be present in the element-at-risk. Here it is relevant to decide whether to take the maximum number of people or the people present at a given time, or to use specific population scenarios (in case of dealing with rapid events, the time of day/year is also important for the population loss estimation).

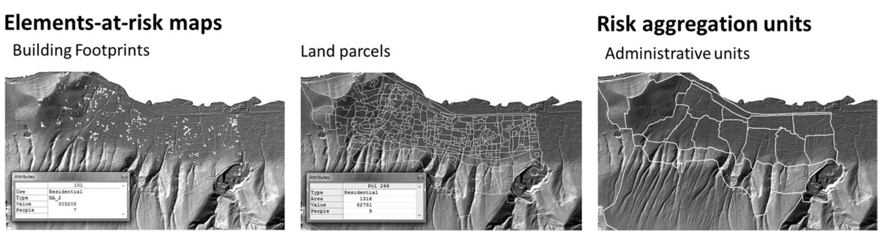


Figure 2.14 Elements-at-risk maps: building footprints and land parcels with related attributes, and administrative units.

The building footprint map and the land parcel maps have the same number of people for the parcels in which buildings are located. For the other parcels, population values per m^2 are used and multiplied these with the area of the land parcel, so that an estimate can be obtained of the total number of people per parcel. For the economic assessment, the values of the buildings are taken from the building footprint map, and used these for the value of the land parcels. For the parcels without buildings, an estimation is conducted based on the value per m^2 and multiplied this with the area.

2.4.4 Input data: vulnerability curves

Vulnerability curves are also very important components in the risk analysis. A vulnerability curve expresses the relation between the hazard intensity (e.g. water depth) and the degree of damage which is expressed between 0 and 1 for a specific type of element-at-risk. Vulnerability curves are derived from past disaster events by correlating observed intensities with observed damage and deriving average regression lines from these. Vulnerability curves may also be derived through computer modelling (e.g. finite element models where a particular building is exposed to a particular intensity and the effect is calculated) or through expert opinion. For this case study, a number of vulnerability curves have been developed for all the combinations of the hazard intensity types and the elements-at-risk types. Existing curves have been used for the literature, but there is a need for a lot of changes, as the curves were not for all of the units. For the analysis these curves should be implemented in GIS, as tables (See Figure 2.15). Curves have been developed for buildings, and land parcels, and separate curves for the physical losses (required for the economic risk analysis) and for the population losses (people killed). The codes in the table indicate the various aspects of the vulnerability curves. For example: VUL_FL_DE_LP_PH: Vulnerability curves for flooding, expressed in water depth, for land parcels, and showing the physical vulnerability.

2.4.5 Input data: administrative units

For the calculation of risk, there is also need for an administrative unit map, as there is going to be an aggregation of the losses for particular units, and the decision making is based on the risk within these units. The administrative unit map contains 19 administrative units (Figure 2.14).

2.5 ANALYSING THE CURRENT LEVEL OF RISK

This section will further present and discuss the workflow for multi-hazard risk analysis of the current situation, illustrated in Figure 2.12A.

2.5.1 Stakeholders

Central in the whole process are the stakeholders. The envisaged users of the system are organizations involved in spatial planning, planning of risk reduction measures, or emergency preparedness and response. They work in a country with a specific legislation and planning process organizations that have different mandates. These could be subdivided into:

- *Government departments responsible for the construction, monitoring, maintenance and protection of critical infrastructure (e.g. the Ministry of Public Works). Their mandate is to*:

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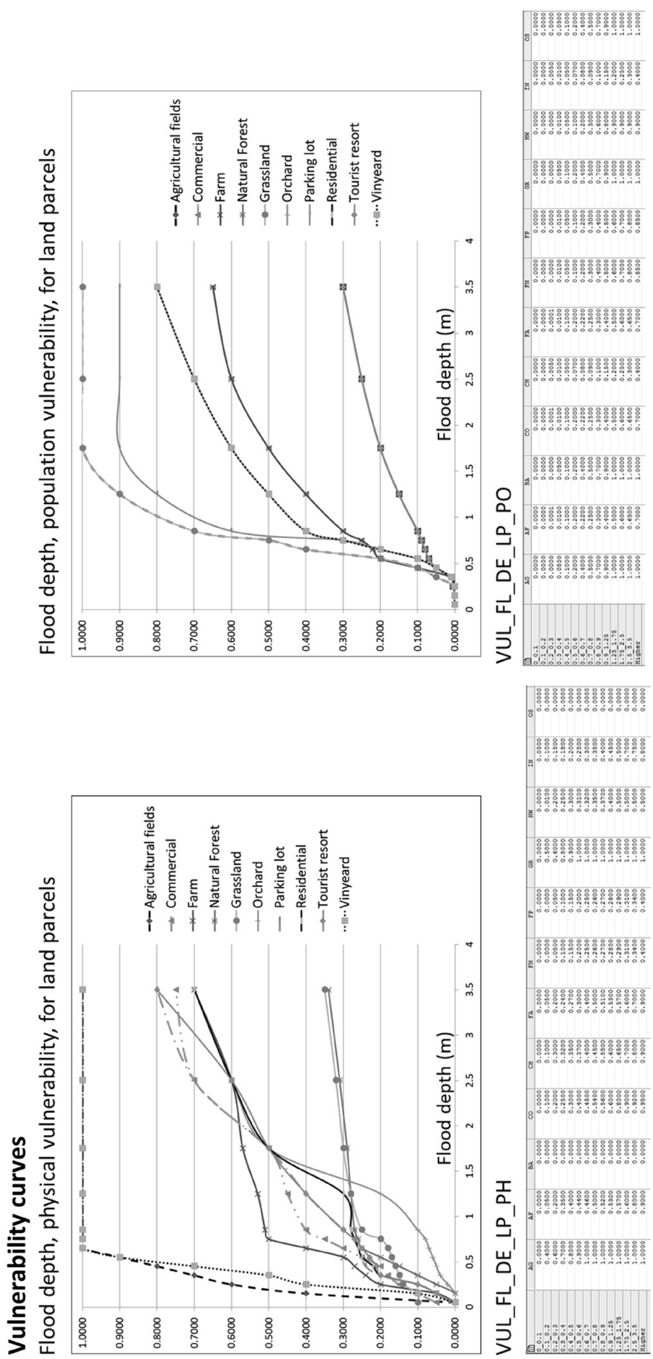

Figure 2.15 Vulnerability curves and related vulnerability tables. Here only some examples are shown.

  - Plan the (re)location of critical infrastructure (roads, buildings and other critical infrastructure);
  - Design guidelines for construction of roads and buildings in potentially dangerous areas;
  - Design of structural and non-structural mitigation measures against flooding and landslides and other hazards;
  - Design of non-structural mitigation measures (e.g. watershed management);
- *Physical planning departments responsible with the mandate to make land development plans at different scales. Their mandate is to*:
  - Develop national or regional physical development plans;
  - Develop local development plans;
  - Develop guidelines for building construction in hazard areas;
  - Evaluate relocation options for settlements in endangered areas;
  - Develop zoning maps with relevant hazard information for building control;
  - Provide relevant hazard and risk information for land subdivision;
- *National Emergency Management Organizations with the mandate to*:
  - Design disaster response plans;
  - Organize volunteers for disaster response planning;
  - Develop and management Early Warning systems;
  - Shelter planning and management.

2.5.2 Hazard modelling and elements-at-risk/ vulnerability assessment

Most government organizations normally have a few persons capable of visualizing spatial data using GIS, but are not sufficiently capable of carrying out the actual spatial hazard and risk analysis required as the basis for their work. Therefore, they will work with external consultants that will carry out this type of analysis for them, and they have to specify the exact Terms of Reference of the work of the consultants. These consultants may work on hazard modelling and the generation of elements-at-risk maps. This should be done for a specific scale of analysis:

- *National scale (for the entire country) with output at a scale of 1*:25.000–1:1.000.000 depending on the size of a country;
- *Local scale (for specific areas) with output at a scale of 1*:5.000 to 1:10.000 for specific planning areas (such as settlement areas). Our case study is at local scale;
- *Site-investigation scale (1*:1000) for specific problem sites.

Part of this work should be done by the government organizations themselves as they have the mandate to collect spatial information on the elements-at-risk. For instance the Public works Department should develop a spatial database of the roads including all relevant characteristics related to road type, culverts, bridges, drainage, road cuts and embankment fills, and slope stabilization works. The Department of Physical Planning, together with other relevant Departments is responsible for collecting and maintaining a national building database with the relevant characteristics of buildings. In the establishment of these databases external consultants may play an important role, however on the long run for the respective government organizations would have the mandate to maintain and update these databases, e.g. using web-based GIS solutions (e.g. http://www.charim-geonode.net/).

2.5.3 Risk analysis

The crucial stage in the analysis of risk, which use the available information to estimate the risk to people, property, or the environment, from hazards. Also this type of work generally is not carried out by the government organizations themselves, but rather by consultants, that have the right expertise to carry out this type of analysis for one or more types of hazards, in combination with one or more types of elements-at risk. This work is done at the appropriate scale related to the objectives of the stakeholders. The risk assessment can be subdivided into the following components:

- **Exposure analysis.** In this analysis hazard scenarios worked out by the hazard assessment consultants for different return periods (e.g. once in 20, 50 and 100 years) are combined spatially with the elements-at-risk and the number of elements-at-risk exposed to a certain hazard intensity is calculated. Also for each element-at-risk the (maximum) intensity is calculated given a certain return period.
- **Vulnerability analysis.** The results from the exposure analysis in terms of the maximum intensity per return period are then used in combination with vulnerability curves or matrices for the respective elements-at-risk types. Through the vulnerability curves a translation is made from the intensities of the hazard to the expected degree of loss for the elements at risk.
- **Loss analysis.** The results from the vulnerability assessment are then used in combination with the quantification of the elements-at-risk to calculate the expected losses. In the case of economic losses, the replacements costs for the elements-at-risk are used, resulting in specific losses per return period. In the case of population losses the number of people are used in combination with the population vulnerability resulting from the vulnerability assessment.
- **Risk assessment.** The resulting losses for different return periods are summed up for given administrative units if the hazards are independent and integrated for the different return periods to provide the average annual losses. These are used as the basis for the risk evaluation and for the formulation of possible risk mitigation measures.

Figure 2.16 gives a detailed overview of the steps involved in loss analysis and risk analysis. The **Loss analysis** has to be done for each combination of a hazard map (for a given return period) and an elements-at-risk map, and for population and/or economic losses. Each loss estimation requires a number of steps, and doing this repetitive analysis manually is very time consuming. Therefore, an automated script is developed in GIS, which combines a number of calculations and operations, and uses parameters. Figure 2.16 shows the input screen of the script. Some of these (alternative, scenario and future year) will be discussed later. This makes that the same script can be used in many different situations. It follows a number of steps:

- Overlay the element-at-risk map with the hazard intensity map;
- The resulting cross table (joint frequency table) contains all combinations of the land parcel/building code and the intensity values (e.g. water depths). The results are classified, according to the classification of the hazard intensity, so that the result is in the form of classes, which can be used to join with the vulnerability tables;
- As land parcels are sometimes large and only part of them might be actually exposed to hazard intensity the script calculates the losses first for the parts of the land parcels with the same intensity;
- In order to know which fraction of each land parcel has a certain intensity, the script reads in in the area of the whole land parcel from the attribute table of the land parcel map, and then calculates the fraction of the land parcel (Area of the unit in the joint frequency table divided by the area of the entire land parcel);
- The joint frequency table is joined with the attribute table of the land parcels/buildings and the *amount* column (either value or people) is entered, depending on the input provided by the user. Also the land use is joined;
- The joint frequency table is then joined with the vulnerability table (of the hazard type indicated) and the vulnerability values for all lands use types are read;
- The vulnerability for each record is calculated by taking the vulnerability value of the column that has the same land use code as in the record;
- A column is calculated that has an indication whether is dealing with a spatial probability map. This is done by creating a column SPCheck and then checking if the entered value is SP (Spatial Probability) or not. If this is the case, the spatial probability is used, otherwise a value of 1;
- The script then calculates the loss by multiplying the amount × vulnerability × spatial probability;
- In order to bring back the information at the level of the land parcels, the script aggregates the loss for the land parcels;
- The script also aggregates the loss for the administrative units , and for the entire study area;

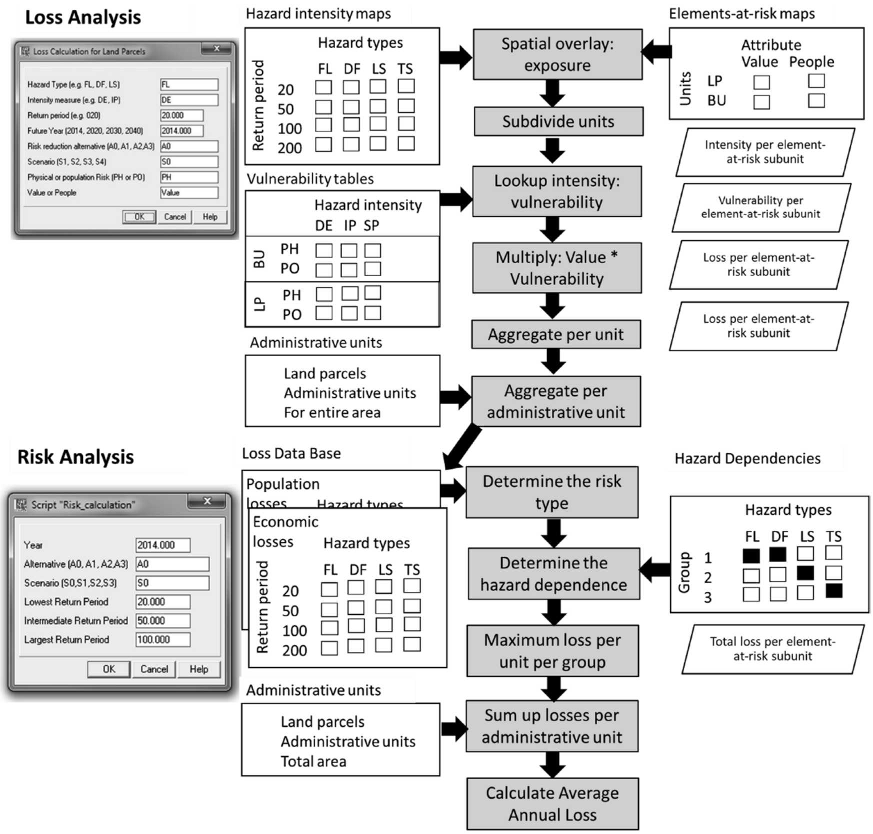

Figure 2.16 Procedure for loss analysis of all combinations of hazard scenarios for specific return periods with elements-at-risk, and the combination in the subsequent risk analysis. The following abbreviations are used: FL = Flooding, DF = Debris flow, LS = Landslides, TS = Tsunami, DE = Water Depth, IP = Impact Pressure, SP = Spatial probability, BU = Building footprints, LP = Land parcels. The two input screen are those used in the loss analysis and risk analysis.

The loss analysis results in a loss database, with the calculated losses for each combination of hazard type, return period, and elements-at-risk type. The user can then select which combinations of losses are used in the subsequent risk analysis. The risk analysis can be carried out if the loss estimation was done for at least three return periods of the hazard type(s) that were selected.

The risk analysis can also be done using a script, that uses a number of parameters, and which has the following steps:

- *The risk type is determined*: either economic risk or population risk is calculated;

- The types of hazard and their dependencies are selected. Here the user can interactively select which hazard types are taken into account. This allows to carry out single risk or multi-hazard risk. In the case of multi-hazard risk, the user has to evaluate whether the hazard types belong to the same triggering event group (See section on Multi-hazard risk in this chapter). For example, tsunami hazard is independent of the other three hazards, whereas flooding and debris flows can occur in the same area, and are triggering by the same event (extreme rainfall).
- *Based on the dependencies that are defined, the script will either sum up the losses for different independent hazards, or take the maximum for dependent hazards in the same group, to avoid double counting of losses. This is done at the lowest aggregation level*: the individual land parcels or building footprints;
- After that the multi-hazard losses are aggregated for the administrative units;
- Annual probability is calculated from the return periods, and the losses are plotted against the probability in loss curves (for economic risk) and FN curves (for population).
- Average annual loss is calculated for economic risk using the equation presented in Figure 2.7.

2.5.4 Risk evaluation

The results of the risk analysis for the case study area are presented in Figure 2.17, both for land parcels, as well as for building footprints. As can be seen from this figure the results differ when we use only building footprints, or land parcels. Economic losses are lower for buildings, because the risk analysis for land parcels also takes into account many other assets (e.g. roads, agriculture, and forest). Also the population risk for land parcels is larger, as it takes into account the persons not present in buildings. After estimating the risk, it is important to determine whether the risk is too high, and where the risk is too high. This is called the risk evaluation stage, and is the stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Important considerations in this respect are:

- **Risk perception among stakeholders.** Risk perception is about how individuals, communities, or authorities perceive/judge/evaluate/rank the level of risk, in relation to many factors;
- **Risk communication.** An important component in determining the risk perception is the communication between the stakeholders of the levels of risk. Do government organizations actively involve other stakeholders in the consultation process of the actual level of risk and the possible risk reduction measures?

- **Risk acceptability.** An acceptable risk is a risk, which the society or impacted individuals are prepared to accept. Actions to further reduce such risk are usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort. The definition of acceptability levels is a responsibility of the national or local government in a country. Risk acceptability depends on many factors, and differs from country to country. Therefore, it is also not possible to simply export them to other countries. Risk acceptability levels are generally done on this basis of individual risk levels or societal risk levels (using so-called F-N curves), some of which are shown in Figure 2.14, based on Ho (2009).

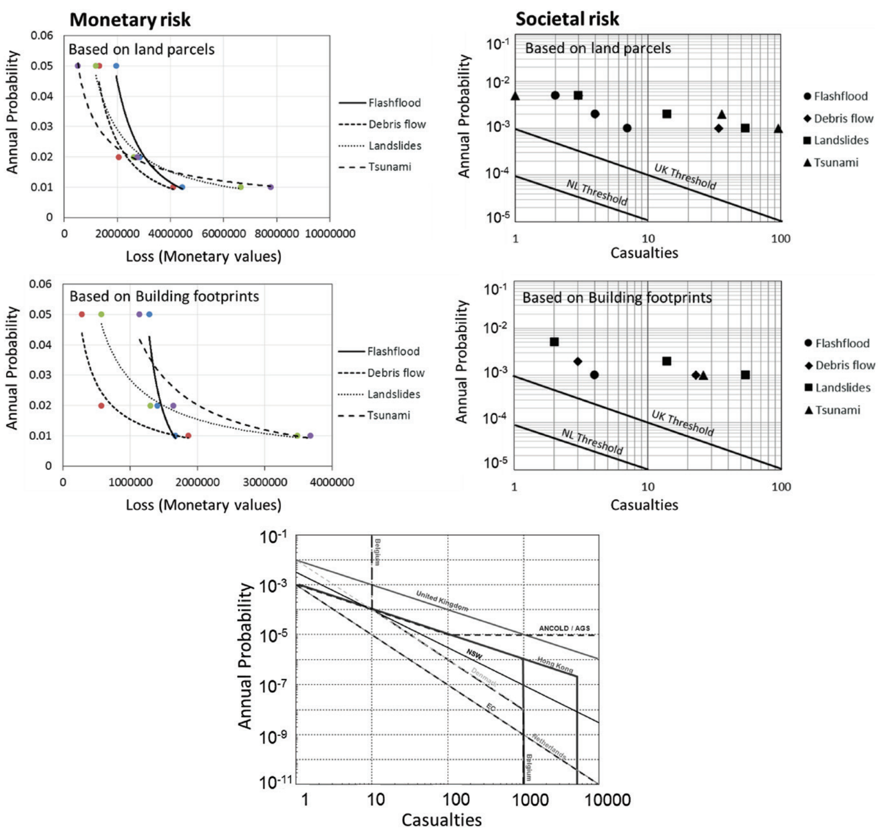

Figure 2.17 Results of the multi-hazard risk analysis for the existing situation in the case study area. Left: economic risk. Right: societal risk with risk acceptability threshold of the United Kingdom (UK) and the Netherlands (NL). Results are shown for two different elements-at-risk data sets: land parcels and building footprints. Below the risk acceptability thresholds for a number of different countries are presented (Source: Ho, 2009).

2.6 ANALYSING THE BEST PLANNING ALTERNATIVE

Once the multi-hazard risk for the current situation is considered unacceptable, which is the case in the case study, a new workflow is introduced for the evaluation of optimal risk reduction measures (Figure 2.12B).

2.6.1 Defining possible planning alternatives

In this workflow the stakeholders want to analyse the best planning alternative, or combination of alternatives. They define the alternatives, and request the expert organizations to provide them with updated hazard maps, elements-at-risk information and vulnerability information reflecting the consequences of these alternatives. Once these hazard and asset maps are available, the new risk level is analysed, and compared with the existing risk level to estimate the level of risk reduction. This is then evaluated against the costs (both in terms of finances, as well as in terms of other constraints) and the best risk reduction scenario is selected. The planning of risk reduction measures (alternatives) involves:

- **Disaster response planning:** focusing on analysing the effect of certain hazard scenarios in terms of number of people, buildings and infrastructure affected. It can also be used as a basis for the design of early warning systems;
- **Planning of risk reduction measures:** which can be engineering measures (such as dikes, check-dams, sediment catchment basins), but also non-structural measures, such as relocation planning, strengthening/protection of existing buildings etc.;
- **Spatial planning:** focusing on where and what types of activities are planned and preventing that future development areas are exposed to natural hazards.

The methods for risk reduction planning can be subdivided into:

- **Structural measures** refer to any physical construction to reduce or avoid possible impacts of hazards, which include engineering measures and construction of hazard-resistant and protective structures and infrastructure. The strategy is to modify or reduce the hazard;
- **Non-structural measures** refer to policies, awareness, knowledge development, public commitment, and methods and operating practices, including participatory mechanisms and the provision of information, which can reduce risk and related impacts. With the aim of modifying the susceptibility of hazard damage and disruption and/or modifying the impact of hazards on individuals and the community.

The planning alternatives that are evaluated may be designed without considering the possible impact of hazard and risk, and in these situation the analysis is carried out to evaluate the impact of the different alternatives on the hazard and risk (will it increase or decrease).

There are mostly different planning alternatives that can be formulated, and each of them may have advantages and disadvantages. The aim of this analysis to quantify their advantages and disadvantages in terms of hazard and risk reduction, and to evaluate these against the costs for implementation through a cost-benefit analysis. Also other criteria that cannot be quantified can be used in deciding the best alternative, using a multi-criteria evaluation.

For example, for the case study are the stakeholders defined three possible sets of risk reduction measures, which are presented in Table 2.5 and Figure 2.18.

Table 2.5 Characterization of risk reduction alternatives in the case study area. The alternatives are also shown in Figure 2.18.

	Alternative 1	**Alternative 2**	**Alternative 3**
Name	**Engineering Alternative**	**Eco-DRR Alternative**	**Relocation Alternative**
Characteristics	• Constructing six retention basins, designed to retain maximum 100 year events; • Soil removal work in selected areas for slope stabilization; • Expropriation of land and existing buildings where construction will take place; • Early Warning System;	• Planting of protection forest at the foot of the steep slope and on fans of the side streams; • Construction of drainage channels and 10 water tanks; • Expropriation of land and existing buildings where construction will take place • Soil removal work in selected areas for slope stabilization;	• Relocation of buildings with people in the most dangerous sectors; • Compensation of owners of buildings or construction of new buildings elsewhere; • Expropriation of existing buildings • Lawsuits of residents that do not want to leave the area; • Early Warning System for other areas;
Time of construction	3 years	2 years	4–10 years, depending on the resistance

(*Continued*)

Table 2.5 Characterization of risk reduction alternatives in the case study area. The alternatives are also shown in Figure 2.18 (*Continued*).

	Alternative 1	**Alternative 2**	**Alternative 3**
Name	**Engineering Alternative**	**Eco-DRR Alternative**	**Relocation Alternative**
Year when benefit starts	4th year	From third year increasing to maximum after 15 years	From fourth year increasing until the tenth year
Annual maintenance	Cleaning retention basins, Slope monitoring. Starts at fourth year	Forest management, cleaning water tanks and channels, slope monitoring. Starts in third year.	Monitoring of areas, prevention of illegal resettlements. Starts at fourth year.
Does the hazard change?	Yes, new hazard maps are needed for landslides, debris flows and floods. Events with return periods of 100 years or less are retained. Higher return periods may overtop the structures. No effect on tsunami	Yes, new hazard maps are needed for landslides, debris flows and floods. Smaller events are completely retained by protection forest, and larger events are retained, but there is still a certain hazard. No effect on tsunami	No.
Do the elements-at-risk change?	Only those units where the retention basins are constructed	Only those land parcels where the protection forest will be constructed.	Yes, the relocation areas will change. A new land parcel map is needed.
Items to estimate costs	Construction costs retention basin: unit costs × number; Soil removal: unit costs × area; Expropriation costs: unit cost × area;	Tree planting: unit cost × area; Soil removal: unit costs × area; Water tanks: unit cost × number; Expropriation costs: unit cost × area;	Number of buildings to relocate; Compensation per building; Number of lawsuits and value of legal costs; Early warning system;

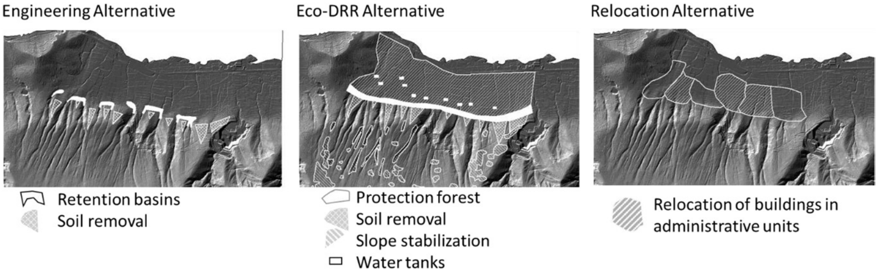

Figure 2.18 Three sets of risk reduction measures presented as three alternatives. The characteristics of these alternatives are given in Table 2.5.

2.6.2 Re-analysing hazards and elements-at-risk

The implementation of certain structural or non-structural risk mitigation measures might lead to a modification of the hazard, exposure and vulnerability. Risk is a function of Hazard × vulnerability of exposed elements-at-risk × the quantification of the elements-at-risk (Figure 2.1). Therefore, there are several possibilities that risk mitigation measures will influence:

- The **hazard.** In terms of the probability (or return period) of specific hazard events, the spatial distribution of the hazard and the intensity of the hazards. For instance, the construction of a flood wall along a river may reduce the area that will be flooded. For certain lower return periods the flood wall may retain all flood water, and therefore the intensity (flood height) outside of the flood wall will become zero for these return periods. For more extreme events the flood intensity may become lower as a result of the flood wall. Therefore, it is required to re-analyse the hazard given the implementation of the risk reduction measure.
- The **exposure of elements-at-risk.** The number of elements-at-risk might change as a result of the risk mitigation measure, or planning alternative. For instance, if one of the alternatives involves relocation, the number of exposed elements-at-risk will decrease, whereas the hazard might stay the same. In other planning alternatives the effect of future development on the number of exposed elements-at-risk might also be evaluated.
- The **vulnerability of the elements-at-risk.** The type of elements-at-risk might change as a result of implementing the planning alternative. For instance, when retrofitting is considered, the number of elements-at-risk might be the same, as well as the hazard, but the vulnerability of these elements-at-risk might decrease, leading to a lower risk level. The same can be said for the implementation of an Early Warning System. It will decrease the number of exposed people, but also their vulnerability, if they would move to shelters where they are better protected.

- The **quantification of the elements-at-risk.** might change. This might refer to planning alternatives where the value of the exposed elements-at-risk changes, e.g. they could increase when more expensive housing is considered in a certain planning alternative.

Therefore, experts should evaluate together with the stakeholders what would be the effect of the proposed alternative on the hazard, elements-at-risk location and characteristics and the vulnerability. If needed new hazard modelling should be carried out, or new elements-at-risk maps should be made representing the new situation.

2.6.3 Analyse risk reduction

After re-analysing the hazard, elements-at-risk and vulnerability for the situation after the implementation of the planning alternative, the next step is to analyse the resulting level of risk, and compare this with the current risk level. The difference between the average annual losses before and after the implementation of the planning alternative, provides information on the risk reduction. This should be done for all the possible planning alternatives. The risk reduction should be done preferable both in terms of economic risk reduction (reduction in the average annual losses in monetary values) as well as in population risk reduction (reduction in the expected casualties or exposed people).

The analysis of risk requires a repetitive procedure which has to be carried out for each hazard scenarios (different hazard types and return periods) in combination with elements-at-risk types, and then also for each possible alternative. This requires the use of the same automated procedures using scripts in GIS described in section 2.5. Figure 2.19 shows the results of the analysis of the three risk reduction alternative for the case study. It is clear from the figure that alternative 1 (engineering solutions) and 2 (Eco-DRR) result in more risk reduction than alternative 3 (relocation).

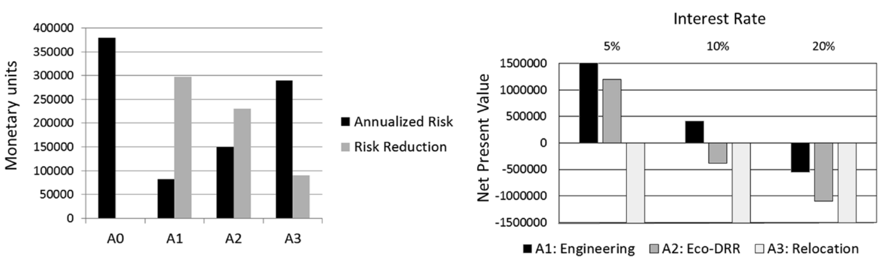

Figure 2.19 Left: Results of the multi-hazard risk analysis for the current situation (A0) and the three risk reduction alternatives: A1 (Engineering alternative), A2 (Eco-DRR alternative) and A3 (Relocation alternative). Right: Results of the Cost-Benefit Analysis showing the Net Present Value (NPV) for the three alternatives for different interest rates.

2.6.4 Compare alternatives

Once the effects of the various planning alternatives are analysed, in terms of their risk reduction, the next step is to compare them and decide which of the alternatives would be the best to implement. This could be done through different methods:

- **Cost-benefit analysis.** Here both the benefits and the costs can be quantified. The benefit of a risk reduction alternative is represented by its annual risk reduction in monetary values, which was calculated in the previous step (risk after implementation minus current risk) (Figure 2.19). The costs for the planning alternative can be quantified, as well in terms of their investment costs, maintenance costs, project life time etc. (See Table 2.5). Cost-benefit analysis can be carried out by calculating relevant indicators, such as the Net Present Value, Internal Rate of Return or Cost-Benefit ratio.
- **Cost-effectiveness analysis.** This is carried out when the costs can be quantified and compared, but the benefits in terms of risk reduction cannot be quantified in monetary values. This is the case for instance when population risk is calculated, as it is generally considered not ethical to represent human lives in monetary values.
- **Multi-Criteria Evaluation.** When both the costs and benefits cannot be quantified in monetary values, or when additional to cost-benefit or cost-effectiveness also other non-quantifiable indicators are used, a (spatial) multi-criteria evaluation is generally considered the best option. In this analysis also social, ecological, cultural and other criteria can be incorporated in the decision making process.

The comparison of alternatives is generally carried in a process, where the other stakeholders are also involved before a decision is taken on the optimal alternative that will be implemented.

2.6.5 Final decision and implementation

The last step of this workflow related to the selection of the optimal planning alternative in relation to the reduction of risk to hydro-meteorological hazards is the consultation with the various stakeholders involved (Figure 2.12B). This includes public hearings with the population, private sector, non-governmental organizations, and various social network groups (e.g. communities, churches). The stakeholders have the opportunity to request adjustment to the proposed plan of action, and if these adjustments are considered valid, and substantial, a new round of evaluation might be needed if the change of expected hazard and risk impact is substantial. Once the plan is approved, the procedures will start for the implementation of the plan.

2.7 ANALYSING POSSIBLE FUTURE SCENARIOS

Risk is changing continuous, as both hazard and elements-at-risk change. Over a longer period of time this may result in considerable changes in multi-hazard risk.

Figure 2.12C shows the workflow to analyse changing risk due to possible future scenarios.

2.7.1 Identification of possible future scenarios

The scenarios are related to possible changes related to climate, land use change or population change due to global and regional changes, and which are only partially under the control of the local planning organizations. The stakeholders might like to evaluate how these trends have an effect on the hazard and elements-at-risk and how these would translate into different risk levels. The possible future could be of the following types:

- **Climate change scenarios.** In that case, the stakeholders require the involvement of experts that would indicate which climate change scenarios would be evaluated and what would be the expected effects in terms of changes in frequency and magnitude of hydro-meteorological triggers would be expected, such as changes in sea-level and extreme precipitation;
- **Land use change scenarios.** In this case, the stakeholders require the involvement of experts that would indicate possible land use changes based on macro-economic and political developments which would be translated into local changes. For instance, scenarios could be envisaged where an increase in tourism would be translated into possible future expansion of tourist facilities would be evaluated. The future land use scenarios would also involve possible changes in population which should also be taken into account.
- **Future planning scenarios.** In the national physical development plans also possible future developments will be outlined and priorities for development indicated which have implications for the spatial distribution of land use and population.

Also combinations of these drivers might be considered. The possible future changes should be expressed for certain years in the future, for instance for 2020 and 2030 and are considered as a basis for long term planning. Table 2.6 shows four possible future scenarios for the case study area, which are combining land use changes and climate changes.

2.7.2 Re-analysing hazards and elements-at-risk for possible future scenarios

The possible future scenarios might lead to a modification of the hazard, exposure and vulnerability in certain future years from now. Therefore it is required to re-analyse:

- The hazard. Possible future scenarios of climate change might lead to a change in the frequency and magnitude of triggering events for floods and landslides. Therefore, a new magnitude-frequency analysis might be required, that take into account changing trends in frequencies of extreme events. The same hazard event

Table 2.6 Definition of four possible future scenarios for the case study.

Scenario		**1**	**2**	**3**	**4**
Name		**Business as Usual**	**Risk-Informed Planning**	**Worst Case**	**Most Realistic**
Land use change		Rapid growth without taking into account the risk information	Rapid growth that takes into account the risk information and extends the alternatives in the planning	Rapid growth without taking into account the risk information	Rapid growth that takes into account the risk information and extends the alternatives in the planning
Climate change		No major change in climate expected	No major change in climate expected	Climate change expected, leading to more frequent extreme events	Climate change expected, leading to more frequent extreme events
2020	Return period: 20	*20* (±*5*)	*20* (±*5*)	*17* (±*6*)	*17* (±*6*)
	Return period: 50	*50* (±*10*)	*50* (±*10*)	*45* (±*12*)	*45* (±*12*)
	Return period: 100	*100* (±*20*)	*100* (±*20*)	*90* (±*23*)	*90* (±*23*)
	Return period: 200	*200* (±*40*)	*200* (±*40*)	*180* (±*44*)	*180* (±*44*)
2030	Return period: 20	*20* (±*5*)	*20* (±*5*)	*14* (±*7*)	*14* (±*7*)
	Return period: 50	*50* (±*10*)	*50* (±*10*)	*35* (±*14*)	*35* (±*14*)
	Return period: 100	*100* (±*20*)	*100* (±*20*)	*75* (±*26*)	*75* (±*26*)
	Return period: 200	*200* (±*40*)	*200* (±*40*)	*150* (±*49*)	*150* (±*49*)
2040	Return period: 20	*20* (±*5*)	*20* (±*5*)	*11* (±*8*)	*11* (±*8*)
	Return period: 50	*50* (±*10*)	*50* (± *10*)	*25* (±*16*)	*25* (±*16*)
	Return period: 100	*100* (±*20*)	*100* (±*20*)	*55* (±*30*)	*55* (±*30*)
	Return period: 200	*200* (±*40*)	*200* (±*40*)	*110* (±*53*)	*110* (±*53*)

that now has an average return period of 50 years, might have an average return period which is much smaller in a number of years from now. Also the intensities of the hazard might change for instance due to changes in land use, which might affect the hazardous processes (e.g. deforestation scenarios). In the case study (Table 2.6), this is represented by a decrease in return periods in future years, and the increasing standard deviations illustrate the increasing level of uncertainty.

- The exposure of elements-at-risk. The possible land use scenarios might lead to substantial changes in land use/land cover, which also has an important effect on the number of elements-at-risk within the various land use classes. The analysis of future changes in land use/land cover is generally carried out based on land parcel maps, rather than on the basis of building footprints maps, as it is generally very difficult to translate the land use changes directly into possible locations of buildings. Figure 2.20 shows the possible land use maps for 2020, 2030 and 2040 for the case study area, following the possible scenarios described in Table 2.6.

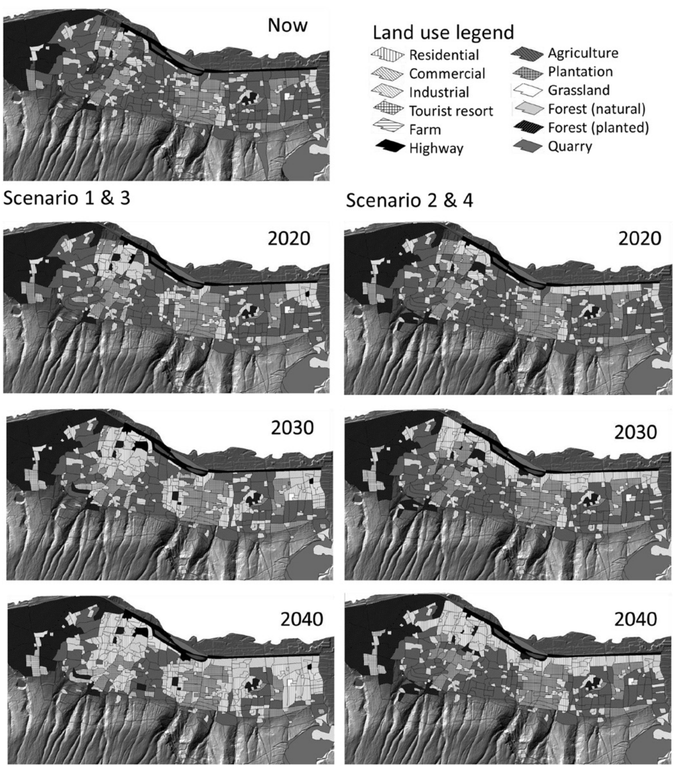

Figure 2.20 Possible land use changes for 2020, 2030 and 2040 for the possible future scenarios described in Table 2.6.

Therefore, experts should evaluate together with the stakeholders what would be the effect of the possible future scenarios on the hazard, elements-at-risk location and characteristics and the vulnerability. If needed new hazard modelling should be carried out, or new elements-at-risk maps should be made representing the new situation.

2.7.3 Analyse possible changes risk for possible future scenarios

After analysing the hazard, elements-at-risk and vulnerability for (a) future year(s) given certain possible future scenarios, the next step is to analyse the resulting change in risk, and compare this with the current risk level. The difference between the current average annual losses and those in a future year under a given change scenario provides information for decision makers on the possible negative consequences of climate change and land use change scenarios. They can be used as a basis for designing appropriate strategies for adaptation. The risk reduction should be done preferable both in terms of changes in economic risk (average annual losses in monetary values), as well as in population risk reduction (expected casualties or exposed people). It is also important to incorporate the uncertainty levels in this type of analysis, thus providing a range of change rather than concrete values. Figure 2.21 shows the differences in risk for the four scenarios for the study area.

2.7.4 Changing risk evaluation

After assessing the possible changes in risk that might result from a number of possible future scenarios related to climate change and land use change, stakeholders should analyse these changes carefully in terms of:

- **Spatial location of changes in risk.** Some areas might be much more impacted by these possible future changes than others. Based on the outcomes of the analysis stakeholders could then prioritize certain areas for critical interventions.
- **Critical sectors.** Changes in risk could be analysed for different sectors of society, such as economy, agriculture, tourism, education, transportation etc.
- **Development of adaptation strategies.** The analysis of the expected level of changes in risk and areas where an increase in risk is expected according to the possible scenarios, should lead to the formulation of adaptation strategies that aim to reduce these possible impacts through planning alternatives that could be implemented now.

When the change of risk is compared for the four scenarios, the risk can be observed including the climate change effects (by reducing the return periods as indicated in Table 2.6) and has a very significant increasing trend. When the effect of land use changes (as shown in Figure 2.17) are examined, it can be seen that the worst case scenario indeed has the largest increase in risk, and the risk informed planning scenario has a lower risk. However, this last scenario focuses on the avoidance of the most hazardous areas for flooding, debris flows and landslides, and the development takes place mostly along the coast (See Figure 2.17). Therefore, tsunami hazard is also included in the analysis, as shown in Figure 2.18, Scenario 2 and 4 have the highest risk levels. This stresses the importance of including all hazard types in multi-hazard risk assessment.

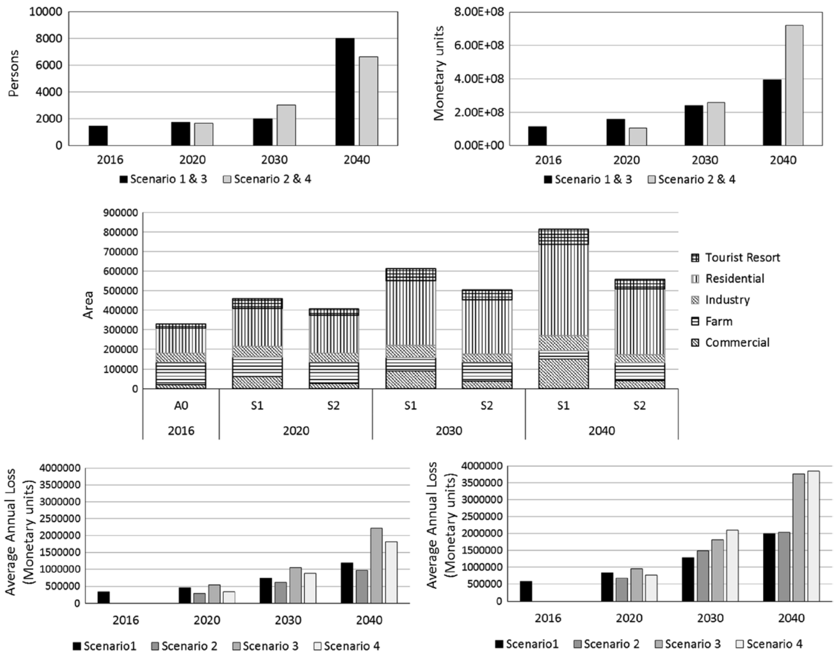

Figure 2.21 Top: changes in population and economic values from 2016 to 2040 according to two land use change scenarios. Middle: changes in some of the land use types from 2016 to 2040 according to two land use change scenarios. Below left: Changes in multi-hazard risk from 2016 to 2040 for the four possible future scenarios, without including tsunami risk. Lower right: Changes in multi-hazard risk from 2016 to 2040 for the four possible future scenarios, including tsunami risk.

2.8 ANALYSING PLANNING ALTERNATIVES UNDER POSSIBLE FUTURE SCENARIOS

The analysis as shown in Figure 2.21 shows that it is relevant to analyse how multi-hazard risk might change in future according to different possible trends. However, it also demonstrates the need to implement risk reduction measures now. In the last workflow, illustrated in Figure 2.12D, it is analysed which of the risk reduction alternatives performs best under different possible future scenarios.

2.8.1 Selection of alternatives, scenarios and future years

The evaluation how different risk reduction alternatives will lead to risk reduction under different future scenarios (trends of climate change, land use change and population change) is the most complicated workflow, as it requires to calculate the present risk level, the effect of different risk reduction alternatives, and the overprinting of these on the scenarios. For each of these combinations of alternatives and scenarios new hazard, assets and risk maps need to be made. This type of analysis allows stakeholders to make the most optimal "change proof" selection of planning alternatives. This type of analysis is entirely based on experts and consultants, which should evaluate both the effects of the planning alternatives, as well as the associated effects of possible future scenarios on hazard, vulnerability and risk. Such type of analysis could be applied to specific critical areas, such as the capitals or important critical infrastructure. Table 2.7 combines all combinations in a matrix. This table indicates the combination of the four scenarios (S1, S2, S3, S4 as described in Table 2.6) and the three risk reduction alternatives (A1, A2, A3 described in Table 2.5) in three future years (2020, 2030, 2040). Due to the large number of input maps it is important to use the coding of the files in a similar way, so that it is possible to use the calculation script to analyse the loss and multi-hazard risk all combinations. Therefore, for example: LP_2020_A1_S2 refers to the land parcels for future year 2020 under alternative A1 (Engineering solutions) and for scenario S2 (risk informed planning).

2.8.2 Re-analysing hazards and elements-at-risk for alternatives/scenarios

The combination of the implementation of certain planning alternatives (structural or non-structural risk mitigation measures) in combination with certain possible future scenarios will certainly lead to a modification of the hazard, exposure and vulnerability. This is why both the hazard maps and the elements-at-risk maps should be updated for each combination.

- The **hazard.** In terms of the probability (or return period) of specific hazard events, the spatial distribution of the hazard and the intensity of the hazards. For instance, the construction of the retention basins reduce the area that will be impacted by flooding and or debris flows. The retention basins are designed for a specific maximum discharge (e.g. 100 years). With climate change scenarios the same discharge may occur more frequently, and events with higher return periods may overtop the basins. Therefore, it is required to re-analyse the hazard given the implementation of the risk reduction measure and the possible future climate change/land use change scenario. In the case study area, different hazard intensity maps are considered for the various risk reduction measures, and change the return periods for future years following Table 2.6.

Table 2.7 Combination of four scenarios, for future years 2020, 2030 and 2040, with three risk reduction alternatives. Each combination is a situation where multi-hazard risk is analysed.

Scenario: Possible Future Trends	**Alternative: Risk Reduction Options**	**Now 2014**	**Future Years**		
			2020	**2030**	**2040**
S0 (Without including any future trends)	A0 (no risk reduction)	2014_A0_S0	No future trends are taking into account, and all hazards, elements at risk and vulnerabilities are considered constant in future.		
	A1 Engineering	2014_A0_S1			
	A2 Ecological	2014_A0_S2			
	A3 Relocation	2014_A0_S3			
S1 Business as usual	A0 (no risk reduction)	Does not exist: use existing situation	2020_A0_S1	2030_A0_S1	2040_A0_S1
	A1 Engineering		2020_A1_S1	2030_A1_S1	2040_A1_S1
	A2 Ecological		2020_A2_S1	2030_A2_S1	2040_A2_S1
	A3 Relocation		2020_A3_S1	2030_A3_S1	2040_A3_S1
S2 Risk informed planning	A0 (no risk reduction)	Does not exist: use existing situation	2020_A0_S2	2030_A0_S2	2040_A0_S2
	A1 Engineering		2020_A1_S2	2030_A1_S2	2040_A1_S2
	A2 Ecological		2020_A2_S2	2030_A2_S2	2040_A2_S2
	A3 Relocation		2020_A3_S2	2030_A3_S2	2040_A3_S2
S3 Worst case (Rapid growth + climate change)	A0 (no risk reduction)	Does not exist: use existing situation	2020_A0_S3	2030_A0_S2	2040_A0_S3
	A1 Engineering		2020_A1_S3	2030_A1_S3	2040_A1_S3
	A2 Ecological		2020_A2_S3	2030_A2_S3	2040_A2_S3
	A3 Relocation		2020_A3_S3	2030_A3_S3	2040_A3_S3
S4 Climate resilience (informed planning under climate change)	A0 (no risk reduction)	Does not exist: use existing situation	2020_A0_S4	2030_A0_S3	2040_A0_S4
	A1 Engineering		2020_A1_S4	2030_A1_S3	2040_A1_S4
	A2 Ecological		2020_A2_S4	2030_A2_S3	2040_A2_S4
	A3 Relocation		2020_A3_S4	2030_A3_S3	2040_A3_S4

- The **exposure of elements-at-risk.** The number of elements-at-risk might change as a result of the risk mitigation measure, or planning alternative, and also as a result of the possible future scenario. For instance, if one of the alternatives involves relocation, the number of exposed elements-at-risk will decrease, whereas the hazard might stay the same. However, under certain land use scenarios the pressure on the land might be so high that previously related areas might become occupied again. In other planning alternatives, the effect of future development on the number of exposed elements-at-risk might also be evaluated. Figure 2.22 shows the land use maps for one scenario (business as usual). Each combination of possible future scenario, future year and risk reduction alternative requires a separate land use map. From this figure it can be observed that under this scenario, the relocation alternative will not be very effective, as the areas that are relocated in 2016 will become occupied again in later years. The different land use situations is combined with increases in economic values and population numbers in the various scenarios (As was shown in Figure 2.22). These will also have an important influence on the estimated multi-hazard risk.

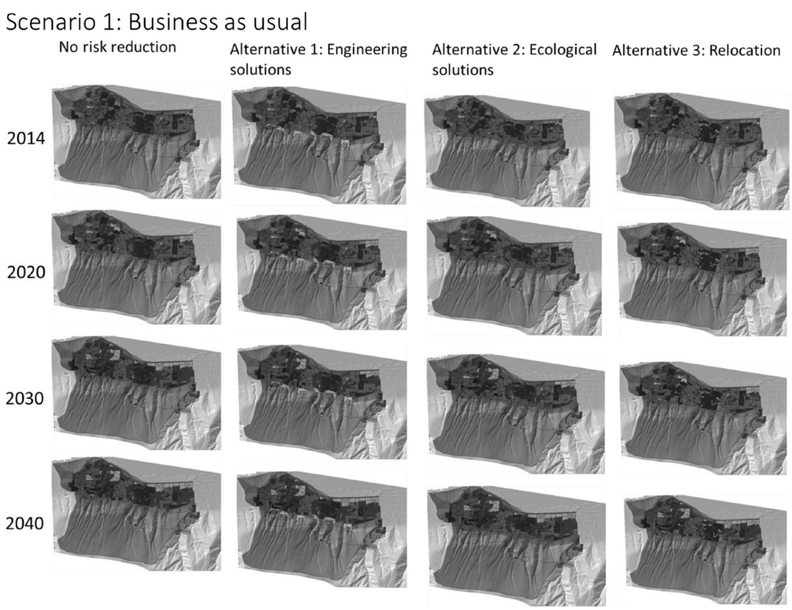

Figure 2.22 Land parcel maps for different years in a possible future scenario (Business as usual) without risk reduction measures (left) and three risk reduction alternatives.

Therefore, experts should evaluate together with the stakeholders what would be the effect of the proposed alternatives and scenarios on the hazard, elements-at-risk location and characteristics and the vulnerability for a given future year. If needed new hazard modelling should be carried out, or new elements-at-risk maps should be made representing the new situation.

2.8.3 Analyse risk reduction for alternatives/scenarios

After re-analysing the hazard, elements-at-risk and vulnerability for the specific combinations of planning alternative, possible future scenario and future year, the next step is to analyse the resulting level of risk, and compare this with the current risk level. The difference between the average annual losses before and after the implementation of the planning alternative, provides information on the risk reduction. This should be done for all the possible planning alternatives/scenario combinations. The risk reduction should be done preferable both in terms of economic risk reduction (reduction in the average annual losses in monetary values), as well as in population risk reduction (reduction in the expected casualties or exposed people).

2.8.4 Compare alternatives under different scenarios

Once the effect of the various planning alternatives has been analysed, under different future years and future scenarios, in terms of their risk reduction, the next step is to compare them and decide which of the alternatives would be the best to implement. In the cost-benefit analysis both the benefits and the costs can be quantified. The benefit of a risk reduction alternative is represented by its annual risk reduction in monetary values, which was calculated in the previous step (risk after implementation minus current risk). However, whereas the benefit would remain constant in the analysis which was presented earlier under "Analysing planning alternative", when the risk reduction of planning alternatives are analysed for different future years under possible change scenarios, the risk reduction might also change considerably over time. The costs for the planning alternative can be quantified, as well in terms of their investment costs, maintenance costs, project life time etc. Cost-benefit analysis can be carried out by calculating relevant indicators, such as the Net Present Value, Internal Rate of Return or Cost-Benefit ratio. When possible future changes are taken into account, the cost-benefit ratios of the various alternatives might be quite different than if no future changes are considered, which might lead to the selection of another planning alternative that may be the most "change proof".

2.8.5 Final decision and implementation

The last step of this workflow related to the selection of the optimal planning alternative in relation to the reduction of risk to hydro-meteorological hazards is the consultation with the various stakeholders involved. This includes public hearings with the population, private sector, non-governmental organizations, and various social network groups (e.g. communities, churches). The stakeholders have the opportunity to request adjustment to the proposed plan of action, and if these adjustments are considered valid, and substantial, a new round of evaluation might be needed if the change of expected hazard and risk impact is substantial. Once the plan is approval the procedures will start for the implementation of the plan.

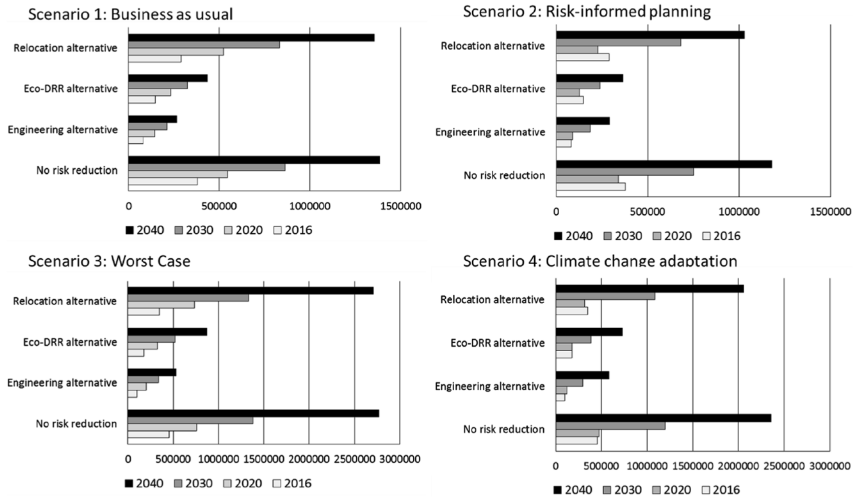

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Figure 2.23 Changes in Average Annual Loss for four scenarios and three risk reduction alternatives for future years.

Here, the environmental impact assessment comes into play (Greiving, 2004). The recently amended Environmental Impact Assessment Directive (2014/52/EU) stats with Art 3 § 2: "Precautionary actions need to be taken for certain projects which, because of their vulnerability to major accidents, and/or natural disasters (such as flooding, sea level rise, or earthquakes) are likely to have significant adverse effects on the environment. For such projects, it is important to consider their vulnerability (exposure and resilience) to major accidents and/or disasters, the risk of those accidents and/or disasters occurring and the implications for the likelihood of significant adverse effects on the environment."

In this context, a broad involvement of the public is requested (see Art 6 § 2 Environmental Impact Assessment Directive and Art. 6 §§ 1–6 Strategic Environmental Assessment Directive) that needs to be adjusted to the different steps of analysis of a risk assessment as shown by Figure 2.24.

However, in many European countries, a legal basis for hazard (and partly risk) zoning exists which means that both, the methods chosen for delineating the zones, but also the legal consequences for subsequent planning activities are laid down by law. Hence, there is no discussion possible about suitable risk assessment alternatives. Table 2.9 gives an overview about existing zoning models and discusses their advantages and disadvantages.

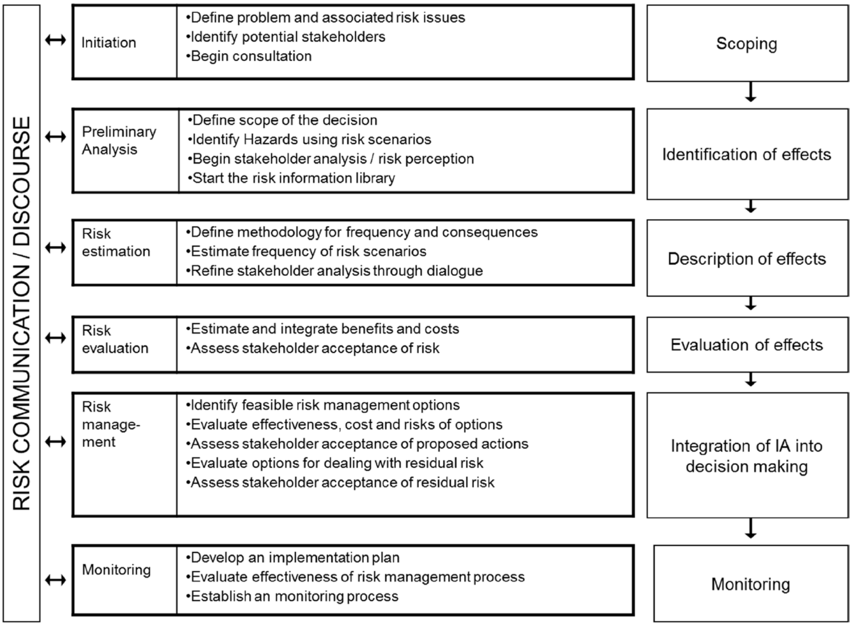

Figure 2.24 Integration of risk assessment into environmental assessments.

2.9 SUMMARY AND CONCLUSIONS

2.9.1 Which method to choose?

The four methods for risk assessment that were treated in the previous sections all have certain advantages and disadvantages, which are summarized in Table 2.8. 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 analysing 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.

The decision depends among other factors in particular from the spatial scale of the project, plan or program, the risk assessment was done for (see Table 2.8). In this

Table 2.8 Advantages and disadvantages of the four risk assessment methods discussed.

Method	**Advantages**	**Disadvantages**	**Suitability for Specific Spatial Scales**
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.	Normally used as basis for investments in structural mitigation measures on project level
Event-tree analysis	Allow modelling of a sequence of events, and works well for domino effects	The probabilities for the different nodes are difficult to assess, and spatial implementation is very difficult due to lack of data.	Normally used as basis for plan approval procedures of dangerous facilities (e.g. nuclear power plants, chemical establishments) on project level
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. The assessment of impacts and frequencies is difficult, and one area might have different combinations of impacts and frequencies.	Basis for hazard zoning in many countries like Austria France, Italy and Switzerland. Good fit for regional and local spatial planning as basis for keeping hazard prone areas free of further development
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 doesn't provide information on actual expected losses.	Suitable for comparing the level of risk on national level (see e.g. World Risk Index)

Table 2.9 Hazard zoning models in Europe.

Model	**Coordinated Zoning in General Land-use Plan (Applied e.g. in Finland, Poland, Germany Except Floods)**	**Specific Hazard Map in General Land-use Plan with Binding Effects (Applied e.g. in Austria, France, Italy, Switzerland, Germany – Floods Only)**	**Independent Map without Binding Effects (Applied e.g. in Greece, Spain, and U.K.)**
Description	Consideration of the hazard prone areas during the compiling or review of the local land-use plan (informed i.e by Strategic Environmental Assessment)	The hazard zones are displayed as a separate map which has a direct effect on land ownership rights	Definition of hazard zones within the scope of expert planning – objections may be raised to decisions that are made on this basis
Advantages	At the local level, no additional instruments are needed; hazards are weighted- up against other concerns and interests	The hazard can be considered in a uniform manner for the whole municipality. Definition of hazard zones can be applied directly in building approval procedures	A simple alteration of a hazard zone plan is possible. Suitable for a cooperative strategy that aims at influencing existing building structures by individual building protection
Disadvantages	Land-use plans only contain information about hazard prone areas when a specific reference is made. An alternation of the danger situation means the plan must be adapted accordingly	An alteration of the risk means that the complete zoning plan has to be adapted accordingly. For legally binding effects, a very exact evidence basis is needed	Not effective if private stakeholders do not want to follow the advise

context, the subsidiarity principle plays a considerable role. Art. 5 § 2 of the Strategic Environmental Assessment Directive (2001/42/EC) lays down: "The environmental report […] shall include […] the level of detail in the plan or programme, its stage in the decision-making process and the extent to which certain matters are more appropriately assessed at different levels in that process in order to avoid duplication of the assessment." This means that a quantitative risk assessment would not fit to the scope of a strategic environmental assessment at the level of preparatory plans or programs, but should be used as evidence basis for an environmental impact assessment at the project level, as long as the project may be threatened by any kind of natural or technological hazard.

2.9.2 Tools for multi-hazard assessment

The analysis of risk requires a repetitive procedure which has to be carried out for each hazard scenarios (different hazard types and return periods) in combination with elements-at-risk types, and then also for each possible alternative. This requires the use of automated procedures using Geographic Information Systems.

Risk assessment is computationally intensive. It can be carried out using conventional GIS systems, although it is advisable to use specific software tools. Loss estimation has been carried out in the insurance sector since the late 1980's using geographic information systems. Since the end of the 1980's risk modelling has been developed by private companies resulting in a range of proprietary software models for catastrophe modelling for different types of hazards. Unfortunately, these are not publicly available, which is a major obstacle to the development of risk assessment for many parts of the world by government organizations. The best initiative for publicly available loss estimation thus far has been HAZUS developed by the Federal Emergency Management Agency (FEMA) together with the National Institute of Building Sciences (Schneider & Schauer, 2006). The first version of HAZUS was released in 1997 with a seismic loss estimation focus, and was extended to multi-hazard losses in 2004, incorporating also losses from floods and windstorms. HAZUS was developed as a software tool under ArcGIS. Several other countries have adapted the HAZUS methodology to their own situation. The HAZUS methodology has also been the basis for the development of several other software tools for loss estimation. One of these is called SELENA. Also an interesting example is RiskScape developed in New Zealand (Schmidt *et al.* 2011).

Another interesting development has been going on in the development of standalone software modules for multi-hazard risk assessment, which are not running as a component of an existing GIS. A good example of this is the CAPRA Probabilistic Risk Assessment Program supported by the World Bank (CAPRA, 2013). The methodology focuses on the development of probabilistic hazard assessment modules, for earthquakes, hurricanes, extreme rainfall, and volcanic hazards, and the hazards triggered by them, such as flooding, windstorms, landslides and tsunamis.

Another recent development is towards Open Source web-based modules for multi-hazard risk assessment.

A tool which is currently under development as part of the Global Earthquake Initiative (GEM), called OpenQuake (https://www.globalquakemodel.org/openquake/support/documentation/), is most probably going to be the standard for earthquake loss estimation, as there are also plans to expand it into a multi-hazard risk assessment tool.

2.9.3 Development of a spatial decision support system

Within the framework of the EU FP7 Marie Curie Project CHANGES (www.changes-itn.eu) and the EU FP7 Copernicus project INCREO (http://www.increo-fp7.eu) a spatial decision support system was developed with the aim to analyse the effect of risk reduction planning alternatives on reducing the risk now and in the future, and support decision makers in selecting the best alternatives. The Spatial Decision Support System is composed of a number of integrated components. The Risk Assessment component allows to carry out spatial risk analysis, with different degrees of complexity, ranging from simple exposure (overlay of hazard and assets maps) to quantitative analysis (using different hazard types, temporal scenarios and vulnerability curves) resulting into risk curves. The platform does not include a component to calculate hazard maps, and existing hazard maps are used as input data for the risk component. The second component of the SDSS is a risk reduction planning component, which forms the core of the platform. This component includes the definition of risk reduction alternatives (related to disaster response planning, risk reduction measures and spatial planning) and links back to the risk assessment module to calculate the new level of risk if the measure is implemented, and a cost-benefit (or cost-effectiveness/Spatial Multi Criteria Evaluation) component to compare the alternatives and make decision on the optimal one. The third component of the SDSS is a temporal scenario component, which allows to define future scenarios in terms of climate change, land use change and population change, and the time periods for which these scenarios will be made. The component doesn't generate these scenarios but uses input maps for the effect of the scenarios on the hazard and assets maps. The last component is a communication and visualization component, which can compare scenarios and alternatives, not only in the form of maps, but also in other forms (risk curves, tables, graphs). The envisaged users of the platform are organizations involved in planning of risk reduction measures, and that have staff capable of visualizing and analysing spatial data at a municipal scale. The Decision Supper System RiskChanges is accessible at: http://www.charim.net/use_case/46.

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