Remote Sensing and GIS for Natural Hazards Assessment and Disaster Risk Management

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Abstract

Many regions in the world are exposed to several types of natural hazards, each with their own (spatial) characteristics. The world has experienced an increasing impact of disasters in the past decades. The main causes for this increase can be attributed to a higher frequency of extreme hydro-meteorological events, most probably related to climate change, and to an increase in vulnerable population. To reduce disaster losses more efforts should be done on Disaster Risk Management, with a focus on hazard assessment, elements-at-risk mapping, vulnerability assessment and risk assessment, which all have an important spatial component. In a multi-hazard assessment the relationships between different hazards should be studied, especially for concatenated or cascading hazards. The use of earth observation (EO) products and geo information systems (GIS) has become an integrated, well developed and successful tool in disaster risk management. Hazard and risk assessments are carried out at different scales of analysis, ranging from a global scale to a community level. Each of these levels has its own objectives and spatial data requirements for hazard inventories, environmental data, triggering factors, and elements-at-risk. An overview is given of the use of spatial data with emphasis on remote sensing data, and of the approaches used for hazard assessment. This is illustrated with examples from different types of hazards, such as earthquakes, windstorms, drought, floods, volcanic eruptions, landslides and forest fires. Examples are given of the approaches that have been developed to generate elements-at-risk databases with emphasis on population and building information, as these are the most used categories for loss estimation. Vulnerability approaches are discussed, with emphasis on the various methods used to define physical vulnerability of building stock and population, and indicator-based approaches used for a holistic approach, also incorporating social, economic and environmental vulnerability, and capacity. Multi-hazard risk approaches are presented which can be grouped in qualitative or quantitative categories. The chapter ends with a number of examples of spatial risk visualization as a component of risk governance.

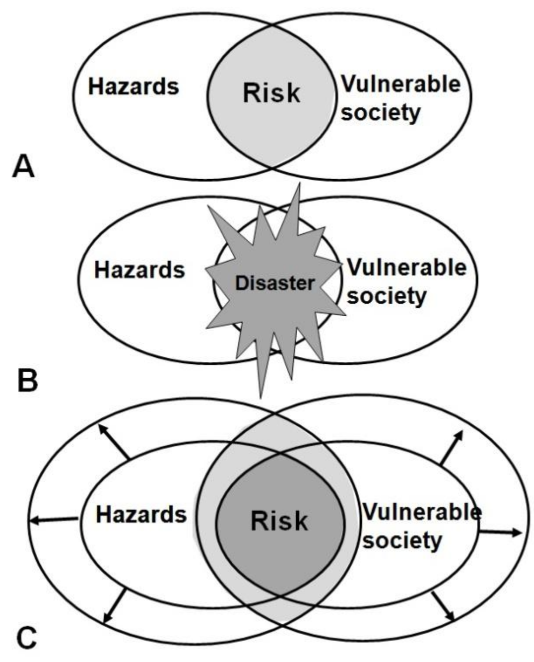
1. Natural Hazards, vulnerability and disasters

Disasters appear on the news headlines almost every day. Most happen in far-away places, and are rapidly forgotten. Others keep the attention of the world media for a longer period of time. The events that receive maximum media attention are those that hit instantaneously and cause widespread losses and human suffering, such as earthquakes, floods and hurricanes. Recent examples are the Indian Ocean tsunami (2004), the earthquakes in Pakistan (2005), Indonesia (2006), China (2008) and Haiti (2010) and the hurricanes in the Caribbean and the USA (2005, 2008). On the other hand there are many serious geomorphologic hazards that have a slow onset such as drought, soil erosion, land degradation, desertification, glacial retreat, sea level rise, loss of biodiversity etc. They may cause much larger impacts on the long run but receive less media attention.

Disasters are defined by the United Nations International Strategy for Disaster Risk Reduction (UN-ISDR, 2004) as 'a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources'. Table 1 gives a summary of the various terms that are relevant in this context (UN-ISDR,2004). It is important to distinguish between the terms disaster, hazard and risk. Risk results from the combination of hazards, conditions of vulnerability and insufficient capacity or measures to reduce the potential negative consequences of risk (O'Keefe, Westgate and Wisner, 1976). When the hazard or threat becomes a reality, when it materializes, the risk becomes a disaster. For example, a certain river valley may be prone to flooding. There is risk if and only if a vulnerable society or property is located within this flood prone area. If the hazard materializes, that is, if the flood actually occurs, it will cause losses to the vulnerable society or property, thus creating a disaster (Fig. 1).

Hazards can be single, sequential or combined in their origin and effects. Each hazard is characterised by its location, area affected (size or magnitude), intensity, speed of onset, duration and frequency. Hazards can be classified in several ways. A possible subdivision is between natural, human-induced and human-made hazards. Natural hazards are natural processes or phenomena in the earth's system (lithosphere, hydrosphere, biosphere or atmosphere) that may constitute a damaging event (e.g. earthquakes, volcanic eruptions, hurricanes). Human-induced hazards are those resulting from modifications of natural processes in the earth's system caused by human activities which accelerate/aggravate the damage potential (e.g. land degradation, landslides, forest fires). Human-made hazards originate from technological or industrial accidents, dangerous procedures, infrastructure failures or certain human activities, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation (e.g. industrial pollution, nuclear activities and radioactivity, toxic wastes, dam failures; transport, industrial or technological accidents such as explosions, fires and oil spills).

Figure 1: Schematic representation of the relation between hazards, vulnerable society, risk and disasters. A: risk indicates the expected losses to a vulnerable society as a result of hazards. B: A disaster occurs when the threat of a hazard become reality, and impacts on a vulnerable society. C: Future trends of increasing hazards and increasing vulnerability will lead to increasing risk.



Although the term 'natural disasters' in its' strict sense is not correct, as disasters are a consequence of the interaction between hazards and vulnerable societies, the term is used extensively in literature and also in daily use. Another subdivision of natural disasters relates to the main controlling factors of the hazards leading to a disaster. Natural disasters may be hydro-meteorological (including floods and wave surges, storms, droughts and related disasters such as extreme temperatures and forest/scrub fires, landslides and snow avalanches), geophysical disasters (resulting from anomalies in the earth's surface or subsurface, such as earthquakes, tsunamis and volcanic eruptions), and biological disasters (related to epidemics and insect infestations).

Table 1: Summary of definitions related to disasters, hazards and vulnerability. Based on UN-ISDR (2004).

Term	Definition
Disaster	A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources'
Natural hazard	A potentially damaging physical event, phenomenon or human activity that may cause 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.
Elements-at-risk	Population, properties, economic activities, including public services, or any other defined values exposed to hazards in a given area". Also referred to as "assets". The amount of elements-at-risk can be quantified either in numbers (of buildings, people etc), in monetary value (replacement costs, market costs etc), area or perception (importance of elements-at-risk).
Exposure	Exposure indicates the degree to which the elements-at-risk are exposed to a particular hazard. The spatial interaction between the elements-at-risk and the hazard footprints are depicted in a GIS by simple map overlaying of the hazard map with the elements-at-risk map.
Vulnerability	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.
Capacity	The positive managerial capabilities of individuals, households and communities to confront the threat of disasters (e.g. through awareness raising, early warning and preparedness planning).
Consequence	The expected losses in a given area as a result of a given hazard scenario.
Risk	The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between (natural, human-induced or man-made) hazards and vulnerable conditions in a given area and time period.

Natural disasters occur in many parts of the world, although each type of hazard is restricted to certain regions. Global studies on the distribution of hazards (e.g. MunichRe, 2010) indicate that geophysical disasters are closely related to plate tectonics. Earthquakes occur along active tectonic plate margins, and volcanos occur along subduction zones (e.g. around the margins of the Pacific plate, so-called 'Ring of Fire'). Tsunamis occur in the neighborhood of active plate margins, but their effects can be felt at considerable distances from their origin as the waves can travel long distances. Tropical cyclones (in North America called 'hurricanes' and in Asia called 'typhoons') occur in particular zones along the coast lines. Landslides occur in hilly and mountainous regions. Under the umbrella of the ProVention Consortium staff from the Hazard Management Unit of the World Bank, the Development Economics Research Group (DECRG) and the Columbia University carried out a global-scale multihazard risk analysis which focused on identifying key "hotspots" where the risks of natural disasters are particularly high (Dilley et al. 2005). The project resulted in a series of global hazard and risk maps which can be downloaded from the CIESIN website (CIESIN, 2005).

1.1 Trends in disaster statistics

Data on disaster occurrences, their effect upon people and their cost to countries are very important for disaster risk management. There are now a number of organizations that collect information on disasters, at different scales and with different objectives.

- Since 1988 the Centre for Research on the Epidemiology of Disasters (CRED) has been maintaining an Emergency Events Database (EM-DAT, 2009). Disasters have to fulfill certain criteria in order to be included in the EM-DAT database: they have to cause at least 10 casualties, 100 or more should be affected, it should result in a declaration of emergency or it should lead to a call for external assistance.

- Data on disaster impacts are also collected by reinsurance companies. For instance the MunichRe data base for natural catastrophes NatCatSERVICE includes more than 28,000 entries on material and human loss events worldwide (MunichRe, 2010). A similar disaster event database (SIGMA) is maintained by SwissRe. However, these data are not publicly available.
- The Asian Disaster Reduction Center (ADRC) has initiated a new disaster database, called Glidenumber (2010). The specific feature of this database is that each disaster receives a unique identifier and a number of relevant attributes.
- At a local level, disaster data have been collected by an initiative of NGOs, called LaRed, initially in Latin America, but later on expanding also to other regions. They generated a tool called DesInventar (2010), which allows local authorities, communities and NGO's to collect disaster information at a local level. Recently the DesInventar database has become available online.
- There are also many disaster databases collected at the national level, or that are related to a specific type of hazard. The Global Risk Identification Program (GRIP) and the Centre for research in Epidemiology of Disasters (CRED) have initiated a service, called DisDAT, which brings together all publicly available disaster databases from different countries (GRIP, 2010). It contains 60 registered disaster databases, of which 13 are global ones.

When we look at the number of reported disasters in these databases, there is a clear increase in hazardous events over the last decades (Figure 2). The number of natural disasters in the last decade has increased by a factor of 9 as compared to the decade 1950-1959 (EM-DAT,2009), which is mainly caused by an increase in hydro-meteorological disasters. In terms of losses, earthquakes resulted in the largest amount of losses (35% of all losses), followed by floods (30%), windstorms (28%) and others (7%). Earthquakes are also the main cause of fatalities, which is estimated in the order of 1.4 million during the period 1950-2000 (47%), followed by windstorms (45%), floods (7%), and others (1%) (MunichRe, 2010; EM-DAT, 2009). It is interesting to note that human fatalities due to natural disasters shows a decreasing trend which may be due to better warning systems and improved disaster management, but the number of people affected follows the increasing trend of the number of events (See Figure 2).

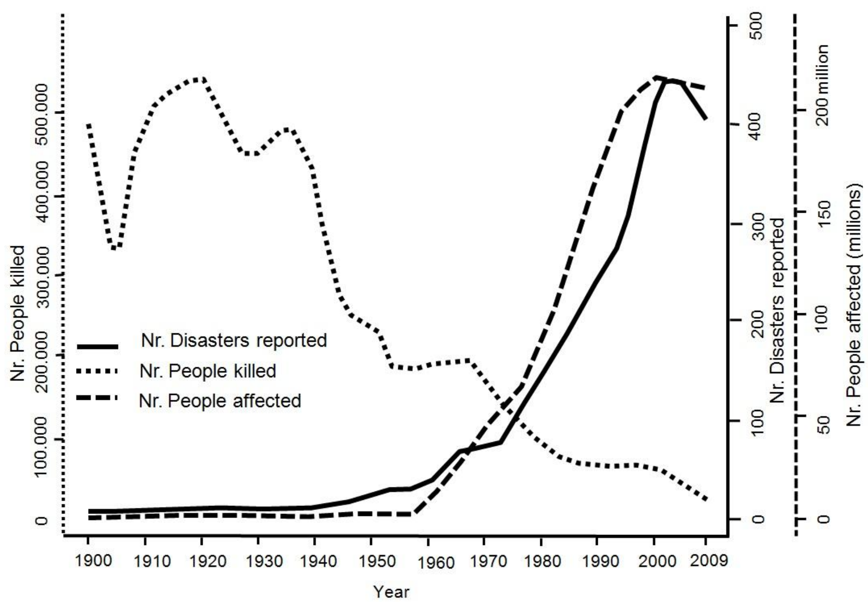


Figure 2: Summary of natural disasters, showing the number of reported disaster, the number of people killed and the number of people affected over the period 1900-2009. Source: EM-DAT (2009)

There are several problems involved in using the disaster statistics from the sources mentioned above for hazard and risk assessment. Official disaster statistics such as those maintained by EM-DAT, suffer from problems in standardizing the information, as it is collected from a variety of sources. Data are often linked to the main type of disaster, and associated disasters such as landslides that are triggered by earthquakes or by tropical storms, are grouped under the triggering event, and are not reported as such. Data on the number of affected people is often difficult to obtain, as it involves a subjective decision of upto what extend people should be affected in order to count them in the database. Data collected by insurance companies suffer the problem that they are collected for particular purposes, and are related to the coverage of the insurance premiums, which may bias the values and the events that are reported. Disaster information collected at the local level (e.g. DesInventar) is more complete as it includes also small magnitude/high frequency events, but the coverage of such database is limited worldwide. One of the major problems with the use of disaster databases for natural hazard and risk assessment, is that they normally lack a proper georeference of the reported events (Verelst, 1999). A comparitive study of the EM-DAT, Sigma and NATCAT databases carried out for fours countries showed that these databases differed significantly (Guha-Sapir and Below, 2002).

The increase in the number of disasters, the losses and people affected cannot be explained only by better reporting methods and media coverage of disasters, lack of which probably made the number too low for the first part of the last century. There are a number of factors that influence the increase in the number of disasters which can be subdived as those leading to a larger vulnerability and those leading to a higher occurrence of hazardous events.

The increased vulnerability is due to a number of reasons. The rapid increase of the world population, which has doubled in size from 3 billion in the 1960s to 6.7 billion in 2010 (World Bank, 2010). Depending on the expected growth rates, world population is estimated to be between 7.9 and 11.0 billion by the year 2050 (UNPD, 2010a). However, the increase in disaster impact is higher than the increase in population, which indicates that there are other important factors involved that increase the overall vulnerability of the world population. One of the main aspects is the large urbanization rate. According to UN figures (UNPD, 2010b) the worldwide urbanization percentage has increased from 29% in 1950 to 50% in 2010 and is expected to rise to 69 in 2050. Another factor related to the population growth is that areas become settled that were previously avoided due to their susceptibility to natural hazards. Many of the largest cities in the world, the so-called 'Megacities' are located in hazardous regions, either in coastal zones, or in seismically active regions (Smith and Petley, 2008; Kraas, 2008)

The increasing impact of natural disasters is also related with the development of highly sensitive technologies and the growing susceptibility of modern industrial societies to breakdowns in their infrastructure. Data from MunichRe (2010) show that the economic losses have increased with a factor of 8 over the past 50 years and insured losses with a factor of 15. There is a rapid increase in the insured losses, which are mainly related to losses occurring in developed countries. Windstorms clearly dominate the category of insured losses (US $90 billion), followed by earthquakes (US $ 25 billion). Insured losses to flooding are remarkably less (US $ 10 billion), due to the fact that they are most sever in developing countries with lower insurance coverage (MunichRe, 2010).

However, it is not only the increased exposure of the population to hazards that can explain the increase in natural disasters. The frequency of destructive events related to atmospheric extremes (such as floods, drought, cyclones, and landslides) is also increasing (EM-DAT, 2009). During the last 10 years a total of 3,750 windstorms and floods were recorded, accounting for two-thirds of all events. The number of catastrophes due to earthquakes and volcanic activity (about 100 per year) has remained constant (MunichRe, 2010). Although the time-span is still not long enough to indicate it with certainty, these data suggest that climate change is related with the increased occurrence of natural disasters.

There is an inverse relationship between the level of development and loss of human lives in the case of disasters. About 85 percent of the disaster related casualties occur in less developed countries, where more than 4.7 billion people live. The greater loss of lives due to disasters in developing countries is due to several reasons such as the lower quality of buildings, lack of building codes or lack of enforcement of them, construction of buildings in hazardous areas due to lack of land use planning, lower awareness and disaster preparedness, less accurate or missing early warning systems, lack of evacuation planning, lack of facilities for search-and-rescues and medical attention. Although 65% of the overall losses due to natural disasters occur in high income countries (with GNI US$ >12,000 per capita) (World Bank, 2010), and only 3% in low income countries (GNI US$ < 1000 per capita), the effect in the latter group is devastating as they may represent as much as 100% of their Gross National Income (UN-ISDR, 2009). Economic losses in absolute terms (billions of dollars) show an increase with the level of development, as the absolute value of elements-at-risk that might be damaged during a disaster increases with increasing level of development. However, in relative terms (percentage of GDP) the trend is reverse (MunichRe, 2010).

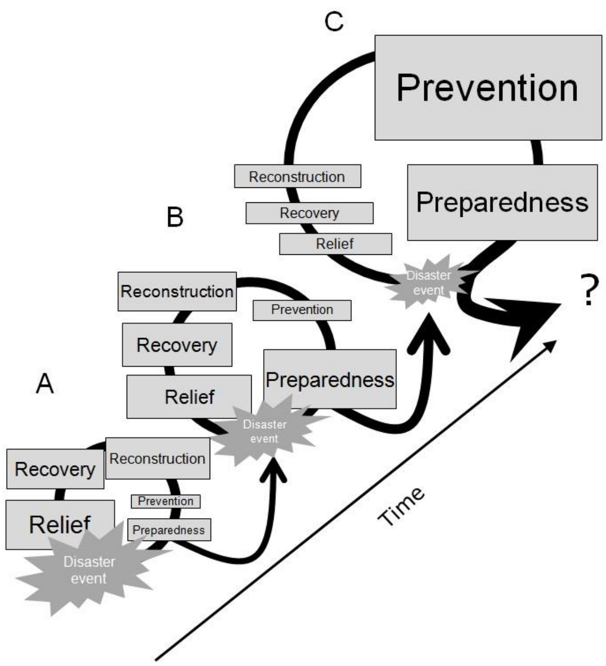
2. Disaster Risk Management framework

As disasters result from the interaction between extreme hazardous events and vulnerable societies, the resulting impact can be reduced through disaster risk management. Disaster Risk Management (DRM) is defined as the systematic process of using administrative decisions, organization, operational skills and capacities to implement policies, strategies and coping capacities of the society and communities to lessen the impacts of natural hazards and related environmental and technological disasters. This comprises all forms of activities, including structural and non-structural measures to avoid (prevention) or to limit (mitigation and preparedness) adverse effects of hazards (UN-ISDR, 2004). Disaster risk management is aimed at disaster risk reduction, which refers to the conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks within the broad context of sustainable development (UN-ISDR, 2004).

The past decades have witnessed a shift in focus from 'disaster recovery and response' to 'risk management and mitigation'. The change was also from an approach that was focused primarily on the hazard as the main causal factor for risk, and the reduction of the risk by physical protection measures to a focus on vulnerability of communities and ways to reduce those through preparedness and early warning. Later also the capacities of local communities and the local coping strategies were given more attention (Blaikie et al., 1994; Lavel, 2000, Pelling, 2003). The Yokohama conference in 1994 put into perspective the socio-economic aspects as a component of effective disaster prevention. It was recognized that social factors, such as cultural tradition, religious values, economic standing, and trust in political accountability are essential in the determination of societal vulnerability. In order to reduce societal vulnerability, and therewith decrease the consequences of natural disasters, these factors need to be addressed (Hillhorst, 2004). The ability to address socio-economic factors requires knowledge and understanding of local conditions, which can – in most cases - only be provided by local actors.

From 1990-2000 the International Decade for Natural Disaster Reduction (IDNDR) and now its successor the International Strategy for Disaster Reduction (ISDR) stress the need to move from top-down management of disasters and a cycle that stresses reconstruction and preparedness, towards a more comprehensive approach that tries to avoid or mitigate the risk before disasters occur and at the same time fosters more awareness, more public commitment, more knowledge sharing and partnerships to implement various risk reduction strategies at all levels (UN-ISDR, 2005b). This more positive concept has been referred to as 'risk management cycle', or 'spiral', in which learning from a disaster can stimulate adaptation and modification in development planning rather than a simple reconstruction of pre-existing social and physical conditions. In Figure 3 this is illustrated by showing the disaster cycle and the various components (relief, recovery, reconstruction, prevention and preparedness) and how these changed through time. Initially (Figure 3A) most emphasis was given to disaster relief, recovery and reconstruction, thereby getting into a cycle where the next disaster was going to cause the same effects or worse. Later on (Figure 3B) more attention was given to disaster preparedness by developing warning systems and disaster awareness programs. Eventually (Figure 3C) the efforts are focusing on disaster prevention and preparedness, thus enlarging the time between individual disasters, and reducing their effects, thus requiring less emphasis in relief, recovery and reconstruction. The eventual aim of disaster risk management is to enlarge this cycle and only reach the response phase for extreme events with very low frequency.

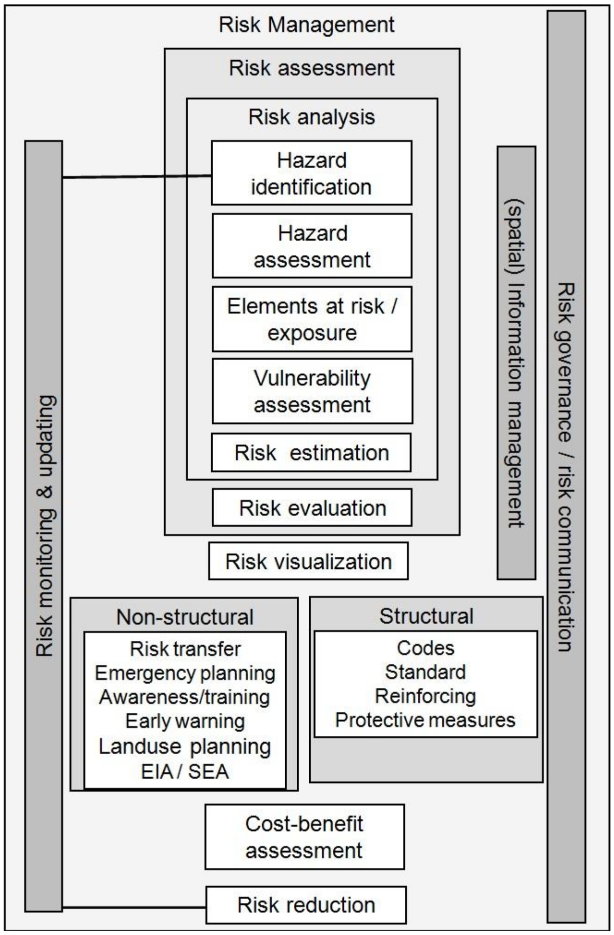
Figure 3: Disaster cycle and its development through time. See text for explanation.



Disaster prevention is achieved through risk management. Figure 4 present the general risk management framework which is composed of a risk assessment block and a block in which risk reduction strategies are defined. A summary of the terminology used in risk management is given in Table 2. Central in the procedure is the risk analysis, in which the available information is used to estimate the risk to individuals or populations, property or the environment, from various hazards. Risk analysis generally contains the following steps: hazard identification, hazard assessment, elements-at-risk/exposure analysis, vulnerability assessment and risk estimation. Risk evaluation is the stage at which values and judgments 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 reducing the risks (UN-ISDR, 2004). Risk assessment is the combination of risk analysis and risk evaluation. It is more than a purely scientific enterprise and should be seen as a collaborative activity that brings professionals, authorized disaster managers, local authorities and the people living in the exposed areas together (O'Brien, 2000; Montague, 2004; Plapp, 2001). Risk governance is therefore an integral component. The final goal, reduction of disaster risk, should be achieved by combining structural and non-structural measures that focuses on emergency preparedness (e.g. awareness raising, early warning systems etc), inclusion of risk information in long term (land use) planning and evaluation of most cost-effective risk reduction measures (See figure 4). In the entire risk management framework, spatial information plays a crucial role, as the hazards are spatially distributed, as well as the vulnerable elements-at-risk.

The use of earth observation (EO) products and geo information systems (GIS) has become an integrated, well developed and successful tool in disaster risk management. New GIS techniques, in particular, are revolutionising the potential capacity to analyse hazards, vulnerability and risks, and plan for disasters. GIS software packages are used for information storage, situation analysis and modelling (Twigg, 2004). Disaster risk management benefits greatly from the use of GIS technology because spatial methodologies can be fully explored throughout the assessment process. One of the key advantages of using GIS-based tools for the risk decision-making process is the possibility to use 'what if' analysis by varying parameters and generating alternative scenarios in a spatial context (Longley et al., 2005). Earlier publications on this topic can be found in Wadge et al. (1993), Coppock (1995), Emani (1996), and Kaiser et al (2003).

Figure 4: Risk Management framework



Risk analysis framework

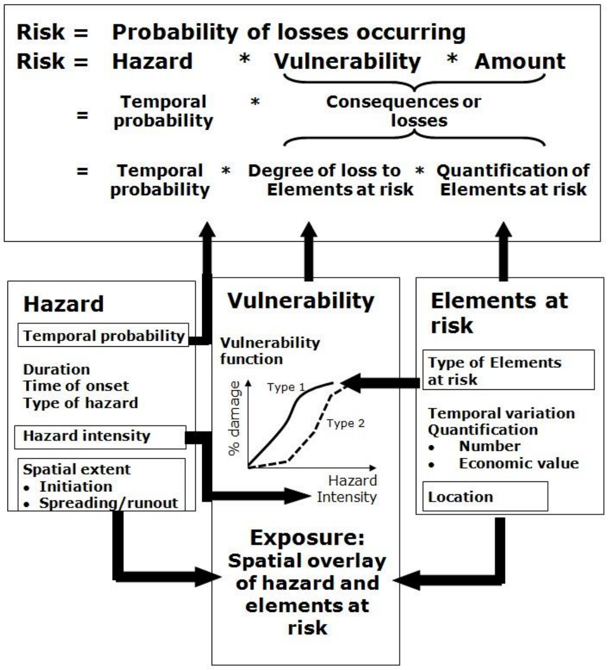
As illustrated in Figure 5 there are three important components in risk analysis: hazards, vulnerability and elements-at-risk (Van Westen et al., 2008). They are characterized by both spatial and non-spatial attributes. Hazards are characterized by their temporal probability and intensity derived from frequency magnitude analysis. Intensity expresses the severity of the hazard, for example flood depth, flow velocity, and duration in the case of flooding. The hazard component in the equation actually refers to the probability of occurrence of a hazardous phenomenon with a given intensity within a specified period of time (e.g. annual probability). Hazards also have an important spatial component, both related to the initiation of the hazard (e.g. a volcano) and the spreading of the hazardous phenomena (e.g. the areas affected by volcanic products such as lava flows) (Van Westen, 2009).

Elements-at-risk are the population, properties, economic activities, including public services, or any other defined values exposed to hazards in a given area (UN-ISDR, 2004).

Table 2: Summary of definitions related to risk management. Based on UN-ISDR (2004).

Term	Definition
Risk analysis	The use of available information to estimate the risk to individuals or populations, property, or the environment, from hazards. Risk analysis generally contains the following steps: hazard identification, hazard assessment, elements-at-risk/exposure analysis, vulnerability assessment and risk estimation.
Risk evaluation	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.
Risk assessment	The process of risk analysis and risks evaluation
Risk control or risk treatment	The process of decision making for managing risks, and the implementation, or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.
Risk management	The complete process of risk assessment and risk control (or risk treatment).

Figure 5: Risk analysis and its components



They are also referred to as "assets". Elements-at-risk also have spatial and non-spatial characteristics. There are many different types of elements-at-risk and they can be classified in various ways (See Section 4.1). The way in which the amount of elements-at-risk is characterized (e.g. as number of buildings, number of people, economic value or the area of qualitative classes of importance) also defines the way in which the risk is presented. The interaction of elements-at-risk and hazard defines the exposure and the vulnerability of the elements-at-risk. Exposure indicates the degree to which the elements-at-risk are actually located in an area affected by a particular hazard. The spatial interaction between the elements-at-risk and the hazard footprints are depicted in a GIS by map overlaying of the hazard map with the elements-at-risk map (Van Westen, 2009).

Vulnerability refers to the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN-ISDR, 2004). Vulnerability can be subdivided in physical, social, economical, and environmental vulnerability. The vulnerability of communities and households can be based on a number of criteria, such as age, gender, source of income etc. which are analyzed using a more qualitative approach involving the use of indicators rather than following the equation as indicated in Figure 5. Physical vulnerability is evaluated as the interaction between the intensity of the hazard and the type of element-at-risk, making use of so-called vulnerability curves (See section 4.2).

For further explanations on hazard and risk assessment the reader is referred to textbooks such as Alexander (1993), Okuyama and Chang (2004), Smith and Petley (2008) and Alcantara-Ayala and Goudie (2010). In the following sections the various components of risk assessment will be further discussed and examples will be given of the use of Remote Sensing and GIS for hazard and risk assessment at different scales of analysis.

3. Hazard Assessment

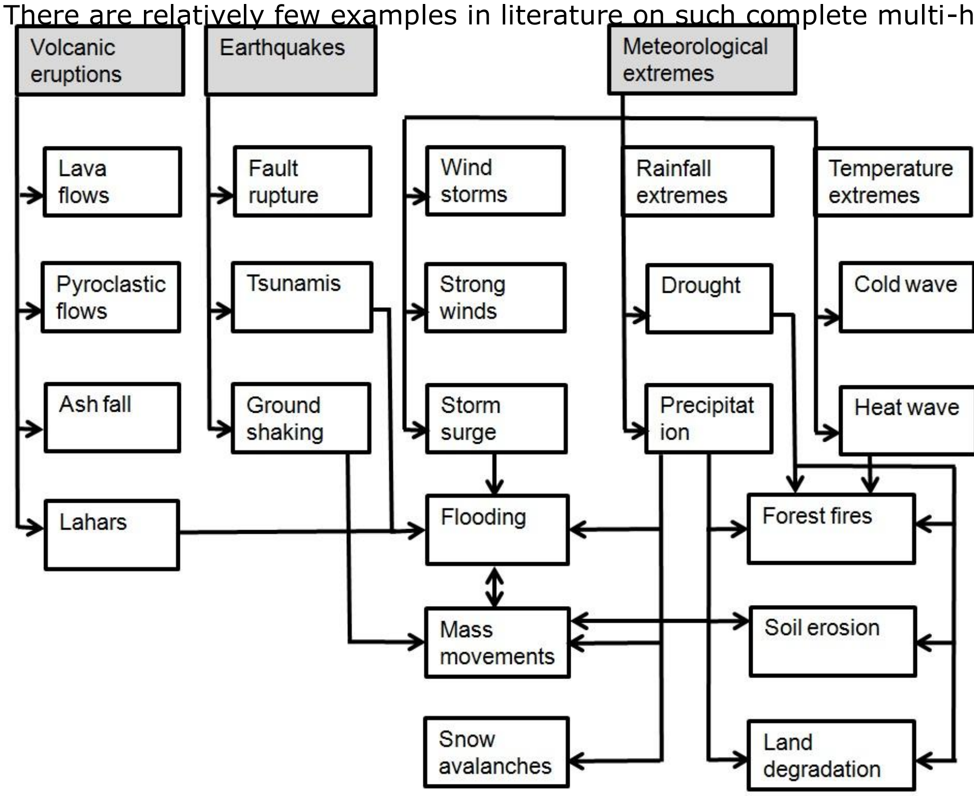
A hazard is defined as a potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. This event has a probability of occurrence within a specified period of time and within a given area, and has a given intensity (UN-ISDR, 2004). Many of the hazards have a relation to Geomorphology. Geomorphology is the science of landforms and of the processes that have formed or reshaped them. These processes that have shaped the Earth's surface can be potentially dangerous if they occur in populated regions and may cause impact to the vulnerable societies if they exceed a certain threshold, e.g. they may result in instability and erosion on slopes, flooding in river- or coastal areas or earthquakes and volcanic eruptions.

The aim of a hazard assessment is to make a zonation of a part of the Earth's surface with respect to different types, severities, and frequencies of hazardous processes. Figure 6 presents a schematic overview of a number of these hazards and the relationships between them. Hazardous processes are caused by certain triggers, which could be related to endogenic (volcanic eruptions or earthquakes) or exogenic (extreme meteorological) processes, and the spatial extent of the hazard is related to a set of environmental factors (geomorphology, topography, geology, land use, climate etc.).

The triggers may cause direct effects, such as ground shaking resulting from an earthquake (Jimenez et al., 2000), drought caused by deficiency in precipitation (Karnieli and Dall'Olmo, 2003), pyroclastic flows and ash fall following a volcanic eruption (Zuccaro et al., 2008), or wind speeds caused by tropical cyclones (Holland, 1980; Emanuel et al., 2006). The direct effects may trigger indirect effect, or secondary hazards, such as landslides caused by ground shaking in mountainous areas (Jibson, Harp, and Michael, 1998) , landslides and floods occurring in recently burned areas (Cannon et al., 2008) or tsunamis caused by earthquake-induced surface displacement in the sea (Priest et al., 2001; Ioualalen et al, 2007). Secondary hazards that are caused by other hazards are also referred to as concatenated hazards or cascading hazards. Figure 6 aims to depict the interrelationships between the triggering factors, the primary hazards and secondary hazards. These relationships can be very complex, for instance the occurrence of floods as a result of the breaking of earthquake-induced landslide dams (Korup, 2002). Given this complexity a multi-hazard assessment, which forms the basis for subsequent risk assessment, should always lead to some sort of simplification in terms of the cause-effect relationships.

Figure 6: Multi-hazards and their interactions required for multi-hazard risk assessment. See text for explanation. Partly based on CAPRA (2009)

There are relatively few examples in literature on such complete multi-hazard assessments, and mos



3.1 Scales of hazard assessment

Hazard assessment using GIS can be carried out at different mapping scales. Although it is possible to visualize and analyze GIS data in many scales, in practice the scale of the input data determines the scale of analysis. There are a number of factors that play a role in deciding the scale of hazard and risk assessment (Fell et al., 2008, Van Westen et al., 2008), such as the aim of the hazard assessment, the type of hazard, the size and characteristics of the study area, the available data and resources, and the required accuracy. Table 3 gives an overview of different scales and approaches for hazard assessment.

Table 3: Scales for hazard assessment, with indication of basic mapping units and the optimal scale for different types of hazards (EQ= Earthquakes, VO= Volcanic hazards, DR= Drought, WS= Windstorms, FL= Floods, CO= Coastal, LS = Landslides, WF = Wildfire). Indicated is the applicability: (••• = highly applicable, •• = moderately applicable, and •= Less applicable)

Scale	Level	Mapping scale (million)	Spatial resolution	Area covered (km^2)	EQ	VO	DR	WS	FL	CO	LS	WF
Global	Global	< 1:5	1-5 km	148 million	•	•	••	••	•	•	•	•
Very small	Continental / large countries	1 – 5	1	5-20 million	••	•	•••	•••	••	••	•	•
Small	National	0.1 – 1	0.1-1 km	30– 600 thousand	•••	•	•••	•••	•••	•••	•	••
Regional	Provincial	0.05 – 0.1	100 m	1000 - 10000	•••	••	••	•••	•••	•••	••	•••
Medium	Municipal	0.025 – 0.05	10 m	100	••	•••	••	••	•••	••	•••	••
Large	Community	> 0.025	1-5 m	10	••	•••	•	•	•••	•	•••	•

Hazard and risk assessment at the global scale is mainly intended to generate risk indices for individual countries, to link them to indices related to socio-economic development, and to make prioritizations for support by international organisations, such as the World Bank, ADB, WHO, UNDP, FAO etc. (Cardona, 2005; Peduzzi et al., 2009). The input data have a scale less than 1:10 million, and spatial resolutions in the order of 1-5 km.

For individual continents or regions covering several countries hazard applications are either focused on analysing the triggering mechanism of hazards that cover vast areas of various millions of km^2, such as tropical cyclones, earthquakes or drought. They are also used for analysing hazards that cross national boundaries (e.g. flood hazard in large catchments like the Rhine, Ganges etc.) or that are related to natural hazard reduction policies at international level (e.g. for the entire European Union). The hazard maps are generated using standardized methodologies, and are aimed both at risk assessment, early warning (De Roo et al., 2007) and post disaster damage assessment. The areas that are evaluated vary in size, as some countries like China, India or the USA are as large as continents like Europe, under one administrative setup. The scale of the input maps can range between 1:100.000 and 1:5 million, and spatial resolutions may vary from 90 meters to 1 km, depending on the application. Both at the global scale and the international scale frequently problems are encountered of data with large differences in spatial resolution and thematic accuracy.

Hazard and risk assessment at national scale cover areas ranging from tens to several hundred thousand km^2, depending on the size of the country. Hazard assessment is carried out at a national scale for national spatial planning purposes, implementation of national disaster risk reduction policies, early warning systems, disaster preparedness and insurance. The applications in spatial planning become more concrete when zooming in on larger scales such as the provincial level. For instance hazard and risk assessment become an integral component of regional development plans and Environmental Impact Assessments for infrastructure developments. At municipal level, hazard and risk assessment are carried out as a basis for land use zoning, and for the design of (non)structural risk reduction measures. At a community level, hazard and risk assessment are carried out in participation with local communities and local authorities, as a means to obtain commitment for disaster risk reduction programmes.

3.2 Spatial data for hazard assessment

The assessment of multi-hazards and the subsequent risk assessment is a very data intensive procedure. The availability of certain types of (spatial) data can be one of the main limitations for carrying out specific types of analysis. Table 4 gives a schematic overview of the main data layers required for hazard and risk assessment, for different hazard types. These can be subdivided into three groups: hazard inventory data, environmental factors, and triggering factors. Spatial information related to the elements-at-risk and to the assessment of their vulnerability will be treated in Section 4.

In the following sections an overview is given of the methods for spatial data collection for these three groups.

Hazard inventories

The hazard inventory data is by far the most important, as it should give insight into the distribution of past hazardous phenomena, their types, mechanisms, causal factors, frequency of occurrence, intensities and the damage that has been caused.

The most straightforward way of generating hazard inventories is through direct measurements of the phenomena. These measurements can be done by networks of stations (e.g. earthquake strong motion data, flood discharge stations, meteorological stations, coastal tide gauging stations, or wave measurement buoys). Seismic networks have been formed globally (NERIES, 2009; ANSS, 2009; GSN, 2009), and the data is managed centrally, for instance by the USGS using web-mapping applications. In the US a similar network has been established for recording stream discharge data for nearly 10.000 sites in a central database linked with a web-mapping service (NWIS, 2010). Although a tsunami warning system has been operational in the Pacific Ocean for a number of decades, the 2004 Indian Ocean tsunami has urged the international community to implement such systems worldwide. For these monitoring networks the spatial coverage is important so that the potentially hazardous areas are monitored. The density of observations required for the monitoring networks differs strongly for various hazard types. This is more problematic for flood discharge stations as each potential hazardous river needs to be monitored, whereas for seismic stations the required density can be much less. Also the spacing between the individual stations is of importance given the variability of the measured characteristics (e.g. rainfall measurements vary strongly over mountainous regions). The period for which measurements are available, and the continuity of the measurements also play an important role, as often the period for which measurements are available is not sufficiently large to capture major events from the past. Catalogues from the measurement networks should be carefully analyzed before being used in a hazard assessment. The monitoring networks located on the ground or in the oceans are supported by a number of satellite systems that are used for transmitting information to central data centres. There is also a large variety of satellite-based monitoring systems that can measure characteristics of hazards over larger areas on a regular basis, such as (sea surface) temperature, rainfall, altitude, clouds, green vegetation indices etc.

Table 4: Overview of spatial data for hazard assessment, and their relevance for different types of hazards. (••• = highly relevant, •• = moderately relevant, and •= Less relevant). EQ= Earthquakes, VO= Volcanic hazards, DR= Drought, WS= Windstorms, FL= Floods, CO= Coastal, LS = Landslides, WF = Wildfire

Group	Data layer and types	EQ	VO	DR	WS	FL	CO	LS	WF
Hazard inventories	Satellite based monitoring	•	•	•	•••	•	•	•	•••
	Ground based networks	•••	•••	•••	•	•••	•	•	•
	Archive studies	•••	•••	•••	•••	•••	•••	•••	•••
	Visual image interpretation	••	••	•	•	••	••	•••	••
	Field mapping	••	•••	•	•	•••	•	•••	•
	Participatory approaches	•••	•••	•••	•••	•••	•••	•••	•••
	Dating methods	•••	•••	•	•	•	•	•••	•
Topography	Relief	•••	•••	•	••	•••	•••	•••	••
	Altitude difference (in time)	•••	•••	•	•	•••	•••	•••	•
	Slope steepness	•••	•••	•	••	••	•••	•••	•
	Slope direction	•••	•••	•	•••	••	••	••	••
	Flow accumulation	•	••	•	•	•••	•	••	•
Geology	Rock types	•••	•••	•	•	•	••	•••	•
	Weathering	•••	•	•	•	•	••	•••	•
	Faults	•••	••	•	•	•	•	•••	•
	Structural geology	•••	•	•	•	•	•	•••	•
Soils	Soil types	•••	•	•••	•	••	••	•••	••
	Soil depth	•••	•	•••	•	•	•	•••	•
	Geotechnical properties	•••	•	•	•	•	••	•••	•
	Hydrological properties	••	•	•••	•	••	••	•••	••
Hydrology	Discharge	•	•••	••	••	•••	••	•	•
	Ground water tables	•••	•	•••	•	••	•	•••	•••
	Soil moisture	••	•	•••	•	•••	•	•••	•••
	Run off	•	•••	•••	•	•••	•	••	••
Geomorphology	Physiographic units	••	••	••	••	••	••	•••	•••
	Origin/genesis	•••	•••	•	•	•••	•••	•••	••
	Landforms	•••	•••	••	••	•••	•••	•••	••
	Active processes	•••	•••	••	•	•••	•••	•••	••
Landuse	Natural vegetation	•	•	•••	•••	•••	••	••	•••
	Land use	••	••	•••	••	•••	••	•••	•••
	Vegetation changes	•	••	•••	•••	•••	••	••	•••
	Land use changes	•	••	•••	•••	•••	••	•••	•••
	Linear infrastructures	•	•••	••	•	•••	••	•••	•••
	Built-up areas	•••	•••	•••	•••	•••	•••	•••	•••
Triggering factors	Rainfall	••	•••	•••	•••	•••	••	•••	•••
	Temperature	•	•	•••	•••	•	••	•	•••
	Wind speed & direction	•	•••	•	•••	•	•••	•	•••
	Wave height	•	•	•	•	••	•••	•	•
	Tides	•	•	•	•	•••	•••	•	•
	Earthquakes	•••	•••	•	•	••	•••	•••	•
	Volcanic eruptions	•	•••	•	•••	••	•••	•••	•••

For larger areas, if no data is available from meteorological stations, general rainfall estimates from satellite imagery can be used, such as from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA), which is used to issue landslide and flood warnings based on a threshold value derived from earlier published intensity-duration-frequency relationships for different countries (Hong et al., 2007b). As another example, GEONETCast is a global network of satellite-based data dissemination systems providing environmental data to a world-wide user community. Products include meteorological satellites (Meteosat, GOES, FengYun), and vegetation monitoring using SPOT-Vegetation data. This information is made available to many users, with low cost receiving station and open-source software (Mannaerts et al., 2009). Another example is the Sentinel Asia programme which is an initiative supported by JAXA and the APRSAF (Asia-Pacific Regional Space Agency Forum) to share disaster information in the Asia-Pacific region on the Digital Asia (Web-GIS) platform and to make the best use of earth observation satellites data for disaster management in the Asia-Pacific region (Sentinel Asia, 2010).

An important initiative that is focused on the provision of space-based information for disaster response is the international charter "Space and Major Disasters" (Disaster Charter, 2010). A number of organizations are involved in rapid mapping activities after major disasters, such as UNOSAT (2010), DLR-ZKI (2010), SERTIT (2010), GDACS (2010) and Dartmouth Flood Observatory (2010). In Europe the Global Monitoring for Environment and Security (GMES) initiative of the European Commission and the European Space Agency (ESA) is actively supporting the use of satellite technology in disaster management, with projects such as PREVIEW (Prevention, Information and Early Warning pre-operational services to support the management of risks), LIMES (Land and Sea Integrated Monitoring for Environment and Security), GMOSS (Global Monitoring for Security and Stability), SAFER (Services and Applications For Emergency Response), and G-MOSAIC (GMES services for Management of Operations, Situation Awareness and Intelligence for regional Crises) (GMES, 2010). The United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER, 2010) has been established by the UN to ensure that all countries have access to and develop the capacity to use space-based information to support the disaster management cycle. They are working on a space application matrix that will provide the satellite-based approaches for each type of hazard and each phase of the disaster management cycle. Overviews on the use of space-based information in hazard inventory assessment can be found in CEOS (2003), Tralli et al. (2005), IGOS (2007) and Joyce et al. (2009).

For a number of hazards satellite-based information is the major source for generating hazard inventories, and hazard monitoring (e.g. tropical cyclones, forest fires, and drought). For others it supports ground based measurements (e.g. earthquakes, volcanic eruptions, coastal hazards). There are hazard types that cannot be recorded by a network of measurement stations, as these do not have specific measurable characteristics (such as landslides, forest fires and snow avalanches). There are also many areas where recorded information is not available. Thus the identification of hazardous phenomena may require techniques such as automatic classification or expert visual interpretation of remote sensing data.

Automatic classification methods make use of reflectance information in different parts of the electromagnetic spectrum captured by different bands in the optical and infrared domain, and by active microwave sensors. For instance for flooding, earth observation satellites can be used in mapping historical events and sequential inundation phases, including duration, depth of inundation, and direction of current (Smith, 1997). Geomorphological information can be obtained using optical (LANDSAT, SPOT, IRS, ASTER) and microwave (ERS, RADARSAT, ENVISAT, PALSAR) data (Marcus and Fonstad, 2008). The use of optical satellite data is often hampered by the presence of clouds, and hazard mapping is also hampered in areas with a vegetation cover. Synthetic Aperture Radar (SAR) is therefore a better tool for mapping hazard events, such as floods (Schumann et al., 2007).

Mapping of forest fires with satellite information is done by mapping the fires themselves using thermal sensors (Giglio and Kendall, 2001), or through the mapping of burnt areas, e.g. using MODIS or AVHRR which have a high temporal resolution (Trigg et al. 2005), or through synthetic aperture radar (Bourgeau-Chavez and Kasischke, 2002).

For visual interpretation of hazard phenomena that cannot be automatically obtained from satellite images (such as landslides) and for geomorphological interpretation of hilly and mountainous areas, stereoscopic imagery with a high to very high resolution is required (Metternicht et al., 2005). Very high resolution imagery (QuickBird, IKONOS, WorldView, GeoEye, SPOT-5, Resourcesat, Cartosat, Formosat and ALOS-PRISM) have become the best option now for visual mapping from satellite images, and the number of operational sensors with similar characteristics is growing year by year, as more countries are launching earth observation satellites with stereo capabilities and spatial resolution of 3 meters or better. The high costs may still be a limitation for obtaining these very high resolution images for particular study areas, especially for multiple dates after the occurrence of main triggering events such as tropical storms or cyclones. Automatic classification of landslides using digital airphotos and very high resolution satellite images has been applied successfully by Hervas et al., (2003), Barlow et al. (2006) and Martha et al. (2010).

Hazard inventory databases should contain information for extended periods of time so that magnitude/frequency relationships can be analyzed. This requires the inclusion of both high frequency/low magnitude events for estimating hazards with a high probability of occurrence, but should also contain sufficient low frequency/high magnitude events to evaluate the hazard for extreme events as well. Therefore, apart from measuring, observing and mapping recent hazard events, it is of large importance to carry out extensive archive studies. For example, one of the most comprehensive projects for landslide and flood inventory mapping has been the AVI project in Italy (Guzzetti et al., 1994). Another example is from China where an analysis was made on extreme precipitation events based on datasets derived from Chinese historical documents over eastern China for the past 1500 years (Zheng et al., 2006). Hazard inventories can also be produced using participatory mapping and participatory GIS (PGIS). Participatory GIS involves communities in the production of spatial data and spatial decision-making. Local people could interpret the outputs from a GIS or contribute to it, for example by integrating participatory mapping of hazardous events to modify or update information in a GIS. Capturing local knowledge and combining it with other spatial information is a central objective. This process may assist communities to look at their environment and explore alternative scenarios based on understanding of their own goals, constraints and preferences (McCall, 2003; Peters Guarin et al., 2005).

The techniques described above are intended to support the generation of hazard inventory databases. Such databases may have a very large degree of uncertainty, which can be related to the incompleteness of historical information with respect to the exact location, time of occurrence, and type of hazard. Table 5 lists a number of sources for global hazard inventories that have been used in the PREVIEW project (Peduzzi et al., 2009)

Environmental factors

The environmental factors are a collection of data layers that are expected to have an effect on the occurrence of the hazardous phenomena, and can be utilized as causal factors in the prediction of future events. The list of environmental factors indicated in Table 4 is not exhaustive, and it is important to make a selection of the factors that are related to a specific type of hazard in each particular environment. However, they give an idea of the types of data included, related to topography, geology, soils, hydrology, geomorphology and land use. The basic data can be subdivided into those that are more or less static, and those that are dynamic and need to be updated regularly. Examples of static data sets are related to geology, soil types, geomorphology and topography. The time frame for the updating of dynamic data may range from hours to days, for example for meteorological data and its effect on hydrology, to months and years for land use data. Especially the land use information should be evaluated with care, as this is both an environmental factor, which determines the occurrence of new events (such as forest fires, landslides and soil erosion), as well as an element-at-risk, which may be affected by the hazards. Table 4 provides an indication on the relevance of these factors for hazard assessment for different types of hazards (Van Westen, 2009).

Table 5: Global data sources for inventory of hazardous events, and hazard assessment used in the PREVIEW project (UNEP/DEWA/GRID, 2010)

Hazard type	Historic events	Hazards
Cyclones	UNEP/GRID-Europe, based on various raw data sources	UNEP/GRID-Europe
Cyclones storm surges:	UNEP/GRID-Europe, based on Cyclones - winds data	UNEP/GRID-Europe
Droughts	UNEP/GRID-Europe based on Climate Research Unit (CRU) precipitation data	International Research Institute for Climate Prediction (IRI), Columbia University
Earthquakes	United States Geological Survey (USGS) ShakeMap Atlas	UNEP/GRID-Europe, USGS, and GSHAP (Global Seismic Hazard Assessment Project)
Fires	European Space Agency (ESA-ESRIN) and World Fires Atlas Program (ATSR).	IONA Fire Atlas
Floods	Dartmouth Flood Observatory (DFO).	UNEP/GRID-Europe
Tsunamis	National Geophysical Data Center (NGDC) Tsunami database, NOAA	Norwegian Geotechnical Institute (NGI),
Volcanoes	Smithsonian Institution Volcanoes of the world	
Landslides	Not available	Hotspots project, International Centre for Geohazards (ICG/NGI)

Digital Elevation Models

As topography is one of the major factors in most types of hazard analysis, the generation of a Digital Elevation Model (DEM) plays a major role. Digital Elevation Models (DEMs) can be derived through a variety of techniques, such as digitizing contours from existing topographic maps, topographic levelling, EDM (Electronic Distance Measurement), differential GPS measurements, (digital) photogrammetry, InSAR, and LiDAR. Many derivate maps can be produced from DEMs using fairly simple GIS operations. These days a wide range of data sources can be selected for the generation of DEMs. The selection depends on the data availability for a specific area, the price and the application.

There are a number of global DEMs available. The oldest is the GTOPO30 (USGS, 1997; Hastings and Dunbar, 1998) developed by the USGS with a spacing between adjacent elevation points of 30 arc-seconds (approximately 1 kilometre) of latitude and longitude. Later also versions were made with a 5-arc-minute spatial resolution (e.g. ETOPO5, TerrainBase and JGP95E), or larger (e.g. ETOPO2). In February 2000, NASA collected elevation data for an area covering a range from 60 degrees south latitude to 60 degrees north latitude of the world using a radar instrument aboard the space shuttle (SRTM) that orbited the earth (Farr and Kobrick, 2000). The resolution of the SRTM data is 30 meters. NASA initially released the data with a resolution of 30 arc-seconds, and later for the entire world at 90 meters resolution (CGIAR-CSI, 2008), free of costs. The vertical accuracy of SRTM data is approximately 4 – 16 m (Falorni et al., 2005), which doesn’t make it suitable for large scale hazard assessments requiring accurate elevation measurements. However it is extensively used for many small scale applications in areas where other sources of DEM are not available, such as in tsunami hazard assessment (Blumberg et al., 2005).

Various optical satellite sensors are widely used for DEM generation, such as Quickbird, IKONOS (2-5 m resolution), the Japanese Advanced Land Observing Satellite (ALOS) PRISM (2.5 m), Indian Cartosat (2.5 m), the French SPOT satellite (5-10m), and ASTER (15-30m). Most of these have been used in hazard assessment studies, at provincial or larger scale.

A very useful source for world-wide medium resolution (30 m) free DEM data is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), launched in

1999, which carries 15 channels, with 4 bands at 15 m resolution, 6 at 60m, and 5 at 90m. The VNIR sensor has in total four bands, of which one is back-ward looking, allowing the generation of DEMs with a pixel resolution of 15 m and a vertical accuracy less than 20 meters (Fujisada et al., 2005). The DEMs generated from ASTER images are now freely available through the ASTER GDEM programme (ASTER GDEM, 2010).

The application of DEMs from very high resolution images (Quickbird or IKONOS) in detailed studies is hampered by the high acquisition costs (30-50 USD/km^2). The recently launched high resolution data from PRISM (ALOS) and CARTOSAT-1, both with 2.5 m resolution, both with two panchromatic cameras that allow for near simultaneous imaging of the same area from two different angles (along track stereo) are able to produce highly accurate Digital Elevation Models, at costs lower than 10 USD/km^2.

DEMs are also derived using radar satellites such as RADARSAT, TerraSAR-X, ALOS PALSAR, ERS-1 and 2, ENVISAT). Synthetic Aperture Radar Interferometry (InSAR) can be used for the generation of Digital Elevation Models, but in practice it is mostly used for detecting changes in topographic heights, related to different hazardous geological processes, such as land subsidence, slow moving landslides, tectonic motions, ice movement and volcanic activity (Massonnet & Feigl, 1998; Ferretti et al. 2001; Hilley et al. 2004; Salvi et al. 2004; Bürgmann et al. 2006). Multi-temporal InSAR analyses using techniques such as the Permanent Scatterers (PSInSAR; Ferretti et al. 2001), PSP (Persistent Scatterers Pairs) and SBAS (Small Base-line Subset) can be used to measure displacement of permanent scatterers such as buildings with millimetre accuracy, and allow the reconstruction of the deformation history (Farina et al. 2008).

For detailed measurement of displacements networks of Differential Global Positioning Systems (DGPS) at fixed points are used extensively, e.g. for mapping strain rates and tectonic plate movements (Vigni et al., 2005), volcanic movements (Bonforte and Puglisi (2003), and landslides (Gili et al, 2000).

More detailed DEMs are nowadays derived using LiDAR (Light Detection And Ranging). Normally LiDAR point measurements will render so-called Digital Surface Models (DSM), which contains information on all objects of the Earth’s surface, including buildings, trees etc., (Ackermann, 1999). Through sophisticated algorithms, and final manual editing, the landscape elements are removed and a Digital Terrain Model is generated. The difference between a DSM and the DTM can also provide very useful information, e.g., on buildings heights, the vegetation canopy height etc. LiDAR has become the standard method for the generation of DEMs in many developed countries already and it is likely that most countries will be having LiDAR derived DEMs within a decade or so. The average costs of LiDAR ranges from 300 – 800 US$/km^2 depending on the required point density. LiDAR data can be acquired through airborne or terrestrial instruments. Airborne LIDAR is used extensively for geomorphologic mapping and terrain classification (Asselen and Seijmonsbergen, 2006). Airborne LIDAR data can be applied to glacial hazards (Favey et al., 2002) coastal hazards (Miller et al., 2008), flood modelling (Cobby et al., 2001; French, 2003), and landslide hazard assessment (Haugerud et al., 2003). Multi-temporal LIDAR can also be used to model the changes and quantify rates of active fluvial processes, for instance river bank erosion (Thoma et al., 2005).

However, Digital Photogrammetry still remains one the most applied methods for DEM generation, using a variety of images, ranging from satellite imagery, air photographs taken on official surveys from National Mapping Agencies, to small format photography taken from helicopters, light aircraft and drones (Henry et al., 2002). Traditionally the most used method for the generation of DEMs as input maps in medium scale hazard assessment was the digitizing of contour lines from topographic maps, and the subsequent interpolation into either raster or vector (Triangular Irregular Networks) DEMs.

Derivatives from DEMs can be used in heuristic analysis at small scales (e.g. hillshading images for display as backdrop image, physiographic classification, internal relief, drainage density), in statistical analysis at regional scales (e.g. altitude zones, slope gradient, slope direction, contributing area, plan curvature, profile curvature, slope length), in physically-based modelling at local scales (local drain direction, flow path, slope gradient) and in spread modelling (detailed slope morphology, flow path) (Moore et al., 2001). The use of slope gradient maps in hazard assessment is greatly affected by the resolution of the DEM (Zhou and Liu, 2004). As a general rule of thumb the use of slope gradient maps is not advisable for small scale studies (Van Westen et al., 2008), although some have used 1 km resolution DEMs to calculate slope angle distribution (Hong and Adler, 2007a). In larger scale studies slope maps, and other DEM derivatives such as aspect, slope length, slope shape etc. can be used as input factors for heuristic or statistical analysis. In local and site investigation scale hazard assessment, DEMs are used in slope hydrology modelling and slope maps are used for physically-based modelling (Kuriakose et al., 2009a).

Other environmental data

Geological maps form a standard component in the hazard assessment of many hazard types (seismic, volcanic, landslides, soil erosion). A geological map of the world (CGMW) was developed in 2009 with maps at scale 1:5 million and 1:25 million. OneGeology is an international initiative of the geological surveys of the world, launched in 2007 as a contribution to the International Year of Planet Earth, with the aim to create a web-based geological map of the world (OneGeology, 2010). Digital geological maps of chronostratigraphy, lithostratigraphy, faults, tectonic lineaments, tectonic units and other themes are available on-line with scales ranging from 1:250.000 (for certain countries) to 1:50 million. For individual countries geological information is often digitally available at much larger scales. For example through the web-portal of the USGS scanned geological maps, as well as the GIS data can be downloaded (USGS, 2010). In medium and small scale analysis the subdivision of geological formations into meaningful mapping units of individual rock types often poses a problem, as the intercalations of these units cannot be properly mapped at these scales. In detailed hazard studies specific engineering geological maps are collected and rock types are characterized using field tests and laboratory measurements. For detailed analysis also 3-D geological maps have been used, although the amount of outcrop and borehole information collected will make it difficult to use this method on a scale smaller than 1:5000, and its use is restricted mostly to a site investigation level (e.g. Xie et al., 2003). Apart from lithological information structural information is very important for hazard assessment (e.g. for earthquakes, landslides, volcanic eruptions). At medium and large scale attempts have been made to generate maps indicating dip direction and dip amount, based on field measurements, but the success of this depends very strongly on the amount of measurements and the complexity of the geological structure (Günther, 2003).

In terms of soil information required for hazard assessment, there are basically two different thematic data layers needed: soil types, with associated geotechnical and hydrological properties, and soil sequences, with depth information. These data layers are essential components for any physically-based modelling approach (e.g. for earthquake amplification studies, landslides and soil erosion). Pedologic soil maps, normally only classify the soils based on the upper soil horizons, with rather complicated legends and are relevant in case of soil erosion, drought and forest fire hazard assessment. Engineering soil maps describe all loose materials on top of the bedrock, and classify them according to the geotechnical characteristics. They are based on outcrops, borehole information and geophysical studies. The soil depth is very difficult to map over large areas, as it may vary locally quite significantly. Soil thickness can be modelled using an interpolation technique which incorporates factors such as land use and slope (Kuriakose et al., 2009b). Digital soil information is available worldwide from the FAO Digital Soil map of the World Information (FAO, 1981), and include soil type classification, clay mineralogy, soil depth, soil moisture capacity, soil bulk density, soil compaction, etc. This product is not based on satellite information directly, but is based primarily on ground surveys and national databases.

Geomorphological maps are made at various scales to show land units based on their shape, material, processes and genesis (e.g. Klimaszewski, 1982). There is no generally accepted legend for geomorphological maps, and there may be a large variation in contents based on the experience of the geomorphologist. An Applied Geomorphological Mapping Working Group has been formed as part of the International Association of Geomomorphologists (IAG) to set guidelines for Geomorphological mapping and develop a digital atlas of Geomorphological maps. Detailed Geomorphological maps contain a wealth of information, but require extensive field mapping, and are very difficult to convert into digital format (Gustavson et al., 2006). Unfortunately, the traditional geomorphological mapping seems to have nearly disappeared with the developments of digital techniques, and relatively few publications on hazard and risk still focus on it (Carton et al., 2005; Castellanos and Van Westen, 2007), or replace it by merely morphometric information. An important new field within geomorphology is the quantitative analysis of terrain forms from DEMs, called Geomorphometry or digital terrain analysis, which combines elements from earth sciences, engineering, mathematics, statistics and computer science (SEE CHAPTER ??) (Pike, 2000; Drăguţ and Blaschke, 2006). Part of the work focuses on the automatic classification of geomorphological land units based on morphometric characteristics at small scales (Giles and Franklin, 1998; Miliaresis, 2001) or on the extraction of slope facets at medium scales (Carrara et al., 1995). Digital geomorphological maps are available only for some parts of the world, for example for Germany (GMK, 2010), Austria (Geomorphology.at, 2010) and New Zealand (GNS, 2010).

Land use can be considered as a static factor in some hazard studies, although most types of hazard assessments are actually focusing on detection of land use changes in relation to the hazard phenomena. Changes in land cover and land use resulting from human activities, such as deforestation, forest logging, road construction, fire, drought and cultivation on steep slopes can have an important impact on hazards. An example is the evaluation of the effect of logging and deforestation on landslides (e.g. Furbish and Rice, 1983). Land use maps are made on a routine basis from medium resolution satellite imagery such as LANDSAT, SPOT, ASTER, IRS1-D etc. Another source for land cover data with higher temporal and lower spatial resolution are MODIS (Moderate Resolution Imaging Spectroradiometer) (Friedl et al. 2002), MERIS (Medium Resolution Imaging Spectrometer), NOAA-AVHRR, Global Imager (GLI), and SPOT-Vegetation imagery with varying resolutions (250 m - 1 km) which are used on a routine basis for monitoring the global distribution of land-cover types (e.g. 10-daily basis) (Cihlar, 2000). Algorithms for bi-temporal change detection (between two images) and temporal trajectory analysis (between a whole series of images covering a certain period) for land cover change detection are reviewed by Coppin et al. (2004). Seasonal and inter-annual variations in land cover that may be caused by natural disasters, and land use changes can be detected using high temporal frequency satellite data.

Several initiatives have produced global land cover maps for different time periods. For example, the CORINE Land Cover 2000 dataset (CLC2000) has been produced using remotely sensed imagery to produce a land cover database at a scale of 1:100,000, a positional accuracy of 150m and a minimum mapping unit of 25ha in Europe and a resolution of 1 km globally. The CLC map contains 50 land cover classes. Later the ESA Globcover initiative generated a global land cover map based on MERIS fine resolution (300 m) mode data acquired between mid 2005 and mid 2006 (Arino et al., 2007). For individual continents more detailed land cover information is available, e.g. the Africover (2010) database for Africa.

Spatial data Infrastructure

Hazard and risk assessment requires a multitude of data, coming from different data sources. Therefore it is important to have a strategy on how to make data available for risk management. Since data is coming from different organizations it is important to look at aspects such as data quality, metadata, multi-user databases, etc. Many project-specific data sets can be used for various purposes (e.g. for resource management was well as risk assessment). This requires that the potential users know what data exist, and have ready access to them. Spatial risk information requires the organization of a Spatial Data Infrastructure, where through internet basic GIS data can be shared among different technical and scientific organizations involved in hazard and risk assessment. A spatial data infrastructure is the foundation or basic framework (e.g. of a system or organization) with policies, resources and structures to make spatial information available to decision makers when they need it, where they need it and in a form where they can use it (almost) immediately. The website where the data is actually exchange is called a clearinghouse. A good example of that is the European ORCHESTRA project (ORCHESTRA, 2009), which designed and implemented the specifications for a service oriented spatial data infrastructure for improved interoperability among risk management authorities in Europe. In the framework of the CAPRA project of the World Bank (CAPRA, 2009), the GeoNode was developed as an open source platform that facilitates the creation, sharing and collaborative use of geospatial data for risk assessment (GeoNode, 2010). Examples of initiatives that focus on spatial data infrastructure for disaster relief are Reliefweb (2010), Alernet (2010), HEWSweb (2010), and GDACS (2010).

3.3 Examples of hazard assessment at different scales.

In this section a number of examples are given of typical hazard assessment examples at the scales of analysis that were outlined in Table 3. Of course it is not possible to give a complete overview of all hazards at all scales; therefore the focus will be on some specific examples for each scale only.

Global scale hazard assessment

As can be seen from Table 3 there are several types of hazardous events that encompass large areas including several countries, such as windstorms, drought, earthquakes, and tsunamis. Therefore the hazard assessment for these hazards should include a global or international mapping scale. For instance the Global Seismic Hazard Mapping Project (GSHAP, 1999), a demonstration project of the UN/International Decade of Natural Disaster Reduction, was conducted in the 1992-1998 period with the goal of improving global standards in seismic hazard assessment. The GSHAP produced regional seismic hazard maps for most parts of the world, that display the global seismic hazard as peak ground acceleration (PGA) with a 10% chance of exceedance in 50 years, corresponding to a return period of 475 years. The procedure involved the identification of seismo-tectonic zones in which the earthquake characteristics were analyzed from historic earthquake databases. For each point seismic hazard is then analyzed using modules, such as SEISRISK (Arnold, 1989).

For windstorms international databases exist for tropical cyclones, in different parts of the world. For the North Atlantic region for example the HURDAT database (Jarvinen et al., 1984) contains all historic Hurricane tracks. Windstorm hazard models generate a set of stochastic events based on historical and modelled windstorm tracks, with parameters on intensity, size and shape. For each simulated track data is calculated for wind velocity together with associated levels of storm surge, and rainfall intensities using empirical relations (Mouton and Nordbeck, 2003). Areas that may inundate due to tidal changes are mapped using a digital elevation model with bathymetric and topographic information in the coastal zones (Lavelle et al., 2003). Drought hazard assessment at an international level is carried out using monthly average precipitation data, e.g. the Weighted Anomaly of Standardized Precipitation (WASP) developed by IRI, computed on a 2.5° x 2.5° grid (Lyon and Barnston, 2005).

For other hazards, such as floods and landslides, information at international levels is too general for estimation of hazards, as the hazard events are too localized, and required more detailed information. Nadim et al. (2006, 2009) made an attempt to generate a global landslide hazard map, making use of general spatial data sets with a global coverage, such as an SRTM Digital Elevation Model with 1 km spatial resolution, the geological map of the world at 1:25 million scale, a soil moisture index, monthly precipitation data, and the GSHAP results. However, given the poor resolution of the data as compared to the specific conditions in which landslides occur, the results are only a general indication of landslide susceptibility. Hong et al. (2007a) present a qualitative method for a global landslide susceptibility map using GIS-based map overlay techniques, combining several layers of different parameters (e.g. elevation, slope, land use, etc.). Recently, an attempt to provide global scale landslide early warnings in near real time using stochastic models combining a global landslide database, TMPA rainfall estimates, SRTM DEM and MODIS landcover products was conducted at Columbia University, the success of which was mainly limited by the lack of completeness of the landslide database and the quality of the rainfall estimates from TMPA (Kirschbaum et al., 2009). Global flood hazard studies are difficult to carry out, as the Digital Elevation Models available at global scale are generally not of sufficient detail for flood modelling applications. One example of an approach used for flood hazard mapping over very large areas is based on an inventory of past flood events (e.g. from Dartmouth Flood Observatory), coupled with a very simple flood model based on the HYDRO1k Elevation Derivative Database (USGS, 1996; Verdin and Greenlee, 1996). HYDRO1k is a geographic database developed to provide comprehensive and consistent global coverage of topographically derived data sets, including streams, drainage basins and ancillary layers derived from the USGS' 30 arc-second digital elevation model of the world.

At global scale few approaches have been carried out for multi-hazard assessment, which aims at providing general indicators or risk indices for countries, or for parts of countries, mainly for comparison of risk levels between countries. Dilley et al. (2005) have developed a methodology for global hazard and risk assessment for the main hazard types of hazards indicated in Table 3. Peduzzi et al. (2009) present a model designed for the United Nations Development Programme as a component of the Disaster Risk Index (DRI), which aims at monitoring the evolution of risk. Four hazards (droughts, floods, cyclones and earthquakes) were modelled using GIS based on the datasets shown in Table 5.

(Inter)national scale hazard assessment

For individual continents or countries many more applications of hazard assessment methods are available, as they are related to the same administrative area, and controlled by national or international governments, such as in the USA, Europe and China. The methodology for hazard and risk assessment is standardized and mostly follows established guidelines that are requested by governments (e.g. the European Floods Directive). The applications at (inter)national level are more refined than those carried out globally and require higher resolution data. For example, the European Flood Directive (EFD) indicated that preliminary flood risk assessments in Europe should be completed by 2011, flood hazard and risk maps should be available by 2013 and flood management plans by 2015 (EFD, 2007). In order to accomplish these advanced methods, datasets and GIS-based tools are used for the assessment and monitoring of flood risk for the whole of Europe. Flood hazard maps are generated based on Digital Elevation Models with a resolution ranging between 100 m and 1 km. The hazard factor is implemented by hydrological methods (e.g. LISFLOOD) at different scales and for many return periods (Barredo, 2007; van der Knijff et al., 2010). Modelling of extreme precipitation and resulting extreme river discharge is calculated in real time and flood forecasts are made for the whole of Europe. In the USA, the Federal Emergency Management Agency (FEMA) has established a national flood hazard mapping project with the Federal Insurance and Mitigation Administration's Hazard Mapping Division through their national Flood Insurance Program (FEMA, 2010).

Similar initiatives in Europe are in the field of forest fires. The European Forest Fire Information System (EFFIS) makes a rapid assessment of the burned areas through a series of daily images from the MODIS instruments on board of TERRA and AQUA satellites and displays fires with burned area of approximately 40 ha or larger in a web-GIS (Ayanza et al., 2003). A third example that is implemented at both the European level as well as globally is the MARSOP-3 project on Crop Yield Forecasting, carried out by the Joint Research Centre (JRC) of the EC, with other partners. This system includes the management of a meteorological database, an agro-meteorological model and database, low resolution satellite information, statistical analyses of data and crop yield forecasting and publishing of bulletins containing analysis, forecasts and thematic maps on crop yield expectations using a Web-GIS application (Reidsma et al., 2009). An overview on the use of satellite data for drought monitoring and hazard assessment can be found in Henricksen and Durkin (1986), Peters et al. (2002) and White and Walcott (2009). The above mentioned tools are used for early warning as well as for hazard assessment at the scale of the whole of Europe.

Another example of hazard assessment from the USA is ShakeMaps, which is a GIS-based tool for earthquake hazard assessment, developed by the USGS is cooperation with regional seismic network operators. ShakeMaps provides near-real-time maps of ground motion and shaking intensity after important earthquakes. It can also be used to generate hazard maps using scenario earthquakes (Wald et al., 1999). As a follow up of this Wald et al. (2004) developed a methodology for deriving maps of seismic site conditions using topographic slope as a proxy, providing the average shear-velocity down to 30 m. (Vs^{30}), using the SRTM30 database. Initiatives to incorporate open-source software in seismic hazard assessment have been taken by OpenSHA (2010) and by the Global Earthquake Model (GEM, 2010), an international initiative to develop uniform and open standards and platforms for calculating earthquake risk worldwide. The GEM brings together all major players in the earthquake risk assessment field, including partners from the insurance sector, international organisations, public organisations and research centres from all over the world.

In terms of landslide hazard assessment this scale is still too general to be able to map individual landslide phenomena. The analysis of landslide hazards at this scale is still done by weighting a number of input maps (e.g. Malet et al., 2009; Castellanos and Van Westen, 2007).

Provincial and municipal scale hazard assessment

In local and municipal scales the spatial information is often of sufficient quality to run more sophisticated models, which can be either statistical or physically-based. An example is given here of flood hazard assessment. The first step is to transform catchment characteristics like topography, relief and land cover, complemented with hydrological boundary conditions into estimates of the discharge at various locations along the river downstream. This can be done with (distributed) 1-dimensional models. These kinds of models are very useful to assess the response of the river to extreme events and to changes in the topography and land cover. Typical models to do this are HEC-HMS and HEC-RAS of the US Army Corps of Engineers, MIKE-SHE (Refsgaard and Storm, 1995), IHDM (Beven et al., 1987), LISFLOOD (De Roo et al. 2000), and HEC-RAS (Brunner, 2002). They require the characterization of the terrain through a series of cross-sections perpendicular to the direction of flow for which the average water depth and flow-velocity are calculated. This type of modelling is often applied for catchment analysis and the underlying assumption is that all flow is parallel to a predefined river-network. In near-flat terrain with complex topography it cannot be assumed that all flow will be parallel to the main river. Also in urban environments and in areas with a dominant presence of man-made structures, models are required that calculate flow in both X- and Y-direction. Such models, like SOBEK (Stelling, et al. 1998; Hesselink et al. 2003), Telemac 2D (Hervouet and Van Haren, 1996) and MIKE21 can also be applied in the case of diverging flow at a dike breach. They require high quality Digital Elevation Models, which ideally are generated using LIDAR data (Dal Cin et al., 2005; Alkema and Middelkoop, 2005). The flood modelling is usually carried out at a municipal to provincial scale, at a selected stretch of the river. These models provide information on how fast the water will flow and how it propagates through the area. It is very suitable to assess the effects of the surface topography, like embanked roads and different land cover types on the flood behaviour (Stelling et al. 1998).

Also for landslide hazard assessment the provincial and municipal scales offer much more possibilities, as sufficient information can be collected on hazard inventories, and the factors that control the location of landslides (Dai, Lee and Ngai, 2002). They differentiate between statistical methods and physically-based models. Guzetti et al. (2005) give an overview of the various statistical methods that can be applied, focusing on the use of multi-variate statistical methods, in which landslide inventories for different periods are used in combination with environmental factors (e.g. geology, slope , land use etc.) for predicting landslide activity within slope units that are defined from a DEM. Van Asch et al. (2007) give an overview of the physically-based modelling approaches that can be carried out at large scales of analysis. Most of the physically-based landslide models make use of the infinite slope model and are therefore only applicable to modelling shallow landslides. They can be subdivided into static models that do not include a time component, and dynamic models, which use the output of one time step as input for the next time step. Physically-based models for shallow landslides account for the transient groundwater response of the slopes to rainfall and or the effect of earthquake acceleration (van Beek and van Asch, 2004).

The provincial and municipal scales are also the most appropriate for volcanic hazard assessment, as a lot of this work depends on the determination of the eruptive history on the basis of geological investigation and age dating (Tilling, 1989). Given different volcanic eruption scenarios, several modelling techniques can be carried out for the various volcanic hazards (ash fall, lava flow, pyroclastic flow, lahars). Most of these hazard assessment methods require some sort of spread modelling, where the volcanic products are distributed over the terrain away from the vent. This requires the use of dynamic models (Zuccaro et al., 2008). The evaluation of volcanic hazards from tephra fallout is determined by the volcanic ash volumes, eruption height, and wind information (Connor et al., 2001). Remote sensing also plays an important role in volcanic hazard assessment (e.g. Kerle and Oppenheimer, 2002)

Community Level

Approaches based on local knowledge and experiences may be a useful resource particularly in developing countries where detailed information required for conventional model-based risk analyses facilitated by GIS is often not available. For instance, historical records on river discharges and rainfall are often missing, whereas knowledge about hazardous events is generally available within the local communities (Ferrier and Haque, 2003). There is a vast quantity of undocumented local knowledge on disaster occurrences in the field, which usually remains untapped because of the lack of funding, a format to systematically collect it and a low commitment to do so (Hordijk and Baud, 2006). Anderson and Woodrow (1989) state that much of the information needed for risk assessment and mitigation can be obtained from local people who usually already know what the situation is but do not always have the skills for understanding and organizing what they know. Several organizations, such as the International Federation of Red Cross and Red Crescent Societies (IFRC), have developed community-based assessment instruments for analyzing disaster situations at the grassroots level and for improving the community's expertise in identifying and articulating its needs and reducing its vulnerabilities. Examples of these are the Capacity and Vulnerability Assessment (CVA), Hazards, Vulnerability and Capacity Assessment (HVCA), and Damage, Needs and Capacity Assessment methods (DNCA) (Provention Consortium, 2010). These methods aim at eliciting tacit local knowledge within communities on historic disaster events, the perception of hazards, characterization of elements-at-risk, identifying the main factors of vulnerability, coping mechanisms, and disaster reduction scenarios. The application of such collaborative approaches is not common in many developing countries, and decision-making about risk is often done in a top-down approach by local authorities where specialists diagnose problems, formulate alternatives and determine options without a meaningful consultation with communities (UN-ESCAP, 2003). Hazard specialists often consider that community participation is difficult to achieve, and the information is perceived unscientific, not always easy to retrieve, difficult to be expressed in quantitative terms or to be converted into spatial formats (Peters Guarin, 2008).

The integration of geo-information systems and local community knowledge relevant to hazards, vulnerability and risk modelling is still in an initial stage (Maskrey, 1998; Ferrier and Haque, 2003; Zerger and Smith, 2003). Very often the sketches, paper maps, historical profiles and other results obtained through participatory mapping, are not kept after a risk project has finished, leading to a loss of valuable information. As Cannon et al. (2003) advise, these products need to be converted from raw data into useful spatial information that allows the community and other actors to develop analytical processes for risk analysis and exploration of management alternatives. Several authors have shown that local communities are indeed the primary sources of information for instance for flood depths, time of occurrence, severity measured in terms of damage, and the like (Whitehouse, 2001; Alcantara-Ayala, 2004; Rautela, 2005). Systematic collection of data from significant events using public participation can provide a very useful component for the development of data-sets to be used as input for risk studies at community level and as a basis for risk management and community planning (Ireland, 2001). Information from local communities can also be useful in calibrating and verifying risk and disaster scenarios (Bassolé et al., 2001; Peters Guarin, 2008).

4. Elements-at-risk and vulnerability

The next step in a risk assessment, after analyzing the hazard, is to evaluate the elements-at-risk. Elements-at-risk are the population, properties, economic activities, including public services, or any other defined values exposed to hazards in a given area. There are many different types of elements-at-risk and they can be classified in various ways. In this section several types of elements-at-risk and their data sources are evaluated before, followed by a discussion on how these are used in vulnerability assessment.

4.1 Elements-at-risk information

Elements-at-risk inventories can be carried out at various levels, depending on the requirement of the study. Table 6 gives a more detailed description of the main points.

Elements-at-risk data should be collected for certain basic spatial units, which may be gridcells on a global scale (See tables 3 and 6), administrative units (countries, provinces, municipalities, neighbourhoods, census tracts) or so-called homogeneous units with similar characteristics in terms of type and density of elements-at-risk. Risk can also be analyzed for linear features (e.g. transportation lines) and specific sites (e.g. a damsite). The risk assessment will be done for these spatial units of the elements-at-risk, rather than for the ones used in the hazard assessment. In the HAZUS methodology (FEMA, 2004) the loss estimation is done based on census tracts.

Table 6: Main elements-at-risk, and how they can be spatially represented in the various mapping scales.

	Scale				
	Global	Continental	National	Provincial/Municipal	Community
Basic unit	1 km grid or countries	90 – I km grid & countries	30 – 90 m & municipality	Census tract	Groups of buildings
Population	Gridded population map	Gridded population map	By municipality • Population density	By Census tract • Population density • Daytime/Nighttime	People per building • Daytime/Nighttime • Gender • Age • Education, etc.
Buildings	N.A.	Gridded building density map	By municipality • Nr. Buildings	By Census tract • Generalized use • Height • Building types	Building footprints • Detailed use • Height • Building types • Construction type • Quality / Age • Foundation
Transportation networks	N.A.	Main roads, railroads, harbours, airports	Road & railway networks, with general traffic density information	All transportation networks with detailed classification, including viaducts etc. & traffic data	All transportation networks with detailed engineering works & detailed dynamic traffic data
Lifelines	N.A.	Main powerlines	Only main networks • Water supply • Electricity	Detailed networks: • Water supply • Waste water • Electricity • Communication • Gas	Detailed networks and related facilities: • Water supply • Waste water • Electricity • Communication • Gas
Essential facilities	N.A.	By Municipality • Number of essential facilities	As points •General characterization •Buildings as groups	Individual building footprints Normal characterization Buildings as groups	Individual building footprints • Detailed characterization • Each building separately
Agricultural data	Gridded main land cover types, crops	Gridded maps: • Crop types • Yield information	By homogeneous unit, • Crop types • Yield information	By cadastral parcel • Crop types • Crop rotation • Yield information • Agricultural buildings	By cadastral parcel, for a given period of the year • Crop types • Crop rotation & time • Yield information
Ecological data	Main land cover types, crops	Natural protected areas with international approval	Natural protected area with national relevance	General flora and fauna data per cadastral parcel.	Detailed flora and fauna data per cadastral parcel
Economic data	GDP	By region: Economic production, mport / export, type of economic activities	By Municipality • Economic production • Import / export • Type of economic activities	By Mapping unit • Employment rate • Socio-economic level • Main income types Plus larger scale data	By household • Employment • Income • Type of business Plus larger scale data

Digital information on coastlines, international boundaries, cities, airports, elevations, roads, railroads, water features, cultural landmarks, etc. is available from different sources, e.g. the Digital Chart of the World (DCW, 1992). A more recent example for obtaining spatial information is the Geonetwork established by FAO (2010) with available data comprising base layers (e.g. boundaries, roads, rivers), thematic layers (e.g. protected areas), or a backdrop image (e.g. World Forest 2000).

One of the most important spatial attributes of the mapping units for an elements-at-risk inventory is the land use. The land use determines to a large extend the type of buildings that can be expected in the unit, the economic activities that are carried out, the density of the population in different periods of the day, etc. Land use maps are prepared by image classification at small scales or through visual interpretation at larger scales (See also section 3.2). Ebert et al. (2009) have developed a method using Object Oriented Image classification method for the automatic characterization of the land use types in urban areas.

Collaborative mapping and Mobile GIS

Elements-at-risk information is collected from a wide variety of sources, some of which are discussed in the section below. There are also many areas in the world for which no detailed digital data is available on elements-at-risk. In such situations data should be digitized from analogue maps or in case these also don't exist, be mapped in the field, for instance using Mobile GIS. With the use of Mobile GIS it is possible to directly collect the spatial information, based on a high resolution image that can be uploaded into a palmtop computer, or smart phone and link it with attribute information that is collected in the field. Some of the most used tools for Mobile GIS in urban elements-at-risk mapping are ArcPad (Montoya, 2003) and Cybertracker (McCall, 2008).

Several initiatives have come up for collaborative mapping of topographic features. For example OpenStreetMap is a free editable map of the whole world, which is made using collaborative mapping by volunteers. It allows users to collect, view, edit and use geographical data in a collaborative way from anywhere on Earth (OpenStreetMap, 2010). Another example, Ushahidi (2010) which means "testimony" in Swahili, is a website that was initially developed to map reports of violence in Kenya in 2008. It is an open source platform that any person or organization can use to set up their own way to collect and visualize spatial information. Other applications that are specifically directed to post disaster relief coordination are Sahana (2010) and Virtual Disaster Viewer (2009). Sahana is a free and Open Source web-based Disaster Management system, developed after the Indian Ocean tsunami, as a collaboration tool that addresses the common coordination problems during a disaster. The Virtual Disaster Viewer is a social networking tool for collaborative disaster impact and damage assessment, which has proven to be very effective after the Haiti earthquake in 2010. Hundreds of earthquake and remote sensing experts were assigned specific areas (tiles) of the affected areas to review and provide their assessment by comparing before and after high-resolution satellite images, that became available on Google Earth immediately after the disaster, and which served as the basis for the collaborative mapping. Such collaborative mapping applications might become a very important tool for the future.

Population data

People are the most important elements-at-risk, with a static and dynamic component. The static component relates to the number of inhabitants per mapping unit, and their characteristics, whereas the dynamic component refers to their activity patterns, and their distribution in space and time. Population distribution can be expressed as either the absolute number of people per mapping unit, or as population density. The way population data is collected and represented in a risk assessment depends on the scale of analysis (See Table 3) and the availability of information (Rhind, 1991).

Census data are the obvious source for demographic data. They are used as benchmark data for studying population changes, and are key input for making projections concerning population, households, labour force and employment. Census data is costly to collect, and updating of population information is carried out on average every 10 years. Census data is aggregated to census tracts, and normally data at an individual household level is confidential. This is also the reason why risk assessment is normally carried out at the census tract level (FEMA, 2004). Census tracts are divisions of land that are designed to contain 2500-8000 inhabitants with relatively homogeneous population characteristics, economic status and living conditions. Census data may also contain other relevant characteristics that are used in risk assessment, such as information on age, gender, income, education and migration.

For larger areas census data may be aggregated into larger administrative units. However, for large parts in the world census data is not available, outdated, or unreliable. Therefore also other approaches have been used to model population distribution with remote sensing and GIS, based on a number of factors, such as land cover, roads, slopes, night time illumination etc. Basically two approaches are used: one is to use remote sensing as the main source for the estimation of population distribution, and the other is to use it refine the spatial resolution of population data from available population information (so-called dasymetric mapping) (Balk et al., 2006). Global population data is available from the LandScan Global Population Database (Bhaduri et al., 2007; LandScan, 2010) which provides the average population over 24 hours, in a 1 km resolution grid. The Global Rural-Urban Mapping Project (GRUMP) is another examples of modelling human populations in a common geo-referenced framework (GRUMP, 2004), as is the African Population Database (APD, 2010). Higher resolution population databases have also been developed for specific areas. Especially in low income countries where limited information is available, there is a need to generate population information using satellite data. Tatem et al. (2007) made a comparison between semi-automated population distribution mapping for several countries in East Africa, based on 30 m LANDSAT ETM data, and concluded that these produced more accurate results than existing products at a cost of $0.01 per km^2.

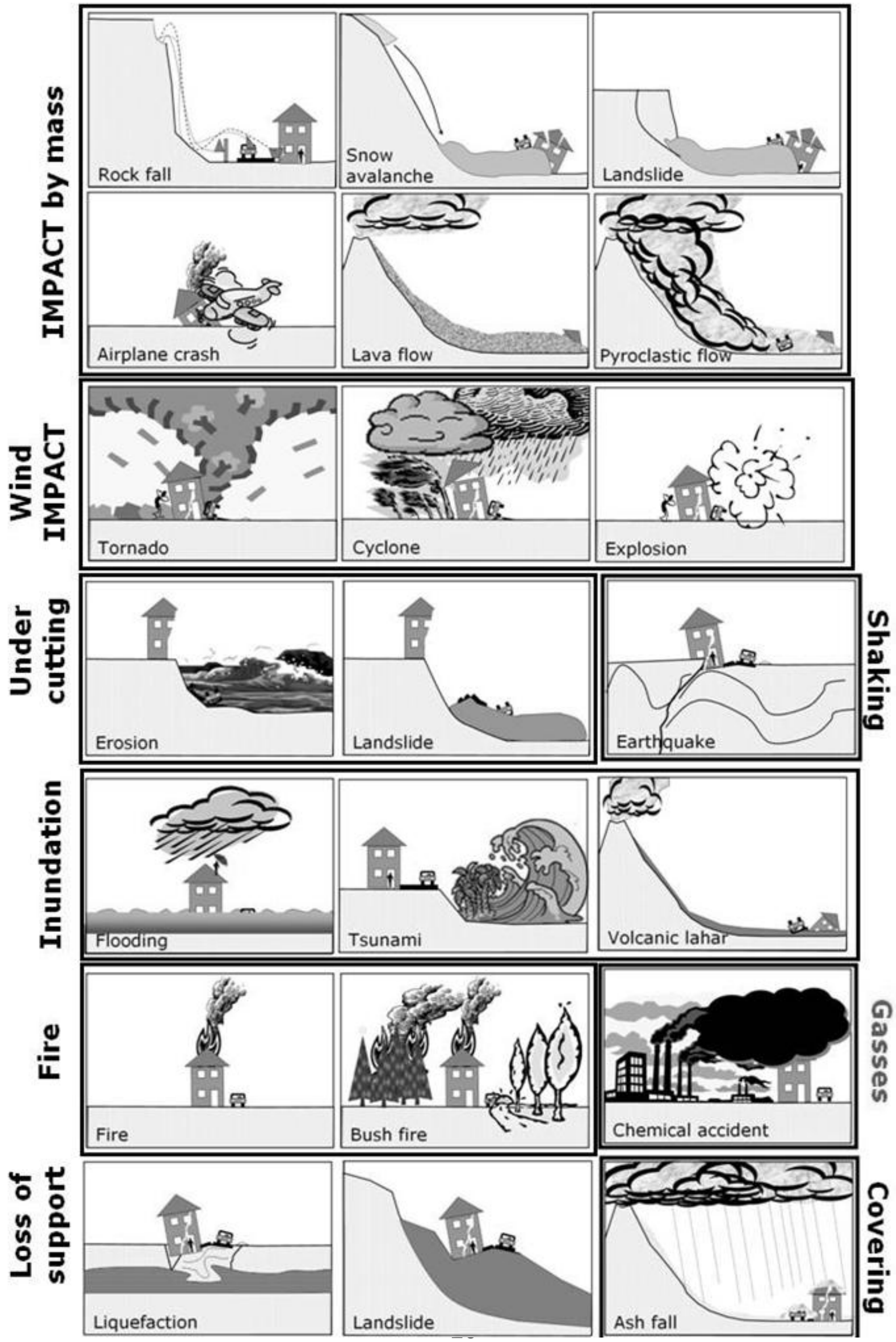
For large scale risk assessment at municipal or community level, much higher details are required of population information. In the absence of census data static population information can be derived directly using high resolution satellite imagery (e.g. Harvey, 2002) or through a building footprint map, where the land use type and the floorspace are used to estimate the number of people present in a particular building (Chen et al., 2004; Lwin and Murayama, 2009).

Building data

After population, buildings are the second most important group of elements-at-risk. They house the population and the behaviour of a building under a hazard event determines whether the people in the building might be injured or killed. In order to be able to assess the potential losses and degree of damage of buildings, it is important to analyze the type of negative effects that the event might have on the building exposed to it, and the characteristics of the building. The negative effects of hazardous events on buildings can be classified in a number of groups, depending on the type of hazard (Blong, 2003, Hollenstein, 2005). Figure 7 gives a schematic overview of the various hazard processes that may occur and that have a different effect on buildings. For instance a building may be impacted by a mass, and the damaging effects would be determined by the volume of the mass, speed of impact and the medium of impact, such as rocks, soil, debris, snow, water, air etc. Buildings could also be affected by undercutting (erosion or landslides), shaking (earthquakes), inundation, fires, loss of support (subsidence), gasses, or loading (e.g. volcanic ashes). In each of these situations particular building characteristics are important for evaluating the damaging effects, such as structural type, construction materials, application of building code, age, maintenance, roof type, height, floor space, volume, shape, proximity to other buildings, proximity to hazard source, proximity to vegetation, and openings (FEMA, 2004; Jones et al., 2005; Grünthal et al, 2006; Douglas, 2007).

For risk maps that express losses in economic terms also an estimation of building costs needs to be done. Several sources of information can be used, such as data on house prices from real-estate agencies, information from cadastres, which indicate the value used as the basis for taxation, engineering societies, which calculate the replacement costs, or insurance companies (Grünthal et al, 2006). It is often difficult to get hold of the building values used by the cadastres, whereas it is easier to use the values from real estate agencies. Samples are taken from each type of building in the various land use classes. In some countries building societies produce a monthly index that allows updating property prices. Cost estimation can be carried out by using the replacement value or the market value. Apart from building costs also the content costs are very relevant, especially for those hazards that have less structural damage such as flooding.

Figure 7: Examples of the type of hazardous processes to which buildings can be exposed. Each type of processes will have different effects.



Building information can be obtained in several ways. Ideally data is available on the number and types of buildings per mapping unit, or even in the form of building footprint maps. If such data is not available, building footprints maps can be generated using screen digitizing from high resolution images (Van Westen et al., 2002). Automated building mapping has also been carried out using high resolution satellite images (Fraser et al., 2002), InSAR (Stilla et al., 2003), and specifically using LiDAR (Priestnall et al., 200; Brenner, 2005; Oude Elberink and Vosselman, 2009). LIDAR data also allows the extraction of other relevant features, and the calculation of shapes, building height and volumes which are needed in risk assessment.

4.2 Vulnerability

Vulnerability is the most complicated component of risk assessment indicated in Figure 5, because the concept of vulnerability has a wide range of interpretations. The concept originated from the social sciences in response to the pure hazard oriented perception of disaster risk in the 1970s. Since that time different disciplines have developed their own concepts. Multiple definitions and different conceptual frameworks of vulnerability exist (e.g. Blaikie et al., 1994; Pelling, 2003). An overview of the approaches is given Birkmann (2006). The definition of vulnerability given in Table 1, indicates that vulnerability is multi-dimensional (physical, social, economic, environmental, institutional, and human factors define vulnerability); dynamic (it changes over time); scale-dependent (it can be expressed at different scales from individuals to countries) and site-specific (each location might need its own approach) (Bankoff et al., 2003). In the risk assessment methods a differentiation can be made between the quantitative and qualitative methods. Figure 8 presents a framework for multi-hazard risk assessment which will be further explained in section 5. Relevant to mention here is that quantitative methods focus mostly only on physical vulnerability, whereas many qualitative methods also incorporate the other aspects.

Physical vulnerability is the potential for physical impact on the built environment and population. It is defined as the degree of loss to a given element at risk or set of elements-at-risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage). As can be seen from Figures 3 and 7 vulnerability is related to the characteristics of the elements-at-risk, and to the hazard intensity. Physical vulnerability as such is therefore not a spatial component, but is determined by the spatial overlay of exposed elements-at-risk and hazard footprints (Van Westen et al., 2009). Economic vulnerability is defined as the potential impact of hazards on economic assets and processes (i.e. business interruption, secondary effects such as increased poverty and job loss). Social vulnerability is the potential impact of events on groups within the society (such as the poor, single parent households, pregnant or lactating women, the handicapped, children, and elderly), and it considers public awareness of risk, ability of groups to self-cope with catastrophes, and the status of institutional structures designed to help them cope. Environmental vulnerability evaluates the potential impacts of events on the environment (flora, fauna, ecosystems, biodiversity etc.) (Birkmann, 2006).

Vulnerability can be expressed or presented in various ways (Calvi et al., 2006). Vulnerability indices are based on indicators of vulnerability and are mostly used for holistic vulnerability, capacity and resilience assessment. Vulnerability tables show the relation between hazard intensity and degree of damage in the form of a table. Vulnerability curves display the relation between hazard intensity and degree of damage for a group of elements-at-risk (e.g. a certain building type) ranging from 0 to 1. Different types of elements-at-risk will show different levels of damage given the same intensity of hazard (See Figure 3). Vulnerability curves can be relative curves (showing the percentage of property value damaged) or absolute (show the absolute amount of damage). Fragility curves provide the probability for a particular group of element at risk to be in or exceeding a certain damage state (e.g. complete destruction, extensive damage, moderate damage, and slight damage) under a given hazard intensity (FEMA, 2004). A damage probability matrix (DPM) indicates the probability that a given structural typology will be in a given damage state for a given intensity.

Measuring physical vulnerability is a complicated process, and can be done using either empirical or analytical methods (Lang, 2002). Empirical methods are either based on damage data from historical hazard events, or on expert opinion. For events that are relatively frequent and widespread it is possible to collect information on the degree of physical damage to buildings or infrastructure after the event has occurred (e.g. Reese et al., 2007). This method is particularly suited for flooding and for earthquakes, which normally affect many buildings that are of the same type, and allow generating large enough samples in order to make a correlation between the hazard intensity (e.g. modified Mercalli intensity, ground acceleration, water depth etc) and the degree of damage. The result is either a damage probability matrix (DPM) or a vulnerability curve. In many situations expert opinion will be the most feasible option for obtaining vulnerability information, either because there is no prior damage information, not enough funding to apply analytical methods or because building classifications used elsewhere do not reflect the local building stock (Douglas, 2007). This method involves the consultation of a group of experts on vulnerability to give their opinion e.g. on the percentage damage they expect for the different structural types with different intensities of hazard.

Analytical methods study the behaviour of buildings and structures based on engineering design criteria, analyzing e.g. seismic load and derive the likelihood of failure, using physical modelling tests (e.g. shake tables or wind tunnels), as well as computer simulation techniques. In the analytical methods the information on the intensity of the hazard should be more detailed. For instance in the case of earthquake vulnerability analysis of buildings it is important to have geotechnical reports to establish the value of the effective peak acceleration coefficient, the value of the effective peak velocity-related acceleration coefficient and the soil profile type. Also spectral acceleration should be obtained. One of the common tests is using a shake table. This is a device for shaking structural models or building components with a wide range of simulated ground motions, including reproductions of recorded earthquakes time-histories (Calvi et al., 2006).

Most of the work on the measurement of physical vulnerability is done for earthquakes, floods and windstorms (FEMA, 2004). Even though flood vulnerability has been defined in a rather detailed manner (Moel et al., 2009) there are still many uncertainties involved. For volcanic hazards much progress in defining vulnerability has been made in recent years (Spence et al., 2004; 2005). For mass movement there is much less work done on defining vulnerability (Glade, 2003), partly due to the large variation in mass movement processes, the difficulty in expressing landslide intensity versus the degree of damage, and limited amount of landslide damage data. Some approaches exist for single landslide types such as debris flows (e.g. Fuchs et al., 2007), but an integrated methodology is still lacking. Hollenstein (2005) has developed an approach for multi-hazard vulnerability assessment, by defining hazards with a common set of parameters, (for example acceleration, pressure and temperature change) and fragility functions are defined in terms of these common parameters so that they are applicable to all risks.

Population vulnerability can be subdivided in direct physical population vulnerability (injury, casualties, and homelessness), and the indirect social vulnerability and capacity. Physical population vulnerability is mostly carried out after a building vulnerability study by analyzing the effect of the building damage on the population inside of the buildings, using different injury severity classes. Empirical relations exist for different types of hazards, although most information is available for earthquakes (Coburn and Spence, 2002; FEMA, 2004). For different types of volcanic hazards, such relations were made among others by Spence et al. (2005), for landslides by Glade et al. (2005), for drought by Wilhite (2000) and for flooding and windstorms by FEMA (2004).

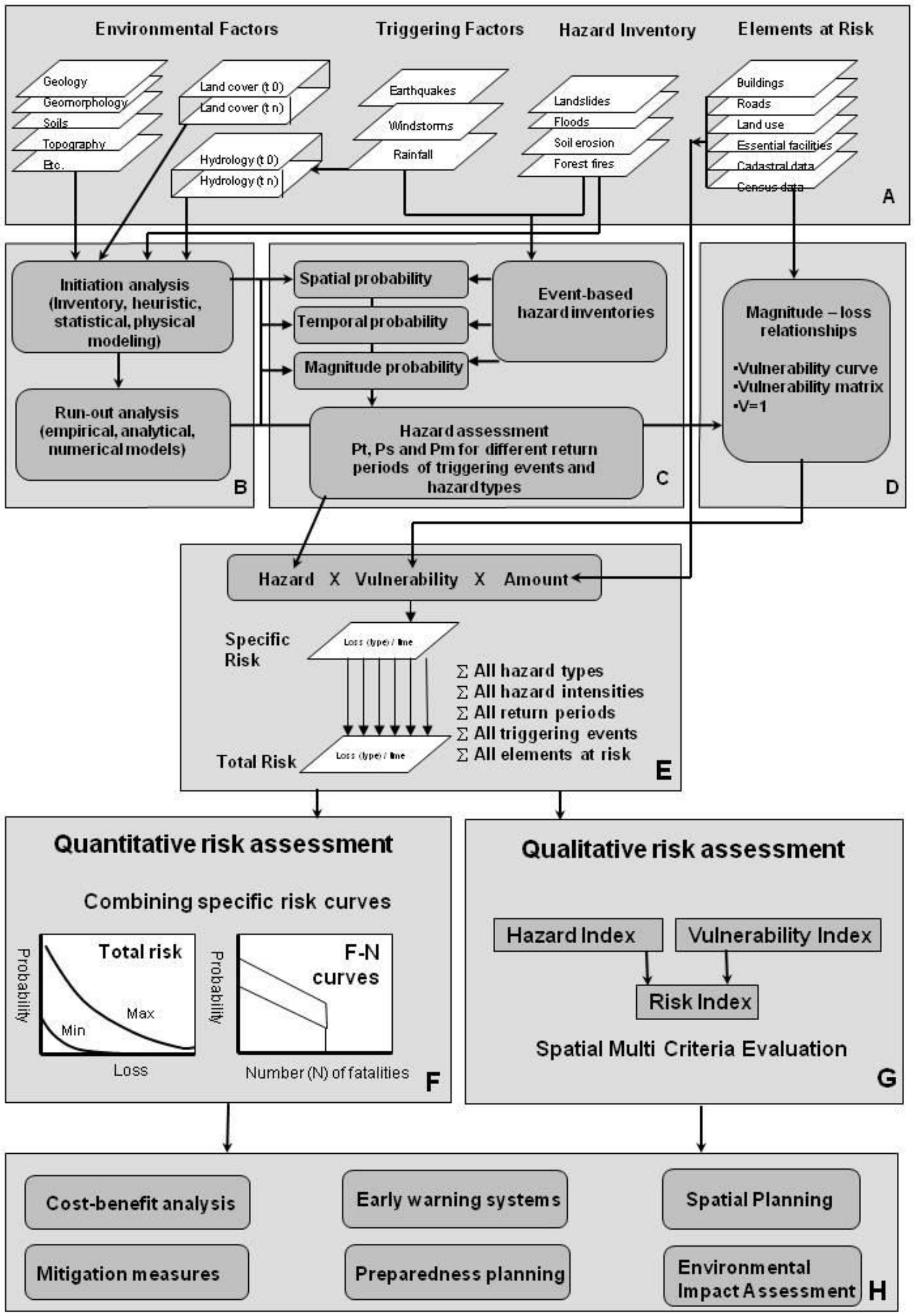
The methods described above aim at quantifying physical vulnerability to natural hazards, and are mostly following an engineering approach and are often restricted to quantifying the physical effects of disasters on buildings, and other infrastructure, and secondary effects of these related to casualties and economic losses. There is also another set of approaches that look at vulnerability in a holistic way, and try to incorporate all the components of vulnerability using an indicator approach. These methods will be discussed in the next section under qualitative risk assessment, as they do not specifically separate the vulnerability from the risk component.

5. Multi-hazard risk assessment

Figure 8, based on Van Westen et al (2005, 2008), gives the framework of multi-hazard risk assessment with an indication of the various components (A to H). The first component (A) deals with the input data, focusing on the data needed to generate susceptibility maps for initiation and spreading, triggering factors, multi-temporal inventories and elements-at-risk (treated in section 3.2). The second component (B) focuses on susceptibility assessment, and is divided into two parts. The first one dealing with the modelling of areas where the hazard may initiate (e.g. earthquakes, landslide initiation, hydrological modelling, soil erosion, volcanic eruptions), which can make use of a variety of different methods (inventory based, heuristic, statistical, physically-based models). The resulting maps form the input as source areas in the modelling of potential spreading of the phenomena (e.g. spreading of volcanic deposits, landslide run-out, flood extent modelling, seismic amplification, forest fire spreading). The third section (C) deals with hazard assessment, which heavily depends on the availability of magnitude-frequency information. The susceptibility maps together with the magnitude-frequency relations of the triggering events are used to determine three components that are needed for the hazard assessment: the spatial probability (indicating the probability that a given area will be affected by the hazard of a given intensity), the temporal probability (indicating the probability of the event to happen in time), and the magnitude probability (indicating the probability that the hazard event will have a given magnitude) (Corominas and Moya, 2008). The fourth section (D) focuses on vulnerability assessment and indicates the various types of vulnerability assessment approaches that can be used (treated in section 4.2). Section E in Figure 8 gives the concept of risk assessment which integrates the hazard, vulnerability and amount of elements-at-risk. The specific risk is calculated for many different situations, related to hazard type, hazard intensity, return period of the triggering event, and type of element at risk. The integration of hazard, vulnerability and risk can be done in two ways: quantitative or qualitative. Section F present the quantitative risk approach in which the results are shown in risk curves plotting the expected losses against the probability of occurrence for each hazard type individually, and expressing also the uncertainty, by generating two loss curves expressing the minimum and maximum losses for each return period of triggering events, or associated annual probability. The individual risks curves can be integrated into total risk curves for a particular area and the population loss can be expressed as F-N curves. The risk curves can be made for different basic units, e.g. administrative units such as individual slopes, road sections, census tracts, settlements, municipalities, regions or provinces. Section G deals with methods for qualitative risk assessment, which are mostly based on integrating a hazard index, and a vulnerability index, using Spatial Multi Criteria Evaluation. The last session (H) deals with the use of risk information in various stages of Disaster Risk Management.

Hazards will impact different types of elements-at-risk, and it is therefore important to calculate the risk for different sectors, e.g. housing, agriculture, transportation, education, health, tourism, mining and on the natural environment (protected areas, forests, wetlands etc). Risk assessment should involve the relevant stakeholders which can be individuals, businesses, organizations, and authorities. As was introduced in section 3 the scale of analysis is also very important in risk assessment. Risk assessments can be carried out with a range of methods that can be broadly classified into qualitative and quantitative approaches.

Figure 8: Framework of the use of GIS for multi-hazard risk assessment.



5.1 Qualitative approaches

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 simplest form of qualitative risk analysis is to combine hazard maps with elements-at-risk maps in GIS using a simple risk matrix in which the classes are qualitatively defined (AGS, 2000). This method is widely applied, mostly at (inter)national or provincial scales where the quantitative variables are not available or they need to be generalized. Qualitative approaches consider a number of factors that have an influence on the risk. The approaches are mostly based on the development of so-called risk indices, and on the use of spatial multi criteria evaluation. One of the first attempts to develop global risk indicators was done through the Hotspots project (Dilley et al. 2005). In a report for the Inter-American Development Bank, Cardona (2005) proposed different sets of complex indicators for benchmarking countries in different periods (e.g. from 1980 to 2000) and to make cross-national comparisons. Four components or composite indicators reflect the principal elements that represent vulnerability and show the advances of different countries in risk management: Disaster Deficit Index, Local Disaster Index, Prevalent Vulnerability Index and Risk Management Index. Each index has a number of variables that are associated with it and empirically measured. The DDI can be considered as an indicator of a country's economic vulnerability to disaster. The method has been applied thus far only in Latin America and the Caribbean. 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 based on data from 1980 to 2000. In the DRI, countries are indexed for each hazard type according to their degree of physical exposure, their degree of relative vulnerability, and their degree of risk.

Also at local scale risk indices are used, often in combination with spatial multi criteria evaluation (SMCE). Castellanos and Van Westen (2007) present an example of the use of SMCE for the generation of a landslide risk index for the country of Cuba, generated by combining a hazard index and a vulnerability index. The hazard index is made using indicator maps related to triggering factors (earthquakes and rainfall) and environmental factors. The vulnerability index was made using five key indicators: housing condition and transportation (physical vulnerability indicators), population (social vulnerability indicator), production (economic vulnerability indicator) and protected areas (environmental vulnerability indicator). The indicators were based on polygons related to political-administrative areas, which are mostly at municipal level. Each indicator was processed, analysed and standardized according to its contribution to hazard and vulnerability. The indicators were weighted using direct, pair wise comparison and rank ordering weighting methods and weights were combined to obtain the final landslide risk index map. The results were analysed per physiographic region and administrative units at provincial and municipal levels. Another example at the local level is presented by Villagrán de León (2006) which incorporates 3 dimensions of vulnerability, the scale or geographical level (from human being to national level), the various sectors of society, and 6 components of vulnerability. The method uses matrices to calculate a vulnerability index, which was grouped in qualitative classes (high, medium and low).

5.2 Quantitative approaches

Quantitative approaches aim at expressing the risk in quantitative terms either as probabilities, or expected losses. They can be deterministic (scenario-based) or probabilistic (taking into account the effect of all possible scenarios and uncertainties). They mostly follow an engineering approach and focus on the evaluation of the direct physical losses resulting directly from the impact of the hazard, for instance buildings that are flooded, or that collapse due to an earthquake, wind damage to infrastructure. Some also analyze indirect losses due to loss of function, for example, disruption of transport, business losses or clean up costs. The focus is on tangible losses that have a monetary (replacement) value, for example, buildings, crops, livestock, infrastructure etc. Disasters also cause a large amount of intangible losses for example, lives and injuries, cultural heritage, environmental quality, biodiversity etc. Quantitative risk assessment aims at quantifying the risk according to the equation given in Figure 8. There are several approaches, which differ in the way to calculate the hazard or to calculate vulnerability and consequences. For a number of different hazard scenarios the consequences are plotted against the temporal probability of occurrence of the hazard events in a graph. Through these points a curve is fitted, the so-called risk curve, and the area below the curve presents the total risk. This procedure is carried out for all individual hazard types, and care should be taken to evaluate also interrelations between hazards. Since the risk is normalized into annual risk, it is then possible to evaluate the multi-hazard risk, and use the risk curves as the basis for disaster risk reduction. The (epistemic and aleatory) uncertainties are incorporated in the modelling and used to calculate Exceedance Probability Curves, Average Annual Losses (AAL) and Probable Maximum Losses (PML).

Loss estimation has been carried out initially from the early days of insurance and has evolved to computer-based catastrophe modelling since the late 1980's using advanced information technology and geographic information systems (GIS) (Grossi, Kunreuther and Patel, 2005). Since the end of the 1980's risk modelling firms such as AIR Worldwide, Risk Management Solutions (RMS), EQECAT and others have lead the industry of probabilistic risk modelling. A range of proprietary software models for catastrophe modelling was developed, for different types of hazards. For instance EQECAT has developed a platform (WORLDCATenterprise) that includes 181 natural hazard models from 95 countries (EQECAT, 2010). However, as these tools are proprietary, and were used for the insurance market, publicly available tools had to be developed by the scientific community for disaster risk management.

One of the earliest open source methods for loss estimation was the RADIUS method (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Dis-asters), which was designed using very simple tools that enable users to perform an aggregated loss estimation using a gridded mesh, in terms of number of buildings damaged, length of lifelines damaged, and as a number of casualties and injured people (RADIUS, 1999).

The best initiative for loss estimation using public domain software has been HAZUS (which stands for "Hazards U.S.") developed by the Federal Emergency Management Agency (FEMA) together with the National Institute of Building Sciences (NIBS). The goal of FEMA was to create a methodology that was the standard national loss methodology for assessing losses from natural hazards (FEMA, 2004). 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 ArcView and later ArcGIS. Although the HAZUS methodology has been very well documented, the tool was primarily developed for the US, and all data formats, building types, fragility curves and empirical relationships cannot be exported easily to other countries.

Several other countries have adapted the HAZUS methodology to their own situation, e.g. in Taiwan (Yeh et al., 2006) and Bangladesh (Sarkar et al., 2010). The HAZUS methodology has also been the basis for the development of several other Open Source software tools for loss estimation. One of these is called SELENA (SEimic Loss EstimatioN using a logic tree Approach), developed by the International Centre for Geohazards (ICG), NORSAR (Norway) and the University of Alicante (Spain)(Molina et al., 2010). Whereas most of the above mentioned GIS-based loss estimation tools focus on seismic hazard, the Central American Probabilistic Risk Assessment Initiative (CAPRA, 2009) has a true multi-hazard risk focus. The aim of CAPRA is to develop a system which utilizes Geographic Information

Systems, Web-GIS and catastrophe models in an open platform for disaster risk assessment, which allows users from the Central American countries to analyze the risk in their areas, and be able to take informed decisions on disaster risk reduction. 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. These are based on event databases with historical and simulated events. This information is combined with elements-at-risk data focusing on buildings and population. For the classes of elements-at-risk, vulnerability data can be generated using a vulnerability module. The main product of CAPRA is a software tool, called CAPRA-SIG, which combines the hazard scenarios, elements-at-risk and vulnerability data to calculate Loss Exceedance Curves.

In New Zealand a comparable effort is made by developing the RiskScape methodology for multi-hazard risk assessment (Reese et al., 2007; Schmidt et al., 2010). Another good example of multi-hazard risk assessment is the Cities project in Australia, which is coordinated by Geoscience Australia. Studies have been made for six cities of which the Perth study is the latest (Durham, 2003; Jones et al., 2005). Also in Europe several project have developed multi-hazard loss estimations systems, such as the ARMAGEDOM system in France (Sedan and Mirgon, 2003) and in Germany (Grünthal et al, 2006).

The above mentioned systems focus on the assessment of losses prior to events, while other systems aim at providing fast assessments of damage directly after the occurrence of major events. For instance the PAGER (Prompt Assessment of Global Earthquakes for Response) system, developed by the USGS is an automated system that rapidly assesses earthquake impacts by comparing the population exposed to each level of shaking intensity with models of economic and fatality losses based on past earthquakes in each country or region of the world (PAGER, 2010).

5.3 Spatial Risk Visualization

Risk management cannot take place without proper risk governance. Risk governance has been promoted in the ISDR, Hyogo framework for action to: "Promote and improve dialogue and cooperation among scientific communities and practitioners working on disaster risk reduction, and encourage partnerships among stakeholders, including those working on the socio-economic dimensions of disaster risk reduction" (UN-ISDR, 2005a). Governance depends on the level of political commitment (on international, national, regional and local levels) and strong institutions. Good governance is identified in the ISDR Framework for disaster reduction as a key area for the success of effective and sustained disaster risk reduction (IRGC, 2005). One of the important processes in risk governance is risk communication, which is the interactive exchange of information about risks among risk assessors, managers, news media, interested groups and the general public. An important component of that is the visualization of risk. Since risk is a spatially varying phenomenon, Geographic Information Systems (GIS) technology is now the standard tool for the production and presentation of risk information as we have seen in the previous sections. Risk can be presented in the form of statistical information per administrative unit (country, province, municipality, or neighbourhood), such as a Risk Index value resulting from qualitative risk assessment, the Probable Maximum Loss (PML) or Average Annual Loss (AAL), Loss Exceedance curve for economic risk, or F-N curves for societal population risk. Risk can also be visualized spatially in the form of maps which shows the spatial variation of risk over an area.

The type of Risk visualization depends very much on the stakeholder to which the risk information is presented. Table 7 gives an overview of the relation between stakeholders and the type of risk visualization.

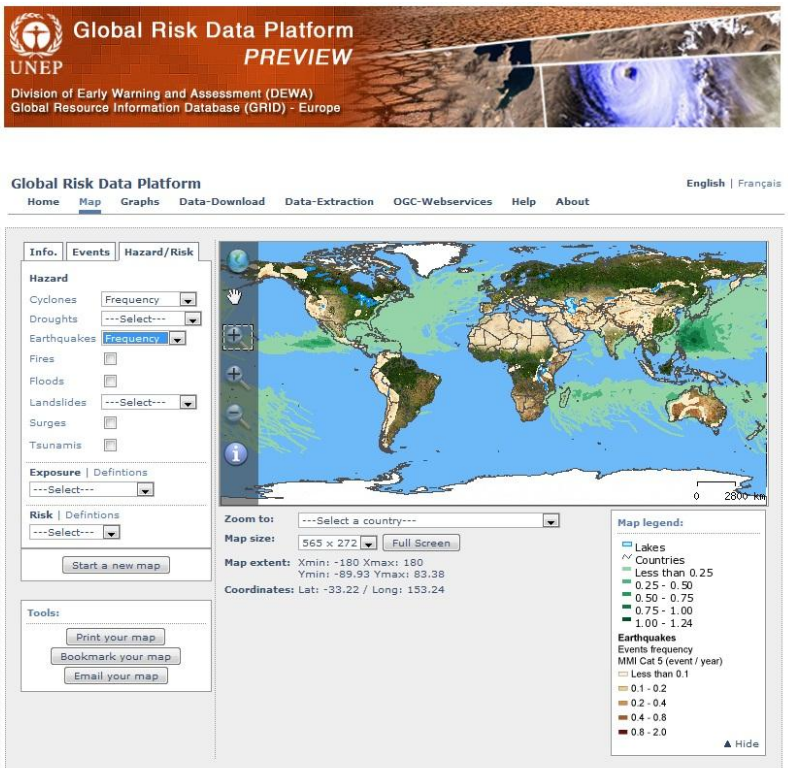
In order to be able to visualize and analyze data that are located somewhere else physically, and do that with many different clients, Internet-based GIS systems have been developed in which all the individual layers are separated (multi-tier approach) thus allowing many clients to access and visualize the geo-data at the same time.

Table 7: Relationship between stakeholders in risk management and risk visualization options.

Stakeholder	Purpose	Type of risk visualization
General public	General information on risks over large areas	Basic WebGIS applications in which they can overlay the location of major hazard types with high resolution imagery or topographic maps.
	Awareness raising	Animations (what if scenarios)
	Community-based DRR projects	Simple maps of the neighborhood with risk class, buildings, evacuation routes, and other features
Businesses	Investment policies, and location planning	General information about hazards and risks in both graphical and map format.
Technical staff of (local) authorities	Land use regulation / zoning	Map with simple legend in three classes: construction restricted, construction allowed, further investigation required.
	Building codes	Maps indicating the types of building allowed (building type, number of floors)
	Spatial planning	Hazard maps, with simple legends related to probabilities and possible consequences
	Environmental Impact Assessment	Maps and possible loss figures for future scenarios
	Disaster preparedness	Real time simple and concise Web-based information in both map and graphical forms
Decision makers / local authorities	Decision making on risk reduction measures	Statistical information, loss exceedance curves, F-N curves, maps.
	Investments	Economic losses, projected economic losses for future scenarios.
	Strategic Environmental Assessment	General statistical information for administrative units.
NGO's	Influence political decisions in favor of environment and sustainable development	This can vary from simple maps to Web-based applications, depending on the objectives of the NGO
Scientists / technical staff of hazard data producers	Hazard information exchange to public and other agencies	WebGIS applications where they can access the basic information
	Exchange of basic information for hazard and risk assessment	Spatial Data Infrastructure / Clearinghouse for exchanging information
Insurance industry	Development of insurance policy	Loss Exceedance Curves of economic losses, F-N curves
Media	Risk communication to public,	Animations of hazard phenomena that clearly illustrate the problems.

A WebGIS is a special GIS tool that uses the Internet as a means to access and transmit remote data, conduct analysis, and present GIS results. WebGIS applications for risk visualization have been developed for different purposes. At the global level the PREVIEW Global Risk Data Platform is the result of efforts of UNEP, UNISDR, UNDP and World Bank, to share spatial data information on global risk from natural hazards through the internet. Users can visualise, download or extract data on past hazardous events, human and economical hazard exposure and risk from natural hazards on a platform compliant with OGC Web Services (OWS). It covers tropical cyclones and related storm surges, drought, earthquakes, biomass fires, floods, landslides, tsunamis and volcanic eruptions (See Figure 9 as example). The collection of data is made via a wide range of partners (UNEP/DEWA/GRID, 2010).

Figure 9: Global Risk Data Platform, PREVIEW (UNEP/DEWA/GRID, 2010)

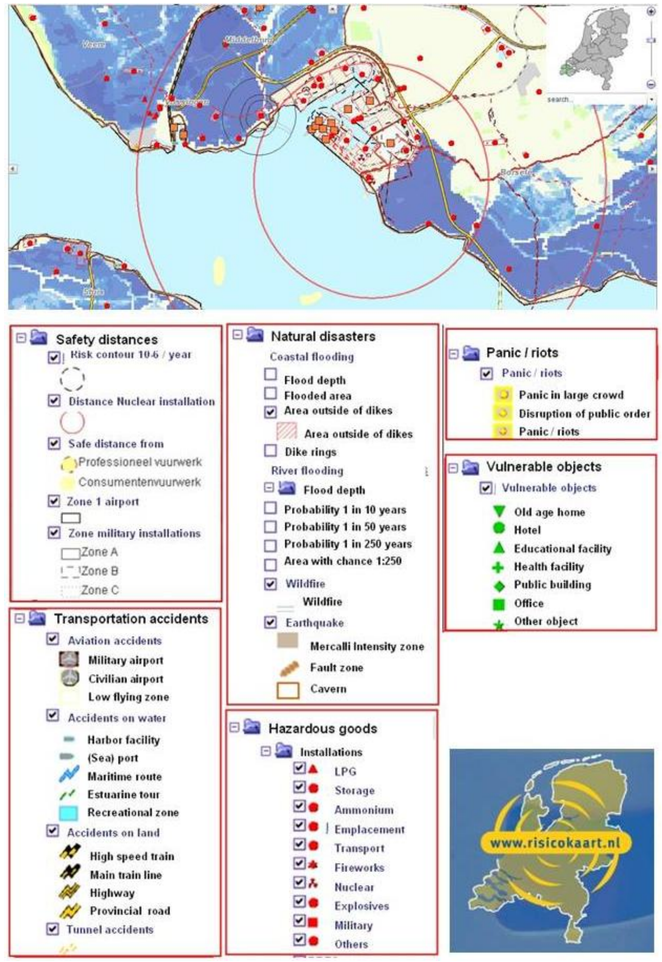


A good example of risk visualization at international level is the multi-hazard risk atlas for the Andean region (Communidad Andina, 2009) which is available both as paper atlas as well as in a Web-based version. This atlas gives a comprehensive overview of the elements-at-risk in the region (population, production, and infrastructure), the hazard phenomena (earthquakes, tsunami, volcanic eruptions, landslides, flooding, cold waves and drought) and the risks in a very well designed manner. Examples of different approaches for visualizing flood hazard and risk maps from 19 European countries, USA and Japan are presented in EXCIMAP (2007). Many countries are also developing their own Web-based risk maps. For example the CEDIM Risk Explorer Germany is a web-based map viewer that interactively presents the results of the CEDIM project "Riskmap Germany" (Müller et al., 2006). For the Netherlands a more complicated system has been developed which aims at both the general public as part of the risk communication strategy, as well as at professionals involved in risk management. National scale risk mapping in the Netherlands was carried out after the occurrence of major technical and flood disasters in the last decades. The Web-GIS application (See Figure 10) shows information on natural hazards (flooding, natural fires and earthquakes), technological hazards (transportation accidents, hazardous substances, nuclear) and vulnerable objects (Risicokaart, 2008). The flood prone areas are defined by more than 1 meter flooding depth with a frequency larger than 1/4000 per year.

6. Conclusions

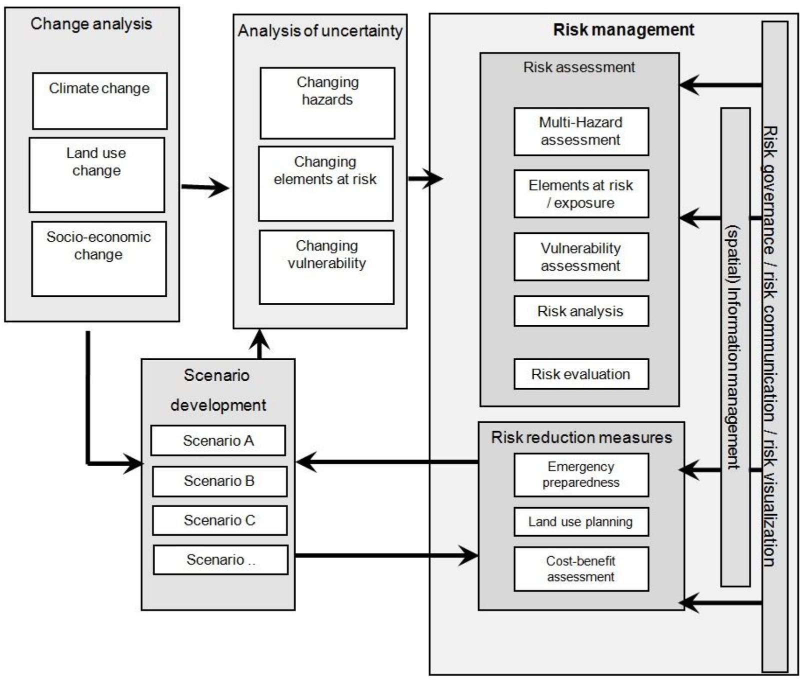
This chapter reviewed the spatial data requirements and techniques for multi-hazard risk assessment. It should be emphasized that this is not a simple task, even more so because risk is not a static aspect, but is constantly changing. This is illustrated in Figure 11. It is evident that the world undergoes rapid changes in terms of fast population growth, urbanization, economic development and socio-political structures. On top of that, there is convincing evidence that the emission of greenhouse gasses (GHSs) causes changes in the earth's climate that are expected to lead to an increase in hazardous events with a hydro-meteorological trigger (IPCC, 2007).

Figure 10: Example of the national risk atlas of the Netherlands, which is publicly available on the internet (www.risicokaart.nl)



The difficulty to predict the magnitude of these changes and the frequency of occurrence of extreme events, reiterates the need for a thorough change in our adaptation management of hydro-meteorological risks (EEA, 2004). According to recent studies at a European level the projected impact of flooding in Europe would increase dramatically in the coming decades. By 2080 it is estimated that between 250,000 and 400,000 people will be affected each year by flooding and the total annual expected flood damage is estimated to range between 7.7 and 15 billion Euros. These values are more than double of those in the period 1961-1990 (Ciscar, 2009). Very limited work has been carried out up to now to include the cascading or conjoint (also called domino) effects in the analysis of future impacts of environmental changes to hydro-meteorological hazards. The exposure of elements-at-risk also increases and therefore the risk of natural hazards is constantly growing. Land use changes will occur as a result of technological, socio-economic and political developments as well as global environmental change. The type and effects of these changes will strongly depend on policy decisions. Many environmental problems are caused by unplanned rapidly expanding urban areas. By 2050, approximately 70 % of all people will be living in urban areas, while in several countries the proportion will be 90 % or more. The global economy, cross border transport networks, large scale societal, economic and demographic changes and differences in national planning laws are some of the major drivers of change to the urban environment. As the level of uncertainty of the components used in the risk equation (hazard, vulnerability, quantification of the exposed elements-at-risk) is very high, the analysis of the changes in future risk should incorporate these uncertainties in a probabilistic manner. Impacts of natural hazards on the environment and on the society are still tackled by mono-disciplinary approaches. The focus is reflected in the domains of scientific research (single approach and tools for each type of hazard), in the existing management tools and in the legislative basis of these activities. Management tools, models, and local-to-regional technical solutions have been proposed by numerous projects for single hazards. However only a few of them have tackled the issue of risk assessment and management from a multi-hazard perspective, especially including possible combined and domino effects. Probabilistic tools for multi-hazard risk assessment are not available to stakeholders at the local level. Insurance companies and specialized risk assessment consultants have developed models but these are not open for public use. The implementation of risk management measures such as disaster preparedness programmes, land-use planning, regulatory zoning and early warning systems are considered essential. Fleischauer et al. (2006) conclude that spatial planning is only one of many aspects in risk management and that it is, in general, not properly implemented. Further, multi-risk assessment approaches are not used in planning practice: risk indicators are hardly used and vulnerability indicators are not at all used.

Figure 11: Framework of the implementation of environmental change scenarios in risk management.



Therefore approaches are needed for integrating disaster risk assessment in long term resource allocation and land use planning at all levels of administration. Additionally, scientific advances in hazard and risk assessment and demands of stakeholders/end-users are still not well connected. In many cases, the scientific outcomes remain rooted solely within the scientific community or new knowledge is not fabricated enough to be implemented by stakeholders and end-users (IRGC, 2005). A key cause of the gap between the science community and stakeholders/end-users is in the complexity of human-environment interactions. This has led to the development of a diversity of approaches, often not easy to implement by the end-user community. There is a need for the development of a harmonized decision-making structure for applying hazard and risk mitigation through spatial planning in risk prone areas. There is also a need for capacity building in the field of multi-hazard risk assessment, and the transfer of the knowledge from developed countries to developing countries using Open source software tools and methods adapted to the data availabilities in these countries (Van Westen et al., 2009). The Hyogo framework of action 2005-2015 of the UN-ISDR (indicates risk assessment and education as two of the key areas for the development of action in the coming years.

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Biography

Dr. Cees van Westen graduated in 1988 for his MSc in Physical Geography from the University of Amsterdam. He joined the Division of Applied Geomorphology of ITC in 1988, and specialized in the use of Remote Sensing and Geographic Information Systems for natural hazard and risk assessment. He obtained his PhD in Engineering Geology from the Technical University of Delft in 1993, with a research on "Geographic Information Systems for Landslide Hazard Zonation". During his work at ITC he has been working in various positions, and became associate professor in 2000. Dr. Van Westen has worked on research projects, training courses and consulting projects related to natural hazard and risk assessment in many different countries, such as Austria, Switzerland, Italy, Spain, France, Georgia, Mexico, Guatemala, El Salvador, Honduras, Costa Rica, Colombia, Peru, Bolivia, Argentina, Sri Lanka, Indonesia, Thailand, India, Nepal, China, Vietnam and Philippines. Since 2005 he is Director of the United Nations University - ITC School on Geoinformation for Disaster Risk Management.

Cees van Westen received the ITC research award in 1993 and the Richard Wolters Prize of the International Association of Engineering geology (IAEG) in 1996. He has been principal investigator in a research project called Strengthening Local Authorities in Risk Management (SLARIM) from 2000 to 2007. He is currently contributing to the research theme on Disaster Risk Management in ITC. He has been involved as co-promotor with a number of PhD researchers, on topics related with the use of spatial information for landslide hazard and risk assessment, Participatory GIS for flood risk assessment, volcanic hazard assessment, seismic hazard and risk assessment, technological risk assessment, and multi-hazard risk assessment. Most of the research is in the field of landslides, dealing with topics such as: generation of event-based landslide inventories using remote sensing (e.g. LiDAR, object oriented image classification), historical records and field mapping; combination of heuristic and statistical models for landslide susceptibility analysis; dynamic modeling of landslide initiation; landslide run out analysis, and different approaches for landslides risk assessment. PhD research has been carried out in Colombia, Cuba, Philippines, China, India, Malaysia, and Europe.

In 1997 he worked as training material coordinator on preparation of the training materials for the ILWIS (Integrated Land and Water Information System) version 2.1 , and made over 10 application case studies on the use of GIS for hazard assessment, dealing with floods, landslides, volcanic eruptions and earthquakes. From 1998 to 2000 he was Programme Director of the "Earth Resources and Environmental Geosciences" educational programme, and he has been coordinating the specialization on Natural hazards for a number of years. He has produced several training packages, on landslides (GISSIZ), hazard and risk assessment (Nepal, Central America) and Multi-hazard risk assessment. The latter one has been developed into a distance education course using the RiskCity training package. He has been active in the development of joint educational programmes with IIRS (India), UGM (Indonesia), ICIMOD (Nepal), ADPC (Thailand), CLAS-UMSS (Bolivia) and UNAM-CIGA (Mexico), and CDUT (China). He is also a member of the UN-SPIDER Capacity Building Working Group.

He has been involved in many projects funded by the EU (FP6, FP7), World Bank, ADB, Dutch government, US-AID. He is currently project coordinator of the CHANGES project, an EU FP7 Marie Curie International Training Network.