Guide book
Session 3:
Hazard Assessment

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Objectives
After this session you should be able to:
- understand the general concept of Hazard
- identify spatial/temporal characteristics and triggering phenomena for each hazard type
- understand the concept of occurrence probability and perform frequency assessment based on historical data using statistical methods
- select the most suitable hazard assessment method considering the hazard type, scale, data availability
- carry out a complete hazard assessment study

This chapter of the guide book is organized as follows:
- 3.1 Introduction: this section refers to the general concept of hazard and hazard assessment. Basic definitions will be provided for general concepts like hazard and hazard assessment. Hazard characteristics will be defined and discussed. Different hazard types will be briefly described.
- 3.2 Climate change and hazards: the main impacts of climate change scenarios on natural hazard will be described in this section.
- 3.3 Frequency analysis: in this section, the basic knowledge related to the estimation of the occurrence probability for different hazard types will be explained.
- 3.L–3.C Choice topics: after a general overview of Hazard assessment, the main hazard types will be extensively described. The student will select the hazards according to his/her interest.

Material	Task	Required time
Introductory part of this guidance note on different hazards and their assessment methods	Small tasks and assignments included in the guidance notes	1h
Choice topic: selection of a specific hazard type	- RiskCity: Flood hazard assessment - RiskCity: Earthquake hazard assessment - RiskCity: Landslide hazard assessment - RiskCity: Technological hazard assessment - RiskCity: Volcanic hazard assessment - RiskCity: Coastal hazard assessment	2 to 3h
Exercise based on choice topic	Exercise on hazard assessment related to the choice topic	h

3.1 Introduction to Hazard Assessment

We live in an environment that exposes us continuously to hazards, hazards that we somehow have to deal with. Some of these hazards are within our own realm of influence, like participating in traffic, or catching the flu. Other hazards are so extreme that we hardly consider them in everyday live, like a large asteroid impacting on Earth. In fact the whole field of hazards is so large that no introduction text is capable of covering it completely. Many attempts have been made to categorize hazards, like Smith (1991) who identifies three distinct classes:

Natural Hazards (extreme geophysical and biological events)		
	Geologic	Earthquakes, volcanic eruptions, landslides, avalanches
	Atmospheric	Cyclones, tornadoes, hail, ice and snow
	Hydrologic	River floods, coastal floods, drought
	Biologic	Epidemic diseases, wildfires
Technological Hazards (major accidents)		
	Transport accidents	Air crashes, train crashes, ship wrecks
	Industrial failures	Explosions and fires, release of toxic or radioactive materials
	Unsafe public buildings and facilities	Structural collapse, fire
	Hazardous materials	Storage, transport, miss-use
Context hazards (global change)		
	Climate change	Sea-level rise, frequency change of extreme events
	Environmental degradation	Deforestation, desertification, loss of natural resources
	Land pressure	Intensive urbanization, concentration of essential facilities
	Super hazards	Catastrophic Earth changes, impact of near-Earth objects

Table 3.1.1 Classification of hazards (Smith 1991).

However, no unambiguous classification system has been constructed yet. Take for instance landslides, in the classification of Smith (table 3.1.1) they fall in the category of geologic hazards, but one may argue that they should be classified as hydrological, because the trigger is often related to rain. On the other hand, landslides may also be triggered by earthquakes, or by human activities ……

In the context of this course we will limit ourselves to those hazards that are a consequence of geological and geomorphological processes (earthquakes, volcanic eruptions, landslides and floods). We will call these Geo-Hazards from now on although it should be realized that human activities often have a great impact on the occurrence of these events. Another limitation is that in this course we disregard the slow hazards, such as erosion, drought, desertification, sea-level rise, etc.

3.1.1. Definition of Hazard

The word hazard is a normal English word that is used frequently in daily speech. This may cause confusion because the scientific definition differs from the 'intuitive' common meaning. Webster's dictionary of the English language (edition 1990) defines hazard as: "*a risk or associated with danger*"*. As a verb it is defined as: "1) to place (something) in a dangerous or risky situation wittingly or unwittingly; 2) to attempt (an answer, guess, etc.)*". On Wikipedia we find the following entry (9 Febr. 2009): "*A hazard is a situation which poses a level of threat to life, health, property or environment. Most hazards are dormant or potential, with only a theoretical risk of harm, however, once a hazard becomes 'active', it can create an emergency situation*".

But also in scientific literature it has been used imprecisely and with different implicit meanings. For the study of hazards, a more restricted definition is required. In literature and on the internet you'll find many definitions that are similar but not exactly the same (feel free to check this). In this course we will use the definition of hazard as proposed by the UN-ISDR (2004):

> **Definition:** "A hazard is 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."

Especially the last sentence makes this definition workable; it contains four important elements:

1) Hazard is expressed as a probability; the likelihood that something may happen in the future. When, where and how much is not sure, but it is possible to identify areas where a hazard is more likely to occur than in other areas.

2) The hazard probability is restricted to a specified period of time; usually a year. The annual probability is the likelihood that an event will happen in the next year. Without this restriction, the probability expression would be useless. The likelihood that a floodplain will be flooded is 100%, but it could take a 1000 years before it actually happens. It is more relevant to know what the probability is that it is flooded in the coming year, or the year after, …

3) It is valid for a specified area; Earthquakes happen near fault zones, floods on floodplains, landslides on slopes. The site specific characteristics co-define the hazard conditions.

4) The intensity – or magnitude – of the event. To be capable of causing loss of life or damage, the event must be of a certain intensity or magnitude. The intensity may be expressed as the energy released by an earthquake or volcanic eruption, the volume of water during a flood or the size and speed of a landslide. It is clear that the more energy or momentum released by the event, the more damaging potential it has. A mass movement of a few kilograms may cause no problems (unless it is a rock falling on someone's head), but a mud flow of several thousand cubic meters can be quite devastating.

Another aspect of this definition that should be noted is the condition that it may cause damage or loss of life. Of course we study hazards because they may have negative effects on things that we care about, but in principle the concept of hazard is value-free. Risk on the other hand is the potential for disaster. It includes the characteristics of the receiving community; its vulnerability and the value of the exposed elements (see also chapter 4). One should understand that the terms hazard and risk are often mixed, also because hazard assessment is always done from an anthropocentric viewpoint; we do hazard assessment because they may have consequences for "our" society. In this respect one can say that a disaster is the materialization of "high risk". However, high hazard does not necessarily result in damage or loss of life. The flood hazard in Northern Siberia is very high because every year large parts are inundated in spring as result of the melting of snow and frozen rivers. The fact that there is nothing (or at least very little) to be damaged does not diminish the hazard. The risk however, is very low. Hazard is likelihood, no more, no less, something that may happen in the future.

Definition:
"The hazard related study is named ***Hazard Assessment*** *and it involves the analysis of the physical aspects of the phenomena through the collection of historic records, the interpretation of topographical, geological, hydrological information to provide the estimation of the temporal and spatial probability of occurrence and the magnitude of the hazardous event.*

3.1.2. On the origin of hazards

Hazards do not arise spontaneously. They are the results of continuous processes that we do not always notice (e.g. tectonic movements) or, when we do notice them, we consider them as "normal", such as river flow. As long as these processes operate within a certain band-width, they are not considered as a hazard. Only when the deviation from the mean exceeds some critical threshold beyond the normal band of tolerance, the variable becomes a hazard (Smith (1991). This is illustrated in figure 3.1.1 with annual rainfall. There is a fluctuation around a mean value. As long as the fluctuations are within an acceptable range, the rain is a useful resource. When a disruption threshold is exceeded, and there is too much or too little rain, negative side effects will occur. Notice that at this point the anthropocentric viewpoint enters the equation. Lack of rain will decrease agricultural productivity and will increase costs because crops must be irrigated. Too much rain will swamp farm lands and may cause rivers to flood. When a coping threshold is exceeded, it means that the deviation has become an extreme to such an extend that the local communities cannot deal with the hazard anymore and/or recover from it with their own means. Floods and drought are the results.

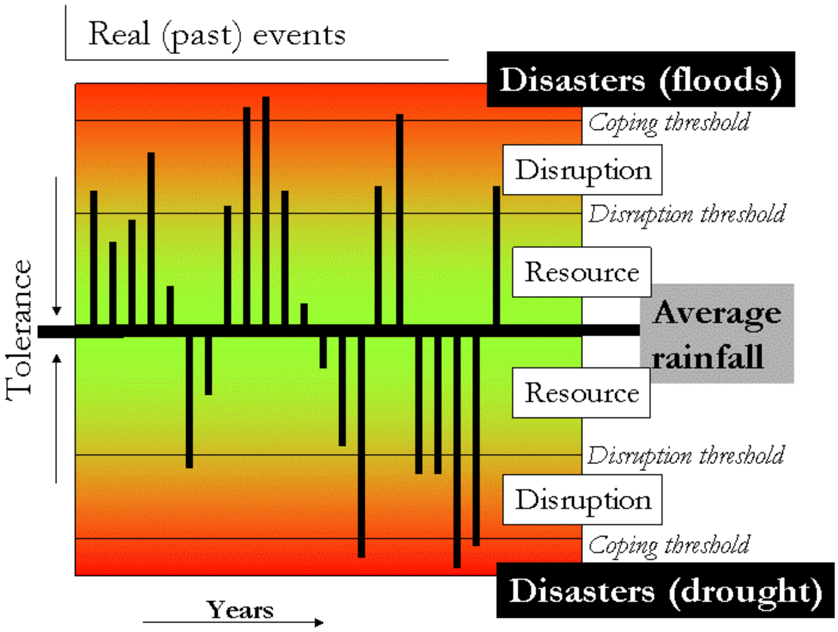


Figure 3.1.1 Example of the possible consequences of deviations from the mean annual precipitation. As long as the deviations are below a given disruption threshold, the precipitation is a resource. Above (or below) the disruption threshold negative consequences due too much or too little rain are being felt. Above or below a coping threshold the deviation has consequences beyond the coping capacity of the affected communities.

In the case of landslides the underlying processes are related to the dynamics of slopes. Gravity exerts a continuous force upon the slope material. This strain is balanced by the strength of the slope material. However the strength is not a constant but depends for instance on soil water content and ground water levels. Also weathering processes change the characteristics of the slope materials. This is illustrated in figure 3.1.2. These processes are less visible than rivers, but they are continuously active nevertheless.

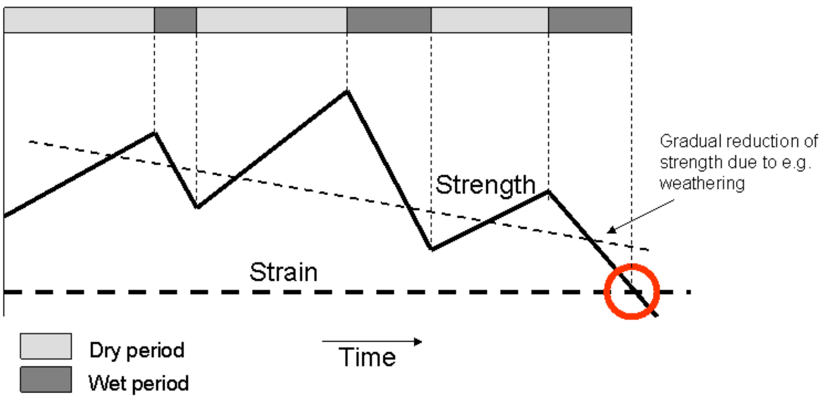


Figure 3.1.2 The bold line indicates the fluctuations in soil strength. The fluctuations are due to (season related) changes in soil moisture content and ground water levels. The strain is the continuous (and constant) force exerted on the slope by gravity. The dotted decreasing line illustrates the gradual reduction of strength due to e.g. weathering processes. When the strength becomes less than the strain, slope instability occurs.

The same holds for earthquakes and volcanoes. They are the manifestation of tectonic plate movements driven by convective currents in the upper mantel of the Earth. Along the plate boundaries this movement is not continuous, but results in the build up of strain. When the strain exceeds the friction strength a rapid and sudden movement occurs that we notice as an earthquake along a fault line. The more strain is build-up the larger the amount of energy that is released during the movement.

3.1.3. Hazard characteristics

The term hazard include a wide variety of phenomena, ranging from local events like tornadoes to events at continental scale like climate change, or from very fast phenomena like lightening to very slow events as desertification. In order to describe the different hazard types, six main characteristics can be defined.

- Triggering factors
- Spatial occurrence
- Duration of the event
- Time of onset
- Frequency
- Magnitude
- Secondary events

In the following section, each of the six characteristics will be introduced and briefly described. The aim is to homogeneously characterize the different hazards in order to compare them among each others.

- **Triggering factors**

Natural causes of hazards can be divided into two main groups: exogenic and endogenic factors. The first class contains all the triggering processes that occur on the Earth's surface. Exogenic factors are mainly related to atmospheric conditions like precipitation, wind, temperature and other atmospheric parameters that can trigger natural hazards like landslides, rivers and coastal floods, and land degradation. Atmospheric phenomena have been widely studied in the last decades and many progresses in forecasts have been achieved; nowadays different techniques of weather forecasting are available. Over the last decades, climate related phenomena have been widely studied and much progress was achieved in forecasting the hazards; nowadays different techniques of weather forecasting are available. A good example is the deterministic medium range forecast information and probabilistic weather forecast techniques based on Ensemble Prediction System (EPS) that allows weather forecasts up to 8-10 days (Demeritt et al., 2007; Persson and Grazzini, 2007). But even considering the new tools available, the forecasting issue is still affected by main uncertainties due to the complexity of the phenomena involved. Forecast information can be gathered through providers' websites like the World Meteorological Organization (WMO, http://www.wmo.int/pages/index_en.html) or the European Centre of Medium-range Weather Forecasts (ECMWF, http://www.ecmwf.int/). Real-time data regarding precipitation, hurricanes, typhoons, are provided by space borne sensors' websites; a useful example is the Tropical Rainfall Monitoring Mission (TRMM http://trmm.gsfc.nasa.gov/). In the case of earthquakes, the triggering factors are unlikely to be predicted with the same accuracy and temporal resolution of the weather-related causes previously described.

Task 3.1.1: Weather forecast information for hazard assessment (10-15 minutes).

- *Explore the meteorological Service of your own country (go to WMO website and enter the "National Meteorological Centers" page. Are precipitation forecasts available for your country? If not, where do you think you can find such data?*
- *From the TRMM homepage, chose "global floods and landslides monitoring" and then "heavy rain areas". Did extreme precipitation events affect your country during the last 24 hours?*
- *Go to "Meteoalarm" page (from WMO homepage) and identify which is the European country (and its regions) that will be mostly affected by rainfall and coastal storms in the coming 2 days.*

Fig. 3.1.3: Chernobyl nuclear power plant after the explosion.

The second group of natural triggers is represented by the endogenic factors that take place below the Earth's surface. Let's consider for instance earthquakes; they are triggered by the accumulation of enormous quantities of energy during tectonic displacements: the convective movements in the liquid part of the mantle apply massive forces to the tectonic plaques that, after certain thresholds, release the accumulated stress in the form of sudden fractures in rock bodies. The waves travel through the crust and produce earthquakes when they reach the surface. Such triggering factors are unlikely to be predicted with the same accuracy and temporal resolution of the weather-related causes previously described. The result of this difference in monitoring the triggering factors is that the natural hazards caused by exogenic factors have more probability to be predicted than earthquakes. Other examples of hazards triggered by endogenic factors are volcanoes and tsunamis.

Next to the natural causes, hazards can be directly caused by malfunctioning or accidents due to human activities. Man–induced hazards can have local effect but may also have widespread consequences Probably the best known example of a man-made disaster that had widespread consequences is the explosion at the reactor number 4 in Chernobyl's nuclear power plant on the 26th of April 1986 (see figure 3.1.3). Man-induced hazards are unpredictable, can cause property damage and loss of life, and can significantly affect infrastructure in many areas worldwide. FEMA (U.S. Federal Emergency Management Agency) classifies such events under the general definition of Technological Hazards.

The boundary between natural and man-induced hazards is far from clearly defined. A landslide can be triggered by heavy rainfall but deforestation or road construction may also have played a role. Landuse changes can affect areas by increasing the occurrence of erosion phenomena. River dams' constructions can lead to inundations during periods of extreme discharges or due to dam failures. The identification of the triggering factors is one of the first steps in hazard assessment.

- **Spatial occurrence**

In understanding the various dynamics related to natural/man induced hazards, spatial characteristics of single events play a very important role.

Definition: *Spatial occurrence related to hazards has a double meaning: on one hand it refers to the* ***location*** *of the area affected by a certain hazard type, thus the characteristics of such zone and the presence of triggering factors; on the other hand it refers to the* ***dimension*** *of the affected area.*

One of the main targets of hazard assessment activities is to identify which areas are more prone to hazard events considering topographical, geological, hydrological, climatic characteristics. Hazards don't occur in random areas, but they often follow defined patterns identified by the presence of certain characteristics. Landslides can occur only in areas with sufficient slope gradients, but not all the slopes are prone to landslides; activity of previous mass movements in an area in combination with additional stability-affecting conditions (landcover-landuse, internal and external drainage system, precipitation rates) may be used to forecast the occurrence of future landslides in that area. This basic concept is illustrated in figure 3.1.4-1; it represents the earthquakes location in South America during the last decade of the XX century. The observed seismic events occur mainly along the Andes Range, at the oceanic ridge between Nazca Plate and Antarctic plate (Pacific Ocean), and at the ridge location between South American plate and African plate (Atlantic Ocean, northern part). After having observed this map, even without further knowledge on seismic hazard assessment will recognize the seismic hazard map shown in figure 3.1.4-2. This map shows the peak ground acceleration with a 10% chance of exceedance in 50 years; at each location, the map indicates the expected magnitude of seismic activity which has the 10% of probability to be exceeded in 50 years. As is clear from the comparison between the two maps, the red zone in map 2 (high hazard area) represents the area in which the epicenters of earthquakes are located in map one.

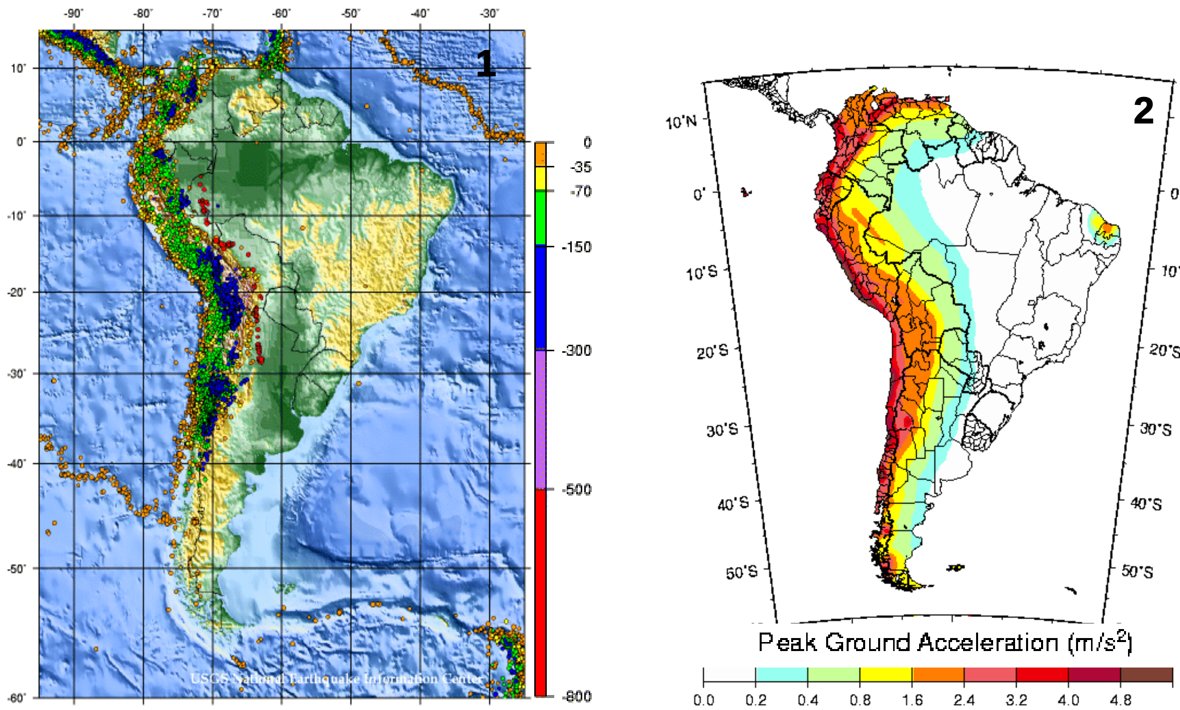


Fig. 3.1.4: 1) Seismicity map of South America (1990-2000); the legend refers to the sources' depth in Km.
2) Seismic hazard map of South America. PGA with a 10% chance of exceedance in 50 years is depicted in m/s^2. Source: USGS-NEIC Earthquakes hazard program.

Key concept: *In hazard assessment, the hazard events occurred in the past represent an important key to understand and predict the future spatial occurrence of such hazards.*

Regarding the dimension of the hazardous phenomena, single events can affect specific areas (**concentrated** events), examples are flash floods, small landslides, or lightening; they affect limited areas. Other phenomena can occur at regional or continental scale (**diffuse** events), for instance, desertification, el Niño, and climate change related phenomena. The areal extension of the hazardous event is a key point in order to choose the appropriate mapping and analysis tools. As already discussed in section 2, awareness of the spatial characteristics of the hazard will help to select the tools. Single landslides can have dimensions varying from few cubic meters up to millions cubic meters; flood events can be small and affect a small village crossed by a seasonal stream in a mountainous area or a wide floodplain area covering many square kilometers. But the areal extension of such hazards is not comparable to the extension of events related to continental or global scale. Figure 3.1.5 shows the spatial and temporal distribution of the main natural and man-induced hazards. The X axis refers to the spatial extension of the single hazards according to the observation scale. This classification represents just a simplification; the areal dimension can widely vary among the same hazard type: if we consider technological hazard, it is referred to the city (large) scale, considering events like the explosion of a gasoline tank. At the same time, the extraordinary Chernobyl reactor explosion described in the previous section belongs to the same category and it had effects at continental scale. Once again, the analysis and the mapping tools have to be appropriate to the hazard's dimension; at the same time the observation scale can depend on the nature of the hazard and on the purpose of the hazard study; a site scale landslides hazard study can't be used by decision-makers in order to plan funding for national activities; on the other hand, a pan-American landslide susceptibility map can't support an urban planning project at municipality level.

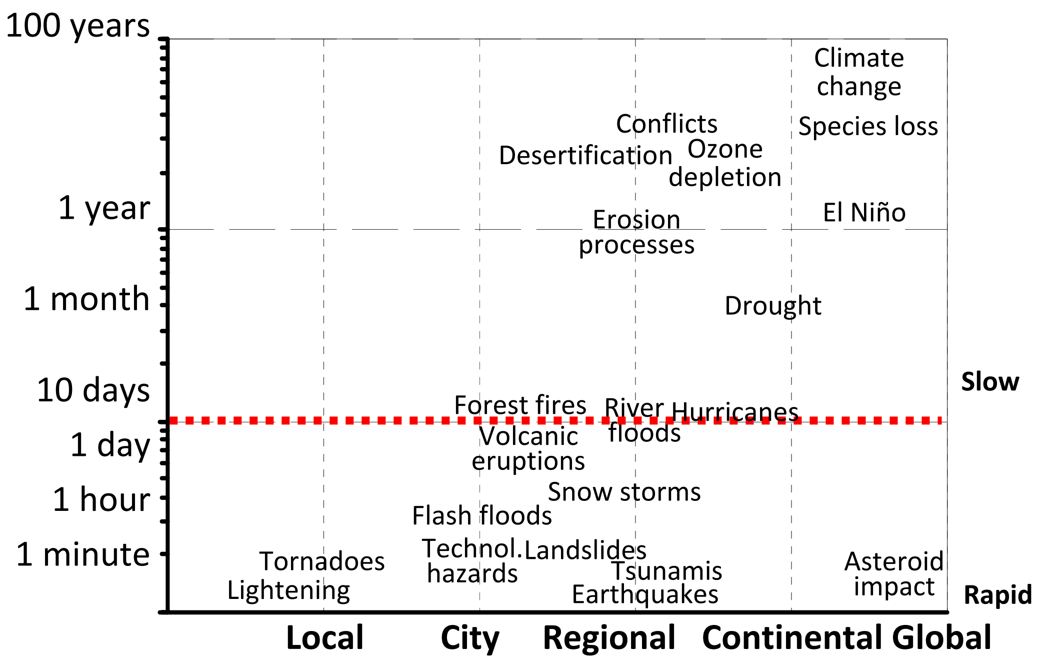


Fig 3.1.5: Spatial and temporal distribution of the major natural and human-induced major hazardous events (the red line represents the boundary between fast and slow processes, with the threshold set on 10 days).

Definition: Scales of Hazard maps

– *Investigation site scale: 1:200 – 1:2.000 hazard maps accurately describe hazards in areas where detailed designs of engineering works have to be planned.*
– *Large/local scale: 1:2.000 – 1:25.000 representing the hazard assessment for a town or part of a city; they represent basis for quantitative risk assessment, disaster prevention plans, and for preliminary phase of engineering designs.*
– *Medium scale: 1:25.000 – 1:100.000 including entire municipalities or small catchments, such hazard maps are used as basis for projects regarding urban planning or environmental impact at municipality level.*
– *Regional scale: 1:100.000 – 1:500.000 Hazard maps regard large catchment areas, or political entities of the country like regions or federal districts. Such maps aim at providing support for: planning projects for construction of infrastructural works, agricultural development projects, decision – making at regional scale.*
– *National–Continental scale: less than 1:1.000.000 including entire countries or even continents; hazard maps at this scale intend to generate awareness among decision makers and the general public. They are created using qualitative assessment techniques, such as the use of general indices or the use of susceptibility scales.*

A good example of hazard assessments at different scales is represented by the following two maps. They both represent flood hazard assessment studies carried out by applying flooding simulation tools. In figure 3.1.6, a subset of the official flood hazard map provided by Federal Emergency Management Agency (http://www.fema.gov/) of the US government is shown. The map represents a flood event with a return period of 100 years for the section of Santa Clara River in the North area of Los Angeles City, California. The map is part of the project Flood Insurance Rate Maps (http://www.fema.gov/media/fhm/firm/ot_firm.htm, FEMA-FIRM). The main aim of this project is to provide useful information for floodplain management, regulation, and insurance at administrative level. In details it is used to assess whether or not single buildings need insurance assistance, and if it is the case with which risk level they have to be insured. The flooded area is represented at investigation site scale (1:2000). If you want to learn more about FEMA-FIRM, explore its online tutorial (http://www.fema.gov/media/fhm/firm/ot_firm.htm).

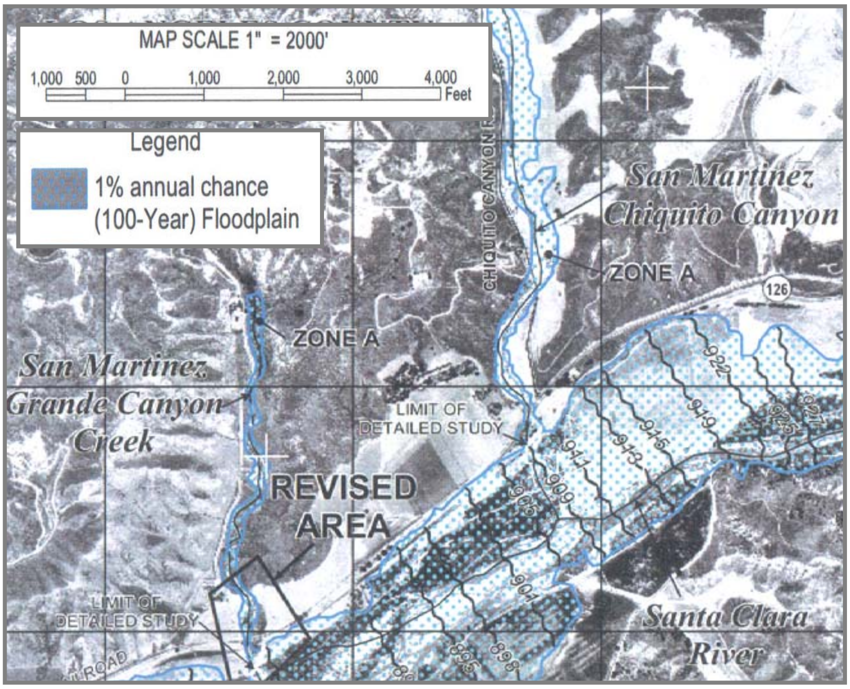


Fig. 3.1.6: Flood hazard map regarding an event with occurrence probability of 1 into 100 years for the Northern part of the city of Los Angeles (1% annual chance). The map is provided by the Federal Emergency Management Agency (FEMA) within the project called Flood Insurance rate maps (FIRM). The flood hazard map is calculated by simulating the 100 years return period flood event through a detailed two dimensional flood propagation model. The scale allows the map to be used in flood hazard assessment for insurance companies.

Figure 3.1.7 represents the flood hazard map based on a 100 years return period flood event calculated at pan-European scale (less than 1:1000.000) by the Natural Hazard

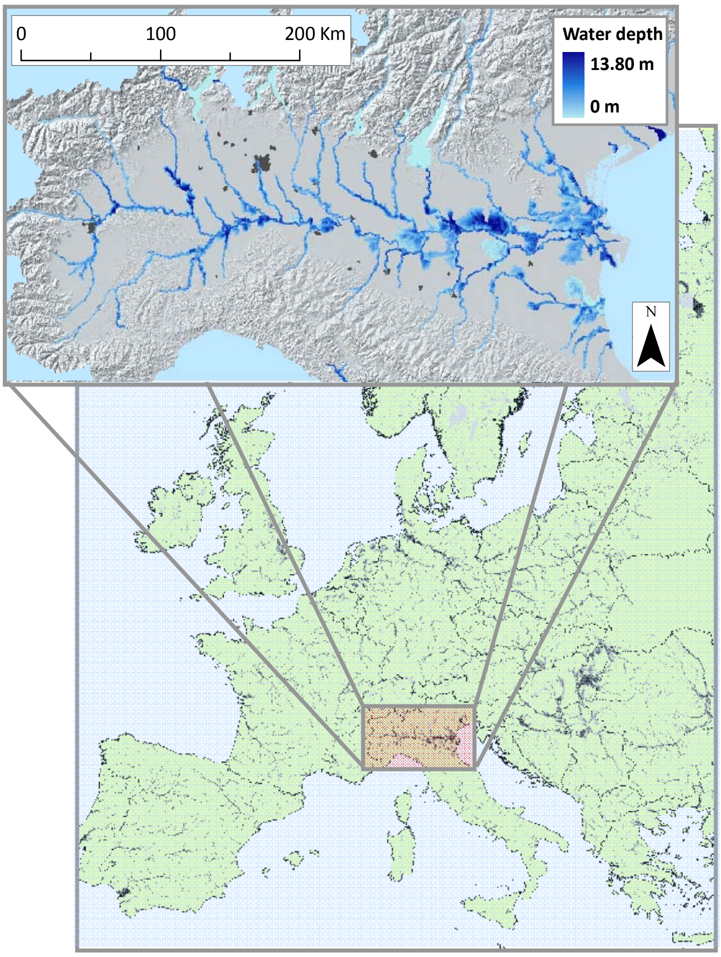


Fig. 3.1.7: Pan-European hazard map calculated on the basis of EFAS (European Flood Alert System). The map represents water extent and depth for a general 100 years return period flood event.

Action of the Institute for Environment and Sustainability (IES, Join Research Centre, http://ies.jrc.ec.europa.eu/). This high research institute was created by the European Community (EU) in order to promote the scientific research on natural hazards management at an European level. The map was calculated by applying the flood simulation model used in the European Flood Alert System (EFAS, http://efas.jrc.ec.europa.eu/). EFAS is a project at a pan-European scale that aims at providing forecast information three to ten days in advance. EFAS is based on the one dimensional (1D) LISFLOOD distributed hydrologic model (Van Der Knijff and De Roo, 2008) driven by harmonized data regarding soil, topography, landcover, and by real-time weather forecasts from the European Centre for Medium-range Weather Forecasts (EMCWF) and from the Deutche Wetterdienst (DWD German Weather Forecasts Centre http://www.dwd.de/). The LISFLOOD model provided the discharges for a flood event with a probability of 1 in 100 years. The discharges were transformed into water levels and the flood extent and depth were extrapolated through a GIS technique based on the intersection of the flood wave, considered as a plane, and a 100m resolution Digital Elevation Model (Bates and De Roo, 2000). The resulting hazard map at pan-European level is the basis for further studies and assessments at continental level. LISFLOOD was run on the basis of different climate change future scenarios from the HIRHAM model to assess the impact of climate change on flood hazard in Europe (Dankers and Feyen, 2008).The availability of a pan-European flood hazard map suggested more advanced applications; the EFAS team developed a methodology to carry out from the flood extent and depth map, the potential damage assessment based on stage damage functions (http://natural-hazards.jrc.ec.europa.eu/downloads/public/2008map_Barredo_et_al_MAP_Flood_damage_potentia.pdf). It is clear form the two examples described above that the analysis scale has to be chosen in relation to the hazard type and to the purpose of the study. The first example aims at providing information to single house owners or local organizations, while the second one targets to support other authorities and organizations in decision-making at Continental or National level.

- **Duration of the event**

Definition: *The duration of a hazardous event refers to the time span in which such event takes place. To quantify the duration, the starting and the ending points have to be defined.*

Fig. 3.1.8: Lightening during a storm in Oklahoma City, U.S.A. an example of a fast process.

Fig. 3.1.9: sand dunes advancing on Nouakchott, the capital of Mauritania; an example of a slow process.

For sudden phenomena like earthquakes or landslides it is easy to define the beginning and the ending points; but for other gradual events this is more complex. An appropriate example is represented by river floods: high discharge conditions periodically alternate with normal or low discharge periods. When does the high discharge phase become a flood? When does it end? Usually, when the water level exceeds the bankfull conditions the high discharge condition turns into a river flood hazard (see flood hazard section 3.F for more explanations). For gradual processes like desertification or erosion the determination of the duration is even more difficult. Concerning the duration, natural and man-induced hazards can be classified into two main categories: fast and slow processes. In the first class, hazards like tornadoes, earthquakes, and tsunamis are included; such events happen in a very short lapse of time, from few seconds, in the case of lightning (see figure 3.1.8), up to few days like volcanoes eruptions. Moreover, their sudden nature makes them being perceived as dangerous situations by the majority of the people. On the other hand, slow processes have a duration ranging from months, for instance desertification (see figure 3.1.9) and erosion, to hundreds years in the case of temperature rise or greenhouse gases' increase caused by climate change. Due to their extremely wide temporal extension and their gradual development, they are perceived in many cases only as gradually degrading situations. In figure 3.1.5, the Y axis represents the duration of the event; the red bar indicates the arbitrary boundary between the slow and rapid processes.

However, duration and dimension can widely vary within the same hazard class: volcanic eruptions, for instance, are considered in the graphic as fast events. Plinian eruptions occur in volcanoes with acid lava (more viscous), they are the most powerful and they involve huge explosions; such kind of eruption can be considered as a fast event: examples are Vesuvius (Italy, 79 AD), Mount St. Helen (USA, 18th May 1980), Pinatubo (Philippines 15th June 1991, http://www.youtube.com/watch?v=Lf1PWap_GTw). On the other hand volcanic eruptions on Etna Mountain in Italy are slow and less destructive events, due to the high fluidity of its basic lava; the volcano has picks of activity where huge and slowly moving lava flows can erupt for various months (Etna's eruption in 2008, it is the most recent event of three years of continuous activity from 2006 to 2008 http://www.youtube.com/watch?v=j4lkyyD4Vmk&feature=related,). According to the scale in the graph, such eruptions can be classified as slow processes.

This example states that the duration of a hazard type has a wide range of variety. Each event has a series of characteristics that often significantly differ from other events of the same type.

- **Time of onset**

Before a hazard occurs, some foregoing events can anticipate the main phenomenon. These events are defined as **precursors**. Depending on the hazard type, such "signs" can occur days, hours, or seconds before or there cannot be at all. In order to better explain the concept, few examples will be shown.

Landslides and mass movements are hazardous phenomena that can be triggered by various causes like heavy rainfalls, earthquakes, soil weathering, increase of superficial load due to snow, etc. Areas prone to landslides can show forewarning features that "announce" the occurrence of such events. Especially after heavy rainfalls, in hazardous areas, new cracks can suddenly open; springs and/or saturated ground can appear in slope areas not typically been wet before; the water level in creeks can unexpectedly increase, or can suddenly decrease even during rainfall. Such phenomena are typical precursors of landslides (see figure 3.1.10). To explore more signs that can predict the occurrence of a landslide, check the USGS website: http://landslides.usgs.gov/learning/prepare/.

Fig. 3.1.10: precursors of landslides. Image 1: multiple crack array in the area of Upper Killha, Azad Kashmir; failure of these slopes in the forthcoming monsoon looks to be very probable. Image 2: springs on a slope after heavy rainfalls.

Floods are mostly caused by heavy and/or persistent precipitations. Rainfall can be considered flood triggering factors and a precursor of flood hazards as well; because when heavy rainfall is observed in a flood prone area, it is likely to expect a flood event in a short period of time. There is a delay between the occurrence of rainfall and the flood wave arrival. It depends on the morphologic characteristics and on the landuse of the entire catchment. Figure 3.1.11 represents a graph showing the temporal relation between discharge rate and rainfall in a monsoonal area. In the graph, two flood events are recorded: the first at the 11th day, and the second, smaller than the previous, at the 29th day; they are caused mainly by the rain fallen in the 8th day, and in the 21st day. Once the concept of precursor is clear we can define the time of onset as follows.

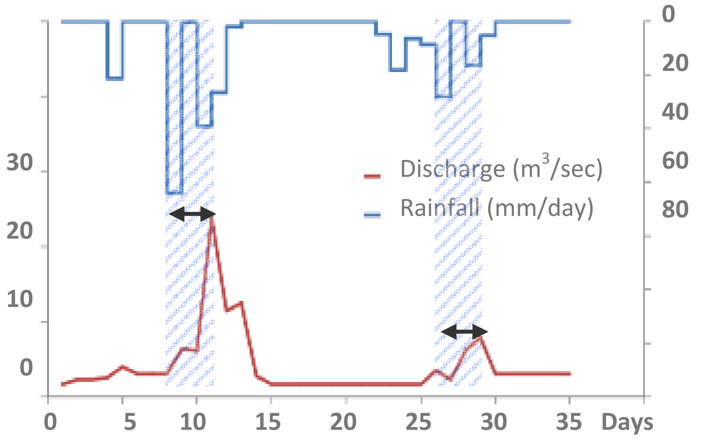


Fig. 3.1.11: A Discharge-Rainfall relation graph: the area with blue stripes and the two arrows show the time lapse between the precursor (rainfall) and the hazard pick (flood max discharge).

Definition: *The time of onset is the lapse of time from the occurrence of the first precursor to the intensity peak of the hazardous event.*

In the last example, time of onset is represented by the delay between the rainfall and the discharge peak (area with blue stripes in figure 3.1.11). The time of onset can be very short or even null like in the case of earthquakes.

- **Magnitude / Intensity**

In general, a hazard is a phenomenon that, for its intensity, represents an exceptional and harmful condition. Rainfalls and storms are common atmospheric events that occur everywhere; but if those phenomena exceed certain thresholds of intensity they become hazardous hurricanes, or they trigger floods, landslides etc. The same concept is valid for other natural hazards: every year, more than ten thousands earthquakes are recorded by seismic stations worldwide. Out of them, the hazardous events are very few in number. What does transform a normal event into a hazard? A natural event becomes a hazard when it exceeds certain common magnitude or intensity thresholds. In hazard assessment, magnitude and intensity have different meanings:

Definitions:

– ***Magnitude*** *is related to the amount of energy released during the hazardous event, or refers to the size of the hazard. Magnitude is indicated using a scale, consisting of classes, related to a (logarithmic) increase of energy.*

– ***Intensity*** *is used to refer to the damage caused by the event. It is normally indicated by scales, consisting of classes, with arbitrarily defined thresholds, depending on the amount of damage observed.*

Richter	Mercalli	Damages according to Mercalli's scale
1.0-3.0	I	**I**: Not felt except by a very few under especially favorable conditions.
3.0-3.9	II-III	**II**: Felt only by a few persons at rest, especially on upper floors of buildings. **III**: Felt by few persons indoors. Many people don't recognize it as earthquake.
4.0–4.9	IV-V	**IV**: Felt indoors by many, outdoors by few. Sensation like heavy truck striking building. **V**: Felt by nearly everyone; windows broken. Unstable objects overturned. Pendulum clocks may stop.
5.0–5.9	VI-VII	**VI**: Felt by all, many frightened. Some heavy furniture moved. Damage slight. **VII**: Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in badly designed structures.
6.0–6.9	VII-IX	**VIII**: Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. **IX**: Damage considerable in specially designed structures; Damage great in substantial buildings, with partial collapse.
7 more	X-XII	**X**: Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. **XI**: Few, if any structures remain standing. Bridges destroyed. Rails bent greatly. **XII**: Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Table 3.1.2: Relations between Magnitude (Richter) and Intensity (Mercalli) scales for earthquakes.

An example is represented by earthquakes. They can be classified into magnitude or intensity scales depending on the purpose of the study. The Richter magnitude scale expresses the amount of seismic energy released by an earthquake. It is a base-10 logarithmic scale obtained by calculating the logarithm of the amplitude of seismic waves recorded by a Wood–Anderson torsion seismometer. Richter Magnitude scale goes from 0 to 10 (even if a magnitude 10 was never recorded). Mercalli Intensity scale measures the damages produced by an earthquake on the Earth surface to human beings, and man-made structures; it was estimated using historic damage records and personal experiences from individuals involved in earthquakes. It ranges from level I to level XII; for each level the damages to buildings bridges, roads, and the impact on human beings are described.

A magnitude scale measures the absolute dimension of a seismic event in terms of energy involved; an intensity scale measures the effects of an event related to the presence of damageable assets or human beings in the area: an earthquake of magnitude 9 in an uninhabited areas has intensity 0.

Other natural hazards are described through magnitude or intensity scales: hurricanes, tornadoes, and tsunamis. For further readings on the topics above mentioned the following websites are suggested.

Task 3.1.2: Magnitude / Intensity scales (5-10 Min)

Search on the web examples for Magnitude/Intensity scales for at least one other hazard type among the ones listed below, or chose a hazard outside the list according to your interest. We suggest considering the following websites:

- *Earthquakes: http://pubs.usgs.gov/gip/earthq4/severitygip.html.*
- *Hurricanes: http://www.weather.com/encyclopedia/charts/tropical/saffirscale.html; http://powerboat.about.com/od/weatherandtides/tp/Saffir-SimpsonScale.htm.*
- *Tornadoes: http://library.thinkquest.org/16132/html/tornadoinfo/types.html.*
- *Tsunamies: http://geology.about.com/library/bl/bltsunamiscalenew.htm; http://www.riskfrontiers.com/scales/scalespage16.htm.*

- **Frequency**

While studying geo-hazards, the most important aspects are spatial and temporal characteristics of the events. As described before, the word spatial has a dualistic meaning: the identification of the location, and the evaluation of the dimension of the affected area. On the other hand, temporal characteristics refer to different aspects of the phenomena; we have already discussed about the duration and the time of onset of different hazards. Another temporal characteristic of a hazardous event is the frequency of occurrence.

Definitions:

- ***"Frequency is:*** *the rate of occurrence of anything; the relationship between incidence and time period; the number of occurrences within a certain period of time; the property of occurring often rather than infrequently; the quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: f = n / t" (from different sources in the web).*
- ***Related to geo- hazards, Frequency is:*** *the (temporal) probability that a hazardous event with a given magnitude occurs in a certain area in a given period of time (years, decades, centuries etc.).*

In hazard assessment, frequency is a key point to study the occurrence probability of hazardous events in the future. The analysis of historical records and their frequency allows scientists to understand when a certain hazard with a certain magnitude is likely to occur in a given area. In most of the cases there is a fixed relation between magnitude and frequency for natural events (see figure 3.1.12). The frequency of events with a low magnitude is high, while the frequency of events with great magnitude is low: i.e. small flood events occur every year while enormous and devastating inundations are likely to happen once every one or more centuries. Table 3.1.3 shows the number of

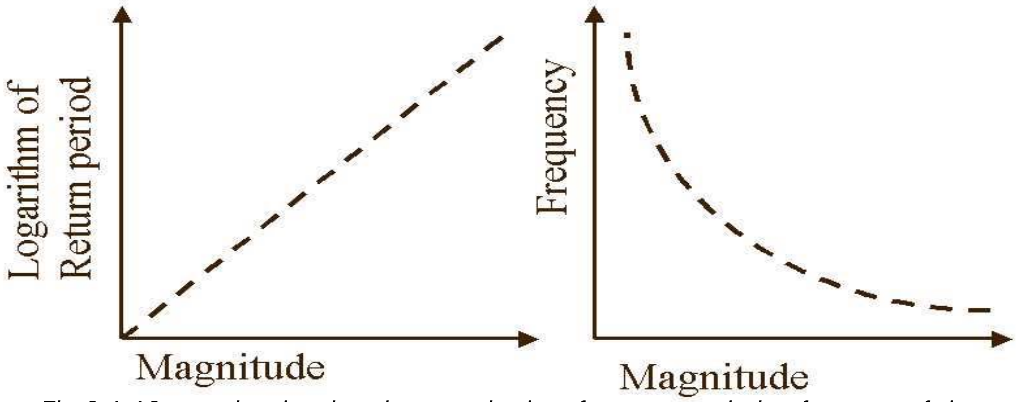


Fig.3.1.12: graphs showing the magnitude – frequency relation for most of the natural hazards.

earthquakes of different magnitudes expected per year based on historical records. The table clearly demonstrates how the frequency-magnitude relation described in figure 3.1.12 is followed. Few hazards don't follow this rule; an example of events with random relation between magnitude and frequency is lightening.

Average annually	Magnitude (Richter)
1[1]	8 or higher
17[2]	7.0-7.9
134[2]	6.0-6.9
1.319[2]	5.0–5.9
13.000	4.0-4.9
130.000	3.0-3.9
1.300.000	2.9 or less

Tab. 3.1.3: frequency-magnitude relation for earthquakes based on observations since 1900[1] 1990[2] (source USGS)

Frequency is generally expressed in terms of exceedance probability; which is defined as the chance that during the year an event with a certain magnitude is likely to occur. The exceedance probability can be shown as a percentage: a hazard, that statistically occurred once every 25 years, has an exceedance probability equal to 0.25 (or 25%). Another method is the calculation of the return period: it indicates the period in years in which the hazards is likely to occur based on historic records; an example can be a flood with a return period of 100 years (100 years return period flood = 1 event in 100 years = 0.01 probability). In part 3.3 of this section the frequency analysis will be explained in depth and different tools and methods for its calculation will be provided.

- **Secondary events**

When hazards hit an area, they cause directly potential damages to human beings and man-made structures according to their magnitude and the vulnerable elements in the affected area. But hazards can hit people and their properties indirectly by triggering other harmful events. When a natural hazard is studied the interactions with other events have to be taken into consideration. In the Sichuan province of China a violent earthquake occurred on May, 12th 2008. It killed approximately 69.000 inhabitants of the province. Such amount of casualties was not caused directly by the earthquake itself but also by other hazardous events. The earthquake caused hundreds of landslides in the mountainous area of the province. When occurred next to rivers courses, such landslides obstructed the streams causing devastating floods (see image 2 and 3 in figure 3.1.13). In the affected area 12 quake-lakes were created. Moreover, other harmful events were triggered by the earthquake, like debris flows and other mass movements, fires in the cities (see image 1 in figure 3.1.13) interruption of lifelines.

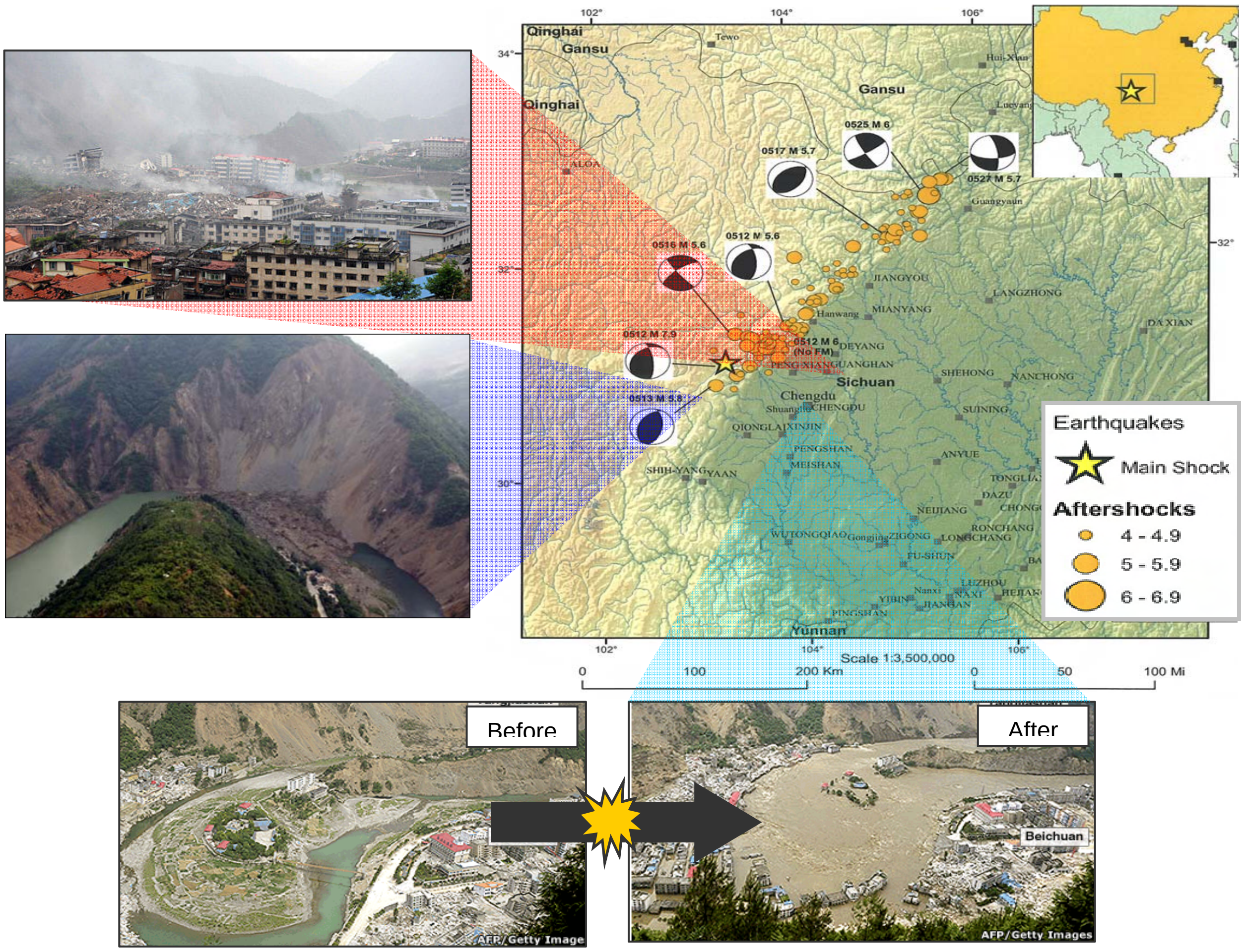
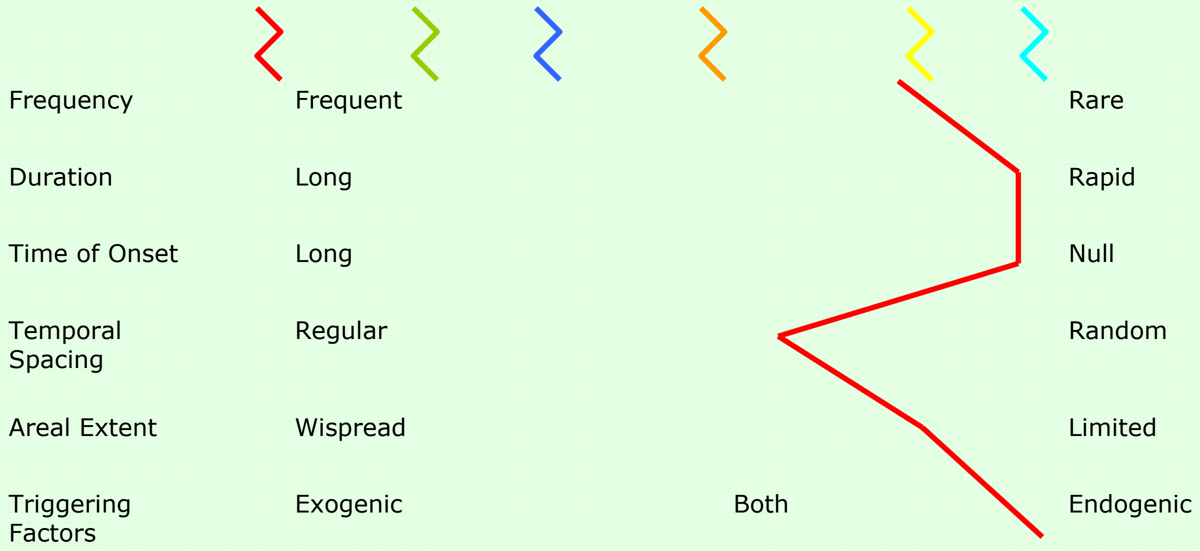


Fig. 3.13: Earthquake occurred on May 12, 2008 in Sichuan province of China, at least 69,000 people were killed. Image 1: fires triggered by the earthquakes. Image 2 and 3a/b The main earthquake triggered landslides that obstructed rivers streams and produced floods. Sources: http://mceer.buffalo.edu/infoService/disasters/china-earthquake-sichuan.asp; www.eeri.org/cds_publications/newsletter/2008_pdf/Wenchuan_China_Recon_Rpt.pdf

Task 3.1.3: According to the example, try to characterize each of the given hazards by drawing a line through the graph.

Earthquakes; Landslides; Floods; Volcanic Eruptions; Lightening; Tsunami



3.1.4 Hazard types

In the next part the main 6 hazard types will be briefly described according to their nature, spatial and temporal characteristics: landslides, floods, earthquakes, volcanic, coastal and technological. Afterward, in choice sections 3.4 to 3.9 the single hazard types will be introduced and discussed more in depth.

- **Landslides**

Landslides are classified among the main category of geologic hazards, together with land subsidence and expansive soils; geologic hazard are defined as non-seismic ground failures. The term "Landslide" refers to the downward and outward movement of slope-forming materials reacting under the gravity forces. A wide category of processes falls under the definition of landslides: mudflows, mudslides, debris flows, rock falls, debris avalanches, earth flows. Landslides may involve movement of natural rock or soil, artificial fill, or a combination of such materials. Landslides can be triggered by many factors, exogenic, endogenic or man-induced and they can trigger other hazards like floods. They occur in slope areas where one or many of the triggering factors co-exist. Frequency and magnitude are related to each other through an inverse proportion. The study of previous events is the key point in landslides frequency analysis, and more in general in hazard assessment; the old landslides catalogue is compiled through mapped past events analyzed using dating methods for determining the age of large historical events.

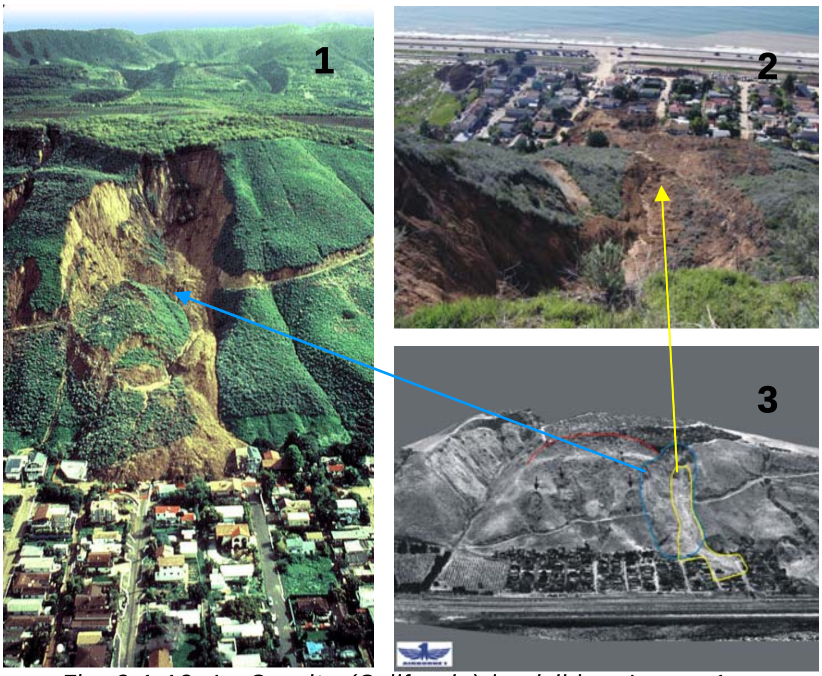


Fig. 3.1.13: La Concita (California) landslides. Image 1: landslide event of 1995. Image 2: reactivation event of 2005. Image 3: oblique view after the landslide in 2005 (http://www.youtube.com/watch?v=W4KWxglDL3o&feature=related).

Landslides	
Triggering factors	Exogenic: heavy rainfalls, land degradation, weathering; Endogenic: earthquakes; Man-induced: deforestation, wrong landuse plans.
Spatial occurrence	Location: slope areas with previous landslide activity and/or under the effect of heavy rainfalls and/or with weathered soil.
Duration of the event	Rapid: from seconds to minutes.
Time of onset	From seconds to months.
Frequency/Magnitude	It depends on the location but they follow an inverse relation: the higher is magnitude the smaller is frequency.
Derived events	They can trigger floods if the body falls into a river, fires in cities. Tsunamis (if they fall into water bodies and the dimensions are sufficiently large)

Two events in La Concita town, California are highlighted in figure 3.1.13; the first landslide occurred in 1995, the second in 2005 right at the same location of the first. Both phenomena were triggered by heavy rainfall and by the unsafe conditions of the slope: weathered material, slope cuts to build roads.

- **Floods**

Floods fall within the main category of hydrologic hazards, which include also storm surges, coastal erosions and droughts. Different definitions can be adopted to describe flood events:

"A flood is any high stream flow which overtops the natural or artificial banks of a stream"

"A flood is a body of water that inundates land that is infrequently submerged and, in doing so, causes or threatens to cause damages and loss of lives"

"Flooding is a natural and recurring event for a river or stream"

By summarizing the meaning of the previous definitions, rivers and water courses in general are subject to cyclical periods of low and high level during every year, in relation to the atmospheric conditions on the different locations. During high level periods, rivers can effort in containing the exceeding quantity of water until a certain point, according to the morphology of the area, and the impact of human-made structures that can affect positively or negatively the river capacity. When the mass of water exceeds that threshold (represented by the natural or artificial levees) a flood occur. Next to the causes related to the precipitation rate, other factors can trigger flood events.

The term flood includes several types of events. According to FEMA Multi Hazard Identification and Risk Assessment (MHIRA, see further reading), six major classes can be recognized.

- Riverine floods are events occurring in downstream wide low-land floodplains (it is the adjoining channel of a river or stream that is susceptible to flooding). They are triggered by large-scale rainfall events over a wide system of catchments that drain to major rivers. Annual spring floods can result from seasonal snowmelt. The floodwaters are typically slow-moving and relatively shallow (ratio between depth and width very small) and they can remain several days on the flooded areas.
- Flash floods occur in upstream areas with high slope gradient and involve smaller areas than riverine floods. They are characterized by a rapid rise of water level, very high velocity, and large debris content; they are triggered by heavy and localized rainfall events. Flash floods may also result from dams' failure or sudden break-up of an ice jam. The time of onset is short to null in the case of dams' failure.
- Fluctuating lake levels: water level in lakes can fluctuate on short-term or seasonal basis due to heavy rainfalls or snowmelt. Fluctuations can occur also in long-term; they can cause flooding problems lasting for years or even decades. Water bodies completely landlocked or without adequate outlets are the most affected.
- Local drainage or high ground water levels: both are events that affect areas outside direct influence of rivers or water bodies in general; local heavy precipitations cannot be accommodated through infiltration and runoff and the water may accumulate and cause local drainage problems. High ground water levels occur in prone areas with specific hydro-geologic characteristics, especially after long period of extraordinary rainfalls.

Floods	
Triggering factors	Exogenic: heavy or elongated rainfalls. (endogenic: earthquakes)
Spatial occurrence	Flash floods (ff): valleys bottom in mountainous areas, small inundated areas; River floods (rf): floodplains, large areas, up to hundreds hectars; Dams/bank failure floods (dff): randomly wherever rivers are located, dimension varying according to the location.
Duration of the event	Ff: rapid from less than one hour to few hours; rf: from less than one day up to ten days
Time of onset	From seconds (dff) to few days (rf)
Frequency/Magnitude	They follow an inverse relation: the higher is magnitude the smaller is frequency (ff and rf). Totally random (dff)
Derived events	Downslope erosion and possible landslides (ff).

In 2002, a series of heavy and prolonged rainfall caused a series of flood events in the major European rivers (Rhine, Danube, Odra, Vistula) culminating in the disastrous August flood in the river Elbe (see image 1 in figure 3.1.14) and part of the Danube. Losses for the Elbe basin were estimated around 3 billion Euros in Czech Republic and 9 billions Euros in Germany. Elbe is one of the major rivers in Europe (1,091 Km), and around 18 million people live in the German part of the catchment. The flood hit the major cities along the river; Dresda, located in the Southern part was the most affected city (see images 2 and 5). That flood event can be classified as a riverine flood; the inundation was destructive also for the erosive power of the flow that damaged many networks (see image 4).

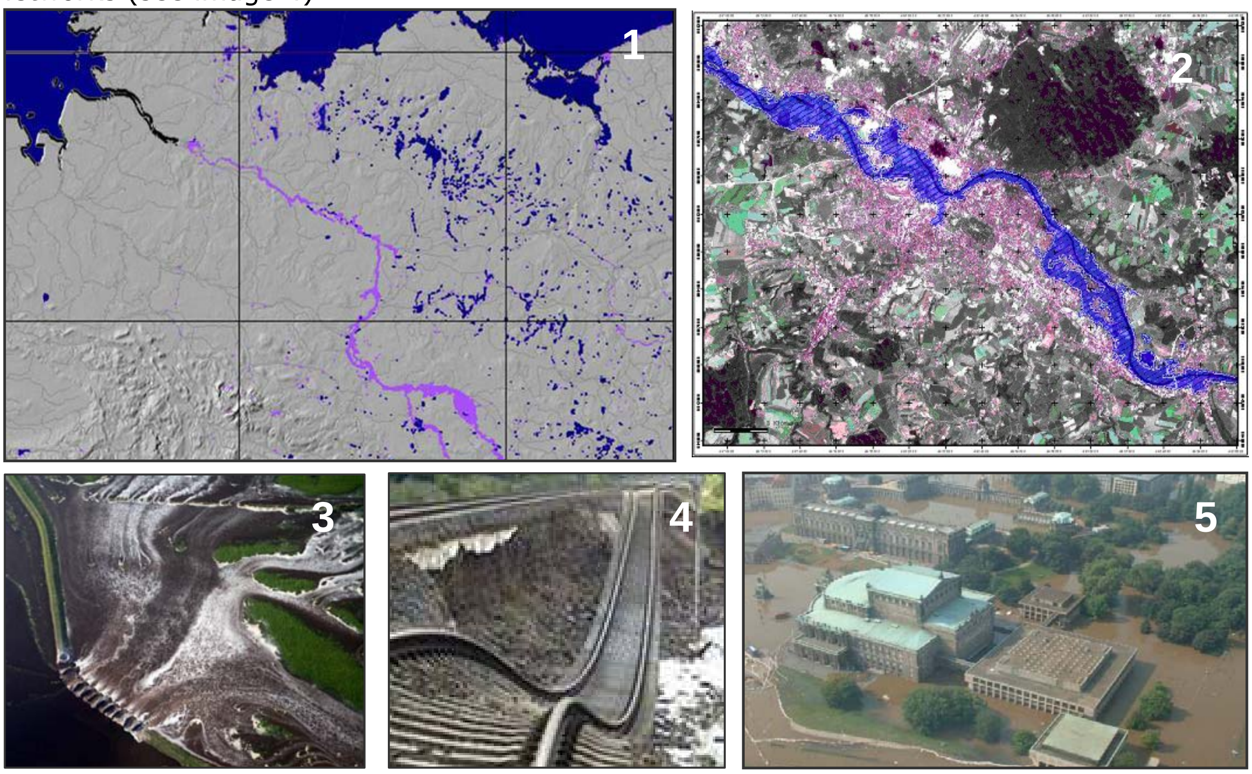


Fig. 3.1.14: 2002 Elbe flood. Image 1: Satellite image of flood extension in Northern Germany. Image 2: flood extent in the city of Dresda. Image 3: dike failure in a polder area. Image 4: damages to railways network caused by flood erosion. Image 5: flood effects in the city of Dresda.

- **Earthquakes**

An earthquake is a sudden motion or oscillation caused by a sudden release of strain accumulated on tectonic plates that form the Earth's crust. Tectonic plates theory explains the evolution of the crust as formed by many rigid (70 to 90 km thick) plates slowly and continuously moving over the liquid external part of the mantle, meeting in some areas (subduction zones) and separating in others (rifts and oceanic ridges). The movements are from less than one cm up to 4-5 cm per year. The "engine" is represented by the convective fluxes in the mantle. The plates (continental crust) are separate by oceanic crust, thinner than the other. They form together a rigid system that, when moved accumulates stress until the rupture; faults are formed instantaneously in the plates at different depths. The stress caused by the rupture creates two waves (shear and compressional), when those waves reach the surface, they generate other two kind of waves (Love and Rayleigh) responsible for the horizontal and vertical ground shaking (see figure 3.1.15). Earthquakes are not spread randomly on the planet, but they focus in zones with high seismic activity. The dimension of earthquakes can be measured as function of magnitude (amount of energy) or intensity (amount of damages). The dimension of the affected areas is a function of the magnitude and of the depth at which the earthquake occurs. Earthquakes don't have any forewarning sign and the duration of the event is from less than one to few seconds.

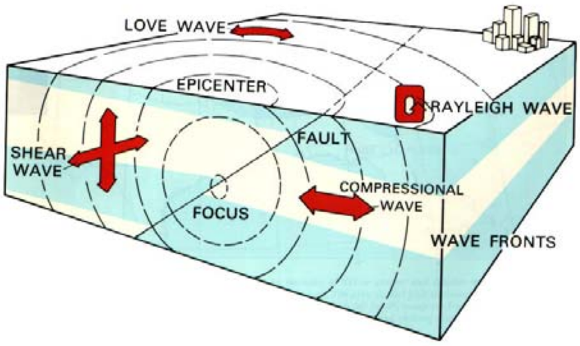


Fig. 3.1.15: Schematic representation of an earthquake caused by a fault.

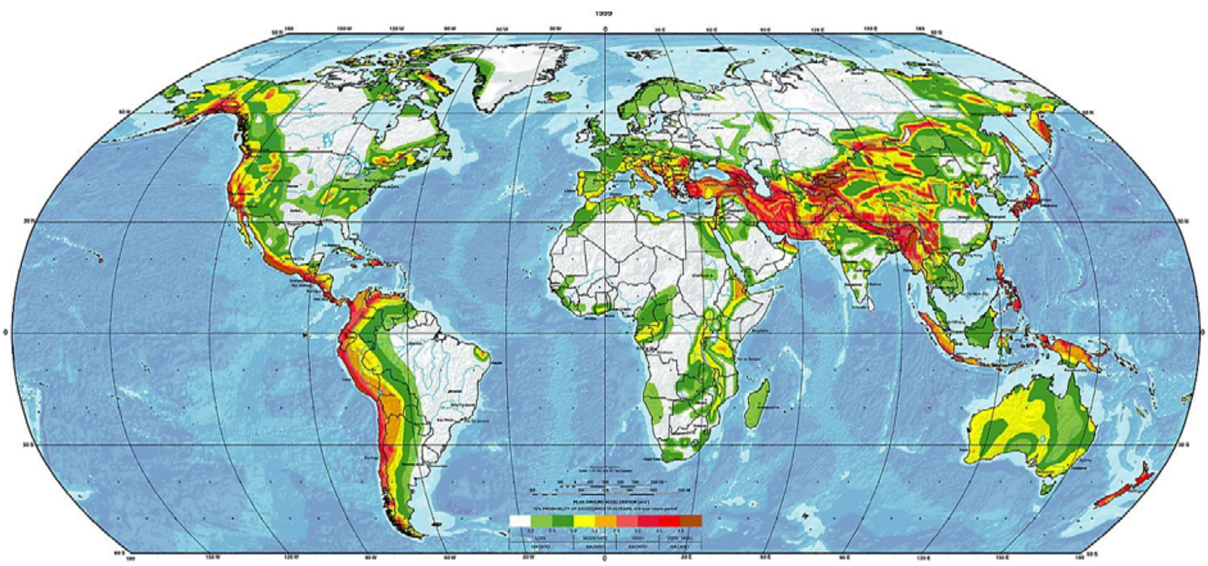


Fig. 3.1.16: Global Seismic Hazard Map: Global Seismic Hazard Assessment Program (GSHAP), United Nations- International Decade of Natural Disaster Reduction.

As mentioned before, the last devastating event occurred in the Sichuan province of China a violent earthquake occurred on May, 12th 2008. For further reading on this catastrophe, refer to the websites listed in the previous part on the derived events.

Earthquakes	
Triggering factors	Endogenic: tectonic movements
Spatial occurrence	Depends on the magnitude (from local to regional scale)
Duration of the event	Rapid, less than one minute
Time of onset	null
Frequency/Magnitude	Inverse relation; dimensions of the event can be expressed through magnitude scale or intensity scale
Derived events	Earthquakes can trigger: Tsunamis (in marine environment) landslides debris flows, floods, fires, etc.

Task 3.1.4: earthquakes (15 minutes).

How many earthquakes with a magnitude higher than M 4.5 happened in your country/continent in the last 7 days?
http://earthquake.usgs.gov/eqcenter/recenteqsww/; follow the link and check in the World regional maps.
Which is the largest earthquake from 1900 up to now? Which devastating other disaster did it cause?
http://earthquake.usgs.gov/eqcenter/eqarchives/year/byyear.php

- **Volcanic eruptions**

Volcanic eruptions affect large areas worldwide; they are related to the tectonic movements of the crust and the focus mainly on the areas in which fractures are created within or among plaques. Eruptions can be broadly classified as non-explosive or explosive. Non explosive eruptions occur in volcanoes with a basic (iron- and magnesium-rich) magma, which is relatively fluid and allows gas to escape. Such eruptions are characterized by fluid lava flows; they have very long activity periods with frequent eruption phenomena. Such events are the less destructive and usually they don't cause a restrict number of victims among the population because they have relatively long time of onset. Examples of this kind are the Hawaii Island volcanoes (USA) and the Etna Volcano (Italy).

The explosive type of eruptions consists of violent explosions caused by acid (silica-rich) magma colder (500-800°C) than the basic one (950-1200°C). Such explosions occur because the top of the volcano is occupied by a thick hat of consolidate rocks that retains all the gasses released in the magma chamber. Explosive eruptions produce large amount of debris in the form of airborne ash, pyroclastic flows, bombs, debris flows; large explosions can produce very high red hot ash columns that can collapse and flow along the volcano flanks at more than 300 Km/h devastating everything on their route. Examples of such kind of eruptions occur at the Vesuvius Volcano (Italy) and in the volcanic chain in Alaska. In the following paragraphs the main events involved in an eruption will be listed and shortly described.

Fig. 3.1.17: Lahar flow caused by the Mount St. Helens' eruption in 1980.

– Lava Flows: are flows that form proper streams of molten lava that erupt without huge explosions. The dimension and the length depend on: viscosity and temperature, slope steepness, obstructions; they can reach 40 Km of length. They totally damage everything they meet on their path. They are associated mainly with non-explosive eruptions; they are not dangerous for people because of their relatively slow movement.

They can cause related hazards like floods and mudflows (Lahars see figure 3.1.17) caused by ice and snow melt, and wildfires.

- Pyroclastic Flows: are high density mixture of hot, dry rock debris and gases ejected by the volcano's craters that flow over wide areas tens of kilometers away from the sources. They result from ash columns collapse, from the fall of rocks from volcanic domes, or from explosive lateral eruptions. Rock debris consists of mainly pumice fragments (volcanic rock formed during fast cooling with porosity higher than 70%). Debris flows are extremely dangerous especially when associated with explosive eruptions.

- Pyroclastic surges: are turbulent clouds of rock debris mixed with gases and air; they can reach high temperatures and fast speeds. They can trigger casualties and destructions in wide areas up to six kilometers far from the sources.

- Volcanic ash (Tephra): is a wide cloud of rock fragments with various dimensions carried upward by the column of red hot gases or by the explosion. The fragments fall on the ground forming ash deposits. Close to the source the dimension of fragments can cause disruption and victims; due to the high temperature tephra can also cause forest wildfires. Away from the source the danger for lives is caused by the effect of ash on respiratory system of animals and humans.

- Volcanic gases: consist mainly in carbon dioxide and compounds of sulfur and chlorine, in minor part of carbon monoxide and fluoride. The spread of gases is controlled by the wind direction and speed. Gases can have deadly effects on humans and animals and they can corrupt metals.

Volcanic eruptions' characteristics differ according to the eruption types. The duration can vary from few minutes or hours, in explosive cases, to months or years, when they are formed by basic magma. They occur in localized volcanic areas well known and mapped worldwide. Various forewarning signs may occur before an eruption like fumaroles, gas evacuations, small earthquakes, depending on the type of volcano. The time of onset can vary from minutes in the case of explosive eruptions, to months during non-explosive events. The frequency and the magnitude are related to the type of event: a volcano causing explosive events has less frequency and more devastating eruptions: non explosive basic volcanoes like Enta have frequent eruptions but are less dangerous.

One of the most important causes of disasters during eruptions is represented by the hazards of different nature triggered by the volcano's activity. Floods, debris flows or mudflows otherwise called lahars can occur during an eruption caused by snowmelt or rupture of lakes on the volcano. Landslides can be triggered by the seismic activity that usually follows an eruption. Atmospheric pollution can occur over large areas, even hundreds of kilometers far from the sources due to the gases or the presence of thin ashes.

Volcanoes	
Triggering factors	Endogenic: tectonic movements that create ruptures in the continental/oceanic crust
Spatial occurrence	Localized in particular locations
Duration of the event	From minutes to years
Time of onset	From minutes to weeks
Frequency/Magnitude	It depends on the characteristics of single volcanoes
Derived events	Lava flows, debris/mud flows, landslides, earthquakes, glaciers melting or crater lake outbreaks and subsequent flood or mudflows, bombs, pyroclastic flows, ash-tephra, gas clouds into the atmosphere

Fig. 3.1.18: Mount. St. Helens' eruption in 1980. (USGS source).

In the 80's volcanoes caused more than 28,500 victims worldwide; that decade experienced more volcanic activities than any other according to recorded history. Mount St. Helens is one example of that devastating series; it erupted explosively in 1980; more than 10.000 local earthquakes and hundreds of stream blasts were triggered by the explosion. The eruption caused destructions in a 596 Km^2 area; over 290 tons of ash were spread over 57.000 Km^2. A column of ash invaded the atmosphere around the volcano and it deposited in during several days afterward on eleven neighboring US states. During the eruption glaciers and snows melted. Landslides and mudflows occurred along the volcano's flanks travelling in the worst cases for more than 22 Km and destroying bridges and temporarily interrupting all the communication networks (roads railways shipping on the Columbia River). More than 60 casualties were recorded and the losses exceeded 1.5 billion dollars.

More information can be found exploring the numerous websites that treat the Mount St. Helens' eruption. Most of the information listed in this paragraph come from the official USGS web page: http://vulcan.wr.usgs.gov/Volcanoes/MSH/May18/framework.html. Another interesting webpage is: http://www.fs.fed.us/gpnf/volcanocams/msh/ where links to real-time webcams on the volcano can be found.

- **Technological hazards**

The field of technological hazards is even more complicated than the one related to natural hazards. This category includes all the disasters related to disruption or malfunctioning of human activities that occur in habited areas or natural environments. Such events widely differ from each other in terms of temporal and spatial characteristics, but they are usually totally unexpected and they seriously affect human beings and their activities directly or indirectly.

Technological hazards can be differentiated into three main categories, according to the

Technological	
Triggering factors	Casual accidents
Spatial occurrence	From localized to widespread, it can occur wherever there are hazardous human-made structures or activities
Duration of the event	From seconds to months
Time of onset	Sudden events without any foregoing
Frequency/Magnitude	Random
Derived events	Explosions can trigger fires; pollutant dispersion can cause environmental disasters etc.

nature of the event and to their direct and indirect impact on population and environment.

– Explosions, fires in populated areas due to accidents related to hazardous industries and plants, or any other human activity. This class includes sudden and fast events that involve relatively small areas with a short duration (from seconds to few days). The triggering factors can be malfunctioning or accidents to: factories, plants, single buildings, tanks containing inflammable materials or storage sites located in or next to urban areas. Accidents consist of explosions and/or fires; the severity of the events is related to the nature of the materials involved. Usually the damages are caused by the direct impact of the event on buildings and the population; other hazardous situations can be derived from the smoke clouds in case of toxic substances involved. Such events don’t show any clear relation between frequency and magnitude. They mostly depend on the development of security controls of single countries and regions about the treatment and the storage of hazardous materials.The event occurred in the Netherlands well represents this category. On May 2000, in the City of Enschede in the Eastern part of the Twente Region, what is recalled as the Fireworks Disaster was caused by an explosion in the fireworks factory located in the city. The blasts were felt up to 30 Km far from the source: roughly 1.500 houses were damaged or destroyed. The fireworks deposit went on fire during the day. The chain reaction of explosions caused 22 casualties and more than 900 people were injured (see figure 3.1.19); the damages related to insured houses only exceeded 500 million ***f*** (Dutch guilders, ca. 302 million US$).

Fig. 3.1.19: Fireworks factory explosion on May 13th 2000 in Enschede, the Netherlands. It caused more than 20 victims

– Hazardous material events: uncontrolled release of dangerous materials from storage sites or during transportation activities; it can occur in the atmosphere, in water bodies in groundwater, in the subsoil. This category includes events that occur when hazardous materials are accidentally or illegally released into the environment; they involve relatively large populated or inhabited areas and usually the duration of the events is longer than the first class (from days to months); it depends on the nature of the substance (gas liquid or solid) and on the environment in which such substance is released (atmosphere, soil and groundwater, or water). Duration can also be related to the possibility and the rapidity of intervention by specialized task forces. The severity and the area involved are usually related to the dispersion velocity of the material: in the case of uncontrolled gas dispersion in the atmosphere, the propagation is much higher than the leakage of dense oil in a clayey soil. Frequency and magnitude don’t seem to have any relation but casual. The damage is mainly related to environment contamination; population can be affected indirectly through air, water or food long term contamination. One of the worldwide most dangerous examples of this kind of disasters is the well known Exxon Valdez oil spill; it occurred in the Prince William Sound located in the Gulf of Alaska. On March 29th, 1998 the vessel struck a reef off the Bligh Island and it spilled about 200 million liters of oil (see figure 3.1.20). When the spill stopped, the oil had covered 28.000Km^2 of ocean. The consequences for the environment were devastating; in 2007 a study conducted by NOAA stated that more than 98.000 liters of oil were present in the pores of the sandy soil of the contaminated shoreline. About 500.000 seabirds, more than 1.000 sea otters died immediately and many animals showed high death rates in following years mainly due to oil ingestion.

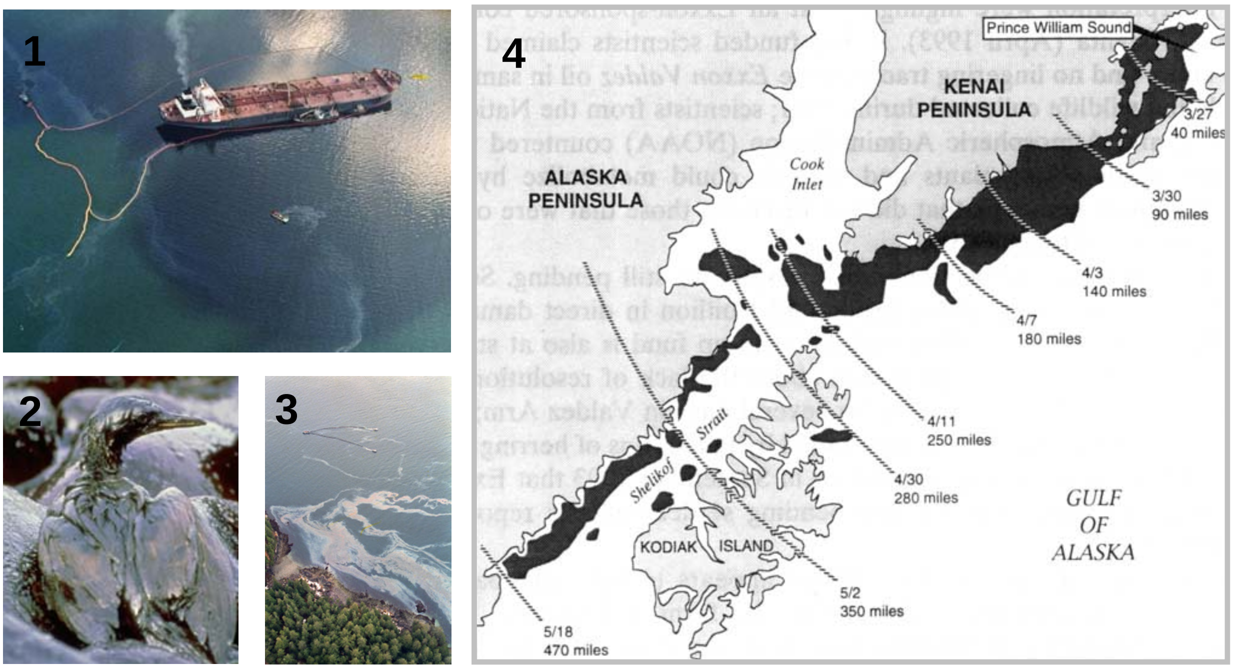


Fig. 3.1.20: Image 1, 2, 3 are related to the ecological disaster due to the Exxon Valdes oil spill. Image 4 represents the development of the contamination in the subsequent days.

– Nuclear accidents: unexpected and uncontrolled nuclear contamination caused by accidents to nuclear plants or any other nuclear reactor facility. Hazards related to nuclear activity or radioactive materials can be mainly of two kinds. They can derive from malfunctioning or failures in nuclear plants that can cause explosions or hazardous material leakage; they can occur if radioactive material is handled without sufficient protections, or it is lost, stolen, or abandoned. Such hazards are extremely dangerous for lives in general and the environment because the persistent effects can affect lives for many years. The dispersion of radioactivity is uncontrollable and can occur at continental scale. In the case of Chernobyl in 1989, products like vegetables and milk were forbidden for children until various months after the disaster all over the Europe.

Task: Technological hazards (15 minutes).

Watch the following videos related to the disasters described above:
(Fireworks disaster)http://www.youtube.com/watch?v=MVqCWErj2Pc&feature=related
(Exxon Valdes spill) http://video.google.com/videoplay?docid=5632208859935499100
Next to the example showed in these pages, can you find other three cases of technological hazards possibly related to your country/continent?

- **Coastal hazards**

Coastal zones represent one of the mostly densely inhabited areas worldwide; about 70% of the entire world's population lives in coastal environments; most of the megalopolises are located in delta areas or at the coasts of estuaries. Such areas are affected by a combination of hazardous events: degradation in the form of surface and groundwater pollution such as salt water intrusion, coastal flooding, erosion & accretion, land subsidence as impact from land-based settlements activities, mining activities of oil and gas. Due to the strong interactions among the effects that such phenomena have on the coastal areas, the hazards affecting this kind of environments are described in this guide book within a single category.

A selection of few coastal hazards is chosen for this section; the most devastating phenomena are the rapid hazard: cyclones and tsunamis. Other slow processes can trigger to hazardous situations in particular cases; therefore they will be mentioned apart.

Rapid Coastal Hazards

In this class two events are included, cyclones and tsunamis; these phenomena have dramatic and destructive effects on the population and the coastal environment. They are recognized as extremely dangerous events because the seriously affect people and their properties in a very short lapse of time.

Cyclones (also known as hurricanes or typhoons) are caused by tropical revolving storms caused by low pressure systems. This pressure drop might cause the sea level to rise, which accompanied by very strong winds (over 90 km/hr) gives storm surges of 5 meter or more, causing severe damage to agriculture and infrastructure and many casualties. About 80 cyclones are formed every year. They move fast (up to 160 km/h) affecting large coastal areas. The duration can vary from hours to days depending on the magnitude of the event; usually they grow up on the oceans and they dissipate over land. They evolve from compact storms to cyclones through the increase of wind speed and the formation of the circular movement (see figure 3.1.21). This gradual growth can allow evacuation or the placement of shelters and protections to limit the impact of the event. The relation between frequency and magnitude is inversely proportional: small cyclones are more frequent than the bigger ones. Cyclones bring heavy rainfalls and strong winds; they frequently trigger correlated hazards like coastal floods, landslides and mudflows in hilly areas.

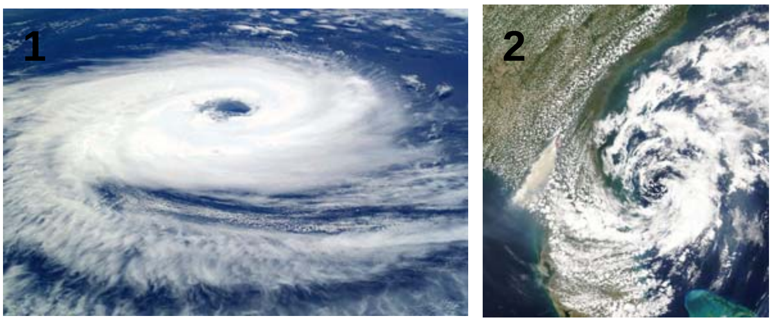


Fig. 3.1.21 Image 1 is the devastating South Atlantic tropical cyclone Catrina (2004). Image 2 is the subtropical cyclone Andrea (2007).

A tsunami is an exceptional disturbance of the sea level caused by an earthquake, landslide or volcanic eruption in and around the oceans. This can generate a sea wave of extreme length and period, travelling outwards in all directions from the source area with speeds up to 500 km/hr. Tsunami waves may attain heights of more than 30 meters by the time they hit the coast. The duration can vary from few seconds to hours; several waves may follow each other at intervals of 15 – 45 minutes, but the most hazardous ones are the first. The frequency-magnitude relation is dependant on the occurrence of the triggering factors.

The well known tsunami of December 26, 2004, was caused by an earthquake of a magnitude of 9 and with the epicentre located off the West coast of Sumatra, Indonesia. It is know as one of the most devastating phenomena ever happened. The main wave that reached the closest Indonesian coasts to the epicentre was more than 30 metres high and travelled at a speed of more than 500 Km/h. The United Nations established that the tsunami killed over 180.000 people and caused approximately 125.000 injuries and damages for more than 1.69 million dollars (see figure 3.1.22).

Fig. 3.1.22: Destructive effects of the 2004 tsunami in Sumatra, Indonesia; left image before; right image after the event

Rapid coastal hazards	
Triggering factors	Cyclones: Atmospheric conditions. Tsunamis: earthquakes, volcanic eruptions and landslides next to water bodies
Spatial occurrence	From hundreds to thousands kilometers of coasts
Duration of the event	Cyclones: from hours to days. Tsunamis: from seconds to hours
Time of onset	Cyclones: from hours to days. Tsunamis: from seconds to hours
Frequency/Magnitude	The most devastating events are the most rare
Derived events	Coastal floods

Slow Coastal Hazards

Enhanced sea level rise. Due to global warming and the Greenhouse Effect, the sea level will rise substantially in the near future. The International Panel of Climate Change (IPCC) has developed various scenarios for this. In the "Business as Usual" scenario this rise will amount up to 40 cm or even more until the end of this century. The enhanced Sea level rise has to be differentiated from long term sea-level change. These changes are so slow, that they are not considered as a hazard. World-wide changes in average sea level are described as eustatic to distinguish them from local influences, such as tectonic uplift or land subsidence. Eustatic sea-level changes result from two main causes: (1) changes in the volume of the ocean basins; and (2) changes in the volume of sea water. An example of the last course is sea level rise due to melting of glaciers after the last ice age.

Subsiding coasts can be considered as severe hazards, especially in urban areas situated in geologically young and "soft' sedimentary deposits. They can be caused by excessive ground-water extraction through industrial or private wells, as well as decreased discharge of the coastal aquifer. Subsiding rates up to 15 cm a year or even more might occur. The subsided land is prone to flooding both from sea and rivers. A good example is Semarang city, Indonesia with subsidence rates up to 11.5 cm /year.

Coastal erosion & accretion is basically a natural process, which can become a risk to coastal infra-structure or other types of land uses, such as shrimp and fishponds or rice fields. The combined effect of wind-generated waves, tidal waves and currents from rivers, produce a highly variable and complex near-shore hydrodynamic system. By the movements of sediment on the sea floor and onshore, offshore and alongshore the shaping of the coastline is taking place in a dynamic system in a continuous process.

3.2 Climate Change and Hazards

3.2.1. Introduction

Climate change that we experience nowadays can partly be ascribed to human activity. Since the industrial revolution, more and more greenhouse gases (GHGs) are being emitted into the atmosphere, causing an increasing trapping of the heat (see Box). These gasses are mainly released during the burning processes of fossil fuels such as coal, oil and gas and due to the changes in land use and land cover. GHGs include carbon dioxide, methane, water vapor, nitrous oxide, ozone and halocarbons. The increase in the emission of GHGs equals 70% between 1970 and 2004 (IPCC).

Definitions of climate:

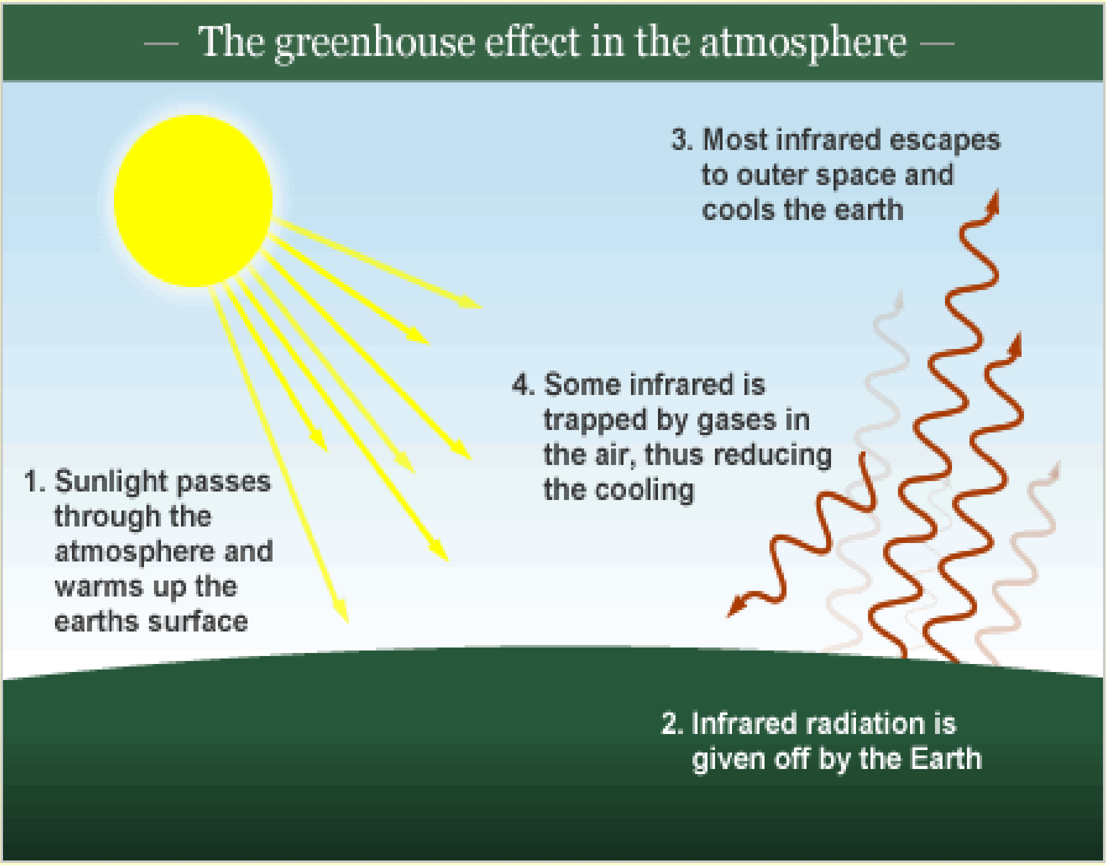
- The long-term average weather pattern of a region.
- The long-term average weather of a region including typical weather patterns, the frequency and intensity of storms, cold spells, and heat waves. Climate is not the same as weather.
- The historical record of average daily and seasonal weather events.

The life time of carbon dioxide molecules in the atmosphere is around 100 years, and the concentration of CO2 now stands at about 385 parts per million (ppm), compared to a pre-industrial concentration of about 280 ppm. The current concentration of carbon dioxide is at least a quarter higher than at any other time during the past 650,000 years. If we carry on burning fossil fuels in a "business as usual" way, the concentrations will rise to 600 or 700 ppm by the year 2100. Even in case where the whole world would work very hard to limit emissions, carbon dioxide concentrations are unlikely to stabilize below 450 ppm.

Evidently, the trapping of the heat by greenhouse gasses causes a global temperature rise. This rise is responsible for numerous secondary effects on our climate. Examples of these secondary effects include a widespread retreat of glaciers with an increase in the global mean sea level as a result (one to two millimeters per year over the course of the twentieth century), a decrease in snow cover, thawing of permafrost and ice sheets, shifts of plant and animal ranges (pole ward, and upward in elevation), earlier flowering of plants, bird breeding seasons and emergence of insects, and increased frequency of coral bleaching events, particularly during El Niño episodes.

The global surface temperatures rise equals over 0.7 °C during the 20th century – making it the warmest period in at least the past 1,300 years. And climate change is accelerating: 11 out of the 12 years in the period between 1995 and 2006, rank among the warmest years since records began (see figure 3.2.1).

Greenhouse Effect



When sunlight strikes the Earth's surface as short wave radiation, a part of this radiation is reflected back to the atmosphere as long wave radiation, also called the infrared radiation (heat). This causes a cooling of the earth. However, the GHGs present in the atmosphere absorb this infrared radiation and trap the heat in the atmosphere. Many gases exhibit these "greenhouse" properties. Some of them occur in nature (water vapor, carbon dioxide, methane, and nitrous oxide), while others are exclusively human made (certain industrial gases). Most GHGs occur in nature, but are also emitted by the burning of fossil fuels. The best example is carbon dioxide.

The trapping of the heat caused by GHGs makes life on earth possible. Without the greenhouse effect, the earth surface will cool down to temperatures that are unsuitable for life. However, over time, if atmospheric concentrations of greenhouse gases keep increasing, the amount of heat trapped in the atmosphere will increase as well, leading to an enhanced greenhouse effect and consequently, what we experience nowadays already, in an increase of the mean global temperature, the global warming.

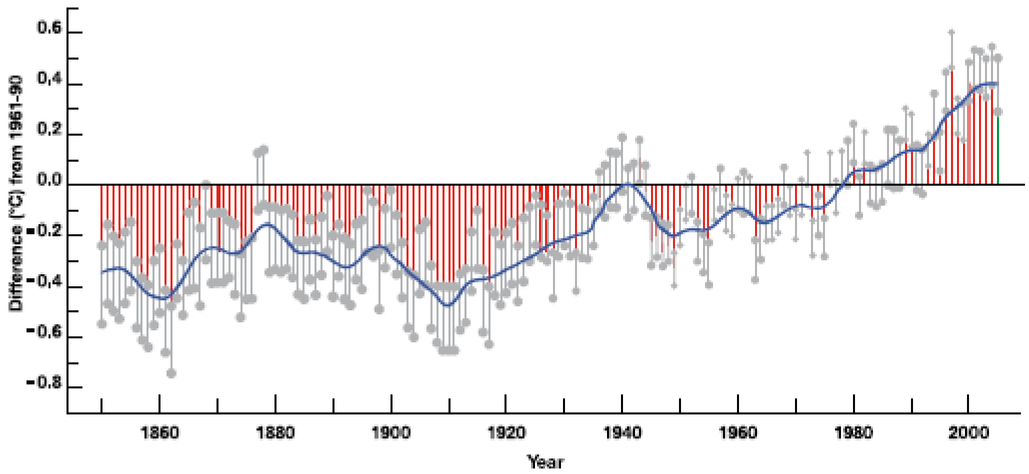


Figure 3.2.1: Observed changes in global average surface temperature (source: IPCC, 2007)

As these changes in climate started to occur around the 1970s, it is hard to tell what effect they have on extreme events. By definition, extreme events are rare, with return periods at a specific location usually in excess of 10 to 20 years, as the environment is generally designed to endure the impacts of more frequent extremes. Thus, not enough years have passed yet, since the onset of anthropogenic climate change, to be able to present solid facts concerning the change in occurrence of natural hazards related to the climatic change.

Task 3.2.1: See the effects of climate change for yourself (duration 10 minutes)

Go to www.google.com and type in the search balk: google earth outreach showcase. Choose the first hit named Google Earth Outreach – Showcase.
On the left side you can find Showcase: Environment & Science. Check out different KMLs, as for example "Per Capita CO2 Emissions" and "Climate Change in Our World".

3.2.2. Effects of climate change on hazards

There are, however, many changes observed that have a high possibility to be related to climate change. According to IPCC, the increase in geomorphologic hazards with hydro-meteorological grounds is clearly linked to the effects of climate change, which are complex and have a large spatial variation.
In the past years, there has been a large rise in the number of disasters (from between 200 and 250 in the period 1987–97 to about double that in the first seven years of the 21st century). This rise is caused almost entirely by an increase in weather-related disasters (see figure 3.2.2). For instance, the number of disastrous storms has doubled. Disaster statistics also show that floods are occurring not just more often but that they also cause damage to greater areas than they did two decades ago. And these rises are accompanied by a rapid increase in socio-economic losses and in the number of people affected. Although since the 1970s, the number of people killed by natural disasters has decreased, largely due to better disaster preparedness, in the past years that decrease has been tapering off and even reversing.

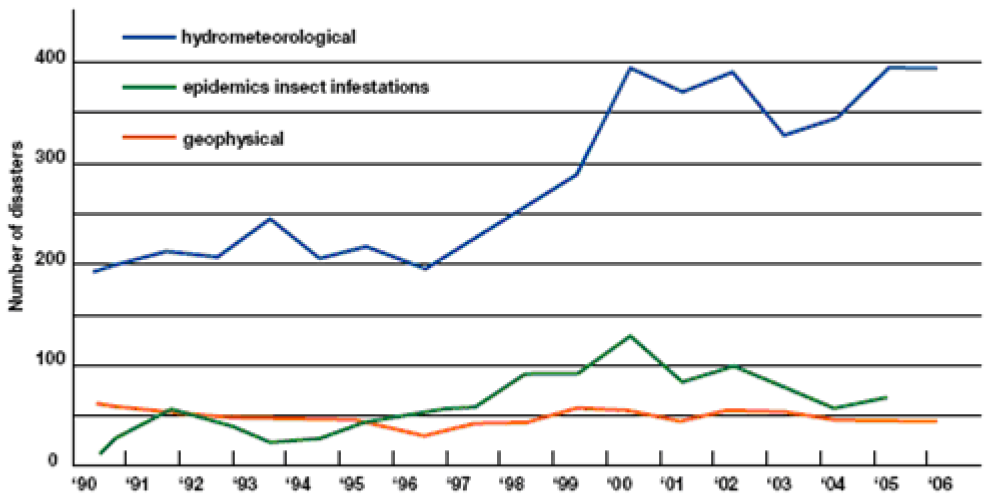


Figure 3.2.2: Annual number of natural disasters (source: CRED EM-DAT)

Temperature

Following the consensus of scientists, the most likely changes related to climate change are an increase in the number of hot days and nights (with some minor regional exceptions), or in days exceeding various threshold temperatures, and decreases in the number of cold days, predominantly including frosts. These are virtually certain to affect human comfort and health, natural ecosystems and crops.

Extended warmer periods are also very likely to increase water demand and evaporative losses, increasing intensity and duration of droughts, assuming no increases in precipitation takes place. Thereupon, long periods of dry condition are very likely to enhance the possibility of the occurrence of heat waves.

Precipitation

According to climate models, precipitation is generally predicted to increase in high latitudes and to decrease in some mid-latitude regions, especially in regions where the mid-latitude westerlies move pole wards in summer seasons, and thus steer fewer storms into such 'Mediterranean climates' (Meehl et al., 2007 in IPCC, 2007). These changes, together with a general intensification of rainfall events (Meehl et al., 2007), will very likely cause an increase in the frequency of flash floods and floods of large areas in many regions, especially the regions at high latitudes. This will be exacerbated, or at least seasonally modified in some locations, by earlier melting of snow packs and melting of glaciers. Contrariwise, regions of constant or reduced precipitation will very likely experience more frequent and more intense droughts, particularly in Mediterranean types of climates and in mid-latitude continental midlands.

Sea level rise

Due to global warming, the mean sea level is rising with the rate of approximately 3 mm/year. This is mainly caused by the melting of the glaciers and by the rise in sea water temperature, and thus the expansion of the water volume. The rise in sea level can have serious effects on countries with low lands. Increased floods are the main effect of the sea level rise. But also salinization of land, water pollution and increase of vector-borne diseases are consequences of sea level rise.

Forest Fires

Extended warm periods and increased dry conditions will increase water stress in forests and grasslands and increase the frequency and intensity of wildfires (Cary, 2002; Westerling et al., 2006 in IPCC), especially in forests and peat land, including thawed permafrost. Forests are a major depot for carbon dioxide. The burning down of forest areas may lead to large losses of accumulated carbon from the soil and from the biosphere into the atmosphere, thereby amplifying global warming (see Langmann and Heil, 2004; Angert et al., 2005; Bellamy et al., 2005 in IPCC, 2007).

Tropical cyclones
Tropical cyclones (including hurricanes and typhoons) develop over large bodies of warm water. With the increasing sea surface temperatures, tropical cyclones are likely to become more intense and more wide-spread. Moreover, several data reanalyses suggest that since the 1970s, tropical cyclone intensities have increased far more rapidly in all major ocean basins where tropical cyclones occur (Trenberth et al., 2007 Section 3.8.3), and that this is consistently related to the increasing sea surface temperatures. Some researchers have doubts about the reliability of these reanalysed data, in part because climate models do not predict such large increases; however, the climate models could be underestimating the changes due to inadequate spatial resolution. This issue currently remains unresolved. Some modelling experiments suggest that the total number of tropical cyclones is expected to decrease slightly (Meehl et al.), but it is the more intense storms that have by far the greatest impacts and constitute a key vulnerability.

The combination of rising sea level and more intense coastal storms, especially tropical cyclones, would cause more frequent and more intense storm surges, with damages exacerbated by more intense inland rainfall and stronger winds. With the increase of coastal populations, the exposure to intense storm surges increases as well.
A summary of the expected effects of climate change on disasters is given in the table 3.2.1.

Task 3.2.2: Internet assignment (duration 10 minutes)

Hurricanes of 2005

Read the CNN article about the hurricane season of 2005:
http://www.cnn.com/2005/WEATHER/11/29/hurricane.season.ender/index.html

Task 3.2.3: Internet assignment (duration 15 minutes)

Go to the website of EM-DAT (www.em-dat.be) and find out which year since 1970 had the largest number of storms for south-east Asia.

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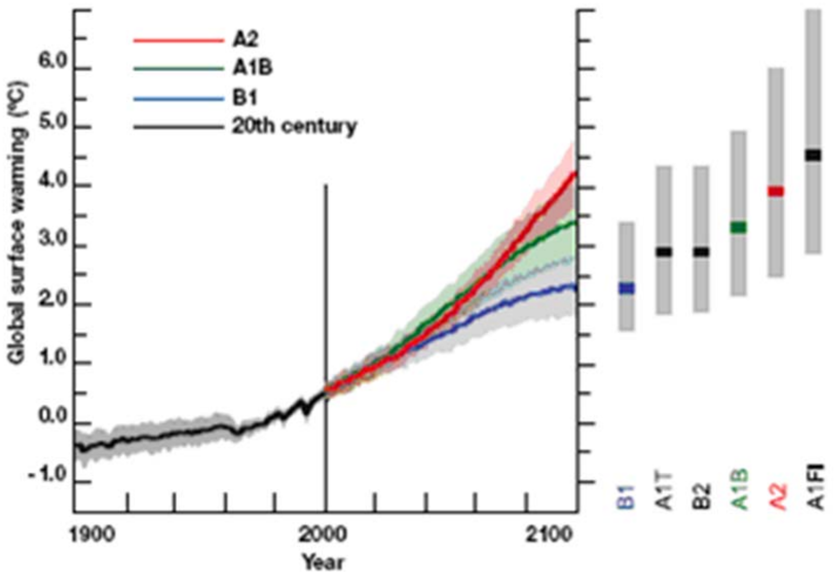
Expected effect of climate change on disasters (IPCC 2007 WG 2)			
Phenomenon and direction of trend	**Likelihood that trend occurred in late 20th century**	**Likelihood of future trend**	**Examples of major impacts**
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Very likely	Virtually certain	• Increased agricultural yields in colder environments, decreased yield in warmer environments • Increased insect outbreaks • Effects on water resources relying on snow melt • Reduced mortality from cold exposure • Declining air quality in cities.
Over most land areas, more frequent warm spells/heatwaves	Very likely	Very likely	• Reduced yields in warmer regions due to heat stress • Increased risk of bushfire • Increased water demand, water-quality problems • Increased heat-related mortality, particularly for the elderly, chronically sick, very young and socially isolated.
Over most areas, increasing frequency of heavy precipitation	Likely	Very likely	• Damage to crops • Soil erosion • Adverse effects on quality of surface and ground water • Water scarcity may be relieved • Increased risk of death, injuries, and infectious, respiratory and skin diseases • Disruption of settlements, commerce, transport and societies due to flooding • Pressures on urban and rural infrastructure • Loss of property.
Increasing area affected by drought	Likely in many regions since 1970s	Likely	• Land degradation • Lower yields, crop damage • Increased livestock deaths • Increased risk of wildfire • Increased risk of food and water shortage • Increased risk of malnutrition • Increased risk of water- and food-borne diseases • Migration.
Increasing intensity of tropical cyclones	Likely in some regions since 1970s	Likely	• Damage to crops and trees • Power outages causing disruptions of public water supply • Increased risk of deaths, injuries and disease spread through water or food • Post-traumatic stress disorder • Disruption by flood and high winds • Withdrawal by private insurers of risk coverage in vulnerable areas • Migration, loss of property.
Increased incidence of extremely high sea levels	Likely	Likely	• Salinization of irrigation water and fresh water systems, and decreased freshwater availability • Increased risk of deaths and injuries by drowning in floods • Migration-related health effects • Costs of coastal protection versus relocation • Potential for relocation of people and infrastructure • Tropical-cyclone effects.

Table 3.2.1: Summary of the expected effects of climate change on disasters (IPCC 2007 Working Group II, Summary for Policymakers)

3.2.3. The future scenarios

The IPCC has made four different future scenarios to study the possible effects of climate change (see Box for the explanation of the scenarios). As mentioned previously, carbon dioxide molecules can live around 100 years in the atmosphere, so even if the emissions would be cut down totally, the concentration of CO2 is going to rise for the next years. Therefore, no matter what scenario is studied, all of them show a continuing rise in global mean temperature, see fig 3.2.3.



Each colored line represents the likely change in global temperature that would occur for a specific GHG IPCC emission scenario. The shading around it indicates model uncertainty. The bars on the right show the likely temperature in 2100 for the full set of the scenarios.

The black line with gray shading represents the observed global temperatures during the 20th century.

Figure 3.2.3: Warming scenarios for the 21st century (source: IPCC, 2007)

Concerning the change in intensity and frequency of natural hazards related to climate change, no certain predictions can be made. It is hard to predict what effects the climate change will have on different sectors, and thus predicting the whole package is even more difficult. Thereupon, as mentioned previously, not enough years have passed yet since the set on of anthropogenic climate change, to be able to present solid facts concerning the change in occurrence of natural hazards related to this climatic change. This is because of the fact that the return periods of extreme events are in excess of 10 to 20 years.

Scientists are confronted with surprising effects on regularly basis even though the studies done are solid and robust. The only certain fact about the relationship between climate change and natural hazards is that the uncertainty will increase.

However, the expectations of the effects are unanimous: further increases in heat waves, floods, droughts and in the intensity of tropical cyclones, as well as extremely high sea levels. If the extreme events indeed increase with climate change as is the overall expectation, this will have a great effect on the extent of the risk. As can be seen in figure 3.2.4., the increase in the number of extreme events, combined with an increase in the extent of vulnerable societies, will lead to an increased extent of societies at risk.

Figure 3.2.4: Effect of climate change on risk

Task 3.2.4: Video (duration 10 minutes)
Relation climate change and disasters.

- *Watch the video (8 min): http://www.youtube.com/watch?v=ldPT6CuDBZI*

Box: Emission scenarios created by IPCC.

Box SPM.1: The emission scenarios of the IPCC Special Report on Emission Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

This box summarizing the SRES scenarios is taken from the Third Assessment Report and has been subject to prior line by line approval by the Panel.

3.2.4. Climate change and vulnerability

Not only the extent of vulnerable societies is about to increase. Other sectors or systems are likely to have a wide variation in the vulnerability across regions as well, partly as a consequence of climate change. Here we discuss 5 different sectors/systems; ecosystems; hydrology and water resources; food and fiber production; coastal systems; and human health.

Ecosystems
Ecosystems are of primary importance to environmental function and to sustainability, and they provide many goods and services vital to individuals and societies. In addition, natural ecosystems have cultural, religious, aesthetic and intrinsic existence values.
Changes in climate have the potential to affect the geographic location of ecological systems, the mix of species that they contain, and their ability to provide the wide range of benefits on which societies rely for their continued existence. Ecological systems are intrinsically dynamic and are constantly influenced by climate variability. The primary influence of anthropogenic climate change on ecosystems is expected to be through the

rate and magnitude of change in climate means and extremes—climate change is expected to occur at a rapid rate relative to the speed at which ecosystems can adapt and reestablish themselves—and through the direct effects of increased atmospheric CO_2 concentrations, which may increase the productivity and efficiency of water use in some plant species.

Hydrology and Water Resources

Water availability is an essential component of welfare and productivity. Currently, 1.3 billion people do not have access to adequate supplies of safe water, and 2 billion people do not have access to adequate sanitation.

Changes in climate could exacerbate periodic and chronic shortfalls of water, particularly in arid and semi-arid areas of the world. There is evidence that flooding is likely to become a larger problem in many temperate and humid regions, requiring adaptations not only to droughts and chronic water shortages but also to floods and associated damages, raising concerns about dam and levee failures. The impacts of climate change will depend on the baseline condition of the water supply system and the ability of water resources managers to respond not only to climate change but also to population growth and changes in demands, technology, and economic, social and legislative conditions.

Food and Fiber Production

Currently, 800 million people are malnourished; as the world's population increases and incomes in some countries rise, food consumption is expected to double over the next three to four decades. The most recent doubling in food production occurred over a 25-year period and was based on irrigation, chemical inputs and high-yielding crop varieties. Problems associated with intensifying production on land already in use are becoming increasingly evident.

Changes in climate will interact with stresses that result from actions to increase agricultural production, affecting crop yields and productivity in different ways, depending on the types of agricultural practices and systems in place. The main direct effects will be through changes in factors such as temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development, as well as through changes in atmospheric CO_2 concentration (which may have a beneficial effect on the growth of many crop types). In regions where there is a likelihood of decreased rainfall, agriculture could be significantly affected. Fisheries and fish production are sensitive to changes in climate and currently are at risk from overfishing, diminishing nursery areas, and extensive inshore and coastal pollution.

Coastal Systems

Coastal zones are characterized by a rich diversity of ecosystems and a great number of socioeconomic activities. Coastal human populations in many countries have been growing at double the national rate of population growth.

Changes in climate will affect coastal systems through sea-level rise and an increase in storm-surge hazards and possible changes in the frequency and/or intensity of extreme events. Coasts in many countries currently face severe sea-level rise problems as a consequence of tectonically and anthropogenically induced subsidence. Climate change will exacerbate these problems, leading to potential impacts on ecosystems and human coastal infrastructure. A growing number of extremely large cities are located in coastal areas, which means that large amounts of infrastructure may be affected.

Human Health

In much of the world, life expectancy is increasing; in addition, infant and child mortality in most developing countries is dropping. Against this positive backdrop, there appears to be a widespread increase in new and resurgent vector borne and infectious diseases, such as dengue, malaria, Hantavirus and cholera.

Climate change could affect human health through increases in heat-stress mortality, tropical vector-borne diseases, urban air pollution problems, and decreases in cold-related illnesses. Compared with the total burden of ill health, these problems are not likely to be large. In the aggregate, however, the direct and indirect impacts of climate change on human health do constitute a hazard to human population health, especially in developing countries in the tropics and subtropics; these impacts have considerable potential to cause significant loss of life, affect communities, and increase health-care costs and lost work days. Some increases in non-vector-borne infectious diseases—such as salmonellosis and giardiasis—also could occur as a result of elevated temperatures and increased flooding. However, quantifying the projected health impacts is difficult because the extent of climate-induced health disorders also depends on other factors, such as migration, provision of clean urban environments, improved nutrition, increased availability of potable water, improvements in sanitation, the extent of disease vector-control measures, changes in resistance of vector organisms to insecticides, and more widespread availability of health care. Human health is vulnerable to changes in climate— particularly in urban areas, where access to space conditioning may be limited, as well as in areas where exposure to vector borne and communicable diseases may increase and healthcare delivery and basic services, such as sanitation, are poor.

The text on climate change and vulnerability originates from IPPC special report: The regional impacts of climate change: an assessment of vulnerability, 1997

3.3 Frequency Analysis

3.3.1. Introduction

In session 1 an introduction was given to risk, which was defined as the probability of expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions. In this section we will concentrate in particular on the probability aspect, by looking at the magnitude-frequency (M-F)relationship of hazard events.

What is a magnitude-frequency relationship?

Magnitude-frequency relationship is a relationship where events with a smaller magnitude happen more often than events with large magnitudes.

As indicated in figure 3.3.1-a, most hazard events have a relationship between the magnitude of the event and the frequency of occurrence. This means that events with a small magnitude (e.g. small earthquakes) occur more frequently than those with large magnitudes. This is true more or less for all types of hazards, although for some hazards, like lightning, this would perhaps not be the case.
For some events both the occurrence of low magnitudes (e.g. rainfall) leads to a catastrophe (drought) as well as the occurrence of high magnitudes (flooding).

Task 3.3.1: Magnitude of event (duration 5 minutes)

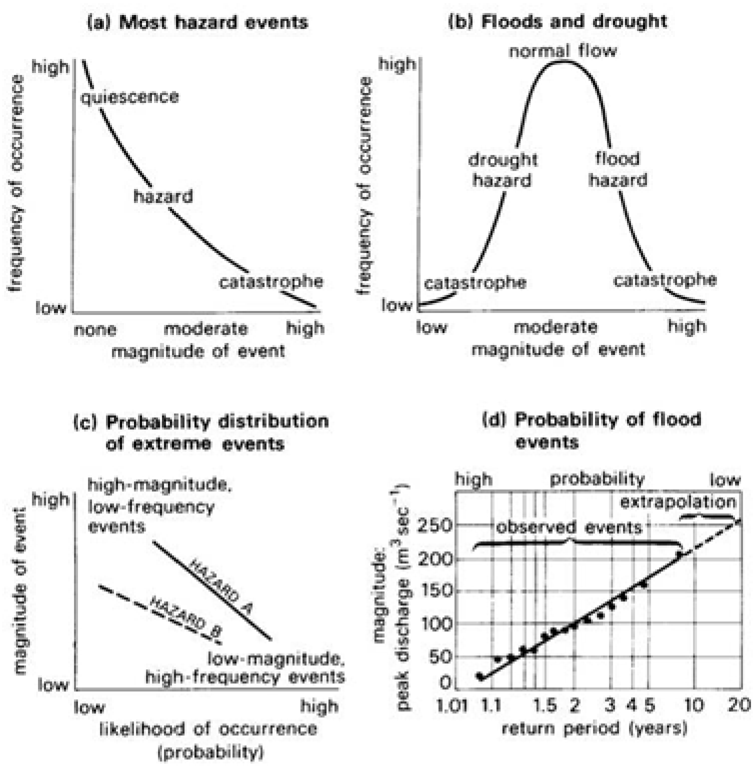
Give another example of an event for which it holds true that low magnitudes as well as high magnitudes can lead to a catastrophe and give examples of the catastrophes.

Most hazard types display a relationship between the likelihood of occurrence (probability) and the magnitude of the event, as shown in figure 3.3.1-c. This relationship might differ substantially depending on the hazard type. Apart from the classification of disasters, which was given in session 1, there is also a classification which is based on the magnitude-frequency relationship and the temporal aspects of the disasters (See table 3.3.1). The frequency magnitude relationship can be valid for the same location (e.g. a particular slope, x-y location, building site). This is the case for events like flooding, where each location will have its own height-frequency relationship depending on the local situation. The flood itself will also have its own discharge-frequency relationship for the entire catchment, but this can be used as input to calculate the height-frequency relationship for a particular point. In other cases the frequency magnitude relationship cannot be established for an individual point, but is done for a larger area (e.g. catchment, province, country, globe). For instance the occurrence of landslides cannot be represented for a particular location as a magnitude-frequency relationship (except for debris flows and rock fall) as the occurrence of a landslide will modify the terrain completely. Thus you cannot say that small landslides occur often in the same location and large landslide less frequently. However, you can say that for an entire watershed.

A frequency-magnitude relationship is normally based on a historical record of hazardous events. These can be in the form of a catalog, which can be derived from:

- recorded information from instruments (e.g. flood levels, earthquakes)- mapped events (e.g. flooded areas, landslides)
- historical archives (e.g. newspapers, municipal archives)
- participatory mapping at community level. - dating methods for determining the age of large historical events (e.g. past earthquakes or landslides).

Figure 3.3.1: Relationship between magnitude and frequency of events. (Source:....)



Historical information is always incomplete, as we can only obtain information over a particular period of time, e.g. the period over which there was a network of seismographs. The length of the historical record is of large importance for accurately estimating the magnitude-frequency relation. If the time period is too short, and didn't contain any major events, it will be difficult to estimate the probability of events with large return periods. The accuracy of prediction also depends on the completeness of the catalog over a given time period. In the case that many events are missing, it will be difficult to make a good estimation.

According to table 3.3.1 the frequency-magnitude distributions can be in different forms. They can be completely random, meaning that there is no relation between the two. The M-F distribution can also be irregular, which means that there is generally a relation but it is not regular, and differs from place to place. In those situations it is also difficult to make an equation that relates probability with magnitude. There are also a number of events that have a relation which can follow different distribution functions: e.g. log-normal, binomial, gamma, Poisson, exponential. In the following section three examples are given of the generation of magnitude-frequency relations: for flooding, earthquakes and landslides.

Table 3.3.1: Classification of disasters by occurrence and by Magnitude-Frequency relationship.

	Disaster type	Occurrence possible	Magnitude - Frequency relationship
Hydrometeorological	Lightning	Seasonal (part of the year)	Random
	Hailstorm	Seasonal (storm period)	Poisson , gamma
	Tornado	Seasonal ("tornado season")	Negative binomial
	Intense rainstorm	Seasonal (rainfall period)	Poisson, Gumbel
	Flood	Seasonal (rainfall period)	gamma, log-normal, Gumbel
	Cyclone/ Hurricane	Seasonal (cyclone season)	Irregular
	Snow avalanche	Seasonal (winter)	Poisson, gamma
	Drought	Seasonal (dry period)	Binomial , gamma
Environmental	Forest fire	Seasonal (dry period)	Random
	Crop disease	Seasonal (growing season)	Irregular
	Desertification	Progressive	Progressive
	Technological	Continuous	Irregular
Geological	Earthquake	Continuous	Log-normal
	Landslide	Seasonal (rainfall period)	Poisson
	Tsunami	Continuous	Random
	Subsidence	Continuous	Sudden or progressive
	Volcanic eruption	Intermittent (magma chamber)	Irregular
	Coastal erosion	Seasonal (storm period)	Exponential , gamma

Task 3.3.2: Frequency distribution (duration 15 minutes)

What would be the relation between magnitude and frequency of events for the following types of hazards? Answer the following questions:

- *Is there a M-F relation for a given location or for an area?*
- *Can the M-F relation be based on historical records?*
- *If so, from where and how should these be obtained?*

A. Flooding
B. Earthquakes
C. Landslides
D. Volcanic eruptions
E. Cyclones
D. Coastal erosion

3.3.2. Flooding frequency

Hydrologic systems are sometimes impacted by extreme events, such as severe storms, floods, and droughts. The magnitude of such an event is inversely related to its frequency of occurrence, very severe events occurring less frequently than more moderate events. The objective of frequency analysis of hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions. The hydrologic data analysed are assumed to be independent and identically distributed, and the hydrologic system producing them (e.g. a storm rainfall system) is considered to be stochastic, space-independent, and time-independent.

Table 3.3.2: Record of annual maximum discharges of the Guadalupe River

Year	1930	1940	1950	1960	1970
0		55,900	13,300	23,700	9,190
1		58,000	12,300	55,800	9,740
2		56,000	28,400	10,800	58,500
3		7,710	11,600	4,100	33,100
4		12,300	8,560	5,720	25,200
5	38,500	22,000	4,950	15,000	30,200
6	179,000	17,900	1,730	9,790	14,100
7	17,200	46,000	25,300	70,000	54,500
8	25,400	6,970	58,300	44,300	12,700
9	4,940	20,600	10,100	15,200	

The hydrologic data employed should be carefully selected so that the assumptions of independence and identical distribution are satisfied. In practice, this is often achieved by selecting the annual maximum of the variable being analysed (e.g. the annual maximum discharge, which is the largest instantaneous peak flow occurring at any time during the year) with the expectation that

successive observations of this variable from year to year will be independent.
The results of flood flow frequency analysis can be used for many engineering purposes: for the design of dams, bridges, culverts, and flood control structures; to determine the economic value of flood control projects; and to delineate flood plains and determine the effect of encroachments on the flood plain.

Return period
Suppose that an extreme event is defined to have occurred if a random variable X is greater than or equal to some level x_T. The recurrence interval t is the time between occurrences of $X \geq x_T$.
For example, table 3.3.2 shows the record of annual maximum discharges of the Guadalupe River near Victoria, Texas, from 1935 to 1978. If x_T = 50000 cfs[1], it can be seen that the maximum discharge exceeded this level nine times during the period of record, with recurrence intervals ranging from 1 year to 16 years, as shown in table 3.3.3

Table 3.3.3: Years with annual maximum discharge equalling or exceeding 50000 cfs on the Guadalupe River and the corresponding recurrence intervals

Years were 50000 is exceded	1936	1940	1941	1942	1958	1961	1967	1972	1977	Average
Recurrence interval		4	1	1	16	3	6	5	5	5.1

The return period T of the event $X \geq x_T$ is the expected value of t, E(t), its average value measured over a very large number of occurrences. For the Guadalupe River data, there are 8 recurrence intervals covering a total period of 41 years between the first and last exceedence of 50000 cfs, so the return period of a 50000 cfs annual maximum discharge on the Guadalupe River is approximately T = 41/8 = 5.1 years. Thus the return period of an event of a given magnitude may be defined as the average recurrence interval between events equalling or exceeding a specified magnitude.

The probability $p = P(X \geq x_T)$ of occurrence of the event $X \geq x_T$ in any observation may be related to the return period in the following way. For each observation, there are two possible outcomes: either "success" $X \geq x_T$ (probability p) or "failure" $X < x_T$ (probability 1-p). Since the observations are independent, the probability of a recurrence interval of duration T is the product of the probabilities of t-1 failures followed by one success, that is, $(1-p)^{t-1}.p$.
Assuming that the series of data is infinite, the E(T) can be expressed as:

$$E(t) = \sum_{t=1}^{\infty} (1-p)^{t-1} \cdot p \quad \text{Eq 1}$$

Developing this expression in terms and after some algebra:

$$E(t) = T = \frac{1}{p} \quad \text{Eq 2}$$

Therefore, the probability of occurrence of an event in any observation is the inverse of its return period.

$$P(X \geq xT) = \frac{1}{T} \quad \text{Eq 3}$$

For example, the probability that the maximum discharge in the Guadalupe River will equal or exceed 50000 cfs in any year is approximately p= 1/t= 1/5.1= 0.195 (19.5%)

Probability and risk
Suppose a certain flood (F) has a probability of occurrence of 10% - meaning a probability of 10% that this flood level will be reached or exceeded.
In the long run, the level would be reached on the average once in 10 years. Thus the average return period T in years is defined as:

[1] Cfs= cubic foot per second ($feet^3/sec$). Equivalence: 1000 cfs = 28.3168 m^3/s

$$T = \frac{1}{P_R(F)} \text{ Eq 4}$$

and the following general relations hold:

1. The probability that F will occur in any year:

$$P_R(F) = \frac{1}{T} \text{ Eq 5}$$

2. The probability that F will not occur in any year

$$P_L = 1 - P_R(F) = 1 - \frac{1}{T} \text{ Eq 6}$$

3. The probability that F will not occur in any of n successive years

$$P_L^n = \left(1 - \frac{1}{T}\right)^n \text{ Eq 7}$$

4. The probability R, called risk, that F will occur at least once in n successive years

$$R = 1 - \left(1 - \frac{1}{T}\right)^n \text{ Eq 8}$$

Extreme value distributions

A large amount of process events in hydrology are right skewed, leading to differences between the mode, median and mean of their distributions (see figures 3.3.2 and 3.3.3).

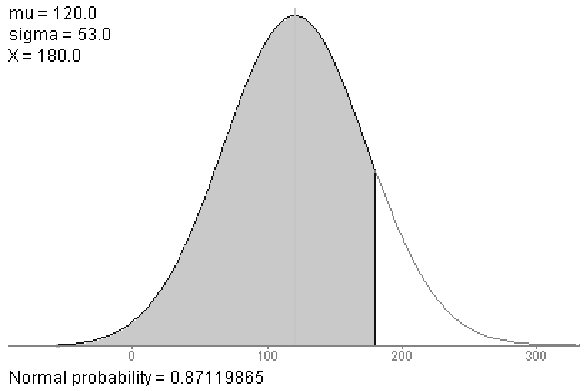


Figure 3.3.2: A normal distribution accurately describes facts in nature that apart evenly for a mean.

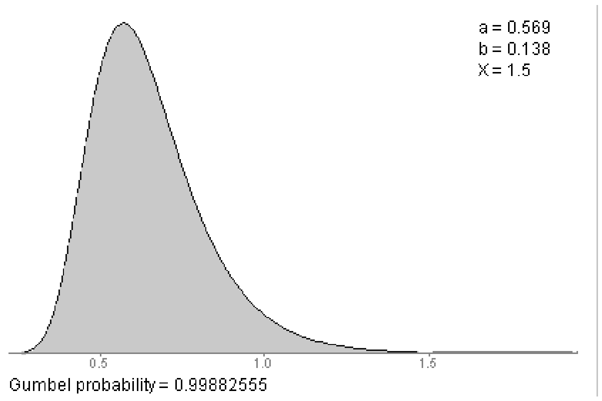


Figure 3.3.3: River discharges and rainfall are right skewed events. Their value cannot be lower than zero and extreme events might occur far form the average.

There are a number of influences that promote this characteristic right-skewness of recorded natural events:

1. Where the magnitude of given events is absolutely limited at the lower end (i.e. it is not possible to have less than zero rainfall or runoff), or is effectively so (i.e. as with low temperature conditions), and not at the upper end. The infrequent events of high magnitude cause the characteristic right skew.
2. The above-mentioned limitation of the lower magnitudes implies that as the mean of the distributions approaches this lower limit, the distribution becomes more skewed.
3. The longer the period of record, the greater the probability of observing infrequent events of high magnitude, and consequently the greater the skewness.
4. The shorter the time interval within measurements are made, the greater the probability of recording infrequent events of high magnitude and the smaller the skewness.
5. Other physical principles tend to produce skewed frequency distributions. For example the limited size of high intensity thunderstorms means that the smaller the drainage basin, the higher the probability that it will be completely blanked by heavy rain and this leads to an increase in skewness in the distribution of runoff as basin

size decreases. Similarly, stream discharge frequencies are extremely skewed where impermeable strata allow little infiltration.

The right skewed distributions present certain problems of description and of inferring probabilities from them. When plotted on linear-normal probability paper, right skewed distributions appear as concave curves.
There are three methods to calculate the extreme value distribution in case of right skewness; Gumbel, Frechet and Weibull, see Fig 3.3.4. These methods are called the Extreme Value methods (EV's) and they are all based on one general equation called the General Extreme Value (GEV) distribution. The extreme value transformation or double exponential transform is extensively used to straighten out cumulative plots of highly skewed distributions. The probability distribution function for the GEV is:

$$F(x) = \exp\left[-\left(1 - k\cdot\frac{x-u}{\alpha}\right)^{1/k}\right]$$

where k, u and α are parameters to be determined.

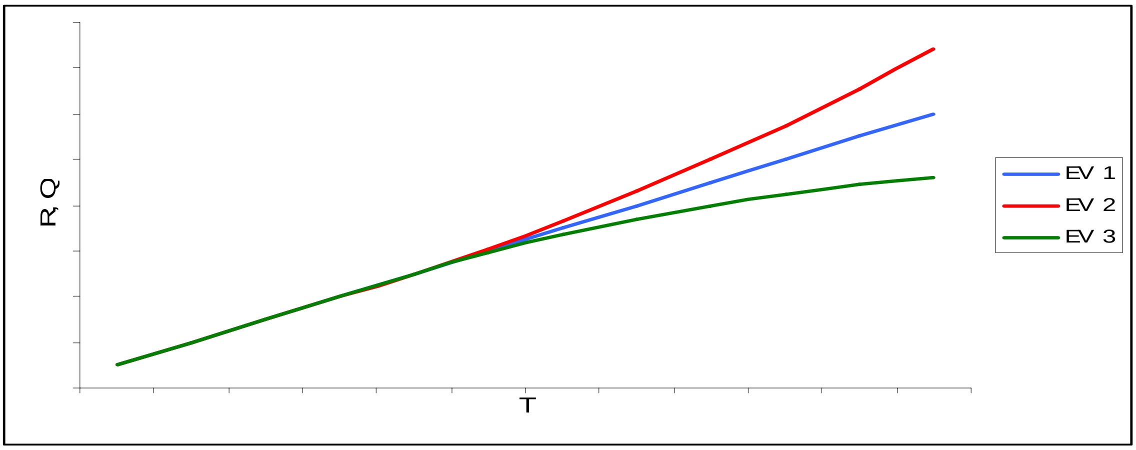


Figure 3.3.4: Gumbel distribution (EV 1), Frechet distribution (EV 2) and Weibull distribution (EV 3) with discharge or rainfall on the y-axis and return period on the x-axis.

The Gumbel distribution is a distribution with a light upper tail and it is positively skewed. It often underestimates the actual situation. Frechet gives a better estimation, but as three variables are needed for Frechet and just two for Gumbel, the Gumbel method is generally used. Frechet is a distribution with a heavy upper tail and infinite higher order moments. The Weibull distribution is a distribution with a bounded upper tail. It used to estimate the drought. For this method, also three variables are needed.

Critical notes extreme frequency analysis
The statistical methods discussed are applied to extend the available data and hence predict the likely frequency of occurrence of natural events. Given adequate records, statistical methods will show that floods of certain magnitudes may, on average, be expected annually, every 10 years, every 100 years and so on. It is important to realize that these extensions are only as valid as the data used. It may be queried whether any method of extrapolation to 100 years is worth a great deal when it is based on (say) 30 years of records. Still more does this apply to the '1000 year flood' and similar estimates. As a general rule, frequency analysis should be avoided when working with records shorter than 10 years and in estimating frequencies of expected hydrologic events greater than twice the record length.
Another point for emphasis is the non-cyclical natural of random events. The 100-year flood (that is, the flood that will occur on average, once in 100 years) may occur next year, or not for 200 years or may be exceeded several times in the next 100 years. The accuracy of estimation of the value of the (say) 100-year flood depends on how long the record is and, for floods, one is fortunate to have records longer than 30 years.

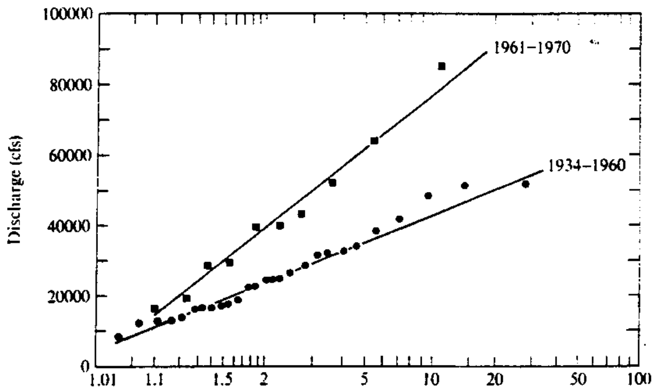


Figure 3.3.5: Changes in climatic conditions might alter the statistics of extremes.

Notwithstanding these warnings, frequency analysis can be of great value in the interpretation and assessment of events such as flood and the risks of their occurrence in specific time periods.

Many parts of East Africa, for example, have undergone a striking change of rainfall since 1960 and it is doubtful whether floods from before and after this date should be mixed in constructing a flood frequency curve. As an illustration, available records have been segregated into two sets of years and re-plotted in figure 3.3.5 as two flood frequency curves that are strikingly different. Unfortunately there are no hard and fast roles to guide the hydrologist in such a situation. So he or she must make a judgement about the significance of the separation of these two curves.

- Does it represent only a short run of wet years?
- Or has the hydrologic regime of the basin undergone a radical change?

If the latter hypothesis is correct, use of the longer but mixed record could lead to a serious underestimation of floods in the new regime. In this case the shorter record, although subject to grave sampling errors, would be the one to use for planning. A question would also arise about the probable duration of the new regime and again there are no precise statistical answers. The hydrologist would have to consult climatologists. We raise the problem here, not because we can give answers, but so that the hydrologist and planner can see that flood frequency curves and the statistics they yield are subject to large uncertainties and that they should be treated conservatively.

For such reasons, flood frequency curves should be checked and updated from time to time. If the record remains homogeneous, its increasing length will reduce the standard deviation and narrow the confidence intervals around the mean. Land use changes, dam construction and channel changes are rendering flood records of little value.

Another factor that may cause a lack of homogeneity in a flood record is the variation of the causative meteorological event. In New England, for example, some annual floods are generated by summer rainstorms others by autumn hurricanes, others by snow melt and still others by rain on melting snow, sometimes coupled with surges following break-up of ice dams. Usually all such floods are included in the frequency analysis. Whether they should be or not is a subject for debate.

Sometimes the observed flood distribution is not fitted well by a straight line on any of the graph papers and the hydrologist must sketch a curve to fit the points. He should be fully aware of the possible errors when using the information obtained in this manner. It is also strongly advisable not to rely on one method of flood prediction, but to use several methods in an attempt to obtain consensus.

3.3.3. Earthquake frequency assessment

The outer shell of the earth is composed of a number of almost rigid "plates" that slowly move against each other. Stresses can build up at these boundaries, caused by the general movement of the plates against each other over time, with stress accumulating at the plate boundaries. It may then be released suddenly, in the form of an earthquake. Most of the extreme magnitude earthquakes occur near the plate boundaries. Most of these boundaries are under deep water, but the effects spread for many miles, and so can be felt on land in these cases too. Earthquakes happening under the sea might trigger tsunamis, bringing damage to coastal communities, in a wide area. The USGS (U.S. Geological Survey) estimates that several million earthquakes occur in the world each year. Many go undetected because they hit remote areas or have very small magnitudes. The NEIC (National Earthquake Information Center) now locates about 50 earthquakes each day, or about 20,000 a year.

Task 3.3.3: USGS and NEIC (duration 15 minutes)

Visit the websites of USGS and of NEIC:

http://www.usgs.gov/
http://neic.usgs.gov/

A measurement of earthquake magnitude is the Richter scale. On a logarithmic scale this measures the size and energy released from an earthquake. That means that larger earthquakes occur less frequently, the relationship being exponential; for example, roughly ten times as many earthquakes larger than magnitude 4 occur in a particular time period than earthquakes larger than magnitude 5. On this scale, there are usually dozens of "earthquakes" occurring daily, with a magnitude of below 2.5. These are usually not felt by humans. It takes a much stronger earthquake for damage to occur. For example, a magnitude 6.0 earthquake is ten times larger than a magnitude 5.0, but it has 32 times the amount of energy released, so is more likely to cause damage. An earthquake registering between 6.0 and 6.9 could be considered fairly major. Above 7.0, the earthquake is considered more serious, with a larger area of damage anticipated. Loss of life is dependent on location (close to settlements etc.) as well as whether or not buildings can withstand the earth tremors. The larger the magnitude, the more likely fatalities will occur. However, earthquake statistics show that this is strongly location dependent. Some of the largest earthquakes ever recorded did not result in any casualties (see http://earthquake.usgs.gov/ for more details).

Richter scale no.	No. of earthquakes per year	Typical effects of this magnitude
< 3.4	800 000	Detected only by seismometers
3.5 - 4.2	30 000	Just about noticeable indoors
4.3 - 4.8	4 800	Most people notice them, windows rattle.
4.9 - 5.4	1400	Everyone notices them, dishes may break, open doors swing.
5.5 - 6.1	500	Slight damage to buildings, plaster cracks, bricks fall.
6.2 6.9	100	Much damage to buildings: chimneys fall, houses move on foundations.
7.0 - 7.3	15	Serious damage: bridges twist, walls fracture, buildings may collapse.
7.4 - 7.9	4	Great damage, most buildings collapse.
> 8.0	One every 5 to 10 years	Total damage, surface waves seen, objects thrown in the air.

Task 3.3.4: Richter scale (duration 10 minutes)

Answer the following questions:

- What the last earthquakes with a magnitude >8.0?
- What magnitude did the last earthquake in or near your country have?

In the past few decades it seems as if earthquake activity has strongly increased. In the 1960's around 5000 earthquake per year were recorded and that number has steadily increased till over 20000 in this century (see also figure 3.3.6). A partial explanation may lie in the fact that in the last twenty years, we have definitely had an increase in

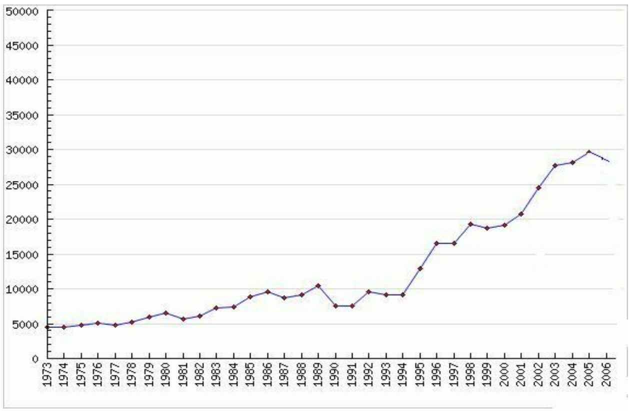


Figure 3.3.6: Number of earthquakes recorded per year (source: DL Research. - http://www.dlindquist.com

the number of earthquakes we have been able to locate each year. Lower intensity earthquakes have been noticed because of a general increase in the number of seismograph stations across the world and improved global communications. This increase has helped seismological centers to locate many small earthquakes which were undetected in earlier decades. In 1931, there were about 350 stations operating in the world; today, there are more than 8,000 stations and the data now comes in rapidly from these stations by electronic mail, internet and satellite. This increase in the number of stations and the more timely receipt of data has allowed us and other seismological centers to locate earthquakes more rapidly and to locate many small earthquakes which were undetected in earlier years. This is illustrated by the fact that the number of large earthquakes (magnitude 6.0-7.0 and greater) has remained relatively constant in the past few decades. Another effect is that people are more aware of earthquakes, because of the improvements in communications and the increased interest in the environment and natural disasters.

In seismology, the Gutenberg–Richter law expresses the relationship between the magnitude and total number of earthquakes in any given region and time period of that specific magnitude and larger.

$$\log N = A - bM$$

or

$$N = 10^{A-bm}$$

Where:

- N is the number of events in of the minimum magnitude M and above
- M is a magnitude minimum
- A and b are constants

The relationship was first proposed by Richter and Gutenberg. The constant *b* is typically equal to 1.0. This means that for every magnitude 4.0 event there will be 10 magnitude 3.0 quakes and 100 magnitude 2.0 quakes. Although the relationship is surprisingly stable for different earthquake prone areas, small deviations (max 0.15) are possible and those indicate areas with relatively more larger or smaller magnitude earthquakes for lower and higher b-values, respectively. An exception is during earthquake swarms when the b-value can become as high as 2.5 indicating an even larger proportion of small quakes to large ones. A b-value significantly different from 1.0 may suggest a problem with the data set; e.g. it is incomplete or contains errors in calculating magnitude. The "roll off" of the b-value is an indicator of the completeness of the data set at the low magnitude end (see also the exercise). The *a-value* simply indicates the total seismicity rate of the region.

3.3.4. Landslide frequency assessment

Temporal Probability-Rainfall Threshold Analysis

The most challenging aspect of landslide hazard evaluation is establishing the temporal component ie., when the slide will take place. For rainfall triggered landslides, this component forms the temporal probability of slide inducing rainfall to occur. Though landslides can be triggered by earthquake also, the rainfall induced slides are relatively most common. They are caused by the build up of high pore water pressure into the ground (Campbell, 1975). The groundwater conditions responsible for slope failures are related to rainfall through infiltration, soil characteristics, antecedent moisture content and rainfall history. It is therefore important to incorporate their effect in evaluating landslide initiation. However, their effect is totally different for condition related to slide type and volume. Shallow translational soil slips are related to intense rainfall periods ranging from 1 to 15 days, while deep slope movements (translational slides, rotational slides and complex and composite slope movements) occur in relation to longer periods of less intense rain, lasting from 30 to 90 days (Zezere et al., 2005). Intense rainfall is responsible for the rapid growth of pore pressure and loss of the apparent cohesion of thin soils, leading to failure within the soil material or at the contact with the underlying impermeable bedrock. Long duration less intense rainfall periods allow a steady rise of groundwater table and result in the occurrence of deep failures through the reduction of shear strength of affected materials. It is therefore important to establish the relation between rainfall and landslide initiation. This is being done by defining minimum and maximum threshold of rainfall require for resulting a landslide.

In general, a “threshold” is defined as the minimum or maximum level of some quantity needed for a process to take place or a state to change (White et al., 1996). A minimum threshold defines the lowest level below which a process does not occur. A maximum threshold represents the level, above which a process always occurs, i.e., there is a 100% chance of occurrence whenever the threshold is exceeded (Crozier, 1996). For ‘rainfall-induced slope failures’ a threshold may represent the minimum intensity or duration of rain, the minimum level of pore water pressure, the slope angle, the reduction of shear strength or the displacement required for a landslide to take place. Thresholds can also be defined for parameters controlling the occurrence of landslides, such as the antecedent hydrogeological conditions or the (minimum or maximum) soil depth required for failures to take place (Reichenbach et al., 1998).

The possible approaches for establishing rainfall threshold for land sliding can be grouped under three models (Armonia Report, 2005):

a) *Statistical or empirical models* (*black-box models*): where a direct correlation between rainfall height, in a defined time interval, and slope movements is analyzed without implementing physical laws that rule the transformation rainfall-infiltration-piezometric response. They are generally presented as lower limit curves separating areas with specific combinations of values of the plotted variables. More rarely, the rainfall conditions that did not result in landslides are considered to better constrain an empirical rainfall threshold.

b) *Deterministic models*: where hydrological models are used for analysis of various parameters (rainfall, run-off, effective infiltration) and hydrogeological models for analysis of piezometric height and aquifer recharge;

c) *Hybrid models*: where the above approaches are usually coupled (e.g. aquifer recharge through a hydrological model and piezometric response by means of a statistical analysis). However, the assessment of temporal and spatial variability of pore water pressure, through statistic, is only possible with routine and high resolution temporal frequency of sampling (Rezaur et al., 2002).

Rainfall triggering thresholds can be *global*, *regional* or *local*. A global threshold is obtained by using all the available data from different regions world-wide. The meaning of these thresholds consists in the possibility of having a general threshold which is independent of local conditions and of typical rainfall patterns. The easiest way to define a global threshold consists in tracing a lower limit line embracing all the recorded rainfall conditions that resulted in landslides i.e. thresholds that define the lowest level above which one or more than one landslide can be triggered (Aleotti, 2004). The threshold at a regional scale is also calculated in the same way except the data limit is defined by the region under consideration. A local rainfall threshold explicitly or implicitly considers the local climatic regime and geomorphological setting. The most commonly investigated rainfall parameters are: (i) total (“cumulative”) rainfall, (ii) antecedent rainfall, (iii) rainfall intensity, and (iv) rainfall duration.

Numerous models are available for calculating rainfall threshold for landslides. Some models are based on direct daily rainfall while others take into account the intensity-duration or soil moisture condition. Glade (1998) calculated the regional thresholds rainfall for landslide initiation on the basis of daily rainfall data in New Zealand. He calculated the maximum and minimum threshold for daily rainfall required to cause at least one or more landslides. Gabet et al., (2004) modeled the rainfall thresholds for land sliding in the Himalayas of Nepal from erosion model. The model suggested that, for a given hill slope, regolith thickness determines the seasonal rainfall necessary for failure, whereas slope angle controls the daily rainfall required for failure. Some researchers have used approaching storms, subtropical moisture flow and the existence of a warm layer, along with a 4-week antecedent rainfall and the 24-h measured rainfall for threshold calculation (Jakob et al., 2006). Rainfall threshold at a local level is successfully calculated by considering antecedent rainfall. It is well known that it is an important predisposing factor in the activation of slope failures (Wieczorek, 1987). Prolonged rainfall causes saturated zone to develop, with elevated pore-water pressures in the substrate and contributes directly to the occurrence of the landslide (Chen et al., 2006), more particularly deep-seated landslides. The influence of the antecedent rainfall is difficult to quantify as it depends on several factors, including the heterogeneity of soils (strength and hydraulic properties) and the regional climate. Variations in permeability and pore water pressure distribution within two layers can greatly influence the onset of the failure (Lourenco et al., 2006). According to Canuti et al., (1985) and Crozier (1986), the impact of a particular rainy event decreases in time due to drainage processes. In order to consider that effect in rainfall landslide analysis, Canuti et al., (1985) developed an index for sites in Italy that accounts for the calibrated cumulative rainfall. It takes into account the loss of water with preceding days. However, in using antecedent rainfall in threshold estimation, it is very important to select the right number of antecedent days. Aleotti, (2004) considered antecedent periods of 7 and 10 days for threshold calculation. On the contrary, Zezere (2005) showed that for shallow landslide episodes, the 5 days calibrated antecedent rainfall (CAR) was required for the failure and 30 days for deep landslide events. Kim et al., (1992) and Glade, (1997) have demonstrated that, in certain regions, antecedent conditions have a major influence on the initiation of landslides, whereas in other regions, storm characteristics appear to dominate. Alcantara-Ayala, (2004) introduced the concept of rainfall event and cycle and total coefficient, as defined as the ratios between event and antecedent rainfalls, respectively, and the mean annual rainfall, are summed to give a total coefficient. For landslide-triggering rainfalls in the Sierra Norte, he calculated the values for the total coefficient of 0.8 and 0.4 for beginning and end of the wet season, respectively. Chleborad (2006), made a scatter plot between the 3 days precipitation immediately prior to the landslide event and 15 days antecedent precipitation that occurred prior to the 3 days incorporating ideas of antecedent wetness and unusual recent rainfall. From this scatter plot, an approximate lower-bound precipitation threshold was defined. He also computed the probabilities based on the number of days on which one or more landslides occurred and rainfall exceeded the cumulative 3-day/15-day precipitation threshold (CT) all or part of the day at one rain gage. For validation of threshold he carried out an exceedance test. The test indicated that, of the 172 days on which landslides in the database occurred, only 53 percent had CT exceedance. The CT failed to predict 47 percent of days on which landslides occurred. He found that a majority of landslides that occurred below the CT had a reported or identified human influence. Failure to predict greatly decreases if the landslide intensity increases.

Crozier et al., (1999) used frequency-magnitude analysis of rainfall events that resulted into slides for calculating threshold and return period. He stressed to distinguish between first-time failures and reactivations of existing landslides as the first-time failures, in a given material, need to overcome higher material strength values than in the case of reactivations. Remier (1995), for example, has noted that two-thirds of the landslides entering reservoirs are reactivations of existing slides. Giannecchini, (2005) also considered rainfall events that have not resulted in any slides for threshold calculation. He analyzed and divided all 152 main rainfall events which occurred in the southern

Apuan area in the 1975–2002 period, into three groups on the basis of the extents of the effects caused by the rainstorms:
Events A- that induced several shallow landslides and floods;
Events B- that locally induced some shallow landslides and small floods and;
Events C – that has no information about the effects induced.
He used duration/intensity, intensity/Normalised Storm Rainfall (NSR) (Corominas, 2001) and duration/NSR relationships and depicted two threshold curves, which could separate field with different degrees of stability.
Crozier, (1999) and Godt (2006) used model, referred to as the Antecedent Water Status Model, that calculates an index of soil water, by running a daily water balance and applying a soil drainage factor to excess precipitation, over the preceding ten days. Together with the daily rainfall input, the soil water status was used empirically to identify a threshold condition for landslide triggering. Glade, (1997) showed that almost all major slope failures occur at water contents in excess of field moisture capacity, indicating that the development of positive pore water pressures is critical for failure.
An alternative approach employed in some regional climate/landslide research, involves the delimitation of triggering thresholds by using characteristics of the triggering storm such as rainfall intensity and duration (Caine, 1980; Brand et al., 1984; Keefer et al., 1987; Julian and Anthony, 1994; Wilson and Wieczorek, 1995). Wieczorek (1987) studied the intensity-duration characteristics of storms that initiated landslides, and concluded that antecedent rainfall is important in determining ***whether*** landslides would initiate, while rainfall intensity and duration are important in determining ***where*** landslide would occur. This model, though used very frequently, fails to account for those landslides that can occur several hours after the end of the rainfall event, and it also does not take into account site specific rainfall conditions. Besides, this model has certain other limitations. It does not consider the antecedent moisture conditions. For this reason, it is less suited to predict the occurrence of deep-seated landslides or of slope failures triggered by low-intensity rainfall events. Besides, intensity-duration thresholds require data of high quality and resolution (at least hourly rainfall data), which are available only locally.
Once the minimum threshold of rainfall is established, the next important step is to calculate the temporal probability of the event to occur. The most established way to achieve this is the assessment of landslide return times. The return period and probability of such events was computed either directly from frequency analysis or using Poisson/ binomial distribution (Guzzetti et al., 2005) or by using Gumbel distribution (Zezere, 2005), a statistical method that establishes relation between the probability of the occurrence of a certain event, its return period and its magnitude (Gumbel, 1958).
In terms of speed and low cost, the statistical or empirical based approach appears to be more convenient. The main advantage of empirical rainfall thresholds lies in the fact that rainfall is relatively simple and inexpensive to measure over large areas. Where information on landslides and rainfall is available, plots can be prepared and threshold curves can be fitted as lower bounds for the occurrence of slope failures. By incorporating antecedent rainfall and ground water variation (measured from physically based dynamic models in different rainfall scenario), there is a certain scope for improving the predictive quality of the threshold.
Limitations:
Operational limitations for the definition of rainfall thresholds refer mostly to the availability of data of adequate quality, resolution and recording length. During an event, a dense network of recording rain-gauges is required, and immediately after the event a detailed inventory of landslides must be compiled. Many times a single event found to be very intense ("extreme" i.e., with a return period exceeding 100 years) and not representative of the local instability conditions. Thresholds based on such extreme events can underestimate the probability of failures. Hence, a long record of rainfall measurements and many events resulting from different meteorological conditions should be analyzed to define reliable rainfall thresholds. Unfortunately, information on an adequate number of events is seldom available.

Temporal probability of landslide initiation

It is assumed that the probability of occurrences of landslides is directly related to the probability of occurrence of the triggering rainfall: the threshold rainfall. The threshold is the minimum amount of rainfall needed to trigger landslides. The input of the threshold rainfall is the time series of daily rainfall $R_d(t)$, expressed in mm day^{-1}. Theoretically, for a landslide {L} to initiate, the threshold must be exceeded which in turn relates to R(t) by some function:

$$R(t) = f[R_d(t), R_{ad}(t)]$$

where, the function R(t) is the amount of rainfall in a given period (e.g. daily), and $R_{ad}(t)$ is the antecedent rainfall. This function of R defines the probability of occurrence of the landslide L: P{L}. If R_T is the threshold value of R then

$$P[L \mid R > R_T] = 1$$

$$P[L \mid R \le R_T] = 0$$

Thus, the landslide always occurs when R exceeds R_T and does not occur when value of R is lower than or equal to R_T. In the former case, the probability of occurrences of landslide P{L} depends on the exceedance probability of $P[R > R_T]$.

$$P[L] = P[R > R_T]$$

In reality, however, the threshold may be exceeded without resulting in any landslide. This may be attributed to some other factors which locally influence the initiation of a landslide and are not fully understood (Aleotti and Chowdhury, 1999). This difference can be reduced when the final probability P_N is viewed as the conditional probability of a given threshold exceedance $[P\{R > R_T\}]$ and the probability of occurrence of a landslide [P{L}] given the exceedance (Floris and Bozzano, 2008). Thus, the probability of landslide occurrences can be given by the intersection of two probabilities

$$P\{(R>R_T) \cap L\} = P\{R>R_T\} P\{L \mid R>R_T\}$$

This means that the probability of occurrence of both $\{R > R_T\}$ and {L} is equal to the probability of $\{R > R_T\}$ multiplied by the probability of occurrence of {L}, assuming that $\{R > R_T\}$ has already occurred. The probability of $\{R > R_T\}$ can be obtained by determining the exceedance probability of threshold rainfall and probability of $\{L \mid R>R_T\}$ rely on the frequency of occurrence of landslide after the threshold has been exceeded. The annual exceedance probability (AEP) is the estimated probability that an event of specific magnitude will be exceeded in any year (Fell et al., 2005). The AEP of threshold $[P\{R > R_T\}]$ in a given rain gauge was determined using a Poisson distribution model. This model is extensively used for calculating the exceedance probability of landslides (Coe et al., 2000; Coe et al., 2004; Guzzetti et al., 2005) using landslide frequency estimates. According to the Poisson model, the exceedance probability or the probability of experiencing one or more landslides during time '*t*' is given by

$$P[N(t) \ge 1] = 1 - \exp(-t/\mu)$$

where, μ is the mean recurrence interval between successive landslides, which can be obtained from the multi-temporal landslide inventory data.

To determine the annual exceedance probability of the rainfall threshold for a particular area, the threshold rainfall (R_T) is calculated from the threshold equation and the result is subtracted from the daily rainfall (R). Each phase of continuous positive values ($R>R_T$) is considered as the period of maximum likelihood of landslide initiation and its recurrences are used in the above equation for calculating AEP. Different thresholds can be obtained for rainfall that can trigger a certain number of landslides in a given area.

Selftest

In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question: Frequency assessment
Which type of hazard does not have a clear magnitude-frequency relation for a particular location (for example, for a house)?
A) Subsidence due to collapse of underground cavities
B) Earthquakes
C) Floods
D) Rainfall

Question: frequency assessment
What is the most appropriate way for the generation of a magnitude-frequency relation for earthquakes?
A) Use the Gumbel distribution
B) Use the Gutenberg-Richter distribution
C) Use the log-Pearson distribution
D) Use a normal distribution

Question: hazard assessment
Which statement concerning statistical and an expert-based method for hazard assessment is true:
A) A statistical method uses weights derived from the correlation between past hazard events and causal factors, whereas an expert-based method tries to model the process physically.
B) A statistical method tries to model the process physically, whereas an expert-based method uses qualitative weights derived from expert opinion.
C) An expert-based method tries to find a correlation between past hazard events and causal factors, whereas a statistical method tries to model the process physically.
D) A statistical method uses weights derived from the correlation between past hazard events and causal factors, whereas an expert-based method uses qualitative weights derived from expert opinion.

Question: Climate change and risk
Which of the following statements is true? The effects of climate change on risk are expected to be highest in these areas because of:
A) Pacific islands because of changes in local risk of extremes
B) Desert areas because of changes in average climate
C) Desert areas because of changes in local risk of extremes
D) Pacific islands because of changes in average climate

Question: Methods for risk assessment
Which method for risk assessment would you recommend in the following situations (briefly explain why)
A. In case we would like to indicated the areas with the highest social vulnerability, using a hazard footprint map (without having information on return periods) and a database containing the characteristics of the population (age, gender, literacy rate etc.)
B. In case we would have three flood hazard footprints, each one with information on the return period and the water depth/flow velocity of the event, and an element at risk database with building information containing different building types.
C. In case you would have a single hazard map with qualitative classes, and a population density map (also classified into qualitative classes)

Further reading:

For more information about the concept of hazard and disaster reduction strategies, check the publications of the United Nations International Strategies for Disasters Reduction (UN-ISDR) publications: http://www.unisdr.org/eng/about_isdr/bd-isdr-publications.htm.

Other interesting definitions for concepts related to hazard and hazard assessment can be found in Coburn et Al. 1994: http://info.worldbank.org/etools/docs/library/229567/Course%20Content/Reading/Introduction%20Reading%20-%20VulnerabilityAndRiskAssessmentGuide.pdf

If you are interested in deepening your knowledge about FEMA-FIRMs program, read the following document: http://www.pdhonline.org/courses/l129/l129content.pdf.

Information related to the hazard types have been partially extracted from the US FEMA Multi-Hazard Identification and Risk Assessment (MHIRA); for further studies, the entire document can be downloaded here: http://www.fema.gov/library/viewRecord.do?id=2214

Another source of information about hazard types used in writing this guide book is the FEMA Mitigation Planning How-To Guide2, the second guide in the State and Local Mitigation Planning How-To Series: http://www.fema.gov/library/viewRecord.do?id=1880.

The Intergovernmental Panel on Climate Change (IPCC) is the official organization reporting on climate change. They have also made http://www.ipcc.ch/ipccreports/ar4-wg2.htm

The Climate Centre of the IFRC is studying the effects of climate change on disasters and focuses on climate change adaptation. They have produced an interesting summary paper on the effects of climate change: http://www.climatecentre.org/downloads/File/reports/RCRC_climateguide.pdf

Journal papers

Bates, P.D. and De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. Journal of Hydrology, 236(1-2): 54-77.

Coburn, A.W., Sspence, R.J.S. and Pomonis, A., 1994. Vulnerability and Risk Assessment. Cambridge Architectural Research Limited. The Oast House, Cambridge, U.K.

Dankers, R. and Feyen, L., 2008. Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. J. Geophys. Res., 113.

Demeritt, D. et al., 2007. Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting. Environmental Hazards, 7(2): 115-127.

Persson, A. and Grazzini, F., 2007. User Guide to ECMWF forecast products, Shinfield Park (UK).

Van Der Knijff, J. and De Roo, A., 2008. LISFLOOD – distributed water balance and flood simulation model, (Revised User Manual 2008).

•Choice sessions•

The following section consists of five choice sessions:

3L: Landslide hazard
3V: Volcanic hazard
3E: Earthquake hazard
3F: Flood hazard
3C: Coastal hazard

Each of these topics has a separate theory part and a separate exercise. Select one of these five sessions. You are of course free to do more then one session.

Guide book
Choice session 3.L:
Landslide susceptibility and hazard assessment

Objectives
After this session you should be able to:
- Explain impact of landslides;
- Differentiate the types of landslides, and outline the classification method;
- Explain causal factors of landslides;
- Explain the difference between inventory, susceptibility, hazard and risk for landslides
- Understand the spatial data used for landslide hazard assessment, including Remote Sensing
- Explain which method (heuristic, statistical, deterministic) can be best used in which situation;
- Use ILWIS for carrying out a basic landslide susceptibility assessment with statistical and deterministic methods;
- Understand the input needed to use landslide hazard maps in risk assessment;

This session contains the following sections and tasks:

Section	Topic	Task	Time required		
3.L.1	Introduction: showing the impact of landslides		Day 1	0.25 h	0.75 h
		3.L.1: Using World Hotspots data		0.5 h	
3.L.2	Definition and classification of landslides			0.5 h	2 h
		3.L.2: Landslide handbook		1 h	
		3.L.3: Landslide interpretation		0.5 h	
3.L.3	Processes and geomorphological setting		Day 2	0.5 h	1.25 h
		3.L.4:Landslide causes		0.25 h	
		3.L.5: Landslide videos		0.5 h	
3.L.4	Spatial data for landslide hazard assessment			1 h	2.25 h
		3.L.6: Landslide data and methods		0.25 h	
		3.L.7: Using permanent scatterers		0.25 h	
		3.L.8: Landslide inventory mapping and monitoring		0.25 h	
		3.L.9: Costs for event-based landslide maps		0.75 h	
		3.L.10: Prioritizing environmental factors		0.25 h	
3.L.5	Landslide susceptibility assessment		Day 3	1 h	10 h
		3.L.11: RiskCity exercise on statistical landslide susceptibility assessment		5 h	
		3.L.12: RiskCity exercise on deterministic landslide susceptibility assessment	Day 4	4 h	
3.L.6	From Susceptibility to hazard			0.5 h	0.5h
3.L.7	Self test	Selftest that should be submitted		1.25 h	1.25h
		Total			**16.5 h**

The session ends with a test, and the answers of this should be submitted through Blackboard.

3.L.1 Introduction

Landslides are recognized as the third type of natural disaster in terms of worldwide importance. Due to natural conditions or man-made actions, landslides have produced multiple human and economic losses. Inventories conducted between 1964–1999 show a steady increase in the number of landslides disasters worldwide. Individual slope failures are generally not so spectacular or so costly as earthquakes, major floods, hurricanes or some other natural catastrophes. This is illustrated in Table 3.L.1, which shows the statistics of landslides disasters per continent from April 1903 till January 2007 from the Emergency Disaster Database, EM-DAT, (OFDA/CRED, 2007). In this period landslides have caused 57,028 deaths and affected more than 10 million people around the world. The quantification of damage is more than US$5 billion. These losses have driven the politicians and the scientific community to produce disaster risk reduction plans for landslides, which imply first of all landslide risk assessment.

Table 3.L.1 World statistics for landslides. Source: EM-DAT database for the period 1903-2007.

Continents	Events	Killed	Injured	Homeless	Affected	Total Affected	Damage US (000's)
Africa	23	745	56	7,936	13,748	21,740	No data
Americas	145	20,684	4,809	186,752	4,485,037	4,676,598	1,226,927
Asia	255	18,299	3,776	3,825,311	1,647,683	5,476,770	1,534,893
Europe	72	16,758	523	8,625	39,376	48,524	2,487,389
Oceania	16	542	52	18,000	2,963	21,015	2,466
Total	**511**	**57,028**	**9,216**	**4,046,624**	**6,188,807**	**10,244,647**	**5,251,675**

Most of the damage and a considerable proportion of the human losses associated with earthquakes and meteorological events are caused by landslides, although these damages are attributed to the main event, which leads to a substantial underestimation in the available statistical data on landslide impact. This is illustrated in figure 3.L.1 which shows the ruined city of Beichuan in China, destroyed mainly by landslides during the earthquake in 2008. Of the total number of casualties during this earthquake (80000) one third is estimated to have been killed by landslides.

Figure 3.L.1: Illustration of the devastating effects of landslides related to the Wenchuan earthquake in 2008. The city of Beichuan was destroyed by 2 large co-seismic landslides, later on flooded by a landslide dammed lake, and the remains were destroyed later on by debris flows during the first rainy season after the earthquake.

Task 3.L.1: Landslide impact (duration 40 minutes)

The Worldbank has carried out a worldwide study on the impact of landslides and other natural hazard in the so-called Hotspots project. You can see the map results in a WebGIS browser from the following website:
http://geohotspots.worldbank.org/hotspot/hotspots/disaster.jsp
If the WebGIS doesn't work you can also consult the maps on the following website: http://www.ldeo.columbia.edu/chrr/research/hotspots/
Check out the landslide impacts in your country, region. Are these in accordance with your expectations?

3.L.2 Definition and classification

In literature a wide variety of names have been used for the denudational process whereby soil or rock is displaced along the slope by mainly gravitational forces. The most frequently used are: *Slope movement; Mass movement; Mass wasting; Landslide*. In the last decades *landslide* is the term most used, though in the narrow sense of the word (sensu strictu) it only indicates a specific type of slope movement with a specific composition, form and speed.

Definition.
Landslide is the movement of a mass of rock, debris or earth, down a slope, when shear stress exceeds shear strength of the material.

The most important classification of landslides was made by Varnes in 1978, and is based on a combination of the type of movement and material type. This was adapted in a new classification of Cruden and Varnes (1996). It nominates primarily type of movement, and secondarily type of material. Factors as activity and movement type, and depth can be added as an adjective to the classification name. For example a moderately rapid, shallow, moist, active, single translational soil slide. This classification was adopted by the IAEG Commission UNESCO Working Party on World Landslide Inventory (WP/WLI). Table 3.L.2 gives an overview of the classification, and figure 3.L.2 an illustration of the main features of a landslides

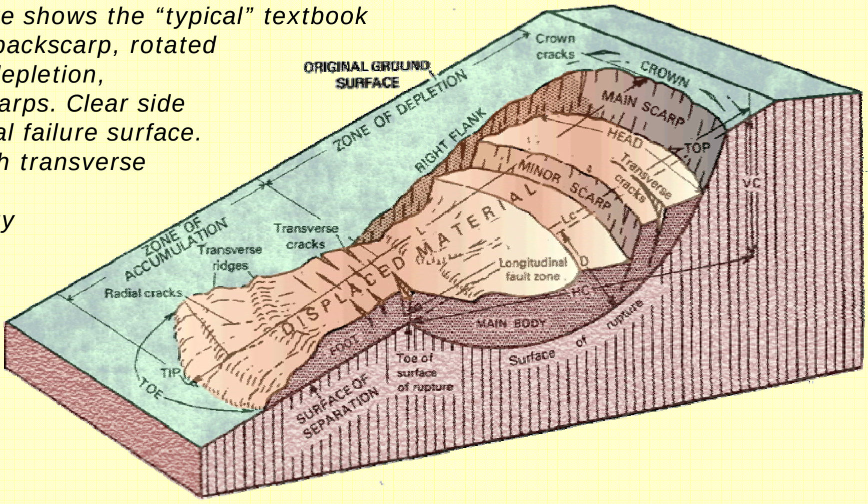


Figure 3.L.2: The figure shows the "typical" textbook landslide with a clear backscarp, rotated blocks in the zone of depletion, separated by minor scarps. Clear side scarps, and a rotational failure surface. Displaced material with transverse cracks in the zone of accumulation. In reality there are many different types and many will not look like this.

The landslide classification displayed in table 3.L.2 is further illustrated with a description of the landslide activity in table 3.L.3, and Figure 3.L.3.

Figure 3.L.3: Illustration of states of activity of a landslide. See table Table 3.L.3 for explanation of the terms

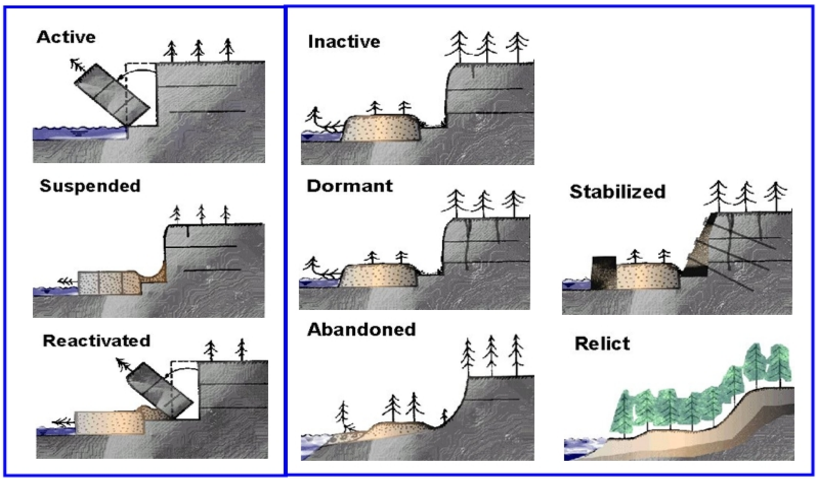


Table 3.L.4 presents examples of the landslide types and the characteristics that can be used to interpret them based on visual image interpretation. Three types of characteristics are shown: morphology, vegetation and drainage characteristics.

		Type of Material		
			Engineering Soils	
Type of Movement		Bedrock	Predominantly Coarse	Predominantly Fine
Fall		Rock Fall	Debris Fall	Earth Fall
Topple		Rock Topple	Debris Topple	Earth Topple
Slide	Rotational	Rock Slump	Debris Slump	Earth Slump
	Translational	Rock Slide / Block slide	Debris Slide	Earth Slide
Spread		Rock Spread	Debris Spread	Earth Spread
Flow		Rock Flow	Debris Flow	Earth Flow
Complex		Combination of Two or More Principal Types of Movement		

Activity		
State	Distribution	Style
Active	Advancing	Complex
Reactivated	Retrogressive	Composite
Suspended	Widening	Multiple
Inactive	Enlarging	Successive
Dormant	Confined	Single
Abandoned	Diminishing	
Stabilized	Moving	
Relict		

Description of Movement			
Rate		Water Content	Depth
Extremely Rapid	m/s	Dry	Very shallow (<2 m)
Very Rapid	m/min	Moist	Shallow (<5 m)
Rapid	m/hr	Wet	Deep (>5 m)
Moderate	m/month	Very Wet	
Slow	m/year		
Very Slow	mm/year		
Extremely Slow	< mm/year		

Table 3.L.2: Classification according to Cruden and Varnes(1996)

	State	Description
Active	Active	currently moving
	Suspended	moved within the last twelve months but is not active at present
	Re-activated	active landslide that has been inactive
Inactive: not moved within the last twelve months	Dormant	inactive landslide that can be reactivated by its original causes or other causes
	Abandoned	inactive landslide that is no longer affected by its original causes
	Stabilized	inactive landslide that has been protected from its original causes by artificial remedial measures
	Relict	inactive landslide that developed under geomorphological or climatic conditions considerably different from those at present

Distribution	Description
Advancing	the rupture surface is extending in the direction of the movement
Retrogressive	the rupture surface is extending in the direction opposite to the movement of the displaced material
Enlarging	the rupture surface of the landslide is extending in two or more directions
Diminishing	the volume of the displacing material is decreasing
Confined	there is a scarp but no rupture surface is visible at the foot of the displaced mass
Moving	the displaced material continues to move without any visible change in the rupture surface and the volume of the displaced material
Widening	the rupture surface is extending into one or both flanks of the landslide

Table 3.L.3: Landslide activity states and distribution.

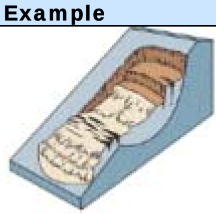
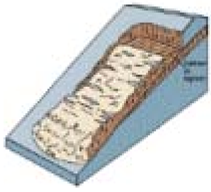
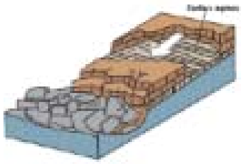
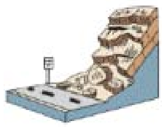
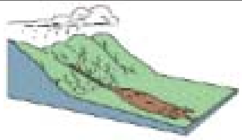
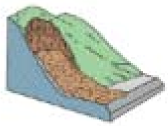
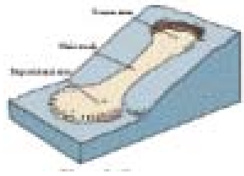
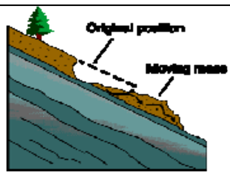
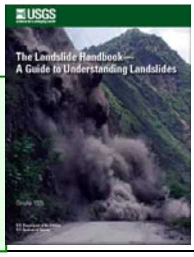
Type	Characteristics	Example
Rotational Slide	**Morphology:** Abrupt changes in slope morphology, characterized by concave (niche) - convex (run-out lobe) forms. Often step-like slopes. Semi-lunar crown and lobate frontal part. Backtilting slope facets, scarps, hummocky morphology on depositional part. D/L ratio 0.3 - 0.1 , **Vegetation:** Clear vegetational contrast with surroundings, the absence of landuse indicative for activity. Differential vegetation according to drainage conditions. **Drainage:** Contrast with not failed slopes. Bad surface drainage or ponding in niches or backtilting areas. Seepage in frontal part of run-out lobe.	
Translational slide	**Morphology:** Joint controlled crown in rockslides, smooth planar slip surface. Relatively shallow, certainly in surface mat. over bedrock. D/L ratio <0.1 and large width. Run-out hummocky rather chaotic relief, with block size decreasing with larger distance. **Vegetation:** Source area and transportational path denudated, often with lineations in transportational direction. Differential vegetation on body, in rockslides no landuse on body. **Drainage:** Absence of ponding below the crown, disordered or absence of surface drainage on the body. Streams are deflected or blocked by frontal lobe.	
Rock Block slide	**Morphology:** Joint controlled crown in rockslides, smooth planar slip surface. Relatively shallow, certainly in surface mat. over bedrock. D/L ratio <0.1 and large width. Run-out hummocky rather chaotic relief, with block size decreasing with larger distance. **Vegetation:** Source area and transportational path denudated, often with lineations in transportational direction. Differential vegetation on body, in rockslides no landuse on body. **Drainage:** Absence of ponding below the crown, disordered or absence of surface drainage on the body. Streams are deflected or blocked by frontal lobe	
Rockfall	**Morphology:** Distinct rockwall or free face in association with scree slopes (20 -30 degrees) and dejection cones. Jointed rock wall (>50 degrees) with fall chutes. **Vegetation:** Linear scars in vegetation along frequent rock fall paths. Vegetation density low on active scree slopes. **Drainage:** No specific characteristics.	
Debrisflow	**Morphology:** Extensive coverage of materials with high content of mud and boulders in a fan shaped form, either deposited on alluvial fans at the outlet of valleys, or on the foot of a slope. **Vegetation:** absence of vegetation everywhere; sometimes large trees still stand and are engulfed in flow, or tree stumps still there. **Drainage:** disturbed on body; original streams blocked or deflected by flow.	
Debris avalanche	**Morphology:** relatively small, shallow niches on steep slope (>35 degrees) with clear linear path; body frequently absent as it eroded away by stream **Vegetation:** Niche and path are denuded or covered by secondary vegetation. **Drainage:** Shallow linear gully can originate on path of debris aval.	
Earthflow	**Morphology:** One large or several smaller concavities, with hummocky relief in the source area. Main scars and several small scars resembles slide type of failure. Path following streamchannel and body is infilling valley, contrasting with V shaped valleys. Lobate convex frontal part. Irregular micromorphology with pattern related to flow- structures. D/L ratio very small **Vegetation:** Vegetational on scar and body strongly contrasting with surroundings, landuse absent if active. Linear pattern in direction of flow. **Drainage:** Ponding frequent in concave upper part of flow. Parallel drainage channels on both sides of the body in the valley. Deflected or blocked drainage by frontal lobe.	
Flowslide	**Morphology:** Large bowlshaped source area with step-like or hummocky internal relief. Relative great width. Body displays clear flowstructures with lobate convex frontal part (as earthflow). Frequent associated with cliffs (weak rock) or terrace edges. **Vegetation:** Vegetational pattern are enhancing morphology of scarps and blocks in source area. Highly disturbed and differential vegetation on body. **Drainage:** As on earthflows, ponding or deranged drainage at the rear part and deflected or blocked drainage by frontal lobe.	

Table 3.L.4: Main landslide types and characteristics as can be observed from image interpretation.



Task 3.L.2: Landslide information (duration 60 minutes)
Download the landslide handbook published by USGS and CGS: Highland, L.M., and Brobowsky, Peter, 2008, The landslide handbook—A guide to understanding landslides: Reston, Virginia, U.S. Geological Survey Circular 1325, 129 p. Link: http://pubs.usgs.gov/circ/1325/

Interpreting landslides through visual image interpretation

The characteristics indicated in the table before cannot all be directly interpreted from image interpretation. Also in the field it is sometimes difficult to determine these afterwards. Therefore, when doing image interpretation often a simplified checklist is used which is illustrated in figure 3.L.4. A simplified checklist that can be used in image interpretation is given below. The figure also shows an example of a landslide and the way it is interpreted using polygons with identifiers and an associated attribute table.

Figure 3.L.4: Example of the use of a simple checklist used in image interpretation.

Interpreted image

Checklist for landslide interpretation

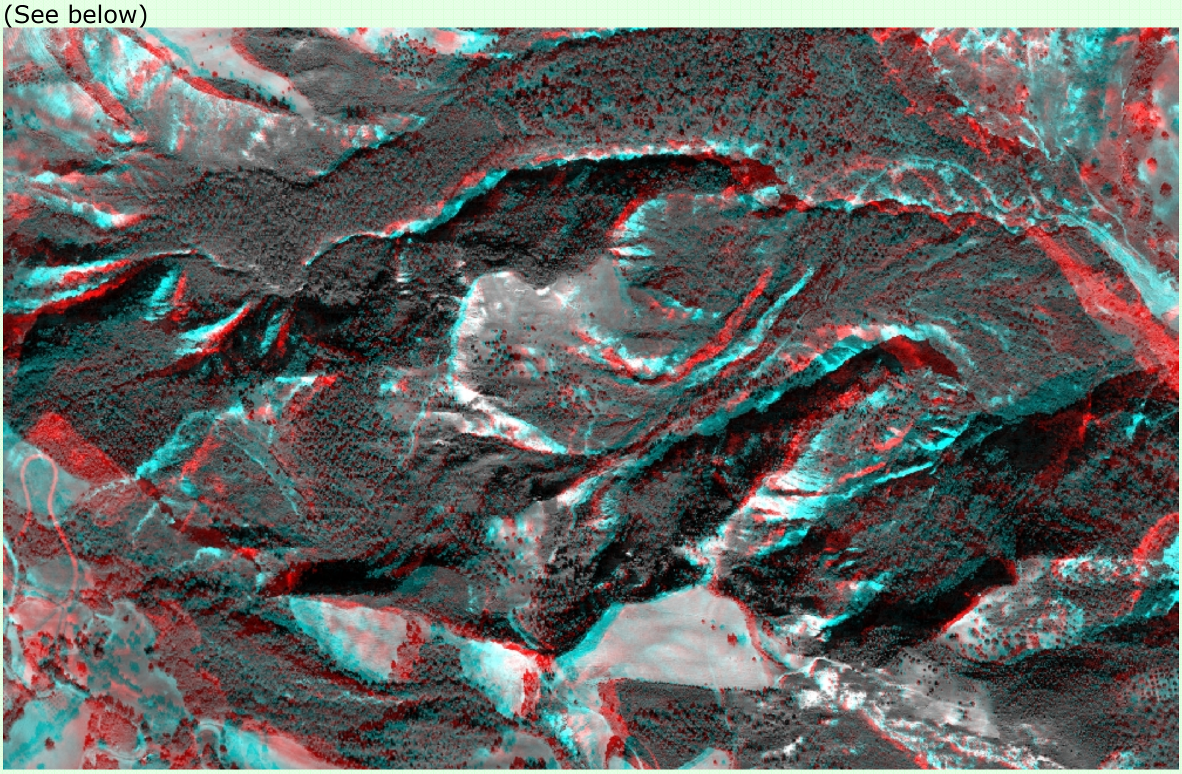
Type	*Subtype*	*Activity*	*Depth*	*Body*
Fall Topple Slide Spread Flow	Rotational Translational Complex Unknown	Stable Dormant Active	Surficial Deep	Scarp Body

Attribute table linked to interpreted image

Slide	*Part*	*Type*	*Subtype*	*Activity*	*Depth*	*Body*
001	01	Slide	Rotational	Active	Deep	Body
001	02	Slide	Rotational	Active	Deep	Scarp

Task 3.L.3: Landslide interpretation (duration 30 minutes)

Below you see an anaglyph image of a landslide area in Italy. Use the red-blue glasses provided to you for the course and interpret the landslides. Try to use the same approach as indicated in the figure above. Map a few landslides in this way, and describe their characteristics in a table (See below)

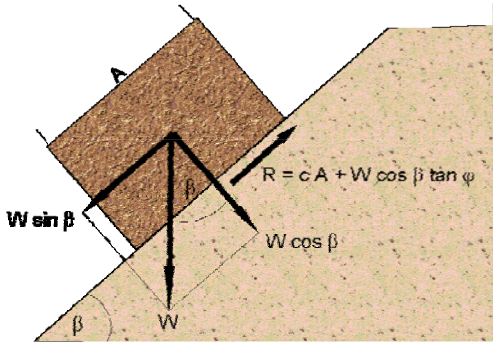


Slide	*Part*	*Type*	*Subtype*	*Activity*	*Depth*	*Body*

3.L.3 Processes and geomorphological setting

The occurrence of landslides is the consequence of a complex field of forces (stress is a force per unit area) that is active on a mass of rock or soil on the slope.

Figure 3.L.5: Forces involved in mass movement.



A = Shear surface [m2];
W = Gravitational force [N];
Wsinβ/A = shear stress [KPa=kN/m2];
s = c + σ tan ϕ : Shear strength
σ = normal stress = W cos β / A
c = cohesion (KPa)
ϕ = angle of internal friction (degrees)

The relationship $s = c + \sigma \tan \phi$ *is what is called the Mohr-Coulomb relationship*
The degree of slope hazard can be expressed by the Safety Factor (F) which is the ratio of the forces that make a slope fail and those that prevent a slope from failing. This is shown in the equation below.

$$F = \frac{c\,A + W \cos\beta \tan\phi}{W \sin\beta}$$

F < 1 unstable slope conditions,
F = 1 slope is at the point of failure,
F > 1 stable slope conditions.

This is the very basic equation, which doesn't take many additional factors into account such as the effect of soil moisture, groundwater table, differences in material types, and seismic acceleration. Basically, slopes become unstable when one of the two components changes, as shown in table 3.L.5.

Table 3.L.5*: Major contributing factors to instability.*

Increase of shear stress	Decrease of material strength
Removal of lateral and underlying support (erosion, previous slides, movement of adjacent areas, road cuts and quarries)	A decrease of material strength (weathering, change in state of consistency)
An increase of load (weight of rain/snow, fills, vegetation, buildings)	Changes in intergranular forces (pore water pressure, solution)
An increase of lateral pressures (hydraulic pressures, roots, crystallization, swelling of clay)	Changes in material structure (decrease of the strength of the failure plane, fracturing due to unloading)
Transitory stresses (earthquakes, vibrations of trucks, machinery, blasting)	
Regional tilting (geological movements)	

The overall component of forces, linked with slope morphology and geotechnical parameters of the material, defines the specific type of landslide that may occur.
The potential causes of landslide can be subdivided into geological causes, morphological causes, physical causes, and human causes. Landslides can also be seen as controlled by **internal factors** that make the slope favourable to instability and **triggering factors** that actually trigger the landslide to happen.

Task 3.L.4: Landslide causes (duration 15 minutes)

Mention some examples of landslide causes?
Differentiate between internal factors and triggering factors.

In this section also some examples are given of landslides together will illustrations and videos. The videos can be seen on Youtube, but are also available on the course DVD.

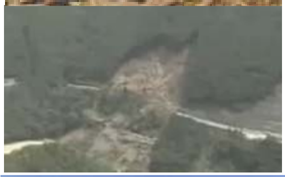
Introduction to landslides

This is a National Geographic movie which give a good introduction into landslides and the factors that cause them.
http://www.youtube.com/watch?v=mknStAMia0Q&NR=1

Riding the storm

This is a video by the USGS explaining the landslide problems in the San Francisco Bay region, with examples of how landslides affect the daily lives of the inhabitants of the region. A short version can be seen at: http://www.youtube.com/watch?v=2-e2JjktQ6A You can download the full version of the movie at:
http://landslides.usgs.gov/learning/movie/

Translational landslide example from Japan



This is an example of a translational landslide, which was predicted to occur. That is why video teams were able to film the event. From this movie the movement of the landslide as if displaced along a conveyor belt is very striking.
http://www.youtube.com/watch?v=ManGanavlL8

Landslides and debrisflows in Sarno, Italy

On May 5 1998 a series of landslides were triggered due to heavy rainfall in pyroclastic deposits in the province of Avellino and Salerno in the Campania region of Southern Italy. The landslides turned into a series of debrisflows, which hit number of towns in the area, especially the town of Quindici, causing around 140 casualties.
http://www.youtube.com/watch?v=7iZzNL1VUWU&feature=related

SLIDE

A very nice internet site with videos on various landslides from British Columbia in Canada. It uses Flash player, and you need a fairly high speed internet connection to view it. It also contains a summary of information on the tools to investigate landslides (Geologist's tool). Other sections are on landslide types and on planning and safety.
http://www.knowledgenetwork.ca/slide/

Wikipedia on landslides

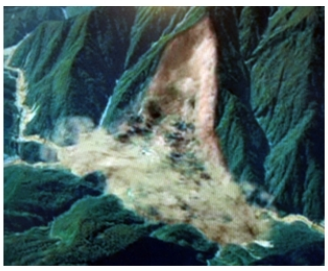
Find out what Wikipedia has on landslide, in particular related to historical landslides. Check out the website:
http://en.wikipedia.org/wiki/Landslide

Massive landslide causing lake breakout in Malaysia.

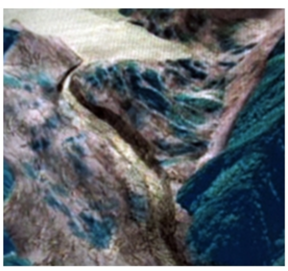
http://www.youtube.com/watch?v=H6Ma0SVjMHA&feature=related

Task 3.L.5: Landslide examples (duration 30 minutes)
Check out the landslide videos by following the indicated links above.
Find also other landslide related videos.
You can also find several related landslide videos on the DVD of the course, in:
Background materials\session 03\ landslides
The following videos are there:

- Debrisflows and landslides in Japan
- Rockfall and landslides in the US
- Rock avalanche in Italy
- Simulation of an earthquake induced landslide causing damming of a river, followed by a break of the dam and a flood wave going in the downstream area.



Earthquake induced landslide damming the river



Landslide dam eroded and broken causing flood wave

Massive flooding in downstream area

3.L.4. Spatial data for landslide hazard assessment

The first extensive papers on the use of spatial information in a digital context for landslide susceptibility mapping date back to the late seventies and early eighties of the last century. Nowadays, practically all research on landslide susceptibility and hazard mapping makes use of digital tools for handling spatial data such as GIS, GPS and Remote Sensing. These tools also have defined, to a large extent, the type of analysis that can be carried out. It can be stated that GIS has determined, to a certain degree, the current state of the art in landslide hazard and risk assessment. Figure 3.L.6 gives a schematic overview of the various components of landslide risk assessment.

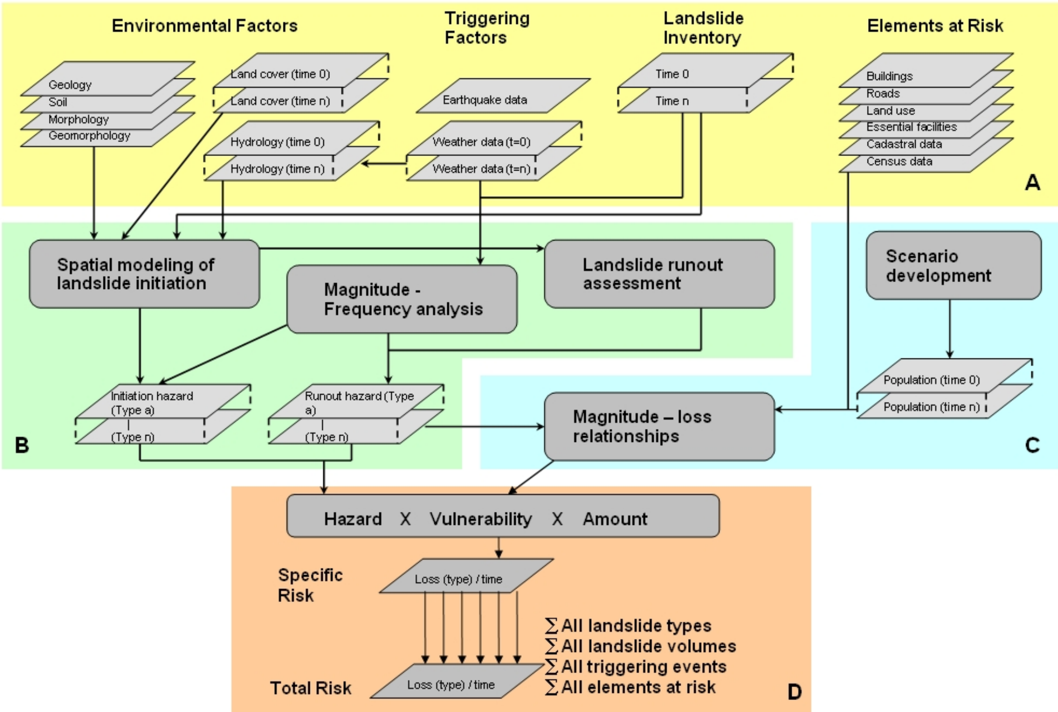


Figure 3.L.6: Schematic representation of the landslide risk assessment procedure. A: Basic data sets required, both of static, as well as dynamic (indicated with "time…") nature, B: Susceptibility and hazard modeling component, C: Vulnerability assessment component, D: Risk assessment component, E: Total risk calculation in the form of a risk curve. See text for further explanation

Table 3.L.7 gives a schematic overview of the main data layers required for landslide susceptibility, hazard and risk assessment (indicated in the upper row of Figure 3.L.6). These can be subdivided into four groups: landslide inventory data, environmental factors, triggering factors, and elements at risk. Of these, the landslide inventory is by far the most important, as it should give insight into the location of landslide phenomena, the types, failure mechanisms, causal factors, frequency of occurrence, volumes and the damage that has been caused. Landslide inventory databases should display information on landslide activity, and therefore require multi-temporal landslide information over larger regions. The environmental factors are a collection of data layers that are expected to have an effect on the occurrence of landslides, and can be utilized as causal factors in the prediction of future landslides. The list of environmental factors indicated in figure 3.L.7 is not exhaustive, and it is important to make a selection of the specific factors that are related to the landslide types and failure mechanisms in each particular environment. It is not possible to give a prescribed uniform list of causal factors. The selection of causal factors differs, depending on the scale of analysis, the characteristics of the study area, the landslide type, and the failure mechanisms. 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 (See figure 3.L.7). Examples of static data sets are related to geology, soil types, geomorphology and morphography. The time frame for the updating of dynamic data may range from hours to days, for example for meteorological data and its effect on slope hydrology, to months and years for land use

and population data (see figure 3.L.7). Landslide information needs to be updated continuously, and land use and elements at risk data need to have an update frequency which may range from 1 to 10 years, depending on the dynamics of land use change in an area. Especially the land use information should be evaluated with care, as this is both an environmental factor, which determines the occurrence of new landslides, as well as an element at risk, which may be affected by landslides.

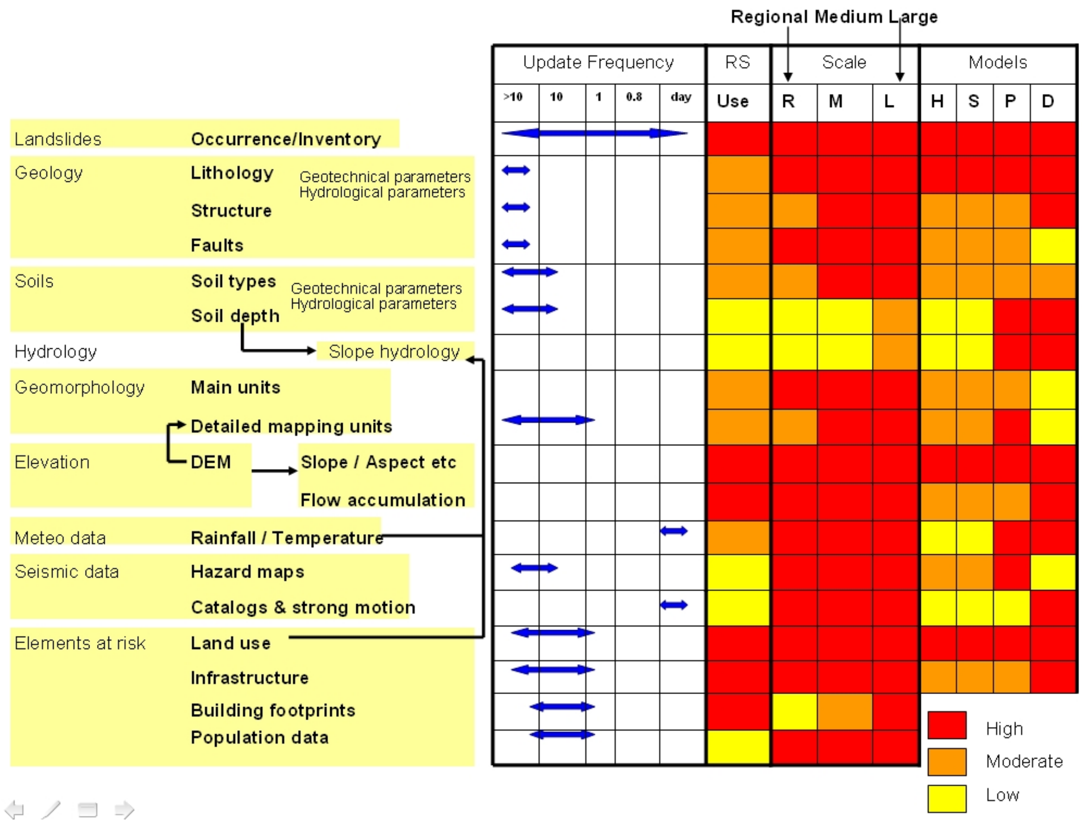


*Figure 3.L.7: Schematic representation of basic data sets for landslide susceptibility, hazard and risk assessment. **Left**: indication of the main types of data, **Middle**: indication of the ideal update frequency, **RS**: column indicating the usefulness of Remote Sensing for the acquisition of the data, **Scale**: indication of the importance of the data layer at small, medium, large and detailed scales, related with the feasibility of obtaining the data at that particular scale, **Hazard models**: indication of the importance of the data set for heuristic models (H), statistical models (S), deterministic models (D), and probabilistic models (P)*

Figure 3.L.7 also gives an indication of the extent to which remote sensing data can be utilized to generate the various data layers. For a number of data layers the main emphasis in data acquisition is on field mapping, field measurements or laboratory analysis, and remote sensing imagery is only of secondary importance. This is particularly the case for the geological, geomorphological, and soil data layers. The soil depth and slope hydrology information, which are very important in physical modeling of slope stability are also the most difficult to obtain, and remote sensing has not proven to be a very important tool for these. On the other hand, however, there are also data layers for which remote sensing data can be the main source of information. This is particularly so for landslide inventories, digital elevation models, and land use maps.

Task 3.L.6: Landslide data and methods (duration 15 minutes)
If you look closely to figure 3.3.L.7

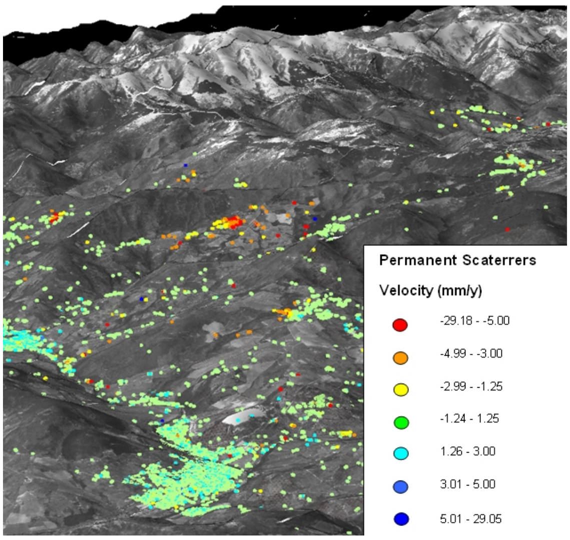
- What is the update frequency of slope hydrology information?
- what do you think will be the most limiting datatypes for the application of Deterministic methods (D) in medium and small scales ?

Landslide inventory mapping

For visual interpretation of landslides, stereoscopic imagery with a high to very high resolution is required. Optical images with resolutions larger than 3 meters (e.g. SPOT, LANDSAT, ASTER, IRS-1D), as well as SAR images (RADARSAT, ERS, JERS, ENVISAT) have proven to be useful for visual interpretation of large landslides in individual cases, but not for landslide mapping on the basis of landform analysis over large areas. Very high resolution imagery (QuickBird, IKONOS, CARTOSAT-1, CARTOSAT-2) has become the best option now for landslide mapping from satellite images. Figure 3.L.8 gives an example of the use of different types of imagery for landslide mapping in RickCity. Another interesting development is the visual interpretation of landslide phenomena from shaded relief images produced from LiDAR DEMs, from which the objects on the earth surface have been removed; so called bare earth DEMs. The use of shaded relief images of LiDAR DEMs also allows a much more detailed interpretation of the landslide mechanism as the deformation features within the large landslide are visible, and landslide can be mapped in heavily forested areas. However, in practice, aerial photo interpretation still remains the most used technique for landslide mapping.

Automated landslide mapping from satellite images has only proven to be possible for recent landslides, with unvegetated scars, e.g. using multi-spectral images such as SPOT, LANDSAT, ASTER and IRS-1D LISS3. Many methods for landslide mapping make use of digital elevation models of the same area from two different periods. The subtraction of the DEMs allows visualizing where displacement due to landslides has taken place, and the quantification of displacement volumes. Satellite derived DEMS from SRTM, ASTER and SPOT do not provide sufficient accuracy, but high resolution data from Quickbird, IKONOS, PRISM (ALOS) and CARTOSAT-1 are able to produce highly accurate DEMs that might be useful in automatic detection of large and moderately large landslides. Light Detection and Ranging (LiDAR) or laser scanning can provide high resolution topographic information (<1 m horizontal and a few cm vertical accuracy), depending on the flying height, point spacing and type of terrain, and may be as low as 100 cm in difficult terrain. Interferometric Synthetic Aperture Radar (InSAR) has been used extensively for measuring surface displacements. Unfortunately, in most environments InSAR applications are limited by problems related to geometric noise due to the different look angles of the two satellite passes and temporal de-correlation of the signal due to scattering characteristics of vegetation, as well as by atmospheric variability in space and time. To overcome these problems, the technique of Persistent Scatterer Interferometry (PSI), or Permanent Scatterers was introduced that uses a large number of radar images and works as a time series analysis for a number of fixed points in the terrain with stable phase behavior over time, such as rocks or buildings.

Figure 3.L.8: Results of a study on landslide displacements using permanent scatterers. (University of Firenze)



Task 3.L.7: Landslide applications from permanent scatterers (duration 15 minutes)

If you look closely to figure 3.3.L.8. The displacement information using this technique can only be done for objects like buildings and large rock blocks.
- How could you use this kind of information for landslide hazard assessment?
- What are the limitations of this technique, if you want to apply this in your own country?

Table 3.L.6: Overview of techniques for the collection of landslide information. Indicated is the applicability of each technique for regional (R), medium (M), large (L) and detailed (D) mapping scales. (H= highly applicable, M= moderately applicable, and L= Less applicable)

Group	Technique	Description	Scale			
			R	M	L	D
Image interpretation	Stereo aerial photographs	Analog format or digital image interpretation with single or multi-temporal data set	M	H	H	H
	High Resolution satellite images	With monoscopic or stereoscopic images, and single or multi-temporal data set	M	H	H	H
	LiDAR shaded relief maps	Single or multi-temporal data set from bare earth model.	L	M	H	H
	Radar images	Single data set	L	M	M	M
(Semi) automated classification : spectral characteristics	Aerial photographs	Image ratioing, thresholding	M	H	H	H
	Medium resolution multi spectral images	Single data images, with pixel based image classification or image segmentation	H	H	H	M
		Multiple date images, with pixel based image classification or image segmentation	H	H	H	M
	Using combinations of optical and radar	Either use image fusion techniques or multi-sensor image classification, either pixel based or object based	M	M	M	M
(Semi) automated classification : altitude characteristics	InSAR	Radar Interferometry for information over larger areas	M	M	M	M
		Permanent scatterers for pointwise displacement data	H	H	H	H
	LiDAR	Overlaying of LiDAR DEMs from different periods	L	L	M	H
	Photogrammetry	Overlaying of DEMs from airphotos or high resolution satellite images for different periods	L	M	H	H
Field investigation methods	Field mapping	Conventional method	M	H	H	H
		Using Mobile GIS and GPS for attribute data collection	L	H	H	H
	Interviews	Using questionnaires, workshops etc.	L	M	H	H
Archive studies	Newspaper archives	Historic study of newspaper, books and other archives	H	H	H	H
	Road maintenance organizations	Relate maintenance information along linear features with possible cause by landslides	L	M	H	H
	Fire brigade/police	Extracting landslide occurrence from logbooks	L	M	H	H
Dating methods for landslides	Direct dating	Dendrochronology, radiocarbon dating etc.	L	L	L	M
	Indirect dating	Pollen analysis, lichenometry, other indirect methods,	L	L	L	L
Monitoring networks	Extensometer etc.	Continuous movement velocity using extensometers, surface tiltmeters, inclinometers, piezometers	-	-	L	H
	EDM	Network of Electronic Distance Measurements	-	-	L	H
	GPS	Network of Differential GPS measurements	-	-	L	H
	Total stations	Network of theodolite measurements	-	-	L	H
	Groundbased InSAR	Using ground-based radar with slide rail	-	-	L	H
	Terrestrial LiDAR	Using terrestrial laser scanning, repeated regularly	-	-	L	H

Task 3.L.8: Landslide inventory mapping and monitoring (duration 15 minutes)

If you look closely to the table 3.3.L.6. Which method of landslide mapping would you recommend in the following cases?

- Mapping old landslides that are covered by forest.
- Fast mapping of hundreds of landslides caused by a hurricane in remote and inaccessible areas?
- Monitoring the movements of a town that is built on a slow moving landslide?
- Regular mapping of an area of 1000 km2 for landslide hazard assessment?

The techniques described above are intended to support the generation of landslide databases. The difficulties involved in obtaining a complete landslide database, and its implications for landslide hazard assessment are illustrated in Figure 3.L.9, with a graph indicating a hypothetical landslide frequency in the period 1960-2006, and the main triggering events (either earthquakes or rainfall events) with the return period indicated. For the area, five different sets of imagery are available (indicated in Figure 3.L.9 with A to E). In order to be able to capture those landslides related with a particular triggering event, it is important to be able to map these as soon as possible after the event occurred. For example the imagery of C and E can be used to map the landslides triggered by rainfall events with different return periods. The imagery of B and D however, are taken either some time after the triggering event has occurred, so that landslide scarps will be covered by vegetation and are difficult to interpret, or they occur after a sequence of different triggering mechanisms, which would make it difficult to separate the landslide distributions. This is also illustrated for the Tegucigalpa area in figure 2, where the landslide inventory of past events is limited by the availability of historical imagery. For instance, if image C in figure 2 (taken directly after the occurrence of Hurricane Mitch) would not have been available, it would have been very difficult to identify the landslide type and mechanism on the later imagery (e.g. D).

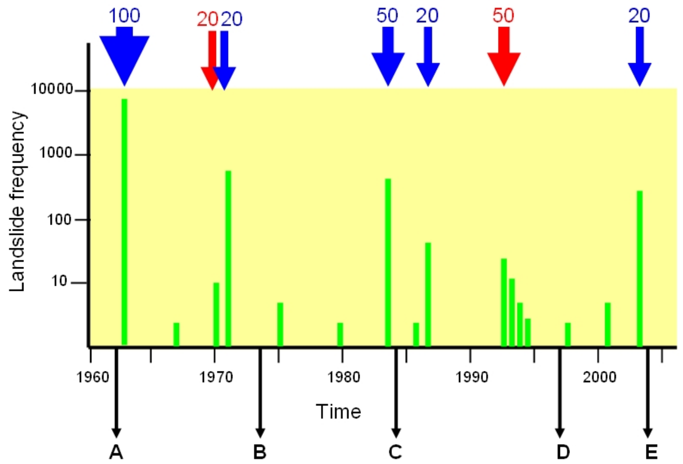


Figure 3.L.9: Schematic presentation of landslide frequency in relation to triggering events and dates of imagery. On top of the graph the rainfall events (in black) and earthquakes (in gray) are indicated as arrows, with an indication of their return periods. The black arrows below the graph (A to E) refer to dates of available remote sensing imagery for landslide inventory mapping.

Task 3.L.9: Costs for event-based landslide maps (duration 45 minutes)

Suppose you wouldn't have any of the sets of data (A to E) as indicated in the graph above. Your study area is 100 km^2. You would have a budget of 50,000 Dollars. Buying Ikonos images costs you 1435 Dollars per image. One IKONOS covers 62 km^2. Buying aerial photo's at 1:10.000 scale costs you 20 $ each. One airophoto is 23*23 cm. Buying ASTER data costs you 60 Dollars per image, and one ASTER image covers 500 km^2. For stereo you need 50 percent overlap, so basically twice as many images. Suppose the mapping department has many flights available, say every even year.

- What is the cost for having a full coverage of the area for one set of airphotos and for one set of Quickbird images? Make the calculation in a spreadsheet.
- How would you spend your budget optimally in order to get the best information on the temporal occurrence of landslide in relation with return periods of rainfall and earthquakes?
- How many acquisitions could you do if you would include interpreter costs (2.5 hour/photo and 5/image at 20 $/hour) ?

This is based on the paper Nichol, J.E., Shaker, A. and Man-Sing Wong, Application of high-resolution stereo satellite images to detailed landslide hazard assessment. Geomorphology 76 (2006) 68– 75
You can use the set-up for the Excel sheet as indicated below.
The results can be found in an Excel sheet on Blackboard after 1 day.

Landslide hazard						
Task	3.3.L.9					
Budget	50000	Dollars				
Size of study area	1000	km2				
Only acquisition						
Airphotos			**Quickbird images**		**Aster images**	
Airphoto scale			Size of image		Size of image	
1 cm is equal to		km				
23 cm is equal to		km				
1 photo area		km2				
photos no stereo		nr	images no stereo		images no stereo	
photos with stereo		nr	images stereo		images stereo	
Costs per photo		Dollars	Cost per image		Cost per image	
Costs per flight			Cost for 1 time		Cost for 1 time	
Possible acuisitions			Possible acquisitions		Possible acquisitions	
With interpretation						
Airphotos			**Quickbird images**		**Aster images**	
time for 1 photo		hours	time per image		time per image	
total time for interpretation			total time for interpretation		total time for interpretation	
Cost per hour		dollars	Cost per hour		Cost per hour	
Interpretation costs		dollars	Interpretation costs		Interpretation costs	
Total costs			Total costs		Total costs	
Possible acuisitions			Possible acquisitions		Possible acquisitions	

Environmental factors

As indicated in Figure 3.L.7, the next block of spatial information required for landslide susceptibility, hazard and risk assessment consists of the spatial representation of the factors that are considered relevant for the prediction of the occurrence of future landslides. Table 3.L.7 provides more details on the relevance of these factors for heuristic, statistical and deterministic analysis. It is clear from this table that the three types of analysis use different types of data, although they share also common ones, such as slope gradient, soil and rock types, and land use types. The selection of the environmental factors that are used in the susceptibility assessment depends on the type of landslide, the type of terrain and the availability of existing data and resources. A good understanding of the different failure mechanisms is essential. Often different combinations of environmental factors should be used, resulting in separate landslide susceptibility maps for each failure mechanism.

Table 3.L.7: Overview of environmental factors, and their relevance for landslide susceptibility and hazard assessment. (H= highly applicable, M= moderately applicable, and L= Less applicable).

Group	Data layer and types	Relevance for landslide susceptibility and hazard assessment	Scales of analysis			
			R	M	L	D
Digital Elevation Models	Slope gradient	Most important factor in gravitational movements	L	H	H	H
	Slope direction	Might reflect differences in soil moisture and vegetation	H	H	H	H
	Slope length/shape	Indicator for slope hydrology	M	H	H	H
	Flow direction	Used in slope hydrological modeling	L	M	H	H
	Flow accumulation	Used in slope hydrological modeling	L	M	H	H
	Internal relief	In small scale assessment as indicator for type of terrain.	H	M	L	L
	Drainage density	In small scale assessment as indicator for type of terrain.	H	M	L	L
Geology	Rock types	Based on engineering properties on rock types	H	H	H	H
	Weathering	Depth of profile is an important factor	L	M	H	H
	Discontinuities	Discontinuity sets and characteristics	L	M	H	H
	Structural aspects	Geological structure in relation with slope angle/direction	H	H	H	H
	Faults	Distance from active faults or width of fault zones	H	H	H	H
Soils	Soil types	Engineering soils with genetic or geotechnical properties	M	H	H	H
	Soil depth	Soil depth based on boreholes, geophysics and outcrops	L	M	H	H
	Geotechnical prop.	Grainsize, cohesion, friction angle, bulk density	L	M	H	H
	Hydrological prop.	Pore volume, saturated conductivity, PF curve	L	M	H	H
Hydrology	Water table	Spatially and temporal depth to ground water table	L	L	M	H
	Soil moisture	Spatially and temporal soil moisture content	L	L	M	H
	Hydrologic components	Interception, Evapotranspiration, throughfall, overland flow, infiltration, percolation etc.	M	H	H	H
	Stream network	Buffer zones around streams	H	H	H	L
Geomorpho-logy	Physiographic units	First subdivision of the terrain in zones	H	M	L	L
	Terrain Mapping Units	Homogeneous units of lithology, morphography and processes	H	M	L	L
	Geomorpholy	Genetic classification of main landform building processes	H	H	M	L
	Slope facets	Geomorphological subdivision of terrain in slope facets	H	H	H	L
Landuse	Land use map	Type of land use/ land cover	H	H	H	H
	Land use changes	Temporal varying land use/ land cover	M	H	H	H
	Vegetation	Type, canopy cover, rooting depth, root cohesion, weight	L	M	H	H
	Roads	Buffers around roads in sloping areas with road cuts	M	H	H	H
	Buildings	Slope cuts made for building construction	M	H	H	H

Task 3.L.10: Prioritizing environmental factors (duration 30 minutes)

1. *Select a scale of analysis (Regional, medium, small, detailed)*
2. *Make a ranking of the 15 most important factors for that scale*

3.L.5. Landslide susceptibility assessment

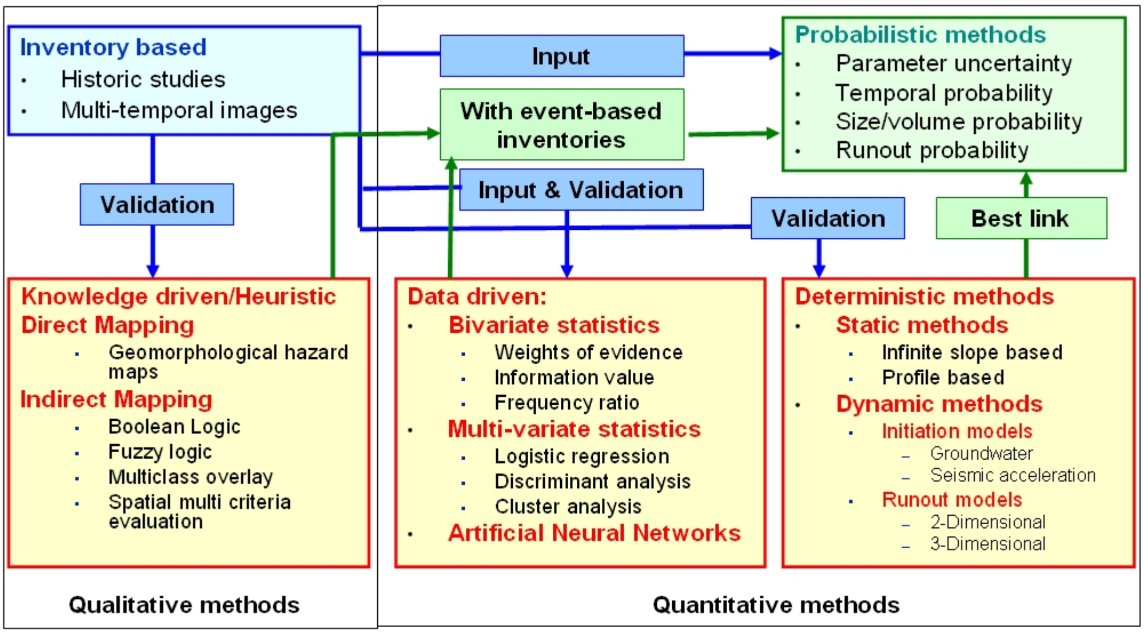
There is a clear difference between landslide susceptibility and hazard assessment, as given by the following definitions (from Fell et al, 2008):

Landslide Susceptibility: the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.
This looks basically at the relative spatial likelihood of landslide occurrence.
Landslide Hazard: A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the likelihood of their occurrence within a given period of time. Landslide hazard includes landslides which have their source in the area, or may have their source outside the area but may travel onto or regress into the area.
A complete quantitative landslide hazard assessment includes:

- **spatial probability**: the probability that a given area is hit by a landslide
- **temporal probability**: the probability that a given triggering event will cause landslides
- **size/volume probability**: probability that the slide has a given size/volume
- **runout probability**: probability that the slide will reach a certain distance downslope.

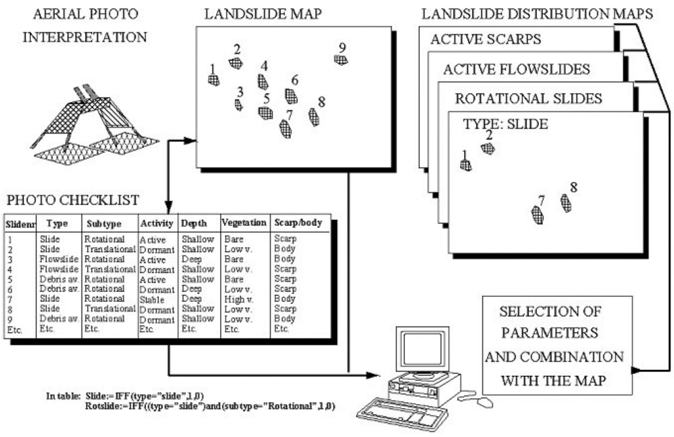
The methods for landslide susceptibility assessment are shown in the figure below. The methods are subdivided in qualitative ones (landslide inventory analysis, and knowledge driven methods) and quantitative ones (data driven, deterministic, and probabilistic methods). The inventory based methods are also required as a first step for all other methods, as they form the input and are used for validating the resulting maps. The probabilistic methods use the inputs from the lower three. In the case of dynamic models the results can be used directly in a probabilistic analysis. For the other methods a link is made with event-based landslide inventory maps.

Figure: 3.L.10: Methods for susceptibility and hazard assessment. Blue relates to landslide inventories. Red to susceptibility and Green to Landslide hazard.



Landslide inventory analysis

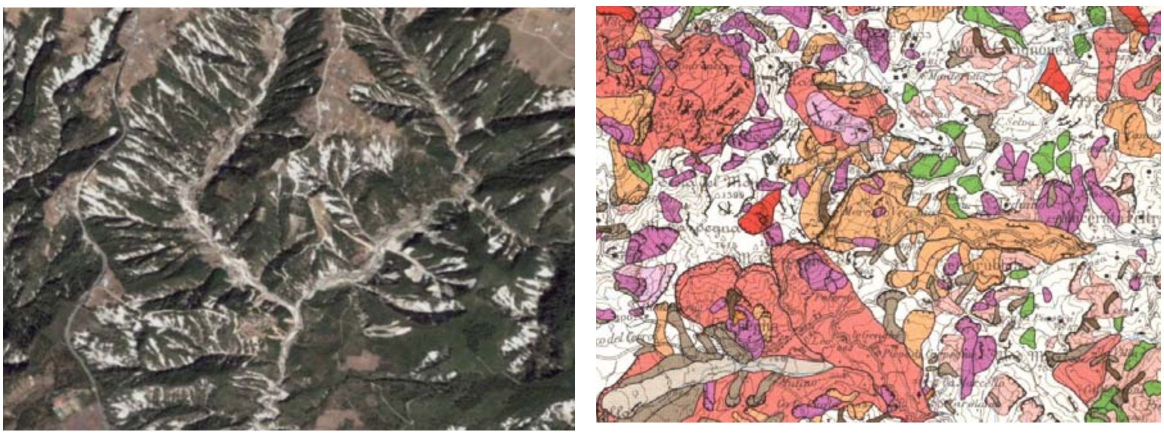
Figure 3.L.11: Landslide inventory method



The most straightforward approach to landslide hazard zonation is a landslide inventory based on aerial photo interpretation, ground survey, and/or historical data of landslide occurrences. The final product gives the spatial distribution of mass movements, represented either at scale or as points.

Mass movement inventory maps are the basis for most of the other landslide hazard zonation techniques. They can, however, also be used as an elementary form of hazard map, because they display where in an area a particular type of slope movement has occurred. See figure 3.L.11. Landslide inventories are either continuous in time, or provide so-called event-based landslide inventories, which are inventories of landslides that happened on the same day due to a particular triggering event (rainfall, earthquake). By correlating the density of landslides with the frequency of the trigger, it is possible to make a magnitude-frequency relation, required for hazard assessment.

Figure 3.L.12: Left: example of a high resolution image taken after a major rainfall event causing hundreds of landslides in the same area. Right: a fragment of a detailed landslide inventory map, with differentiation of type and age of landslides.

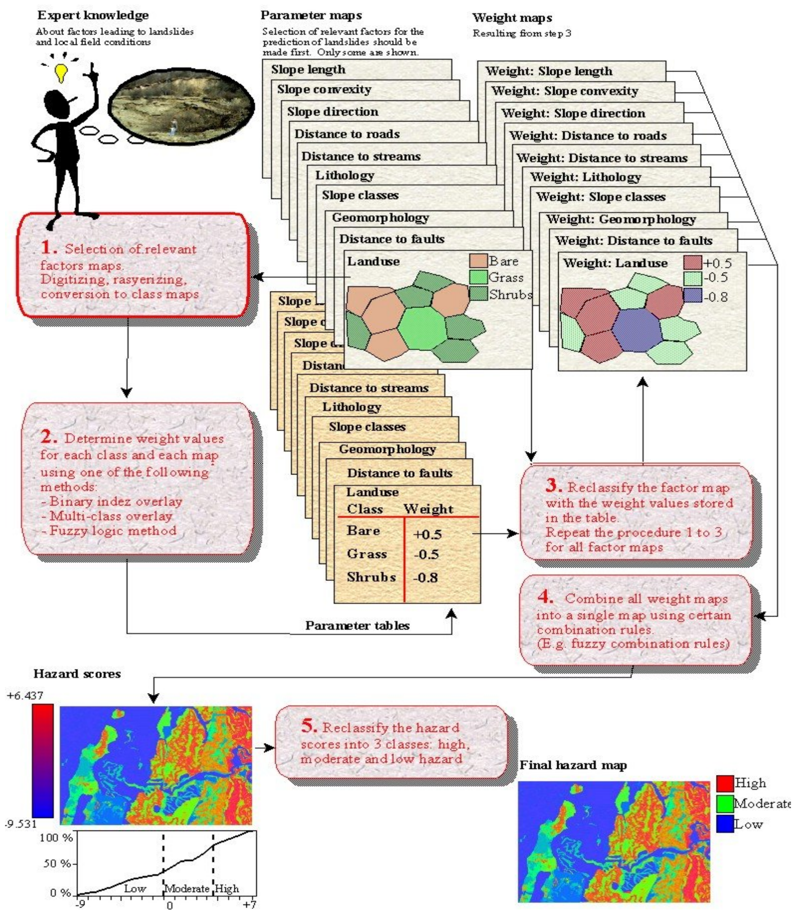


The landslide distribution can also be shown in the form of a density map within administrative units or to use counting circles for generating landslide density contours.

Heuristic landslide hazard assessment methods

In heuristic methods expert opinion plays a decisive role, that is why they are also called knowledge driven method. A landslide susceptibility map can be directly mapped in the field by expert geomorphologist. Very often, however, landslide maps are made indirectly, by combining a number of factor maps, that are considered to be important for landslide occurrence. The mapping of mass movements and their geomorphological setting is the main input factor for hazard determination. From this the experts learn the relative importance of the various factor maps used. Figure 3.L.13 gives a schematic flowchart of the use of knowledge driven methods for landslide susceptibility assessment. In a qualitative map combination, the earth scientist uses his/her expert knowledge to assign weight values to series of parameter maps. The terrain conditions are summated according to these weights, leading to susceptibility values, which can be grouped into hazard classes. This method of qualitative map combination has become widely used in slope instability zonation. Several techniques can be used such as Boolean overlay, Fuzzy logic, multi-class overlay and Spatial Multi-Criteria Evaluation. The drawback of this method is that the exact weighting of the various parameter maps is difficult. These factors might be very site specific and cannot simply used in other area. They should be based on extensive field knowledge and be assigned by real experts with sufficient field knowledge of the important factors. The methods are subjective, but the weights assigned to the factors are transparent and can be discussed among experts, and defended against end users/decision makers.

Figure 3.L.13: Scheme for Qualitative landslide hazard assessment



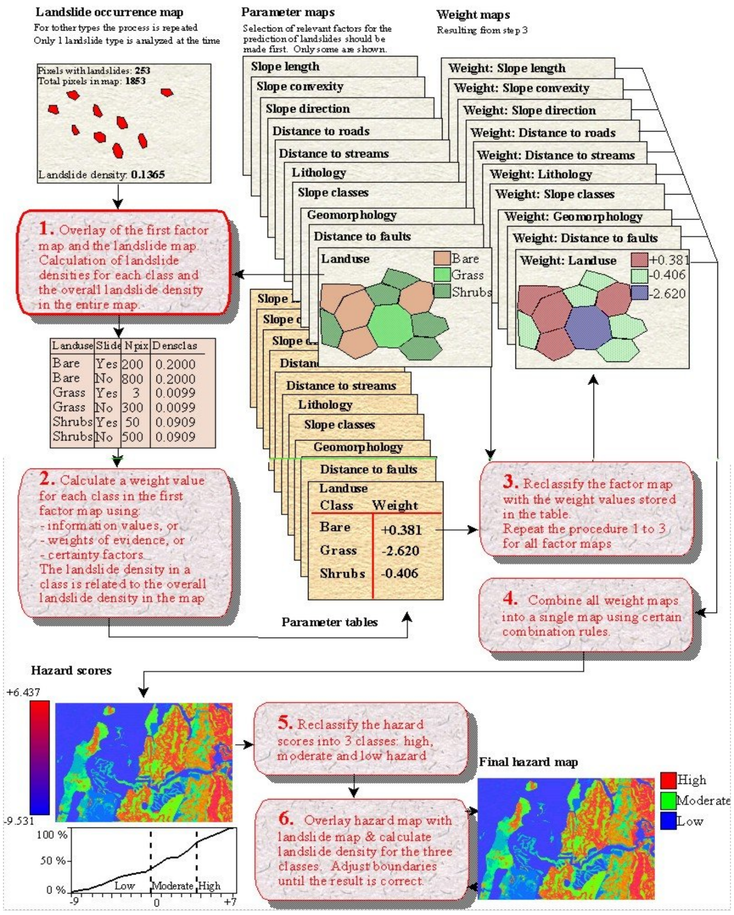
Statistical landslide susceptibility assessment methods

In statistical landslide hazard analysis, the combinations of factors that have led to landslides in the past are evaluated statistically and quantitative predictions are made for landslide free areas with similar conditions. The method assumes that similar conditions that have lead to landslides in the past will do so in future. Two main statistical approaches are used in landslide hazard analysis Bivariate and multi-variate methods (see Figure 3.L.13).

In a bivariate statistical analysis, each factor map (slope, geology, land use etc.) is combined with the landslide distribution map, and weight values, based on landslide densities, are calculated for each parameter class (slope class, lithological unit, land use type, etc). Several statistical methods can be applied to calculate weight values, such as landslide susceptibility, the information value method, weights of evidence modeling, Bayesian combination rules, certainty factors, the Dempster-Shafer method and fuzzy logic. Bivariate statistical methods are a good learning tool for the analysist to find out which factors or combination of factors plays a role in the initiation of landslides. The method is mostly done on a grid level.

Multivariate statistical models look at the combined relationship between a dependent variable (landslide occurrence) and a series of independent variables (landslide controlling factors). In this type of analysis all relevant factors are sampled either on a grid basis, or in morphometric units. For each of the sampling units also the presence or absence of landslides is determined. The resulting matrix is then analyzed using multiple regression, logistic regression or discriminant analysis. With these techniques, good results can be expected. Since statistical methods required a nearly complete landslide inventory and a series of factor maps, they cannot be applied easily over very large areas. These techniques have become standard in medium scale landslide susceptibility assessment.

Figure 3.L.14: Bivariate statistical analysis



One example of a simple bi-variate statistical analysis is the hazard index method: This method is based upon the following formula:

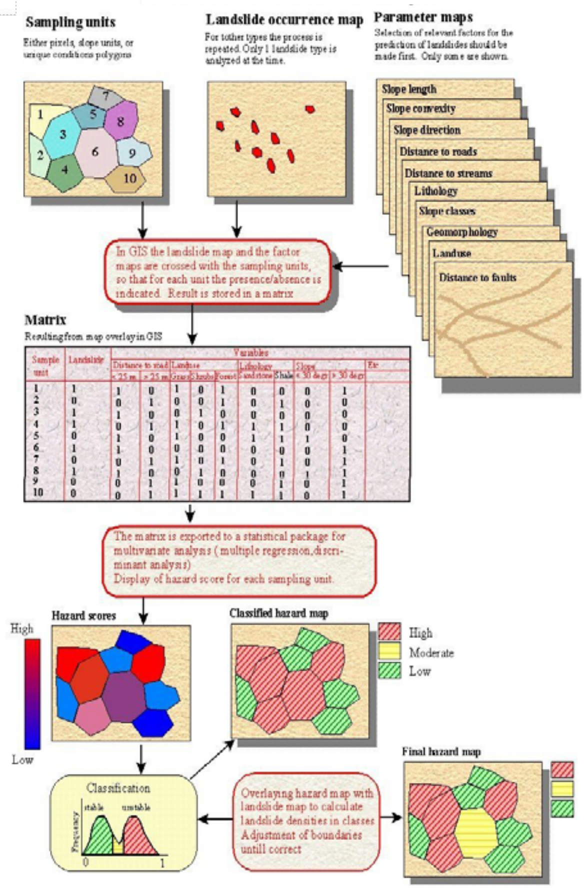
$$W_i = \ln\left(\frac{\text{Densclas}}{\text{Densmap}}\right) = \ln\left(\frac{\dfrac{\text{Area(Si)}}{\text{Area(Ni)}}}{\dfrac{\sum \text{Area(Si)}}{\sum \text{Area(Ni)}}}\right)$$

where,
Wi = the weight given to a certain parameter class (e.g. a rock type, or a slope class).
Densclas = the landslide density within the parameter class.
Densmap = the landslide density within the entire map.
Area(Si) =area, which contain landslides, in a certain parameter class.
Area(Ni) = total area in a certain parameter class.

Task 3.L.11: RiskCity exercise on statistical landslide susceptibility assessment (duration 5 hours)

In order to see how statistical methods can be applied in landslide susceptibility assessment we have prepared a GIS exercise on the use of a simple bi-variate statistical method (information value method). You can find the exercise description in the RiskCity exercise book.

Figure 3.L.15: Flowchart of multivariate statistical analysis.



Deterministic landslide hazard analysis

Deterministic methods are based on modeling the processes of landslides using physically-based slope stability models (figure 3.L.16). They are increasingly used in hazard analysis, especially with the aid of geographic information systems safety factors over large areas can be calculated. The methods are applicable only when the geomorphological and geological conditions are fairly homogeneous over the entire study area and the landslide types are simple. They can be subdivided in 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. Especially the use of dynamic models using GIS software such as PCraster (http://pcraster.geo.uu.nl/) is very powerful. It allows modeling soil moisture changes in the slope over time, and combine this with a slope stability model. Some examples combined slope hydrology and slope stability software are: Shalstab, TRIGRS, SINMAP and STARWARS/PROBSTAB. The advantage of these models is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors). The main drawbacks of this method are the high degree of oversimplification and the need for large amounts of reliable input data. This method is usually applied for translational landslides using the infinite slope model. The methods generally require the use of groundwater simulation models. Stochastic methods are sometimes used for selection of input parameters.

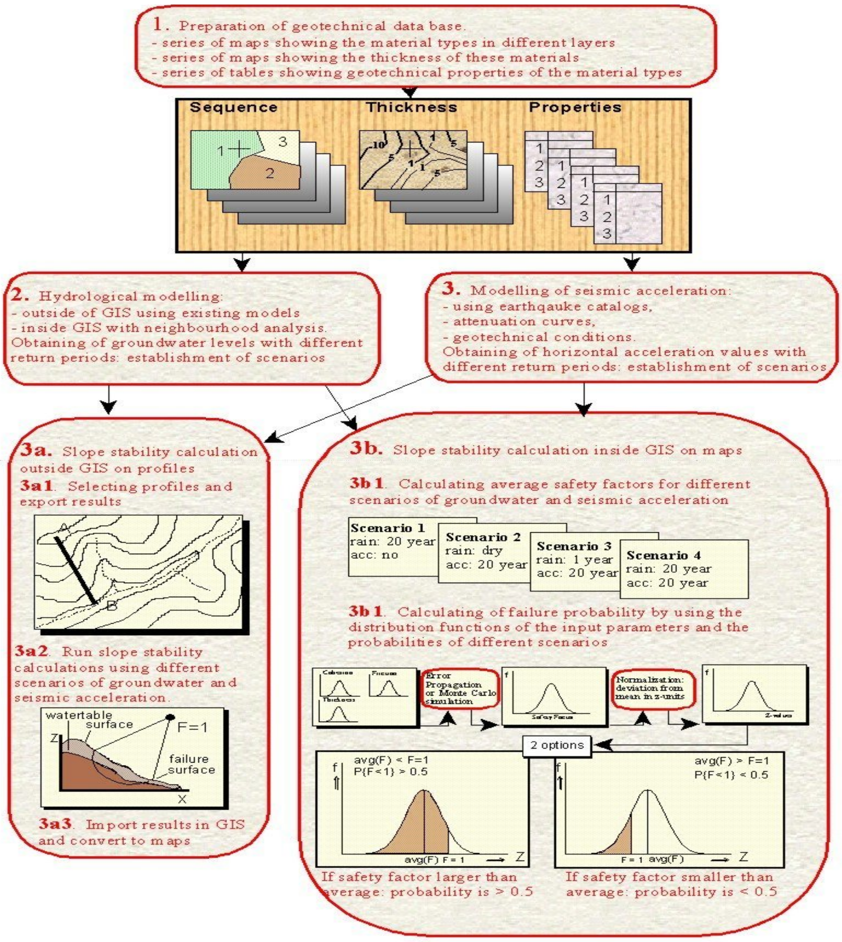


Figure 3.L.16: Deterministic approach to landslide hazard zonation

Task 3.L.12: RiskCity exercise on deterministic landslide susceptibility assessment (duration 5 hours)

In order to see how deterministic methods can be applied in landslide susceptibility assessment we have prepared a GIS exercise on the use of a simple infinite slope model under different scenarios of groundwater levels. You can find the exercise description in the RiskCity exercise book.
The exercise is based on the following formula:

$$F = \frac{c\,A + W \cos\beta \tan\phi}{W \sin\beta}$$

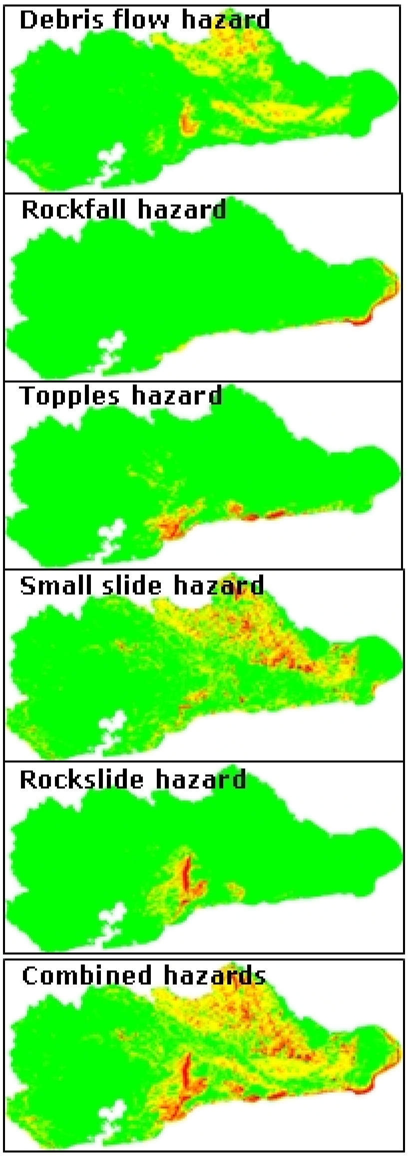
c = cohesion (Pa= N/m^2). A = length of the block (m).
W = weight of the block (kg). β = slope surface inclination (°).
ϕ = angle of shearing resistance (°)

Selecting the best method of analysis.
There is a clear link between the scale of analysis and the type of method that can be used, basically related to the possibility of obtaining the required input data. Table 3.L.8 gives a summary.

Table 3.L.8: Applicability of the methods at different scales.

Scale	Qualitative methods		Quantitative methods		
	Inventory	**Heuristic Methods**	**Statistical Methods**	**Deterministic methods**	**Probabilistic methods**
Large > 1:10000	Yes	Yes	No	Yes	Yes
Medium 25000–50000	Yes	Yes	Yes	No	Yes
Regional > 1:100000	Yes	Yes	Yes/No	No	No

There are several pitfalls in this process that should be avoided:



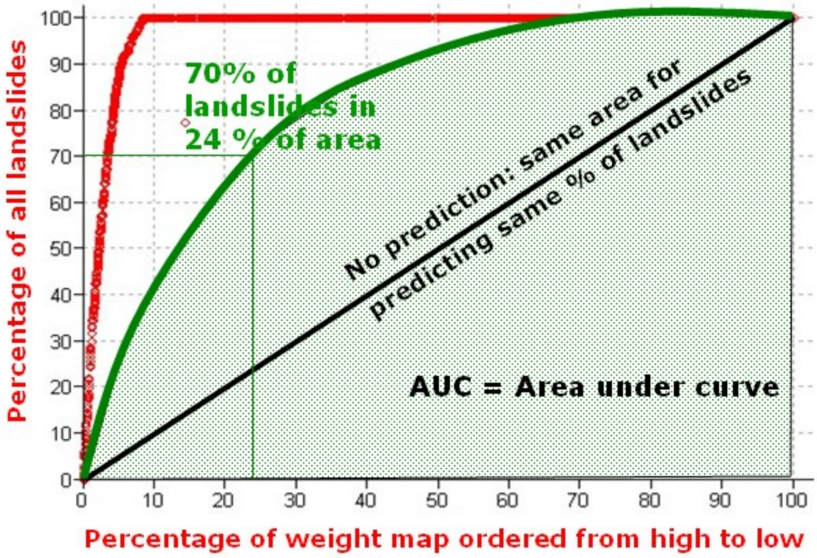
- Selection of a method that does not suit the available data and the scale of the analysis. For instance, selecting a physical modeling approach at small scales with insufficient geotechnical and soil depth data. This will either lead to large simplifications in the resulting hazard and risk map, or to endless data collection.
- Use of incomplete landslide inventories, either in temporal aspect, or in the landslide classification. It is important to keep in mind that different landslide types are controlled by different combinations of environmental and triggering factors.
- Using the same type of data and method of analysis for entirely different landslide types and failure mechanisms. The inventory should be subdivided into several subsets, each related to a particular failure mechanism, and linked to a specific combination of causal factors (See figure 3.?.?). Also only those parts of the landslides should be used that represent the situation of the slopes that failed.
- Use of data with a scale or detail that is not appropriate for the hazard assessment method selected. For instance, using an SRTM DEM to calculate slope angles used in statistical hazard assessment.
- Selection of easily obtainable landslide causal factors, such as DEM derivatives from SRTM data on a medium or large scale, or the use of satellite derived NDVI values as a causal factor instead of generating a land cover map.
- Use factor maps that are not from the period of the landslide occurrence. For instance, in order to be able to correlate landslides with landuse/landcover changes, it is relevant to map the situation that existed when the landslide occurred, and not the situation that resulted after the landslide.
- Much of the landslide susceptibility and hazard work is based on the assumption that "the past is key to the future", and that historical landslides and their causal relationships can be used to predict future ones. However, one could also follow the analogy of the investment market in stating that "results obtained in the past are not a guarantee for the future". Conditions under which landslide happened in the past change, and the susceptibility, hazard and risk maps are made for the present situation. As soon as there are changes in the causal factors (e.g. a road with steep cuts is constructed in a slope which was considered as low hazard before) or changes in the elements at risk (e.g. city growth) the hazard and risk information needs to be adapted.

Validation of susceptibility maps

The most important question to be asked for each hazard study is related to the degree of accuracy. The terms accuracy and reliability are used to indicate whether the hazard map makes a correct distinction between landslide free and landslide prone areas. The accuracy of a hazard prediction depends on a large number of factors such as the models, the input data, the experience of the earth scientists involved, and the size of the study area. The evaluation of the accuracy of a susceptibility map is generally very difficult. In reality a hazard prediction can only be verified by observing if the event

takes (or has taken) place in time ("wait and see"), but this is not a very useful method, for obvious reasons.
Depending on the method used there are several ways to validate the landslide susceptibility maps. In the case of deterministic landslide hazard assessment, using dynamic models, it is possible to compare the predicted unstable pixels with the actual landslides that have taken place. This could even be done to predict them both in space and time. For statistical and knowledge driven method the best way is to use success rate curves.
The success rate is a statistical method to determine how well the resulting hazard map has classified the areas of existing landslides as high hazard areas.
The method first divides the area of the hazard map in equal classes of the histogram, ranging from the highest to the lowest scores. Then for each of these classes the percentage of the landslides that occur in that class is calculated. The result is plotted as the percentage of the map on the X-axis, ad the percentage of the landslides on the Y-axis (see figure 3.L.17).
This method is often unjustly presented as a check of the predicting power of the hazard map. It is merely a method that allows checking how many of the landslides occur in the high hazard areas (well classified) and how many occur in the low hazard areas (wrongly classified). To some extent this is circular reasoning, since the same landslides that are used to calculate the hazard, are used later to check it. This can be avoided by separating the landslide set into two populations: one used for generating the hazard map, and the other for checking it. This can be done by using a random selection of the landslides, or by dividing the area in a checkerboard pattern, and use the landslide falling in the "white" blocks for the generation of the hazard map, while using the ones in the "black" bocks for checking it. When you are using two temporally different inventory maps, the success rate actually becomes a prediction rate. The objective of the prediction rate is to check how well the hazard map can predict the future occurrence of landslides. The hazard prediction, based on an older distribution map, can then be checked with a younger distribution.
The comparison of hazard maps, made by different methods (for example statistical and deterministic methods) may give a good idea of the accuracy of the prediction as well.

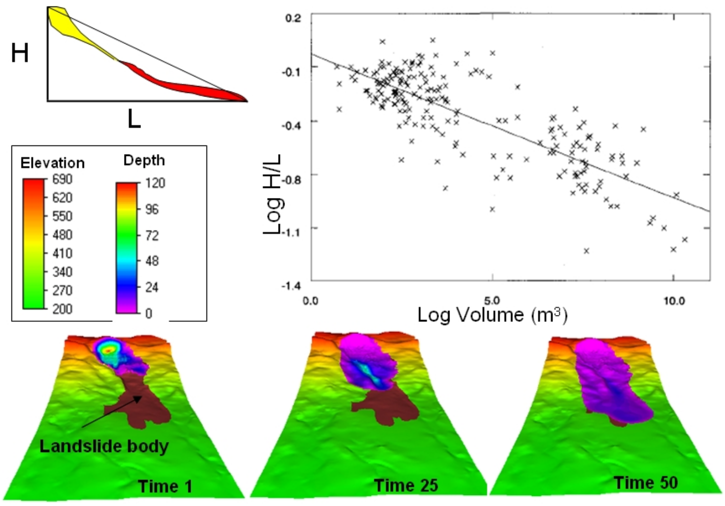
Figure 3.L.17: Success rate: plotting the percentage of the susceptibility map ordered from high to low values against the percentage of landslides. The diagonal is the line where no prediction is made. The AUC (Area under the curve) gives a measure of the accuracy. For the diagonal line AUC=0.5, in case of complete prediction: AUC=1.



Runout assessment
As shown in figure 3.L.6 the methods explained above are intended for landslide initiation modeling. These will serve as input in the prediction of the run out behavior of landslides, where information is required on run out distance, run out width, velocity, pressure, depth of the moving mass;, depth of deposits.
A variety of techniques have been developed to assess the travel distance and the velocity of mass movements. They can be classified into the following groups:

- *Empirical models*. These are based on empirical relationship between the runout length and other factors. For instance the mass-change method is based on the fact that the landslide stops when the volume of the actively moving debris becomes negligible. The average mass/volume-change rate of landslide debris was established by dividing the volume of mobilized material from the landslide by the length of the debris trail. The angle of reach, defined as the angle of the line connecting the crest of the landslide source to the distal margin of the displaced mass, shows a linear correlation with volume for all types of failures (see figure 3.L.18). The angle of reach method is a very generalized method and can only be used as a general indication. Empirical methods are generally simple and relatively easy to use, and they do no used complicated input data.

Figure 3.L.18: Runout modeling. Above: Empirical angle of reach/volume relationship (Corominas, 1996). Below: three time slices of a numerical runout simulation (Castellanos, 2008).



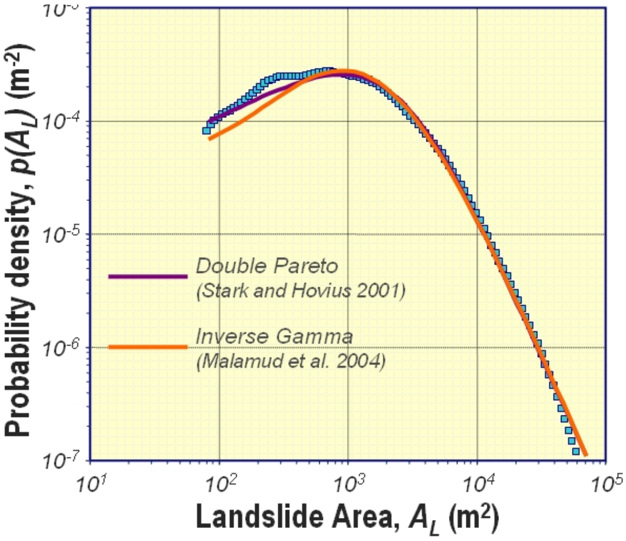
- *Analytical models* are based on energy considerations. They include different formulations based on lumped mass approaches in which the debris mass is assumed as a single point. Observation of the superelevation of the flow around the bends and run-up of the flow against an obstacle also allow an estimate of the velocity.
- *Numerical models*. Numerical methods for modeling run out behavior of landslide debris mainly include fluid mechanics models and distinct element methods. Continuum fluid mechanics models utilize the conservation equations of mass, momentum and energy that describe the dynamic motion of debris, and a rheological model to describe the material behavior of debris. By solving a set of governing equations with a selected rheological model describing the flow properties of the debris, the velocity, acceleration and run out distance of debris can be predicted. Rheological models have to be selected, and the required rheological parameters have to be determined by back-analysis from the landslide cases. After determining the probability of landsliding and the areal extent that would be potentially affected by the landslide, landslide hazard can be delimited, and elements at risk can be defined. Wellknown models are DAN, DAN-3D, RAMMS, FLO-2D, MASSMOV2D etc.

Run out modeling is complicated because of the various physical processes that occur during an event. These depend on the initial composition, the characteristics of the path and the material incorporated during the flow. Runout models for rockfall have been well developed. For landslides and debrisflow runout modeling there are many uncertainties involved related to the spatial and temporal distribution of the release areas, the volume of the release mass, and the input parameters of the rheological model.

3.L.6 From susceptibility to hazards

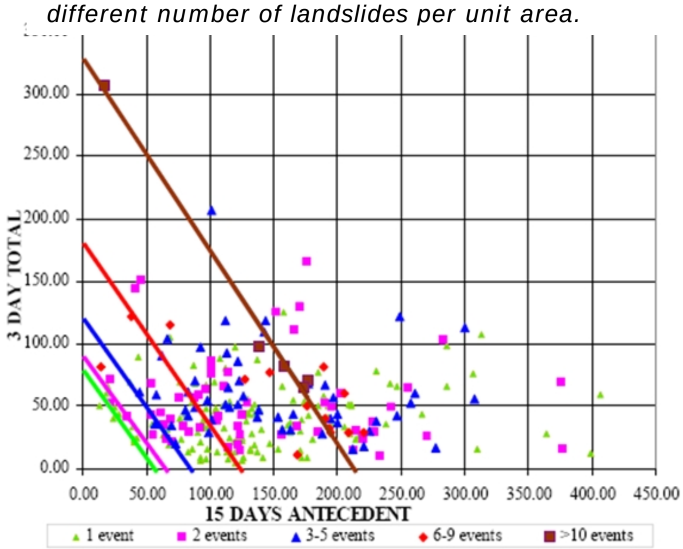
As indicated in section 3.L.5 the difference between susceptibility and hazard is the inclusion of probability (temporal, spatial and size probability). Size probability is the probability that the landslide will be of a particular minimum size. This is done by plotting the size/frequency distribution (See figure 3.L.19).

Figure 3.L.19: Size probability estimation (Guzetti, 2006).



Temporal probability can be established using different methods. A relation between triggering events (rainfall or earthquakes) and landslide occurrences is needed in order to be able to assess the temporal probability. Temporal probability assessment of landslides is either done using rainfall threshold estimation, through the use of multi-temporal data sets in statistical modeling, or through dynamic modeling. Rainfall threshold estimation is mostly done using antecedent rainfall analysis, for which the availability of a sufficient number of landslide occurrence dates is essential. If distribution maps are available of landslides that have been generated during the same triggering event, a useful approach is to derive susceptibility maps using statistical or heuristic methods, and link the resulting classes to the temporal probability of the triggering events. The most optimal method for estimating both temporal and spatial probability is dynamic modeling, where changes in hydrological conditions are modeled using daily (or larger) time steps based on rainfall data. However, more emphasis should be given to the collection of reliable input maps, focusing on soil types and soil thickness. The methods for hazard analysis should be carried out for different landslide types and volumes, as these are required for the estimated damage potential. Landslide hazard is both related to landslide initiation, as well as to landslide deposition, and therefore also landslide run-out analysis should be included on a routine basis.

Figure 3.L.20: Rainfall threshold generation. Plot of antecedent rainfall and threshold lines for different number of landslides per unit area.



A good understanding and quantification of the different hazard aspects (temporal and spatial probability of initiation, magnitude-frequency relation and run-out potential) is essential in order to be able to make further advancements in landslide vulnerability and risk assessment. Also more emphasis could be given to the collection of historic landslide damage information for different elements at risk, and relate these to the characteristics of the landslides that caused the damage (e.g. volume, speed, run-out length).

Eventually, it is the spatial data availability that is the limiting factor in landslide hazard and risk assessment.

3.L.7 Selftest

Self test
In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question 1: Landslide hazard assessment
Which statement concerning statistical and an expert-based method for landslide hazard assessment is true:

A) A statistical method uses weights derived from the correlation between past hazard events and causal factors, whereas an expert-based method tries to model the process physically.
B) A statistical method tries to model the process physically, whereas an expert-based method uses qualitative weights derived from expert opinion.
C) An expert-based method tries to find a correlation between past hazard events and causal factors, whereas a statistical method tries to model the process physically.
D) A statistical method uses weights derived from the correlation between past hazard events and causal factors, whereas an expert-based method uses qualitative weights derived from expert opinion.

Explain your answer:

Question 2: Landslide hazard assessment
For landslide hazards it is very difficult to estimate the probability of occurrence. The most important reason for that is:

A) Most landslide types do not have a magnitude –frequency relation for a particular location, and you cannot say that the same location will be affected often by small landslides, and less often by large landslides.
B) Landslides are mostly occurring as a result of a triggering event, such as rainfall or earthquakes, and these have no clear magnitude-frequency relation
C) Landslides occur randomly, and cannot be predicted in space or time.
D) Landslides never occur twice at the same location.

Explain your answer:

Question 3: Landslide inventory mapping
Which method of landslide mapping would you recommend in the following cases?

- Mapping old landslides that are covered by forest.
- Fast mapping of hundreds of landslides caused by a hurricane in remote and inaccessible areas?
- Monitoring the movements of a town that is built on a slow moving landslide?
- Regular mapping of an area of 1000 km2 for landslide hazard assessment?

Question 4: Statistical susceptibility assessment

Below a number of possible factor maps are indicated that can be used in a bivariate statistical analysis for landslide susceptibility. Indicate for each of the maps:

- Why this could be a good / not so good / bad indicator for landslide occurrence?
- What would be the expected order of magnitude of the weights that are used in the hazard index method.

Slope class of 0-10 degrees.

Distance from faults (indicate which distance range you would use)

Landuse type unvegetated terrain.

Further reading:

If you are new to landslides, one of the best internet sites to look for landslide related information is the USGS landslide website: http://landslides.usgs.gov/learning/

On this site you can also download the following introductory handbook: Highland, L.M., and Bobrowsky, Peter, 2008, The landslide handbook—A guide to understanding landslides: Reston, Virginia, U.S. Geological Survey Circular 1325, 129 p. Link: http://pubs.usgs.gov/circ/1325/

Guidelines for landslide inventory, hazard and risk assessment can be found in:

Fell, R., Corominas, J. Bonnard, C., Cascini, L. ,Leroi, E., Savage, W. on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes. Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Engineering Geology 102 (2008) : 85-98 and commentary on 99-111

AGS, 2000. Landslide risk management concepts and guidelines, Australian Geomechanics Society (AGS), Sub-committee on landslide risk management. This report can be downloaded from: http://www.australiangeomechanics.org/LRM.pdf

Castellanos Abella, E.A., de Jong, S.M. (promotor) , van Westen, C.J. (promotor) and van Asch, W.J. (promotor) (2008) Multi - scale landslide risk assessment in Cuba. Enschede, Utrecht, ITC, University of Utrecht, 2008. ITC Dissertation 154, 272 p. ISBN: 978-90-6164-268-8 http://www.itc.nl/library/papers_2008/phd/castellanos.pdf

For those familiar with landslides that want to know more about the methods for landslide hazards and risk assessment, the following materials can be recommended:

Carrara, A., Guzzetti, F., Cardinali, M., Reichenbach, P., 1999. Use of GIS Technology in the Prediction and Monitoring of Landslide Hazard. Natural Hazards 20, 117-135.

Castellanos, E. and Van Westen, C.J., 2007. Qualitative landslide susceptibility assessment by multicriteria analysis; a case study from San Antonio del Sur, Guant´anamo, Cuba. Geomorphology DOI: 10.1016/j.geomorph.2006.10.038.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes. In: Turner, A.K., and Schuster, R.L., (Eds.), Landslides, Investigation and Mitigation. Transportation Research Board, Special Report 247, Washington D.C., USA, pp. 36-75.

Glade, T., Crozier, M.J., 2005. A review of scale dependency in landslide hazard and risk analysis. In: Glade, T., Anderson, M., and Crozier, M.J., (Eds.), Landslide Hazard and Risk. John Wiley and Sons Ltd., West Sussex, England, pp. 75-138 .

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72, 272-299.

IAEG-Commission on Landslides, 1990. Suggested nomenclature for landslides. Bulletin of the International Association of Engineering Geology 41, 13-16.

IGOS, 2003. Marsh, S., Paganini, M., Missotten, R., (Eds.), Geohazards Team Report. http://igosg.brgm.fr/. Accessed on 30th June 2007.

IUGS-Working group on landslide, 1995. A suggested method for describing the rate of movement of a landslide. Bulletin of the International Association of Engineering Geology 52, 75-78.

IUGS-Working group on landslide, 2001. A suggested method for reporting landslide remedial measures. Bulletin of Engineering Geology and Environment 60, 69-74.

JTC-1 Joint Technical Committee on Landslides and Engineered Slopes, 2008. Guidelines for landslide susceptibility, hazard and risk zoning, for land use planning. Engineering Geology (this volume).

Mantovani, F., Soeters, R., Van Westen, C. J., 1996. Remote sensing techniques for landslide studies and hazard zonation in Europe, Geomorphology 15 (3-4), 213-225.

Metternicht, G., Hurni, L., Gogu, R., 2005. Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. Remote Sensing of Environment 98 (23), 284-303.

Soeters, R., Van Westen, C.J., 1996. Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L., (Eds.), Landslides, Investigation and Mitigation. Transportation Research Board, National Research Council, Special Report 247, National Academy Press, Washington D.C., U.S.A., pp. 129-177.

UNESCO-WP/WLI, 1993a. Multilingual Landslide Glossary. Bitech Publishers Ltd., Richmond, Canada, 34 pp.

UNESCO-WP/WLI, 1993b. A suggested method for describing the activity of a landslide. Bulletin of the International Association of Engineering Geology 47, 53-57.

UNESCO-WP/WLI, 1994. A suggested method for reporting landslide causes. Bulletin of the International Association of Engineering Geology 50, 71-74.

Van Westen, C.J., Van Asch, T.W.J., Soeters, R., 2005. Landslide hazard and risk zonation; why is it still so difficult? Bulletin of Engineering geology and the Environment 65 (2), 167-184.

Guide book
Choice Session 3.V:
Volcanic hazard assessment

Objectives

After session 3.V you should be able to:

- List different volcanic hazard types
- Understand their varying spatial and temporal characteristics
- Understand the basics of volcanic hazard assessment
- Explain in broad terms how optical, thermal, radar and ground-based remote sensing can be used to monitor volcanoes
- Understand how multi-temporal studies can be used to map and assess changes (e.g. in gas emissions, topography etc.)

This session contains the following sections and tasks

Section	Topic	Task	Time required		
3.V.2	What is volcanic hazard?	3.V.1 Visit the Volcano World website and watch a YouTube video on different volcano types		0.5 h	1.0 h
		3.V.2 Visit the website of the US Geological Survey and learn more about hazard assessment and find currently active volcanoes		0.5 h	
3.V.3	Assessing volcanic hazards	3.V.3 Learn about different volcanic subhazards and the spatial reach		0.25 h	0.45 h
		3.V.4 Learn about supervolcanoes		0.30 h	
3.V.4	Remote sensing of volcanic hazards	3.V.5 Google Earth volcanic hazard assessment		0.5 h	1.5 h
		3.V.6 Use the MODVOLC page to find currently active volcanoes		0.5 h	
		3.V.7 Design a simple volcano monitoring strategy		0.5 h	
		Total			**3.25 h**

3.V.1 Introduction to volcanic hazards

No other natural process tends to awe and fascinate people as much as a volcanic eruption. For anyone who has seen footage of an eruption on TV, or even witnessed in person huge eruption clouds or lava flows snaking down a mountain, such display of nature's power will likely seem unparalleled. Volcanic activity is also one of the few hazards where a clear positive side is widely recognised. Just like an annual flood adding nutrients to agricultural fields and thus being seen as a necessary price to pay for a good harvest by societies where such flooding has become part of the culture, volcanic activity creates highly fertile lands, which explains why volcanic slopes tend to be intensively farmed. This combination of threat and benefit has frequently led to reverence towards volcanoes, with divine attributes being attached to those structures. In this section we introduce volcanic hazard, explain its characteristics relevant from a geoinformatics perspective, and explain in detail how remote sensing and GIS can be of use to understand and monitor the hazard.

3.V.2 What is volcanic hazard?

Approximately 50-60 subaerial volcanoes (i.e. on land instead of under water) erupt worldwide every year, posing substantial risks to surrounding communities, the environment and the aviation industry, as well as occasionally affecting the global climate. In total some 1,500 potentially active volcanoes exist in the world. As they tend to occur in well-understood locations, such as along plate boundaries (e.g. the Pacific Ring of Fire), or where known so-called hotspots exist, it seems like we have pretty good knowledge on the source of the hazard. After all, we do not expect new volcanoes to appear overnight (although the growth of a new volcano over the course of a few weeks has happened before!), or for them to move their location (although that too happens, slowly, when a hotspot moves, or the continental plate above it). What is more difficult to determine is whether a volcano is just dormant (sleeping) or actually extinct, and when it will erupt again if still active or just dormant. For people who wish to move to a fertile volcanic area it can be rather important to know whether a volcano might suddenly re-awake. Although volcanoes only account for some 2% of all natural disasters, more than 220,000 documented human fatalities have been attributed to volcanic activity over the last 200 years.

Task 3.V.1: Internet exercise (duration 30 minutes)
Go to Volcano World (http://volcano.oregonstate.edu/volcanoes/index.html) to learn more about volcanoes. In particular check out the "Find a volcano" section to learn more about where volcanoes are concentrated. The watch the following short video on YouTube: http://www.youtube.com/watch?v=DnBggrCdkN0 (3:26).

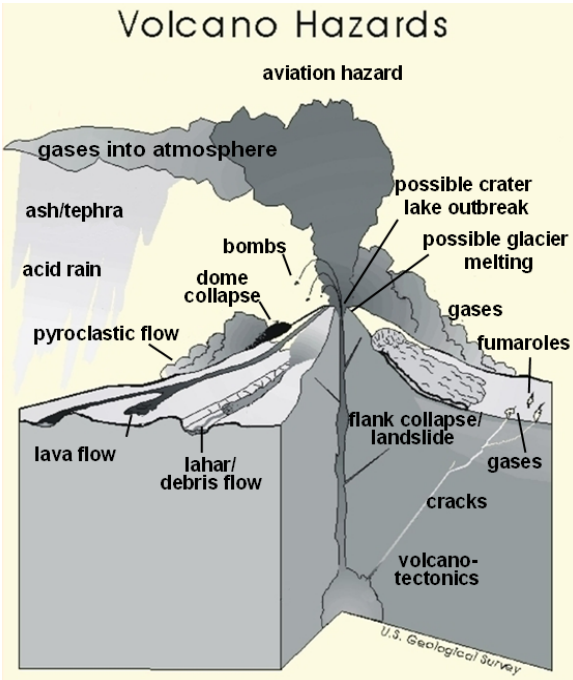


Figure 3.V.1: overview of the different hazards a volcano can pose (modified from United States Geological Survey).

A look at volcanic hazard reveals that we are not actually dealing with a single hazard, thus the term "volcanic hazard" is too unspecific and should always be qualified. Think for a moment about a volcano and consider different hazard aspects – surely more than just lava flows will come to mind. In fact, from a hazard perspective a volcano is the most diverse phenomenon we will address in this course. Figure 3.V.1 gives an overview of the various hazards a volcano can pose – a total of 17 distinct hazards is listed! Several of those are well-known, such as ash fall or lava flows, perhaps even gas emissions or pyroclastic flows. However, in addition there are lesser known hazards, such as volcano-tectonic seismicity (when magma rises within the edifice, leading to earthquakes), acid rain or crater lake outbreaks. Many of those can occur simultaneously during the eruption of a given volcano. Some actually precede an eruption, while others are not even associated with what we consider to be volcanic activity. For example, an extinct volcano may have a crater lake. If the rim that contains the lake becomes unstable because of erosion or seismic activity, a crater lake breakout can occur, leading to vast quantities of water rushing down the mountain, picking up ash and other material, and forming a mudflow that can be deadly for tens of kilometres. At other times volcanic activity has consequences even further away from the edifice. For example, the

Task 3.V.2: Internet exercise (duration 30 minutes)
Go to the USGS Volcano Hazards Program website (http://volcanoes.usgs.gov/) that provides detailed background information of different volcanic hazards, as well as status information on currently active volcanoes. Explore what information is available, both as background and in real time. Summarise briefly how hazard information is being communicated. Who seem to be the users of such information?

famous 1991 eruption of Mount Pinatubo in the Philippines ejected more than 20 million tons of sulphur dioxide (SO_2) into the atmosphere, leading to global cooling of about 0.5ºC. An even larger eruption at Tambora (Indonesia) in 1815 cooled the Earth by as much as 3ºC, and leading to a "year without a summer" in Europe and North America. Thus harvests lost there were a consequence of a volcanic hazard originating thousands of kilometres away.

3.V.3 Assessing volcanic hazards

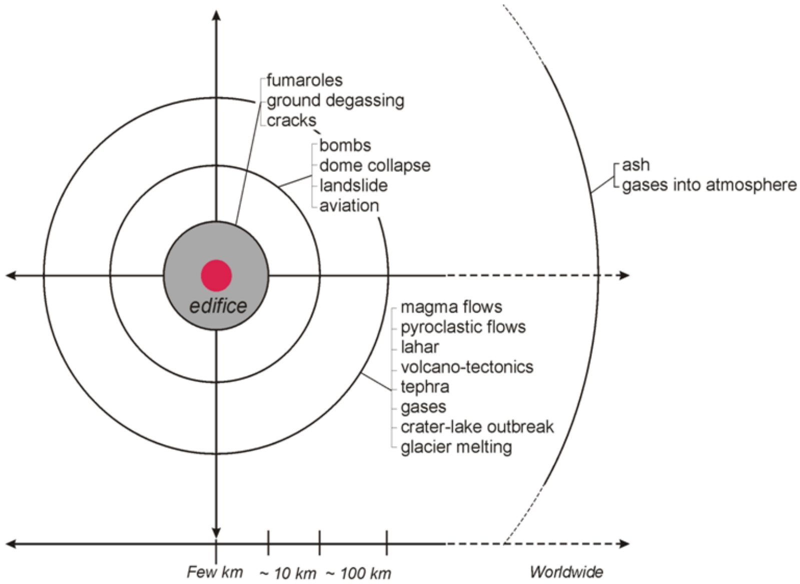


Figure 3.V.2: Spatial reach of different volcanic hazards.

This course deals with multi-hazard risk assessment. Hence, to understand the risk as a precondition to reduce or manage it a detailed understanding of the hazard is needed. Here we face a challenge. Unlike, for example, a river, where we model how high and how fast the water will rise given information on the topography, surface roughness and the rate of rainfall in the catchment, we do not have a single hazard here. In principle each of the 17 sub-hazards has to be considered separately. There are, however, possibilities to reduce this problem somewhat. For example, if a volcano has no glacier or crater lake, there can be no flooding or mudflow formation, except for cases of extreme rainfall. We can also consider the hazards in terms of their reach (Figure 3.V.2). Several hazard types clearly have a very limited impact field. For example, fumaroles (volcanic gases emitted through cracks in the edifice) or crack formation are a problem for buildings standing right on the flank of the volcano, or for cattle and people, but do not reach further. An eruption, however, can fling volcanic bombs more than 1 km away from the crater. During a dome collapse (when parts of a magma plug break up) or a volcanic landslide an area a few kilometres away can still be buried by material, which also happens due to tephra fall. This is still far less though than the reach of magma or pyroclastic flows, as well as volcanic mudflows (lahars) that have been documented to travel up to 100 km when channelled by topography. For example, following the 1985 eruption of Nevado del Ruiz in Colombia, a lahar formed due to melted glaciers, and destroyed the town of Armero 74 km away from the crater, killing more than 23,000 people. Thus seemingly local events (e.g. glacier melting) can have far-reaching consequences. Volcanic gases can also travel great distances. For example, at Masaya volcano in Nicaragua, SO_2 concentrations recorded during non-eruptive times were highest at a ridge 14 km from the crater. In fact, when we talk about volcanic gases as a hazard, we could subdivide it further, as not only SO_2 is dangerous. In 1986 vast amounts of carbon dioxide (CO_2) were released from the Nyos crater lake in Cameroon, travelled some 25 km, and asphyxiated more than 1,700 people in their sleep. As CO_2 is heavier than air it concentrates near the ground, thus leading to deadly concentrations. SO_2, on the other hand, can rise into the stratosphere and remain there for weeks or months, eventually circling the planet and, after conversion to sulphuric acid, leading to the cooling already mentioned. One sub-hazard is rather unique, in that it works in the vertical direction: aviation hazard. If a plane flies into an eruption cloud, the ash entering the engines is melted to glass, which can lead to loss of engine power and planes crashing.

The size of an area a given hazard can affect is only one part of a hazard assessment. It is also important to know the return periods. As for other hazards that occur rarely or infrequently this can be a major challenge. We wish it was as easy as with the so-called *Lighthouse of the Mediterranean* – Stromboli volcano. For 2,600 years this volcano has been continuously active, emitting several small bursts per hour (and only rarely a little more violently). However, often we observe that a volcano "sleeps" for centuries before erupting again, leading to a situation where people do not even recognise a volcano as such, but only think of it as a mountain (e.g. Pinatubo before the 1991 eruption)! Thus for many volcanoes we have a very poor understanding of their history for the different hazard types. While it is possible to carry out detailed stratigraphic analysis around a volcano, to determine date, size and type of a volcanic deposit (e.g. lava, tephra, ash), this has only been done at few volcanoes, and often only after a disaster has happened. As we will discuss below, remote sensing can help here. Another important source of information is historical records. Large eruptions tend to be recorded, sometimes in great detail. For example, the eruption of Vesuvius in Italy that famously destroyed the town of Pompeii in 79AD was meticulously described. Especially for areas that have been inhabited for millennia (such as Italy), we tend to have a seamless record of activity. In the "New World" far fewer data exist, and we have to make do with what we can find in the stratigraphic record. Also for other hazards, such as landslides, crater-lake outbursts or historic gas emissions, typically records are very sketchy.

Task 3.V.3: Exercise (duration 15 minutes)

Figure 3.3.V.2 shows how different subhazard types can affect areas at different distances. Explain why the circular shape used here may not always be appropriate?

Often what we are left with is trying to understand the onset times and durations of different hazards. For example, a volcano gives off certain signs that can signal an impending eruption. Thus even if we do not have sufficient information about historic eruptions, observing such signs can be useful for early warning and to update hazard maps. Also important is the duration of a hazardous event. For example, a small volcano-tectonic shock may crack some roads or building walls that are readily fixed. Another matter is long-lasting missions of gas or ash. A good example is a new "mud volcano" near Surabaya in Indonesia. Since May 2006, a new volcano has been emitting more than 100,000 m^3 of hot mud per day, displacing thousands of people. Figure 3.V.3 gives an overview of the onset times and durations of various volcanic sub-hazards.

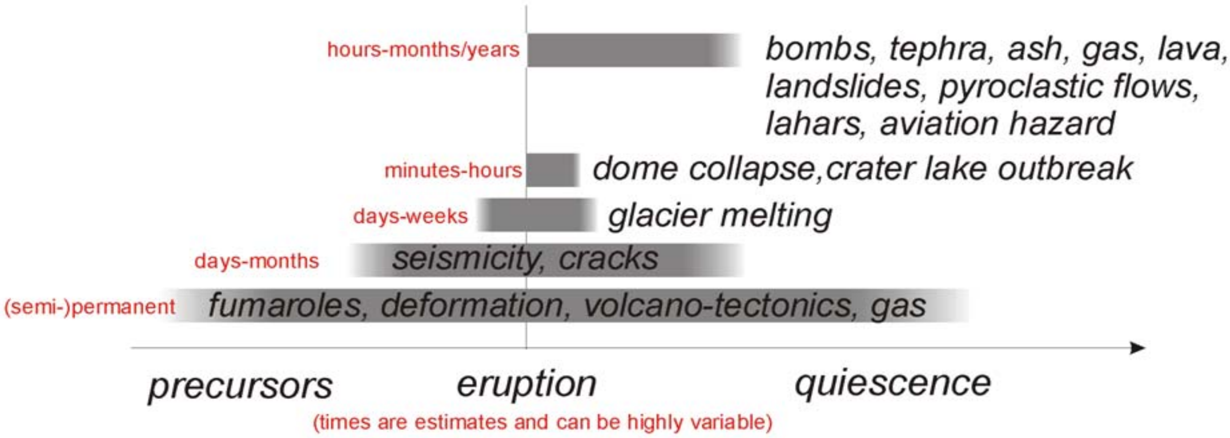


Figure 3.V.3: onset times and duration of different volcanic hazards.

We see that we can distinguish a precursor period, the eruption, as well as quiescence. While the times shown are estimates, they give an idea of when a certain hazard is likely to occur, and how long it might last. For example, fumaroles or low-level gas emissions can occur for very long times. Volcanic seismicity or cracks in the edifice, on the other hand, are associated with ascending magma and can thus signal a coming eruption, but they can also result from the collapse of an empty magma chamber after an eruption. For glaciers to melt, we already need a significant heat source near the summit, though the melting can then last for weeks. Other events, such as a dome collapse, only occur after an eruption has begun, but may only last minutes or hours. If the volcano then remains active, as is often the case, the hazard from tephra falls, degassing lava flows etc. can then persist for months or years.

To understand a hazard fully we also need to consider what impact it might have on people or infrastructure. In terms of infrastructure this is rather easy. Direct contact with lava or a pyroclastic flow will likely lead to a total loss. For a lahar it depends on the height and the speed of the flow, ad we can model the force for a given scenario and whether a structure can withstand it. Similarly, we can calculate the weight of a certain amount of ash on a roof, and up to which point a building can withstand the pressure. Figure 3.V.4 shows how we can conceptualise the impact of volcanic activity on people. Broadly speaking, it can lead to death (e.g. in direct contact with lava or pyroclastic flows), or to traumatic of chronic injuries. Traumas occur when falling volcanic bombs or tephra,

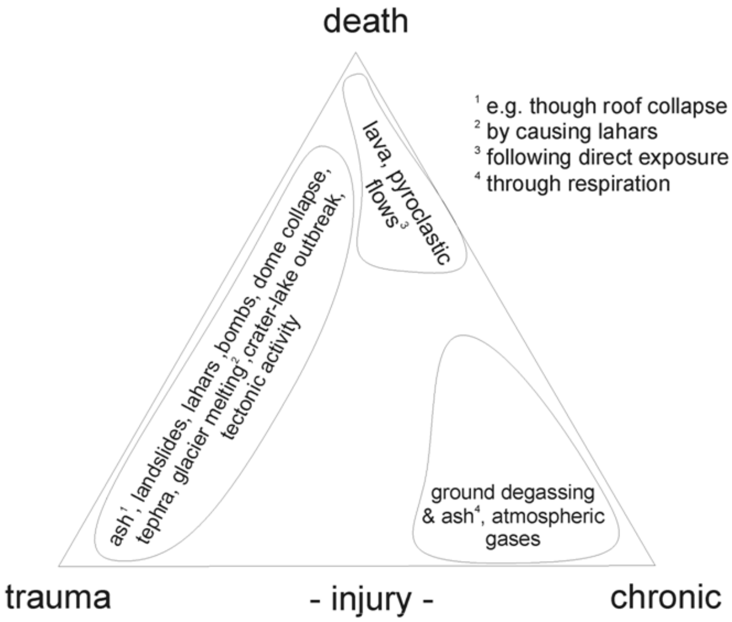


Figure 3.V.4: Impact of volcanic hazard on people.

or for example collapsing roofs injure people who later recover. Inhaling of volcanic gases or ash, on the other hand, can lead to chronic respiratory illness.

We can thus conclude that there is no single volcanic hazard, but rather that there are many sub-hazard types, each with its own spatio-temporal characteristics as well as consequences for people and infrastructure. These various hazards can also occur with variable relation to eruptive activity, compound or reinforce each other, and some can also occur without any eruption activity at all. In the following section we review how remote sensing can help us to map and understand these volcanic hazards.

Task 3.V.4: Exercise (duration 30 minutes)
One volcano type we have not mentioned so far is a supervolcano. Use the internet to find out what this is. Why do you think we do not consider them here?

3.V.4 Remote sensing of volcanic hazards

Volcanoes probably always produce precursory signals prior to eruption, though in many cases these go unobserved. These include changes in quantity and composition of emitted gases such as SO_2, an increase in temperature of (parts of) the edifice or crater lakes, and seismic activity and bulging as signs of ascending magma. While all of those signs are readily detected with *in situ* instrumentation, the cost and risk associated with such efforts has precluded widespread implementation of available technology. However, with the exception of seismic activity, all the above signs can be detected with remote sensing technology. Volcanoes are in fact wonderfully expressive entities, broadcasting much useful information. What we need is to adjust our monitoring means – e.g. through remote sensing – to pick up those signals.

As was explained already in the guidance notes on spatial data sources (and the background box on remote sensing), we need to adjust our monitoring in terms of appropriate spatial, spectral and temporal resolution. This means that we need to understand all sub-hazard types we wish to consider in this respect. This means that for some hazards the low temporal resolution (several days to weeks) of a polar orbiter is sufficient, when it provides a good regular overview of the entire volcano. For other, more dynamic hazards, such as variable magmatic activity, frequent thermal monitoring may be needed. Below we briefly review the main types of remote sensing of different volcanic hazards.

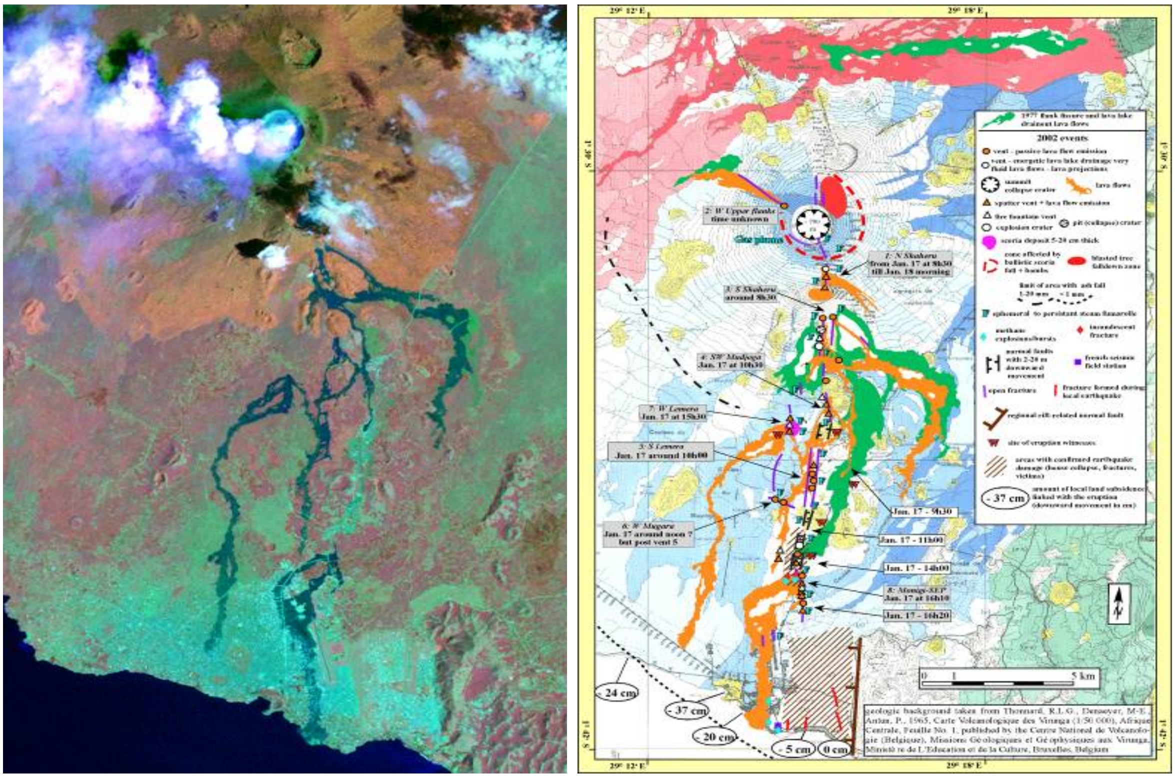


Figure 3.V.5: Hazard mapping for Nyiragongo (Democratic Republic of Congo) based on ground data and satellite image processing (Source: J.C. Komorowski).

Optical remote sensing

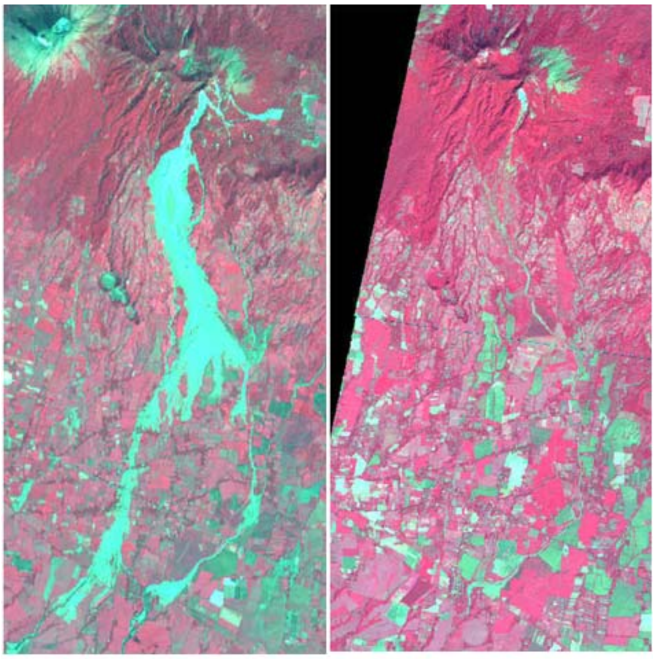


Figure 3.V.6: Traces of a lahar (mudflow) at Casita volcano (Nicaragua) disappearing quickly (note that the flow was some 20 km long!)

Many volcanic hazard types can be detected with optical instruments. For example, present crater lakes or glaciers can be seen in satellite pictures. If detailed data are available it is frequently also possible to see previous lava flows, tephra deposits or the remains of pyroclastic flows and lahars. (See Figure 3.V.5). We need to realise, though, that such traces can disappear very quickly (see Figure 3.V.6), and that we cannot date the observed phenomena. Image resolution is also critical to see hazardous features. Figure 3.V.7 gives examples of low and high resolution images of volcanoes that can be used to asses some of the present hazards.

Figure 3.V.7: Screen shots from Google Earth of Casita volcano (Nicaragua, left), and Mount St. Helens (US, right). Note the radically different level of detail those images provide.

Task 3.V.5: Internet exercise (duration 30 minutes)
Open Google Earth and try to find the 2 volcanoes shown in Figure 3.3.V.7. Explore the volcanoes by using different zoom levels, move around them, and switch the elevation data on and off (using the Terrain *button in the lower left layers menu). Explore which of the hazards shown in figure 3.3.V.1. are evidenced in the Google Earth data.*

Thermal remote sensing

Several volcanic hazards are associated with high temperatures, and in fact monitoring thermal anomalies is a good way to see signs of impending magmatic activity. A peculiar aspect of thermal remote sensing is that the hotter the heat source the lower the required image resolution can be still to see it. This means that to detect a temperature increase in a crater lake or on a volcano flank we need imagery on the order of 10-30 m resolution (e.g. SPOT, ASTER or Landsat TM), while to detect a lava lake much coarser data are sufficient. For example, for imagery with a resolution of 1km x 1km a magmatic feature (which has temperatures of 900-1200ºC) of less than $10m^2$ is sufficient to be detected! The advantage here is that we have geostationary meteorological satellites, such as Europe’s Meteosat Second Generation (MSG) that monitors all of Africa and much of Europe, and provides suitable data every 15 minutes. Asia and the America’s have similar satellites, thus detecting magmatic activity is routinely done. Figure 3.V.8 provides examples of thermal imagery of magmatic activity, from both a high resolution polar orbiter (ASTER [left]) and a geostationary satellite (MSG [right]). We have thus the ability to detect critical changes on the volcano to anticipate magmatic activity, but can also use those data to map lava flows without having to resort to dangerous field visits. There are already automatic systems that detect thermal activity at volcanoes and report it on a webpage (e.g. MODVOLC, http://modis.higp.hawaii.edu/, which is based on daily MODIS images and provides global coverage).

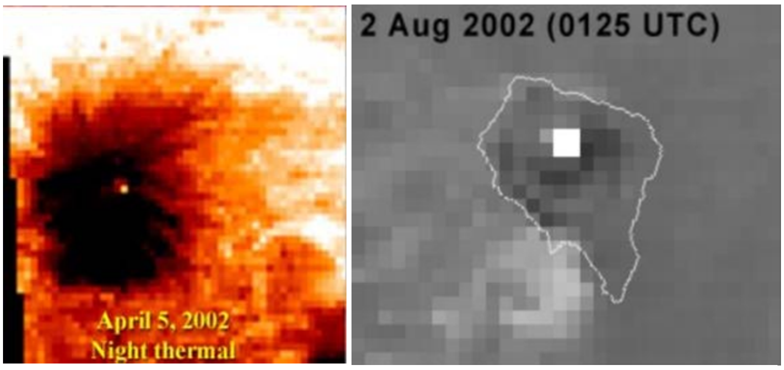


Figure 3.V.8: Sample thermal signals of magmatic activity – Aster night time (left) and Meteosat Second Generation (right).

Even though it has nothing to do with heat, the thermal part of the spectrum is also very useful to detect large gas emissions. For example, SO_2 has been mapped with the Moderate Imaging Spectroradiometer (MODIS, 1000m resolution), as well as with the Total Ozone Mapping Spectrometer (TOMS, ca. 50km resolution).

Task 3.V.6: Internet exercise (duration 30 minutes)
In Task 3.3.V.2 you identified some currently active volcanoes. Go to the MODVOLC page (http://modis.higp.hawaii.edu/)to see if you can find evidence of current magmatic (thermal) activity as well. Try to find 3 volcanoes where the USGS is listing activity and that also show a thermal signal on MODVOLC.

Radar remote sensing

Although there are far fewer operational radar satellites than optical instruments, they are very useful to monitor volcanoes as well, because they provide very different but complementary information. Radar is very sensitive to surface roughness and moisture, but also to subtle surface deformations. Therefore, radar is very well suited to detect a bulging in a volcano's edifice as a result of magma ascending (Figure 3.V.9), when imagery from 2 different dates is used (Differential Interferometry). Vertical changes as small as about 3 cm can be detected this way! However, if the volcano is densely vegetated it can be difficult to do such analysis, as the correlation needed between the images is then lost.

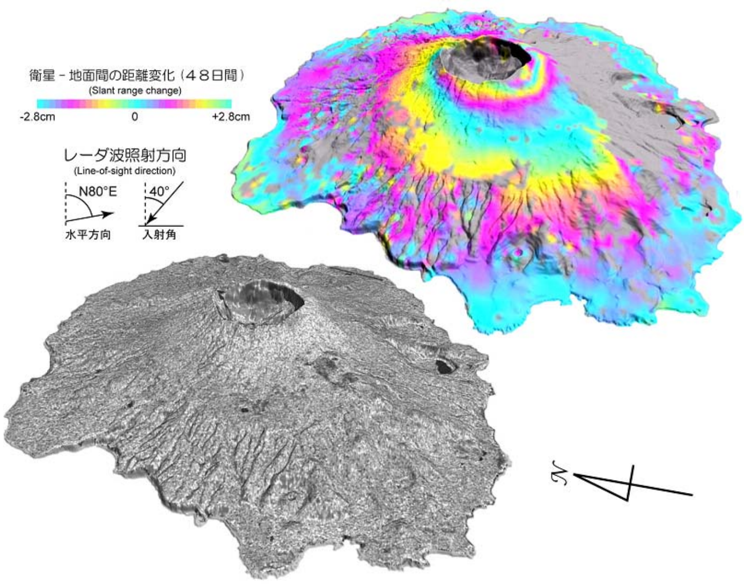


Figure 3.V.9: Crustal deformation after the 2000 eruption of Miyakejima volcano (Japan) detected by RADARSAT (Source: NIED, Japan).

Ground-based remote sensing

Recall that we term any method *remote sensing* where a non-contact measurement of a phenomenon is made. We typically think of satellites or airplanes here, but in fact it also includes measurement devises deployed on the ground that are not in direct contact with the object of investigation. For volcanic hazard assessment and monitoring a variety of instruments are used that are worth mentioning here. In principle, any of the remote sensing types described above can also be used on the ground. For example, a thermal scanner can be hand-carried or mounted on a tripod, and used to map any volcanic thermal features in detail.

Figure 3.V.10: Fourier Transform Infrared Spectrometer (FTIR) deployed at a volcano.

There are also sophisticated devices specifically designed to map volcanic gases, such as a correlation spectrometer (COSPEC) or a Fourier Transform Infrared Spectrometer (FTIR; Figure 3.V.10). Those instruments are usually placed on tripod and pointed directly at a source of the gas, or they “look” through the gas plume at a source of infrared light placed there. The phenomenon used here is that gas constituents such as SO_2 lead to a signal in the recorded infrared energy, allowing the precise calculation of the gas species and the quantity present in the beam.

While we can map deformation using radar, also here we can use ground based instruments. For example, measuring positions over time with a Global Positioning System (GPS) device reveals changes (provided a very detailed so-called Differential GPS is used; Figure 3.V.11). For remote measurements also an electronic distance meter (EDM) can be used that maps the distance between the EDM and reflectors mounted previously on the volcano’s flank. This way, many readings can be made rapidly and safely. However, radar has the advantage that we get a continuous deformation picture, and not only spot measurements (compare with Figure 3.V.9).

Figure 3.V.11: Differential GPS deployed at a volcano.

Other devices that are frequently used to map volcanic hazards are microgravity meters (to look for gravity changes associated with magma movements), or ground penetrating radar (to look for buried fault lines or distinct deposition layers).

Three dimensional analysis

When talking about radar interferometry we also already talked about changes in the 3rd dimension. 3D analysis is a common tool in volcanic hazard assessment. For example, stereo aerial photographs can be used to perform stereoscopic investigations to find faults or steep flanks or cliffs (landslide potential). They can also be used quantitatively to create Digital Elevation Models (DEMs; see guidance notes on DEMs). Such DEMs can also be constructed to asses changes. Figure 3.V.12 shows DEMs depicting the situation East of Mount Pinatubo, before and after the 1991 eruption. The change we see corresponds to the material deposited by pyroclastic flows, leading to a smoothing of the terrain. From this difference we can calculate exactly how much material was deposited. This is important information, as each year following the eruption parts of the loose material were remobilised by rainfall, leading to fresh lahars. Figure 3.V.12 shows the change due to erosion in 1991, following the eruption in June of that year.

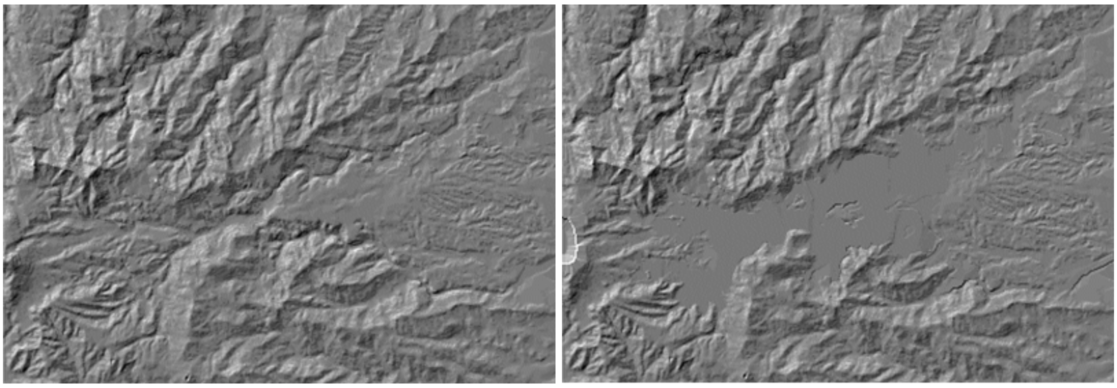


Figure 3.V.12: Digital Elevation Models before (left) and after (right) the 1991 eruption of Mount Pinatubo (Philippines).

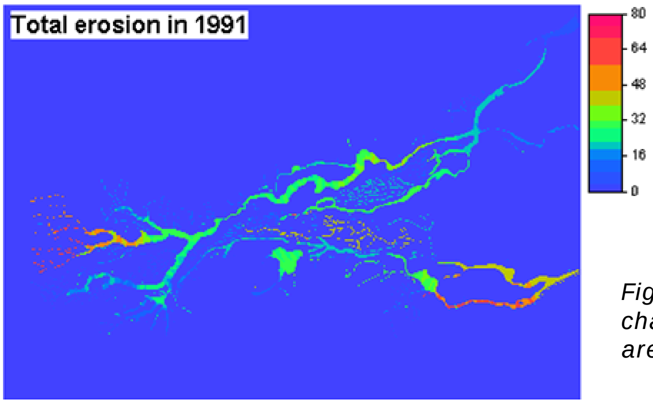


Figure 3.V.13: Digital Elevation Model of change, showing the material lost in the area shown in figure 11 in 1991.

Task 3.V.7: Exercise (duration 30 minutes)

We have reviewed in this session what volcanic hazards exist, and how those hazards can be assessed and monitored using remote sensing methods. Select a volcano of your choice that is located close to a populated area and that is currently active. Design a broad hazard monitoring strategy for that volcano that is based on remote sensing approaches. Consider specifically the following:

- *the hazard types present*
- *the temporal, spatial and spectral characteristics and thus monitoring requirements*
- *make a table listing the hazard, the monitoring type and needed sensor, and how often observations have to be done.*

Refer to the IGOS geohazards report (200&, see further reading list) for guidance on volcano monitoring.

3.V.5 Summary

Instead of a single hazard we see that we have to consider about 17 individual hazards at a single volcano, each with its own spatio-temporal characteristics. To understand the hazard situation comprehensively, we would have to study each of those hazards in terms of its magnitude, frequency and consequences on people, infrastructure and environment. Doing this in the field is time-consuming as well as frequently dangerous. Remote sensing provides many ways to study nearly all hazards not only in an easier manner, but frequently also in a more comprehensive way. For example, instead of spot measurement with a GPS or a thermal scanner we get a synoptic image (covering the whole area continuously). What is vital is that we understand every hazard in terms of its spatial, spectral and temporal aspects, so that we can design a suitable remote sensing based monitoring strategy. For several hazard types (e.g. to look for magmatic activity or large ash emissions that may pose a threat to aviation), automated systems have already been set up.

While we have largely talked about remote sensing in this chapter, it must be made clear that GIS also plays an important role. While remote sensing can provide the data (images, thermal readings, etc.), and image processing can be done to interpret those data, a GIS is the typical environment where all data are integrated and further processed. The DEM change detection shown in Figure 3.V.13, for example, was carried out in a GIS. You will see more examples of this in later chapters, and also learn how to do this yourself.

Self-test

Self test
In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question 1: Volcanic hazard
Which if the following can be considered volcanic hazards?
A) Pyroclastic flows
B) Ash columns
C) Collapsing buildings
D) Volcanic gases (e.g. SO_2 and CO_2)

Question 2: Remote sensing data type I
Which of the following remote sensing types is suitable to assess the increase in water temperature in a volcanic crater lake?
A) Geostationary weather satellite (e.g. Meteosat Second generation)
B) Radar remote sensing
C) Medium resolution instruments such as Landsat TM or ASTER
D) Aerial photos

Question 3: Remote sensing data type II
Which of the following remote sensing types is suitable to assess the surface deformation of a volcano, for example when magma is rising on the inside?
A) Stereo aerial photos
B) GPS
C) Laser scanning
D) Radar (Differential Interferometry)

Question 4: Volcanic hazard assessment
Why is volcanic hazard assessment so difficult?
A) Volcanoes are always in far away places
B) There are many types of hazard that need to be considered
C) Assessing the frequency of some hazard types can be difficult because they do not occur very often
D) Satellite data are too expensive

Question 5: Thermal remote sensing
Why is it sometimes difficult to map volcanic thermal anomalies?
A) The thermal features are too hot to sense them
B) Wildfires can be mistaken for a volcanic thermal anomaly
C) The thermal feature may be too small for a given/available thermal sensor
D) The temporal resolution of our satellites is too low to observe thermal anomalies

Further reading:

Douglas, J., 2007, Physical vulnerability modelling in natural hazard risk assessment: Natural Hazards and Earth System Sciences, v. 7, p. 283-288.

Francis, P. and Oppenheimer, C., 2003, Volcanoes, Oxford University Press.

Integrated Global Observing Strategy (IGOS), 2007, Geohazards Theme Report. www.igosgeohazards.org/pdf/theme_reports/igos_geohazards_report_2007.pdf

Tralli, D.M., Blom, R.G., Zlotnicki, V., Donnellan, A., and Evans, D.L., 2005, Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards: Isprs Journal of Photogrammetry and Remote Sensing, v. 59, p. 185-198.

Vallance, J.W., Schilling, S.P., Devoli, G., and Howell, M.M., 2001, Lahar hazards at Concepción volcano, Nicaragua: USGS Open-File Report, v. 01-457, vulcan.wr.usgs.gov/Volcanoes/Nicaragua/Publications/OFR01-457/OFR01-457_plate_1.pdf

Guide book
Choice session 3.E:
Earthquake hazard assessment

Objectives

After session 3.E you should be able to:

-

This session contains the following sections and tasks

Section	Topic	Task	Time required	
3.E.2	Definition and classification			
3.E.3	Locations and types of earthquakes			
3.E.4	Earthquake related hazards			
3.E.5	Application of remote sensing in earthquake hazard assessment			
3.E.6	Seismic hazard assessment approaches			
3.E.7	Inventory of spatial datasets required in earthquake hazard assessment			
3.E.8	Educational material			
		Total		

3.E.1 Introduction

Earthquakes are the greatest threat to mankind, killing and maiming thousands every year. According to the National Earthquake Information Center (NEIC) USA (2009), from 2000-2008 alone, an average of (almost) 28,000 people per year were killed throughout the world (see table 3.E.1 below). The death toll in most cases is in the least developed countries rather than the developed countries affected by similar magnitude earthquakes. The strongest and most destructive earthquake of 2008 occurred in Eastern Sichuan, China on May 12, claiming at least 69,185 lives. This 7.9 magnitude earthquake injured 374,171 people, while a further 18,467 remain missing and are presumed dead in the Chengdu-Lixian-Guangyuan area. More than 45.5 million people-a total greater than the combined populations of California, Arizona and Nevada-were affected by this earthquake, which struck in one of China's most densely-populated regions. The event also triggered many landslides, some of which buried large sections of some towns including Beichuan.

Table 1.E.1: Earthquake statistics for the period of 2000 to 2008 obtained from the USGS NEIC website (http://neic.usgs.gov/neis/eqlists/eqstats.html).

Magnitude	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
8.0 to 9.9	1	1	0	1	2	1	2	4	0	0
7.0 to 7.9	14	15	13	14	14	10	9	14	12	4
6.0 to 6.9	146	121	127	140	141	140	142	178	166	21
5.0 to 5.9	1344	1224	1201	1203	1514	1693	1712	2074	1600	268
4.0 to 4.9	8008	7991	8541	8462	10888	13919	12838	12078	12463	999
3.0 to 3.9	4827	6266	7068	7624	7935	9193	9990	9889	11723	334
2.0 to 2.9	3765	4164	6419	7727	6317	4637	4027	3597	3858	290
1.0 to 1.9	1026	944	1137	2506	1344	26	18	42	22	4
0.1 to 0.9	5	1	10	134	103	0	2	2	0	0
No Magnitude	3120	2807	2938	3608	2942	864	828	1807	1930	4
Total	22256	23534	27454	31419	31200	30483	29568	29685	31774	1924
Estimated Deaths	231	21357	1685	33819	228802	82364	6605	712	88011	46

It is well known that an earthquake does not kill people, but that it is buildings which do. This is because most deaths from earthquakes are caused by building or other human infrastructure falling down during an earthquake. This warrant the need for carefully designed buildings and other infrastructure. The threat to human activities from earthquakes is sufficient to require their careful consideration in design of structures and facilities.

Why Study Earthquake?

There are two reasons as to why we should study and understand earthquakes:

- Most of the big cities of the world are situated along active major and minor plate boundaries where earthquake activities are predominant.

  The earth's surface does not exist in a static, unchanging "natural" condition interrupted only by the work of humans, but instead it is a dynamic system of which humans are a part. Knowledge about changes to the Earth's surface and the underlying processes that induce them has enormous impact on how society responds to these changes and, ultimately, the cost of responding to change.

- Most of the major towns and cities are situated in Quaternary sediments. In many geological maps Quaternary sediments are colored yellow with no details. The traditional view that Quaternary sediments do not exhibit major earthquakes or large crustal surface deformations; have obscured the fact that several observations have documented the contrary, albeit not on scales comparable with plate margin deformations. A detailed geologic mapping over the last two decades in selected Quaternary areas of the world has revealed several sites of recent or contemporary surface deformations, but still this type of information is poorly integrated and emphasized in the scientific community. Also more recent studies of earthquake occurrence in many parts of the world have revealed several regions of unexplained high seismic activity, but an undisputed correlation between earthquakes and surface deformation is still pending.

3.E.2 Definition and classification

Definition:
Earthquakes are vibrations of the Earth caused by the rupture and sudden movement of rocks that have been strained beyond their elastic limits.

Earthquakes are the expression of the continuing evolution of the Earth planet and of the deformation of its crust and occur worldwide. For millions of years, the force of plate tectonics have shaped the Earth, as the huge plates that form the Earth's surface collided, separated or slide past each other. At times, the movement is gradual while at other times, the plates are locked together, unable to release the accumulating energy. When the later energy is great enough, the plate breaks or shifts along a **fault** (Fig 3.E.1). Displacement happens in a matter of seconds to minutes. The strained rock snaps into a new position and, in the process of rebounding, generates vibrations called **seismic waves**, which we feel during an earthquake. Intensive vibration, or seismic waves, spread out from the initial point of rupture, the earthquake's **focus, or hypocenter** (Fig 3.E.2) in circles outward. The point on the Earth's surface directly above the focus is the **epicenter.** The line along which the fault plane intersects the Earth's surface is the fault **trace**. If there is a vertical movement along the fault, the cliff formed is called a fault **scarp.**

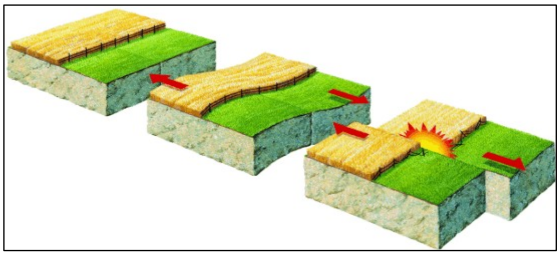


Figure 3.E.1

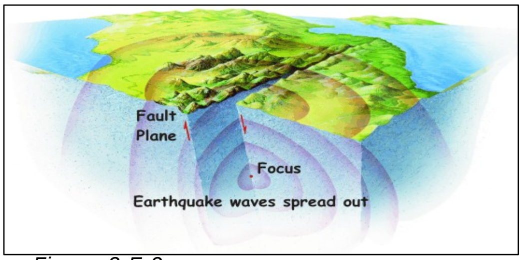


Figure 3.E.2

3.E.3 Locations and Types of Earthquakes:

The locations of major epicenters over nearly a decade show that most earthquakes (with some exceptions) are concentrated in linear belts corresponding to plate boundaries (Fig 3.E.3).

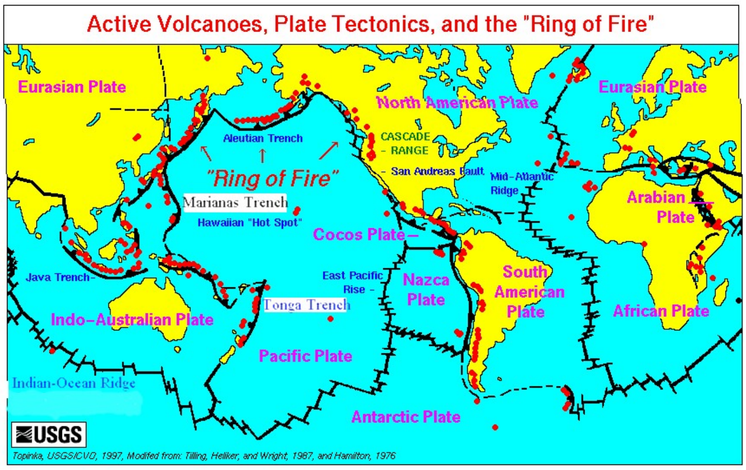


Figure 3.E.3 presents the Earth's outermost surface broken into 12 rigid plates which are 60-200 km thick and float on top of a more fluid zone (magma), much in the way that icebergs float on top of the ocean.

Earthquake Characteristics

The Earth is formed of several layers with different physical and chemical properties. Locations where earthquakes can occur include:

I. InterPlate Earthquake: Earthquakes that occur in the fault zones at plate boundaries (Example: Seismicity associated with the Himalayan seismic belt). Three types of plate boundaries are known (see Fig.5 and 6).

- ***Ocean spreading ridges:*** These are places in the deep ocean basins where the plates move apart. With separation, hot lava from the Earth's mantle rises between the plates, gradually cools, contracts, and cracks, subsequently creating faults. Most of these faults are normal faults. Near the spreading ridges, the plates are thin and weak. The rock has not cooled completely, so it is still somewhat flexible. For these reasons, large strains cannot build, and most earthquakes near spreading ridges are shallow and mild or moderate in severity.
- ***Subduction zones:*** Places where two plates collide and the edge of one plate pushes beneath the edge of the other in a process called <u>subduction</u>. Because of the compression in these zones, many of the faults there are *reverse faults*. About 80 per cent of major earthquakes occur in subduction zones encircling the Pacific Ocean. In these areas, the plates under the Pacific Ocean are plunging beneath the plates carrying the continents. The grinding of the colder, brittle ocean plates beneath the continental plates creates huge strains. The world's deepest earthquakes occur in subduction zones down to a depth of about 700 km. Below that depth, the rock is too warm and soft to break suddenly and cause earthquakes.
- ***Transform faults:*** are places where plates slide past each other horizontally. Earthquakes along transform faults may be large, but not as large or deep as those in subduction zones. One of the most famous transform faults is the San Andreas Fault. The slippage there is caused by the Pacific Plate moving past the North American Plate. The San Andreas Fault and its associated faults account for most of California's earthquakes.

II. Intraplate Earthquake:

Intraplate earthquakes are not as frequent or as large as those along plate boundaries. The largest intraplate earthquakes are about 100 times smaller than the largest interplate earthquakes. Intraplate earthquakes tend to occur in soft, weak areas of plate interiors. Scientists believe intraplate quakes may be caused by strains put on plate interiors by changes of temperature or pressure in the rock. Or the source of the strain may be a long distance away, at a plate boundary. These strains may produce quakes along normal, reverse or strike-slip faults.

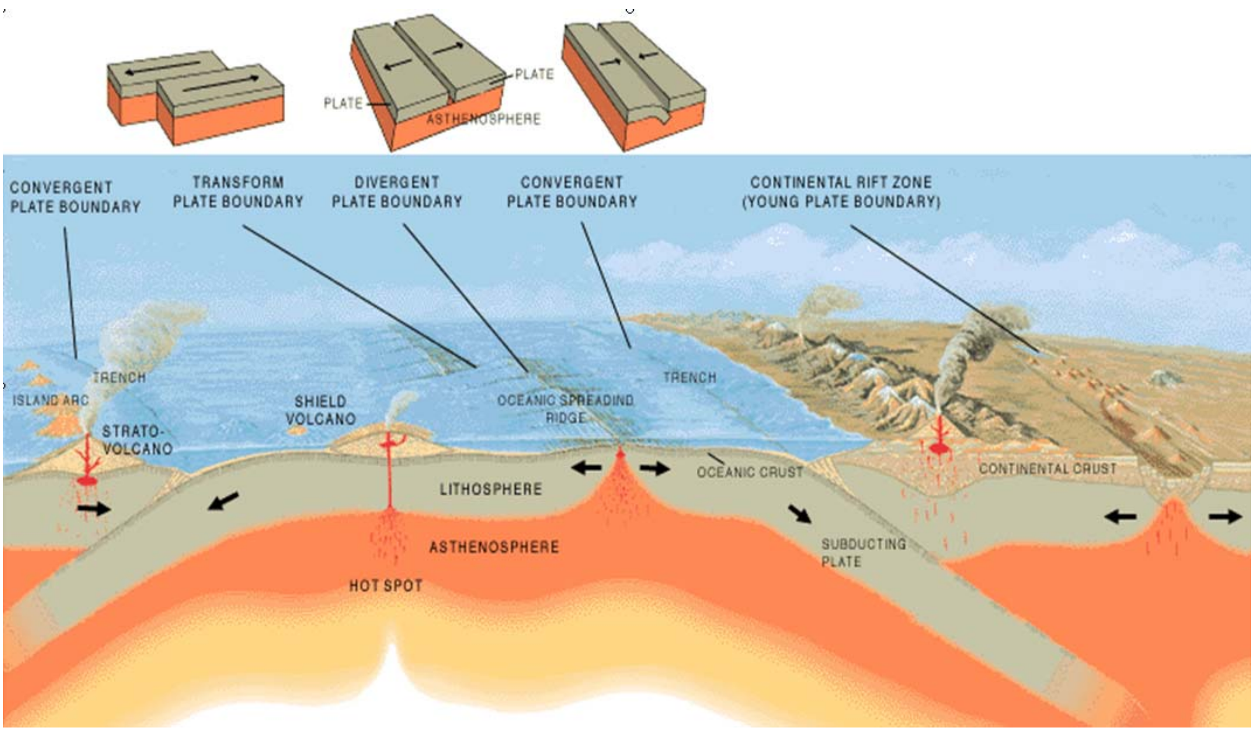


Figure 3.E.4. Earth Plate boundaries (USGS)

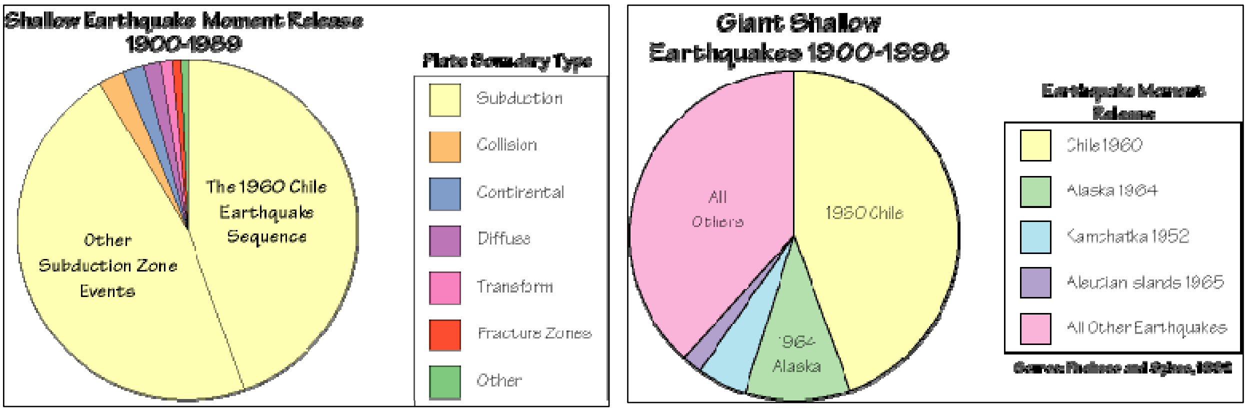


Figure 3.E.5 gives the amount of energy released in the different plate settings (modified after Ammons, 2001).

Types of Earthquakes:

There are three major types of earthquakes: **tectonic**, **volcanic,** and those formed by **human activities**. The region where these earthquakes occur and the geological make-up of that region define the earthquake.

Tectonic Earthquakes. These are caused by the sudden rupturing of rocks in response to various geological forces. Most tectonic earthquakes occur at the boundaries of major and minor plates: transform faults, spreading and subduction zones (see Fig 3.E.4). Perhaps the most famous **transform fault** known is the San Andreas Fault in California, where the North American Plate and the Pacific Plate both move in approximately north-westerly direction, with one moving faster than the other. The land to the east of the fault is moving south while the land to the west is moving north (Fig 3.E.5). Tectonic earthquakes are by far the most common and devastating. Such quakes pose particular difficulties for scientists trying to develop ways to predict them. They are scientifically important to understand the Earth's interior. On the other hand, earthquakes emanating from **subduction-zone** account for almost half of the world's destructive seismic events and 75% of the earth's seismic energy. They are concentrated in a 38,600 km long narrow band that coincides with the margins of the Pacific Ocean and, is known as the 'Ring of Fire' (see Fig. above). The points at which crustal rupture occurs in such quakes tend to be far below the earth's surface, at depths of up to 680 km. The **mid-ocean ridges** (the seafloor-spreading centers of plate tectonics), are also the sites of numerous quakes taking place at relatively shallow depths. Such quakes, account for only about 5% of the earth's seismic energy; are of moderate intensity, and daily recorded by the worldwide network of seismological stations. Other category of tectonic earthquakes includes the infrequent but large and destructive quakes that occur in areas far removed from other forms of tectonic activity but tear apart the earth's crust, forces such as those that created Africa's Rift Valley.

We can measure motion from large tectonic earthquakes using GPS because rocks on either side of a fault are offset during this type of quake.

Volcanic Earthquakes – These type originates as rhythmic earthquakes (or harmonic tremors), occurring as magma and volcanic gas (through conduits in the Earth's crust) which work their way upwards or accompany volcanic eruptions. Given that not all volcanoes are prone to violent eruption, and that most are quiet for the majority of the time, it is not surprising to note that they are by far less common than tectonic earthquakes The eruption of volcano Merapi (Java, Indonesia) in May 2006 for example, resulted in a 6.4 magnitude earthquake off the coast of Java with over 5000 people dead, approximately 40,000 injured and over 130,000 homeless. Similarly, on the island of Hawaii, seismographs may register as many as 1,000 small quakes a day before an eruption occurs.

Human Activity: Humans can induce earthquakes through a variety of activities; some of which include:

- Collapse earthquake**:** small earthquakes in underground caverns and mines that are caused by seismic waves produced from the explosion of rock on the surface.
- Landslides Collapse earthquakes: Earthquakes due to landslides are caused by the release of gravitational potential energy rather than elastic strain energy.
- Explosion earthquakes: produced by the detonation of chemicals or nuclear devices.

3.E.4 Earthquake Related Hazards

The principal ways in which earthquakes cause damage are by strong ground shaking and by the secondary effects of ground failures (surface rupture, ground cracking, landslides, liquefaction, subsidence, etc.). While 20% of death recorded account to crustal movement, the majority (around 80%) are secondary hazard; an indirect result of an earthquake. Very often, earthquakes with different magnitudes trigger different secondary hazardous events, frequently attributed to the epicenter area of a strong earthquake. (See Table 3.E.2).

A. Primary Hazard - Directly related to crustal movement (approx. 20%)-

Ground Motion – The shaking of the ground caused by the passage of seismic waves, especially surface waves near the epicenter of the earthquake are responsible for the most damage (to building and other structures). The strength of ground shaking (strong motion) depends upon:

- **Local geological conditions.** The soil and slope conditions through which the earthquake waves travel through in the area. In general, loose unconsolidated sediment is subject to more intense shaking than consolidated soil and bedrock.
- The **magnitude of the earthquake**. The bigger the earthquake, the more intense is the shaking and the duration of the shaking.
- The **proximity to the epicenter**. Shaking is most severe closer to the epicenter due to amplification (an increase in strength of shaking for some range of frequencies) and drops off as it moves away from the earthquake source (attenuation). The distance factor is dependent on the type of the underlying material involved.

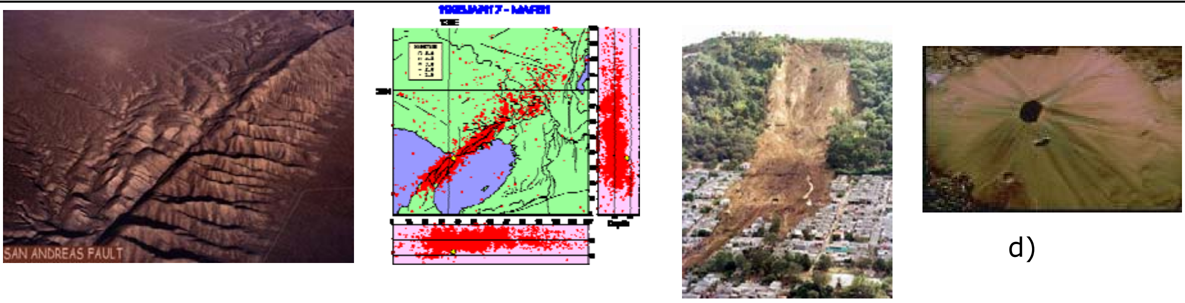
Amplification occurs where earthquake waves pass from bedrock into softer geologic materials such as sediments. Buildings on poorly consolidated and thick soils will typically suffer more damage than buildings on consolidated soils and bedrock.

B. Secondary Hazard - <u>Indirect result of earthquakes (approx. 80%)</u>-
Secondary earthquake hazards are those separate from, but induced by, the primary effects of strong ground shaking and fault rupture. Secondary geologic hazards include ground and slope failures and seiches, discussed below. (More broadly, secondary hazards also include non-geologic effects such as fires).

Fault and Ground Rupture resulting from earthquake happenings almost always follows preexisting faults, which are zones of weakness. During faulting, energy is released. Rocks continue to move until the energy is used up. Thus structures that are built across fault zones may collapse or split, roads disrupted, and many features that lie on or that cross the fault may break whereas structures built adjacent to, but not crossing the fault may survive.

Aftershocks – These usually comprise of smaller earthquakes of different magnitudes that occur after the major earthquake. They occur due to stress pattern changes surrounding the epicenter area and might continue until the crust adjusts to the changes. Aftershocks often cause structural damaged to building and other structures.

Earthquake-Induced Landslides – In mountain regions subjected to earthquakes, ground shaking can trigger all types of seismically induced landslides (e.g., soil slumps, rock falls, debris flows, rock avalanches) many kilometers from their epicenters. They can destroy roads, buildings, utilities, and other critical facilities necessary to respond and recover from an earthquake. Landslides triggered by earthquakes often cause more destruction than the quakes themselves. Since 1964 landslides resulting from large-magnitude earthquakes in Japan have accounted for more than half of all earthquake-related deaths.



a) b) C d)

Figure 3.E.6: Indirect result of earthquakes. a) shows Earth manifestation of fault or ground rupture vivid in Landsat TM; b) shows aftershocks; c) the effect of earthquake induced landslide in Ecuador and the d) liquefaction.

Earth Cracks (earthquake dislocations): This is most dangerous secondary event occurring during the earthquakes. The movement is sudden and may result in considerable vertical (in case of normal or trust faulting) or horizontal (in case of strike slip faults) accelerations that might offset any building construction on its way. It should be absolutely forbidden to build dangerous facilities (like dams, nuclear instalations, factories, etc.), near or over the expressed earth cracks generated by old or recent earthquakes.

Liquefaction occurs when water-saturated materials (sands, silts, or (less commonly) gravels) are shaken so violently that the grains rearrange and the sediment looses strength or shearing resistance, begins to flow out as sand boils (also called sand blows), or causes lateral spreading of overlying layers. Liquefaction-induced horizontal ground movements can range from minor oscillations during ground shaking with no permanent displacement, to small permanent displacements, to lateral spreading and flow slides. Liquefaction can also induce vertical ground movements (settlement) by rearrangement of loose soils into a denser configuration. In the Mexico City earthquake of 1985, the wet sand beneath tall buildings liquefied and most of the 10,000 people who died were in buildings that collapsed as their foundations sank into liquefied sand.

Subsidence or Uplift. Tectonic subsidence or uplift is the sudden relative elevation change of a large area of the earth's surface due to an earthquake. Historically, the impact of subsidence has been more severe than uplift, especially where accompanied by flooding. In the 1964 Alaskan Earthquake for example, some areas were uplifted up to 11.5 meters, while other areas subsided up to 2.3 meters.

Tsunamis and Seiches: Tsunamis are giant ocean waves generated by shallow-focus earthquake, but can also be caused by underwater landslide and volcanic eruption. They can travel at a speed of 700-800 km per hour and can reach heights greater than 20 meters as they approach the coast. The most devastating tsunami to affect California in recent history was the 1964 magnitude 9.2 Alaskan earthquakes. The first wave struck Crescent City about 4 hours after the Alaska event, but the fourth and largest wave arrived 2 hours later. It flooded low-lying communities, destroyed homes and businesses, and killed 11 people. Seiches are waves that slosh in an enclosed body of water, such as a swimming pool, lake, or bay.

Floods from dam and levee failures. Flooding caused due to failure of man-made dams and levees, or due to tsunamis, and as a result of ground subsidence after an earthquake.

Fires. Fire is a secondary effect of earthquakes and it has a devastating effect. Because power lines may be knocked down and because natural gas lines may rupture due to an earthquake, fires are often started closely following an earthquake. The problem is compounded if water lines are also broken during the earthquake since there will not be a supply of water to extinguish the fires once they have started. In the 1906 earthquake in San Francisco more than 90% of the damage to buildings was caused by fire.

Table 3.E.2: table showing the earthquake magnitude versus the secondary effect of the earthquake. Never=0%, very rare= up to 5%; sometimes= 5-10%; rare=10-20%; Frequently=20-50%; very frequently=50-90%; always=100%

Earthquake magnitude/ Secondary effects	Fault Rupture	Aftershocks	Landslides	Rockfalls	Earth cracks	Subsidence/or uplift	Tsunamis or Seiches	Liquefaction	Floods	Fire
M =3.0-4.0	always	always	very rare	very rare	never	vary rare	never	never	never	never
M=4.0-5.0	always	always	sometimes	sometimes	never	sometimes	never	never	frequently	Very rare
M=5.0-6.0	always	always	frequently	very frequently	rare	frequently	very rare	frequently	sometimes	sometimes
M=6.0-7.0	always	always	very frequently	always	very frequently	always	frequently	always	Always	sometimes
M= > 7.0	always	always	always	always	always	always	always	always	always	always

3.E.5 Application of Remote Sensing in Earthquake Hazard Assessment

Over 50,000 earthquakes occur every year on Earth. About a thousand of these are over magnitude 5 on the Richter scale and often cause damage to human settlements. Satellite data provide a unique opportunity to measure fine changes in the earth surface which are often precursors of an earthquake.

A glance at the present activities of the major players in the Earth observation field from the technological perspective, NASA, ESA, etc. shows that long term missions comprise of complementary but far better sensor quality, higher spectral/spatial resolution and better calibration. Potential applications for one-meter and 60 cm satellite imagery, such as IKONOS, Quick Bird in a GIS environment for earthquake hazard are limitless. The modern operational space-borne sensors in the infra-red (IR) spectrum allows monitoring of the Earth's thermal field with a spatial resolution of 0.5–5 km and with a temperature resolution of 0.12–0.5 C. Surveys are repeated every 12 hours for the polar orbit satellites, and 30 minutes for geostationary satellites. The operational system of polar orbit satellites (2–4 satellites on orbit) provides whole globe survey at least every 6 hours or more frequently. Such sensors may closely monitor seismic prone regions and provide information about the changes in surface temperature associated with an impending earthquake. The optical data received by the various remotely sensed sensors can also serve as detailed base map upon which thematic map layers can be overlaid, or it can be used as an up-to-date data source from which various geological and structural features, neotectonics, slope instability features, land cover, soil degradation, hydrology and other activities related to elevation features are extracted to populate multiple GIS layers [25] in an earthquake hazard study.

With the operational use of sensors with higher spectral resolutions, such as ASTER *(Advanced Spaceborne Thermal Emission and Reflection Radiometer)*, the quantification of the composition of earth surface materials becomes feasible. ASTER data also serve to obtain maps of land surface temperature, emissivity, reflectance and elevation.

The European Space Agency (ESA) *Envisat mission* involves a laser altimeter, a SAR interferometry system (ASAR), an imaging spectrometer (MERIS) etc. An important issue within the context of ESA is the Global Monitoring for Environment and Security (GMES; part of a larger framework of three such monitoring systems, the G3OS) initiative. Data collected by *airborne spectrometers* have already demonstrated that it is possible to identify certain types of exposed mineralogy, to label the minerals present along seismic areas and to determine the fractions of the minerals occurring in small, sub-pixel units.

Since the launch of European Synthetic Aperture radar - ERS1/2 and Envisat ASAR, a technique called SAR Interferometry (inSAR) has become available. With the potential to simultaneously operate two platforms, the time between acquisitions can be reduced to ensure an adequate coherence between successive SAR scenes while maintaining each platform in an orbit configuration that ensures a maximum possible coverage of the Earth's surface. SAR Interferometry has greatly helped geophysical hazard analysis, and can provide with unprecedented precision:

- high-resolution images of earthquake-prone areas;
- topographic data (DTM's using stereopairs of radar images with differing viewing angles);
- Measurement of dislocation extent at the source of an earthquake;
- Measurement of small height variations due to the filling and drainage of magma chambers under volcanoes;
- Monitoring earthquake prone regions (with these instruments) to assist in the forecasting of earthquakes, as well as in the management and evaluation of earthquake-associated risks; and
- A map of coseismic deformation generated by an earthquake (Fig 3.E.7).
- The precise monitoring of surface deformation allowing accurate zoning, mapping and prediction of volcanic eruptions, landslides and ground subsidence.

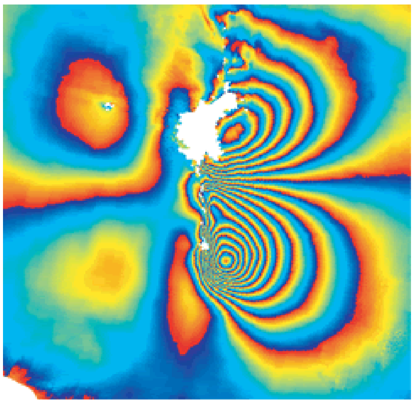


Figure 3.E.7: InSAR Data from the Bam Earthquake, Iran of 2003 showing surface deformation.

Differential interferrometry allows one to measure surface movements with sensitivity of the order of a few centimeters over large surfaces [26]. Similar InSAR data can also be obtained from RADARSAT and ALOS PALSAR.

The successful launch of the Envisat ASAR in March 2002 sparkled the interest for multipolarisation. The new technique, called POLinSAR (SAR Polarimetry and Polarimetric Interferometry) is giving promising results in many application fields, among which the study of Volcanoes and Earthquakes.

In most countries of the world, accurate topographic base map and digital terrain model (DTM) of the area under investigation for earthquake hazard is missing. In any GIS work therefore, this problem remains a handicap. An exciting development towards solving this acute problem is envisaged from the new *Shuttle Radar Topographic Mapping (SRTM*) acquired by Space Shuttle Endeavour in February 2001. The SRTM instrument captured allows one to create very detailed topographic maps of the Earth's surface using interferometry. This radar system gathered data that will result in the most accurate and complete topographic map of the Earth's surface that has ever been assembled. Already immense data covering the world, is processed open to all researchers and end users (either at 30 m or 90 m resolution) to accurately obtain knowledge regarding the shape and height of the land, and to assess: flood, soil degradation, slope instability features, erosion, geological structures especially in neotectonic studies, drainage analysis and landscape changes, all elements of high importance to earthquake hazard mapping (Woldai,2002a).

By combining those data with pre-existing data layers, it is possible to validate existing data to provide a better understanding of the phenomena occurring, and to elucidate previously undetected and unmonitored areas of motion, all at a fraction of the normal survey cost.

3.E.6 Seismic Hazard Assessment Approaches

Probabilistic and **deterministic** methods play an important role in seismic hazard and risk analyses. The two approaches can complement one another in providing additional insights into the seismic hazard or risk problem.

Probabilistic*:* This method incorporates both historical seismicity and geologic information within fault zones (Fig.9) that displays evidence of neotectonic activities (Late Pleistocene and Holocene times) and computes the probable ground shaking levels that may be experienced during, say, a 100-year, 500-year or 2,500-year recurrence period.

The probabilistic assessment derives the long-term likelihood of shaking in each area and, therefore, tells how hazardous a given area is compared to others nearby. The three contour maps, developed by the U.S. Geological Survey (Fig 3.E.9), show the expected intensity of ground shaking (PGA) in the eastern U.S. for the three average return periods (100, 500, and 2,500 years). The three assessments correspond to probabilities of 40%, 10% and 2%, respectively, that in any 50 year-period the mapped ground motion values would be exceeded. These probabilistic estimates serve best for urban planning, particularly land-use zoning, and seismic building code regulations, but they also help to determine risk based earthquake insurance premiums.

Deterministic: This procedure bases the calculation of the seismic design of a facility on the largest earthquake or ground motion at the site of the facility. This method assumes the location and magnitude of specified scenario earthquakes and determines the effects from these particular events.

In contrast to the probabilistic method, deterministic scenarios provide the "what if", answers for particular assumed earthquakes. As we change their magnitudes and locations, we can see how various areas are differentially affected by different events. If you design for the worst thing possible, then you are likely to be safe. For deterministic scenarios, we do not ask how likely each scenarios is. The deterministic scenarios are good for testing a region's emergency preparedness and how it would cope with disaster losses of various magnitudes.

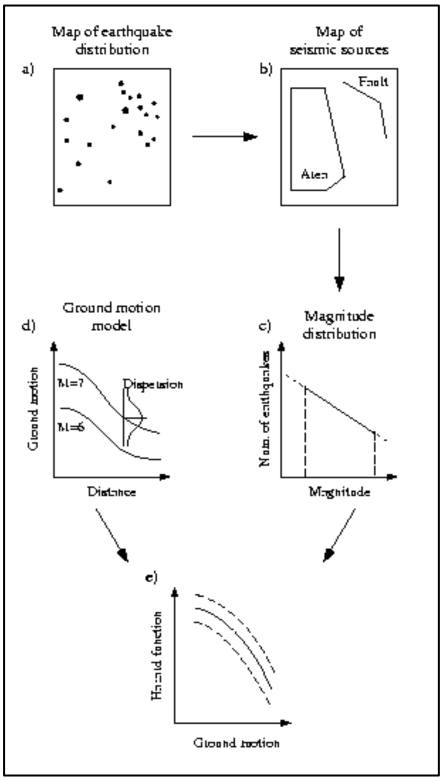


Figure 3.E.8. Characterization of seismic hazard in the probabilistic method achieved by the compilation of earthquake hazard (a), delineation of seismic sources (b), and magnitude-frequency distribution (c) For the evaluation of earthquake hazard, the characterization of attenuation of ground motion is described by attenuation functions (d) *and (e) shows the computation of the probability analysis. After Sellami (???)*

The stages in the deterministic seismic hazard mapping method involves: 1) Finding the nearest active fault; 2) Calculating the largest earthquake that could happen on this fault; 3) Assuming the largest earthquake happens at the closest point to your site and 4) Calculating what the ground motion will be.

The advantages of this method are that (a) it is relatively easily to do, and (b) it gives you a conservative answer (note for the uninitiated: "conservative" in this context means a value that maximizes safety). The disadvantages are that (a) often you don't know where the active faults are (several of the largest Californian earthquakes of recent years have occurred on faults that were previously unknown) and (b) it is easy to come up with grossly over-conservative hazard values.

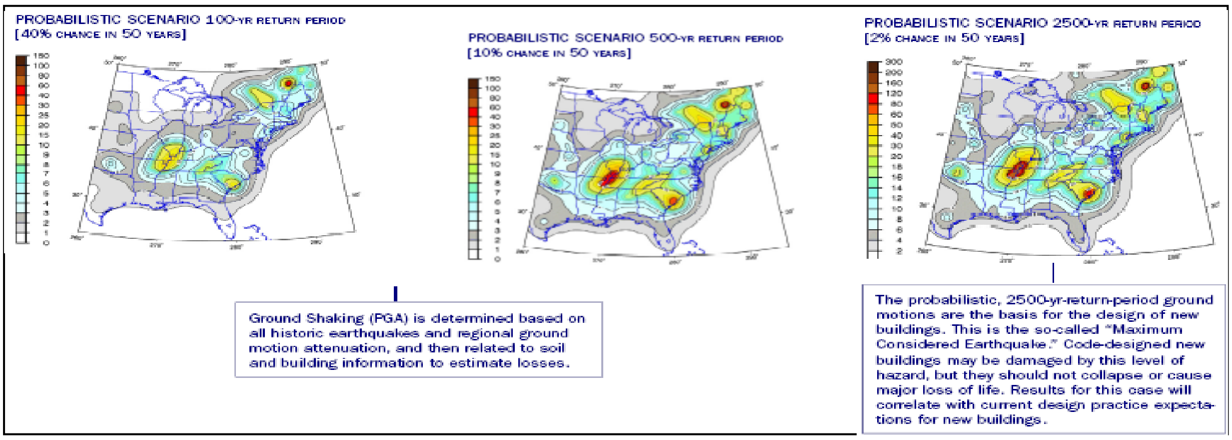


Figure 3.E.9. Maps showing the expected intensity of ground shaking (PGA) in the eastern part of the USA for the return periods of 100, 500 and 2500 years.

In many applications a recursive analysis, where deterministic interpretations are triggered by probabilistic results and vice versa, will give the greatest insight and allow the most informed decisions to be made. The most perspective will be gained if both deterministic and probabilistic analyses are conducted. Probabilistic methods can be viewed as inclusive of all deterministic events with a finite probability of occurrence. In this context, proper deterministic methods that focus on a single earthquake ensure that the event is realistic, i.e. that it has a finite probability of occurrence.

These points to the complementary nature of deterministic and probabilistic analyses: deterministic events can be checked with a probabilistic analysis to ensure that the event is realistic (and reasonably probable), and probabilistic analyses can be checked with deterministic events to see that rational, realistic hypotheses of concern have been included in the analyses.

The basic elements of modern seismic hazard assessment can be grouped into four main categories (*Giardin et al., 1999; Maquaire, Oliver*, 2005*).*

1. Earthquake catalogues and data bases: The compilation of a uniform data-base and catalogue of seismicity for the historical (pre-1900), early-instrumental (1900-1964) and instrumental periods (1964-today).
2. Seismotectonics and earthquake source zones: the creation of a master seismic source model to explain the spatial-temporal distribution of the seismicity, using evidences from seismotectonics, paleo-seismology, geomorphology, mapping of active faults, geodetic estimates of crucial deformation, remote sensing and geodynamic models to constrain the earthquake cyclicity in different tectonic provinces.
3. Strong seismic ground motion: the evaluation of ground shaking as function of earthquake size and distance, taking into account propagation effects in different tectonic and structural environments and using direct measures of the damage caused by the earthquake (the seismic intensity) and instrumental values of ground acceleration.
4. Computation of seismic hazard: the computation of the probability of occurrence of ground shaking in a given time period, to produce maps of seismic hazard and related uncertainties at appropriate scales.

Task: RiskCity exercise 03E: Earthquake hazard assessment (3 hours)

Go to the Riskcity exercise 03E and carry out the GIS exercise on seismic hazard assessment.

3.E.7 Inventory of spatial datasets required in earthquake hazard assessment.

Baseline & Other Thematic Data Needed:

- Topographic maps;
- Elevation, relief, drainage patterns and culture of an area;
- Remotely sensed data
  - o Passive and active remote sensing data;
  - o Interferometric data;
  - o High-resolution seismic reflecting surveys;
  - o Gravity maps;
  - o Magnetic maps, and
  - o Seismic refraction surveys
  - o Spectroscopic data
- GPS network
- Earthquake catalogue
- Etc.

Geomorphologic inputs

- Terrain units
- Slope and aspect map
- Digital Elevation Model
- Erosion map
- Slope Instability map
- Slopes susceptible to landslides (30° or more)

Soil inputs:

- Soil types
- Engineering soil maps showing bearing capacity of soils.
- The thickness of the unconsolidated sediments dawn to real bedrock.
- The age and mineral composition of the soil.
- The depth of the ground-water table.
- Borehole data related to rock types, soil and subsurface groundwater flow

Geological input

A wider range of geological information is applicable to the determination of seismic hazard. These include:

- Inventory of reports and maps on the geology, structure and soil involved
- Surface and sub-surface geology (age and rock types)
- Stratigraphy
- Structural geological & tectonic mapping of the area/region with a detailed account of neotectonic activities
- Mapping of quaternary sedimentary

Structural Input:

Active faults mapping with type of disc placement involved in the Holocene-Pleistocene period

- Fault styles
  - o Dip slip/fault slip/oblique
  - o Normal/or reverse; sinistral or dextral
- Fault type
  - o Normal/reverse/transform faulting
- Deformation style
  - o Extension/compression/transformation
- Fault classification
  - o Active or reactivated
- Fault geometry
  - o Orientation of the fault
  - o Dip and strike, slip
- Average displacement across the fault
- Depth of fault

Types of information derived from the seismogram

- Magnitude of the earthquake
- Seismic energy released by the earthquake
- Moment of the earthquake
- The spatial dimensions of the fault which ruptured
- The elastic constants of the medium in which the fault is located
- Orientation of the fault
- Average displacement across the fault
- Depth of fault
- Velocity with which rupture propagates on the fault
- Known faults and epicenters
- The stress drop across the fault
- The configuration of the fault plane at depth (i.e., whether planar or wrapped)

Seismological input

- Documentation of the earthquake history of the region (location, magnitude and maximum mercalli intensities illustrated by means of regional maps)
- Construction of recurrence curve maps
- Review of historical shaking, damage and other intensity information near the site
- Correlation of epicenter locations and tectonic structures
- Seismic attenuation data
- Seismic response data

Groundwater input:

- Groundwater level
- Drainage network
- Borehole data related to subsurface groundwater flow

Vulnerability data:

- data on damage from historical events;
- vulnerability curves for different structural types

Data for elements at risk:

Reports, publications, maps, etc. on elements at risk:

- Buildings (classification according to age, use, socio-economic class, building material, number of floors, contents)
- Network of roads and railways
- Network of major water conduits
- Distribution of sanitation facilities
- Network of gas and electric lines
- Distribution of hospitals, fire station and other public structureS
- Population (age distribution, average No. of people per house, gender distribution, socio-economic classification)
- Economic activities;
- Lowland areas subject to liquefaction;
- Area subject to salt-water invasion;
- Area subject to freshwater inundation;
- Map of isolated area
- Map of relative seismic safety.

3.E.8 Educational Materials

In this section, various illustrations and videos examples are assembled to facilitate one's understanding of earthquakes and its effects. The links to the videos and illustrations are provided below.

Animations and Films on:

a) Fault Motion:
These animations give very elementary examples of fault motion intended for simple demonstrations. For more about faults see the NOAA slide show and information page - a rich source of images and written information.

(http://www.iris.washington.edu/gifs/animations/faults.htm)

b) Shock Waves: One Hundred Years After the 1906 Earthquake
A 46-minute USGS film that includes dramatic historical footage, colorful animations, and interviews with earthquake experts. The catastrophe of the great 1906 quake spurred a century of progress in earthquake science and engineering. Current and future research includes drilling through the San Andreas Fault at depth in the SAFOD Experiment. Learn what you can do to reduce the risk to yourself and family.
Shock Waves received recognition as an outstanding documentary at the 2006 Telly Awards and has been nominated for an Emmy.

(**http://earthquake.usgs.gov/regional/nca/1906/shockwaves/**)

c) Earthquake – Natural Disaster:
Gives an overview of disasters from various events as a result of earthquake

(http://www.metacafe.com/watch/46548/earthquake/)

d) Animations for Earthquake Terms and Concepts
USGS Videos and Animations: earthquakes, plate tectonics, geology, tsunamis, and more.

(http://earthquake.usgs.gov/learning/animations/)

See also Earthquake facts on
(http://earthquake.usgs.gov/learning/facts.php)

e) World Historical Earthquake Locations – FGDC Metadata

(http://www.pdc.org/mde/full_metadata.jsp?docId=%7B659C82C4-E366-42A0-BEF7-743722067C2A%7D)

f) Earthquake images:
A comprehensive collection of earthquake related slides and photographs

http://www.johnmartin.com/earthquakes/eqshow/index.htm

g) Earthquake learning topics

http://earthquake.usgs.gov/learning/topics/

Selftest

In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question: Earthquake hazard assessment
Which of the following statements is true?
A) An earthquake has a particular magnitude, but can generate different intensities
B) An earthquake has a particular intensity, but can generate different magnitudes
C) An earthquake has a particular magnitude and a particular intensity
D) An earthquake can have several magnitudes and several intensities.

Question: Earthquakes

By means of a block diagram show the following:
- Fault plane
- Fault scarp
- Fault trace
- Hypocenter
- Epicenter
- Seismic waves

Question: Earthquake waves

Name at least 4 differences between a surface wave and a body wave.

Question: Probabilistic / deterministic

What are the main differences between a deterministic and a probabilistic method for earthquake hazard assessment.

Further Reading

The USGS website contains a wealth of scientific information on earthquakes and the associated hazard. To deepen your knowledge in this field, you are advised to look into:

- **Seismic Hazard Maps – on probabilistic hazard maps**

  http://earthquake.usgs.gov/research/hazmaps/products_data/index.php

- **Deterministic and Scenario Ground-Motion Maps - Learning on Shake Map Scientific Background**

  http://earthquake.usgs.gov/eqcenter/shakemap/background.php#scenario

- **Custom Mapping and Analysis Tools**
  Where you can:
  - Re-plot USGS maps for your region of interest.
  - Create a Custom Probability Map of your own
  - Java Ground Motion parameter calculator
  - Interactive hazard maps – Add/subtract GIS layers
  - Seismic design values for building
  - Etc.

http://earthquake.usgs.gov/research/hazmaps/interactive/

References:

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- http://www.nycem.org/techdocs/FinalReport/12Assess.pdf (assessed: March 10, 2009)
- http://www.seismo.ethz.ch/hazard/ndk/homepage.html.back
- http://www.earth-prints.org/handle/2122/769)
- http://earthquake.usgs.gov/eqcenter/recenteqsww/Maps/region/Africa.php

Guide book
Choice session 3.F:
Flood hazard assessment

Objectives
After session 3.F you should be able to:
- Distinguish different flood types and describe their main characteristics;
- Describe the hydrological cycle in general, and in specific those components relevant for floods
- Have a basic understanding of flood modeling approaches
- Describe how remote sensing data may be used for flood hazard and risk assessment

This section contains the following sections and tasks:

Section	Topic	Task	Time required		
3.F.1.	Types of floods	3.F.1: Internet exercise : recent floods 3.F.2: Classification of floods		0.5 h 0.1 h	
3.F.2.	River floods: Alluvial and flash floods	3.F.3: Visit the EFAS website		0.1 h	
3.F.3.	Flood modeling				
3.F.4.	Remote Sensing and floods	3.F.4: Visit the relief-web website		0.1h	
		Total		**0.8 h**	

Floods are among the most damaging and most widespread hazards in the world. They occur every year on every continent. Figure 3.F.1. gives some examples from around the world.

Floods are part of the dynamics of rivers and streams and of coastal areas. Statistically, a river will exceed its mean annual peak discharge once every 2.33 years (Leopold et al., 1964). This will occur when heavy or continuous rainfall – or another source of water - exceeds the absorptive capacity of soil and the flow capacity of rivers, streams, and coastal areas. This causes a watercourse to overflow its banks onto adjacent lands. Also intrusion of sea-water into coastal areas due to storm surges – often in combination with hide tide conditions – are part of the natural dynamics of coastal areas. In general one can define a flood as the intrusion of water into normally non-inundated terrain, but this triggers the question of what is normally inundated terrain?

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Figure 3.F.1: Floods occur on all continents. Clockwise (starting top-left): Europe (Germany, 1997), India (Bihar, 2002), Africa (Mozambique, 2000) and USA (Mississippi, 1993).

Task 3.F.1: Internet exercise (duration 30 minutes)
Which areas are flood prone in your country / region? When was the last the big flood event? Try to locate three (internet) sources that provide information on these flood events.

3.F.1 Types of floods

There are many sources of water that may cause floods. Obviously the location, terrain characteristics and climate play a key role as to what degree an area is susceptible for floods and to what type of flooding. One can distinguish the following types:

Alluvial floods

Alluvial floods usually occur in larger river basins (> 1000 km^2) and are caused by sustained periods of rainfall or snow-melt over a large part of the basin area. The river transports the surplus of water to the sea, accumulating water from tributaries as the flood wave travels downstream. The accumulation of water combined with decreasing flow velocities in the lower parts of the basin due to lower river gradients (see fig xxx), results in an increase of the flood volume. At some point this may exceed the capacity of the river to contain the water within its banks. The excess water will overtop the natural or man-made levees (or breach through them) and flow into the low-lying parts adjacent to the river. These floods usually occur in relatively flat areas in the downstream part of the river basin, the alluvial and coastal plains, although the source of the water, rainfall in the upstream parts of the river basin, may be far away. This has two important consequences: 1) it is possible to monitor the flood wave as it travels downstream and local overbank flooding in the upstream parts should be warning signals for those downstream that a flood may be coming. This warning time may be several days for larger rivers; 2) the weather conditions in the flooded area may be relatively mild which is helpful for relief operations.

This type of flooding is often associated with relatively low flow-velocities in the overbank area, usually less than 1 m/s., although locally higher flow velocities may occur, e.g. due to funneling effects of infrastructure and buildings and behind dike breach locations. In the river itself flow velocities may also be higher. Although usually only a relatively small part of the river discharge enters the overbank area, the area affected is often quite large and the water may remain there for a long time (up to weeks).
The damage caused by these floods is related to the materials that became wet and dirty and to the socio-economic processes that have come to a halt. Most victims die to secondary hazards such as electrocution and hypothermia. If the flood waters remain for a long time the damage may be aggravated due to the deterioration of wooden and brick structures and to the breaking and clogging of underground infrastructure (e.g. sewer systems and water pipes). After the floodwaters have receded a layer of mud and dirt remains behind that needs to be cleaned up (costly!).

Summary characteristics: Slow, widespread, long duration, several day warning times, relatively flat terrain, larger rivers with large basins, and prolonged periods of precipitation, disruptive rather than disastrous.

Flash floods

These floods originate in mountainous catchments (basins) with steep gradients and they are the result of extreme precipitation, not only in quantity (mm of rain) but also in intensity (amount of rain per time unit – e.g. mm/hour). Such events are often associated with thunderstorms or typhoons/hurricanes. The water accumulates as it flows downstream to the river channel which results in an increase in the discharge in the channel. The discharge may rise even further when several river branches within a catchment merge to form a larger river. The shape and other characteristics of the catchment such as geology, vegetation cover and antecedent precipitation may increase or decrease the peak discharge. The high flow velocities of the water within the stream may give it the capacity to cause severe erosion and to transport debris such as boulders and trees. These floods give very little warning time, hence the name **flash floods.** Flash floods cause many casualties because people are swept away, even in shallow water and even in cars! The kinetic energy of the water plus the debris (projectiles) causes physical damage to buildings and infrastructure, up to the collapse of houses. Wooden structures may be swept away. The duration of the flood is usually very short – up to several hours - and the area affected is relatively small. After the flood waters have receded debris (rocks, bricks, trees, mud, etc.) and dirt remain behind which needs to be cleaned up. Sometimes this may require heavy equipment. Because flash floods are local events, the severe weather conditions that caused the floods may also hinder relief operations (heavy rain, strong winds).

Summary characteristics: Fast, small area affected, short duration, little warning time, associated with singular events (thunderstorms, typhoons), physical damage to buildings and infrastructure, casualties due to drowning.

Coastal and estuarine floods

In coastal areas the water may also come from the sea. When the wind is directed towards the land, it will push the water to higher levels due to its drag force. Low pressure systems (e.g. typhoons and hurricanes) may also cause a rise in sea-level due to the decrease in atmospheric pressure. Combined with the regular cycle of the tides and spring tide, this may result in sea water levels far above the regular average level. The shape of the coastline may increase the push-up effect of the wind. Especially in river estuaries the water levels may rise up to several meters. The rise of sea level will hinder the river discharge to the sea and a storm surge may therefore increase the chances of a riverine flood. When the sea breaks through the natural barriers (e.g. dunes) at the coastline or through the man-made protection measures (dikes), the storm winds will help to push the water through the breaches. This, in combination with the high gradient between the water level in the sea on one side and the low-lying areas on the other, will make that the salty seawater enters the low-lying areas with great force. Coastal floods are a deadly combination of storm winds, flood water and little warning times. Large areas may be affected and given the fact that coastal zones are among the most densely populated areas in the world with many of the largest cities located there, it is not hard to conclude that coastal floods are among the most catastrophic natural hazards. If there has been no precautionary evacuation, there will be no time to evacuate all the people from the affected areas. The storm winds will impede or severely hamper search and rescue operations. Once the storm has receded, large areas will remain flooded for a great length of time. This will not only disrupt society and cause severe socio-economic damage; it will also degrade buildings and infrastructure as well as the quality of the arable land due to the salt. See also section 3.C on coastal hazards.

Summary characteristics
Coastal areas, widespread, little warning time, salt water, usually associated with storm conditions.

Urban floods

Although this term may cause some confusion – isn’t any flood occurring in an urban area an urban flood? – it describes a specific type of flood that is actually the result of the urban environment. Urban areas are characterized by a large percentage of sealed surface, that is, areas that do not allow water to infiltrate into the soil. For instance: paved roads, rooftops of houses and parking areas. The consequence is that all surface water will have to be drained through a storm drainage system or along the streets in open ditches. At some locations pumps may be needed for drainage (e.g. tunnels). If the capacity of the drainage system and of the pumps is insufficient to cope with the amount of precipitation or – to be more precise – with the precipitation intensity, the water will accumulate at the lowest areas and will flood tunnels, cellars and other unprotected underground structures. Also roads may be blocked when the water becomes deeper than approximately 50 cm because regular cars will start to float. If there is a current, cars may be swept away. Due to pressure build-up in underground drainage systems, manhole covers may start to float, which results in dangerous holes in the street. Pedestrians falling into these (by dirty water obscured) holes may drown. Even small, localized events may have a significant effect on traffic flow in the city when critical roads and tunnels are blocked. Frequently pumps are needed to drain tunnels, cellars and low-lying areas. Usually the duration of these floods is relatively short. When larger underground structures (parking lots, subway systems, etc.) are flooded, the consequences may be more severe and it will take longer to return to the pre-flood situation. Urban flooding is aggravated by unplanned city expansion (increase of unpaved area, without increase of drainage capacity) and poor maintenance of the drainage systems.

Summary characteristics
Urban environment, high intensity rainfall, inadequate or poorly maintained drainage systems

Other types:

The above four types of flooding are the most widespread and common. However there are numerous other sources that may cause floods. For example:

- **Tsunamis.** They are caused by an undersea earthquake or landslide. The displacement of the crust and/or ocean floor material triggers a series of low-frequency / long wavelength waves that, as they approach the coast, increase in height and may thus inundate the low-lying coastal areas. Tsunami waves can easily travel across the oceans. Tsunami warning systems are difficult to implement because of the little time between the moments that the tsunami is triggered and that it hits the coast. Tsunamis affect coastal communities and cause damage to boats and coastal property – see also section 3.E.4 and 3.C.2.

- **GLOFs: Glacial Lake Outbreak Floods.** In high mountainous areas, glaciers and (frozen) moraine ridges may block the flow of (melt)water and create large glacial lakes. Melting of the ice or permafrost, or another trigger like a landslide, may result in a collapse of the ice- or moraine dam. The water from the lake is (partially) released and water will rush down the steep mountainous streams. This may cause damage and casualties downstream.
- **Landslide Lake Outburst Floods.** Similar to GLOFs, but here a landslide body has blocked the river, resulting in a lake upstream of the landslide. The pressure of the water in the lake may result in a breaching of the landslide body, causing a sudden release of (part of the) lake's water volume.
- **Dambreaks.** Also man-made structures, such as reservoir dams may collapse to engineering failure, earthquakes, overtopping etc.
- **Dike breaches**. Along rivers, lakes and the coast, dikes offer protection to low-lying areas. Continuous processes such a groundwater flow, seepage, weathering, animal activity, tremors due to traffic, etc. but also earthquakes may weaken the strength of the dike resulting in its collapse when water pressure becomes too high. The chance of dike collapse depends on several factors such as:
    - Height difference between the water level on one side and the ground surface on the other
    - Structure of the dike (height and width)
    - Material of the dike (sand, clay, peat)
    - Sub-surface (lithological) conditions
    - Degree of consolidation
    - Maintenance
    - Surface cover (protection against wave action, erosion, etc.)
- **Accidents with water- and sewage pipes**

Figure 3.F.2. River run-off in China

Although the above mentioned types of floods have different characteristics, it is not always possible to classify a given flood event. Often a combination of types occurs. For instance during a typhoon a city may experience urban floods, flash floods, alluvial floods and coastal floods simultaneously.

Task 3.F.2: Flood classification (10 min.)
Have a closer look at the floods you found in Task 3.F.1. How would classify these events? Can you do that without problem, or could they be classified as different flood types (complex floods).

3.F.2 River Floods: Flash floods and alluvial floods

To understand floods and their origin, the hydrological cycle is a good starting point. See figure 3.F.3. The hydrological cycle describes the continuous movement of water on, above, and below the surface of the Earth. Since the water cycle is truly a "cycle," there is no beginning or end. Water can change states from liquid to vapor and to ice at various places in the water cycle but the total volume of water on Earth remains fairly constant over time. The largest reservoir of water is the collection of oceans and seas, accounting for 97.25% of the Earth's water; see table 3.F.1. The next largest reservoirs are ice caps and glaciers (2.05%) and groundwater (0.68%). Although surface water (lakes plus rivers and streams) and atmospheric water account for less than 0.012% of the total, it is this part of the hydrological cycle that requires our attention when we want to study floods.

Table 3.F.1: Water reservoirs (Source: Wikipedia)

Reservoir	Volume of water (10^6 km^3)	Percent of total
Oceans	1370	97.25
Ice caps & glaciers	29	2.05
Groundwater	9.5	0.68
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams & rivers	0.0017	0.0001
Biosphere	0.0006	0.00004

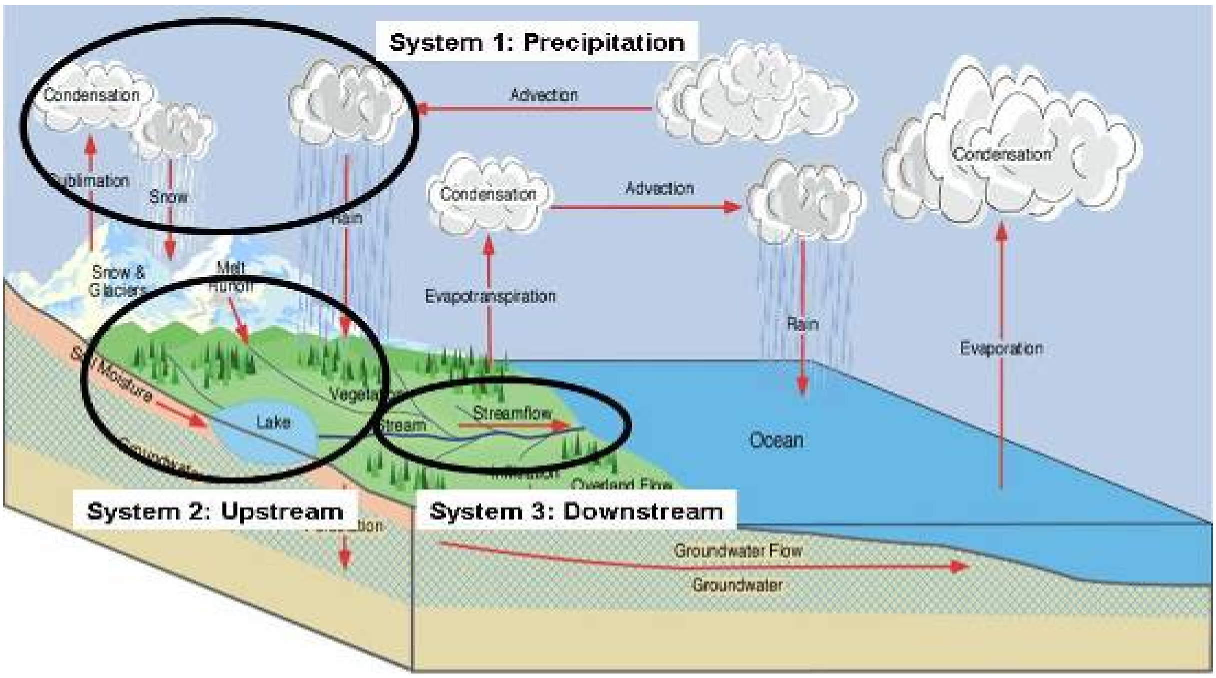


Figure 3.F.3. The hydrological cycle

In figure 3.F.3 three separate sub-systems are highlighted: Precipitation, upstream and downstream. These sub-systems describe that part of the cycle where atmospheric water becomes surface water that flows to the sea. For flood hazard assessment, a good understanding of these sub-systems and how they can be modeled is very important. Each sub-system has a list of questions that needs to be answered. These are described in the following sections:

Sub-system 1: Precipitation

Precipitation that reaches the surface of the earth can occur in many different forms, both in liquid form (rain, drizzle) and in frozen form (freezing rain, snow, ice pellets, and hail). Precipitation is responsible for depositing most of the fresh water on the Earth's surface. Approximately 505,000 km^3 of water falls as precipitation each year, 398,000 km^3 of it over the oceans. Given the Earth's surface area, that means the globally-averaged annual precipitation is about 1 m, and the average annual precipitation over oceans is about 1.1 m. (Source: Wikipedia). Frozen precipitation means that the water volume is not directly available for run-off; that requires a melting period. This is most relevant for high-latitude and high-elevation locations as a significant percentage of the precipitation will fall there in frozen form. A sudden warm period may release a large volume of liquid water which may lead to flood hazard downstream. This means that for flood studies in these regions one should not only forecast precipitation but also periods of higher temperatures and that one has to apply snow- and ice-melt models. In warmer parts of the world rain is the most important form of precipitation causing floods. Rain has two important aspects on flood generation:

Preparatory: Soils and local depressions (lakes, reservoirs) act as buffer that will store rain water. The buffered (or stored) rainwater is not directly available for run-off and will thus not contribute to the peak discharge (see also figure 3.F.5) in the stream. After a sustained period of rainfall, soils will become saturated and lakes and reservoirs will be filled. Once the buffer capacity is reduced to zero, all additional rain will quickly flow towards the streams and rivers as surface run-off.

Trigger: Rain that falls on the surface of the Earth may be stored in the soil or in depressions, or may flow over the surface as run-off towards the rivers. What percentage of water will actually reach the river system depends on many factors and these will be discussed in the following section. In situations where either the buffering capacity is reduced to zero (see section above on preparatory aspects) or where the intensity of the rain exceeds the speed in which the water can be buffered, a large percentage of water will reach the river system very quickly which may result in floods.

The forecasting of precipitation is not really the domain of Earth scientists, but rather of meteorologists. The key question that needs to be answered is how much precipitation will fall somewhere (in mm) and with what intensity (mm/hour). In the case of thunderstorms also the location of the storm is relevant. For other types of rain-depositing phenomena, such as typhoons and frontal systems, the "where-question" is less relevant because these events cover large territories, usually larger than the areas that are investigated in flood studies (with the exception of course of the largest river basins). The prediction of rainfall amounts and intensities, however, is extremely difficult and the same is true for the prediction of where thunderstorms will occur. Only recently have steps been taken to do real-time flood forecasting, that is flood prediction based on (long-term) weather forecasts (see e.g. http://efas.jrc.ec.europa.eu).

Task 3.F.3: Internet task (10 min.)
Go to the website of EFAS (http://efas.jrc.ec.europa.eu) What floods were the "trigger" to initiate EFAS?

Sub-system 2: The upstream

Sub-system 2 is where the spatially diffuse rain is being concentrated into run-off and stream flow. The water converges into the stream channels which transport it further downstream. This overland flow (surface runoff plus stream flow) comprises all gravity movement of water over the surface and through cannels which may vary from very small (rills) to very large (Amazon River). The standard way to express discharge is in volume per time unit, e.g. m3/sec (cumec) or liter per second, or cumec per square kilometer for a given catchment, or as depth equivalent over a whole catchment, e.g. in mm per day or per month. Figure 3.F.4 shows how sub-system 1, 2 and 3 are connected and it raises the main questions that need to be answered. Whereas in sub-system 1 the main question was how much rain will fall, the main question for sub-system 2 is how quickly will the water converge into the stream system and how fast will it move downstream. So apart from the "how much" question we now have added the temporal "when" question.

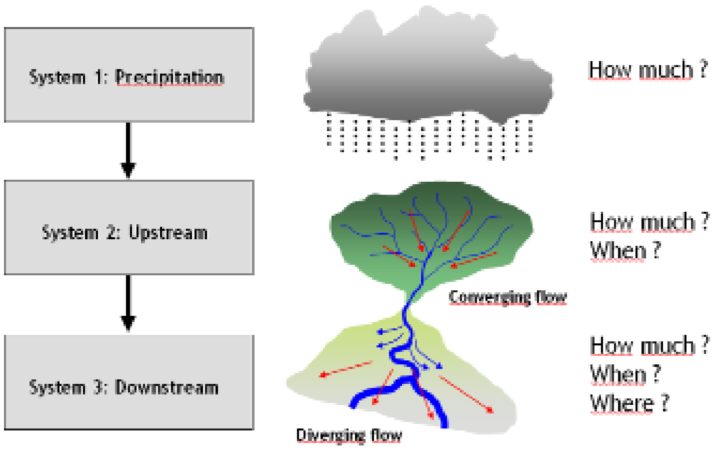


Figure 3.F.4 The three sub-systems connected

Quick flow and slow flow

Figure 3.F.5. gives a typical cross-section of a valley in the upstream sub-system. It shows that the rain (P) may reach the river by one or more of the following flow paths: a) direct precipitation into the waterbodies (CP); b) as overland flow (OF); c) as through flow (TF); and as ground water flow (GWF). The response of the stream flow to precipitation – that is the time between the start of the rain event and the start of the rising of the discharge (figure 3.F.6) - depends on many factors, such as shape of the terrain (morphometry), the hydrological characteristics of the soils, the landcover and the soil moisture content.

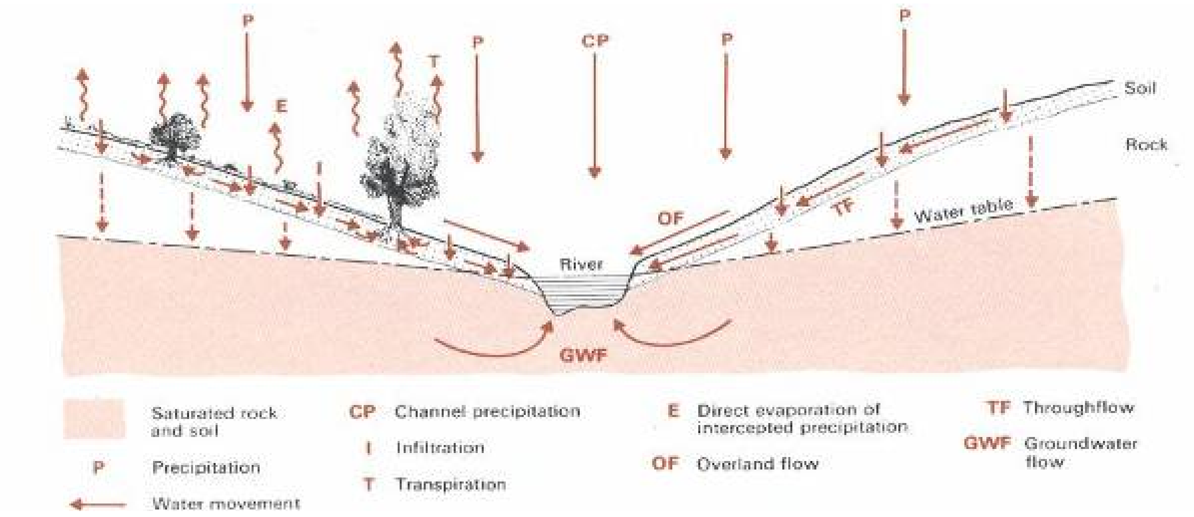


Figure 3.F.5 Water movement towards the stream system

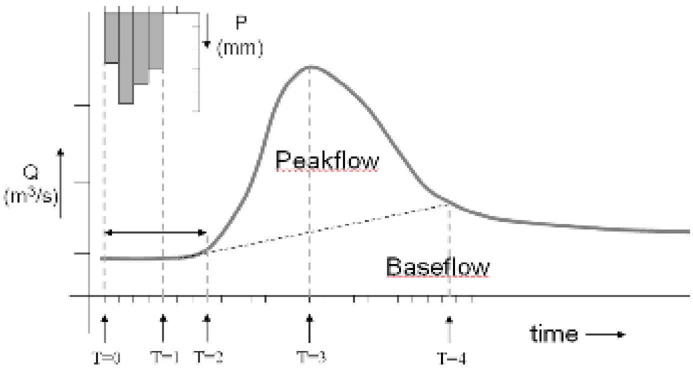


Figure 3.F.6 The stream's response to precipitation (t0 = start of the rain; t1 = rain stops; t2 = start of a noticeable response of the river; t3 = maximum of the peak flow; t4= end of the peak flow, return to base flow conditions)

However, when there is a clear rising of the stream discharge in the hydrograph that can be related to a rainfall event, then it is evident that some part of the precipitation has taken the rapid route to the stream channel, the so-called quick flow. Quick flow comprises precipitation that has fallen directly into the channel and overland flow. In some cases there may also be a rapid component to the through-flow, for instance in karst areas or when piping mechanisms exists. Quick flow is that part of the precipitation that causes the peakflow in the river (see figure 3.F.6).

The rain that infiltrates into the soil may first pass through an unsaturated zone before it reaches the ground water table. In both the unsaturated and saturated zones there is a downhill flow component directed towards the river, the so-called through flow and groundwater flow. Due to the higher resistance in the subsurface, it takes longer for the infiltrated water to reach the river channel. It is this part of the precipitation that contributes to the base flow of the river (see figure 3.F.6). The separation between peakflow and baseflow cannot be made unambiguously. For flood studies the prediction of the maximum peak flow, both in time and in quantity, is paramount, hence the key questions: "how much?", and "when?".

Sub system 3: The downstream

The transition of the "upstream" to the "downstream" part is not clearly defined. In many text books you'll find a third – intermediate – section the so-called "middle reach". In this text-book we'll define the downstream as follows:

In the downstream section of a river, the net long-term deposition of materials carried by the river waters exceeds the erosion capacity of that river.

This definition defines "downstream" as those areas where there is net accumulation of deposits and no clear incision of the river, such as alluvial fans and deltas. The rivers in these areas are characterized by avulsions, i.e. the change in position of the (main) river channel. On these relatively flat plains the flow direction of the water is not easily predicted because small obstacles may have a significant effect on the flow direction of the water. During floods, the water spreads out of wide areas. This raises the number of questions to three: how much, when and where?

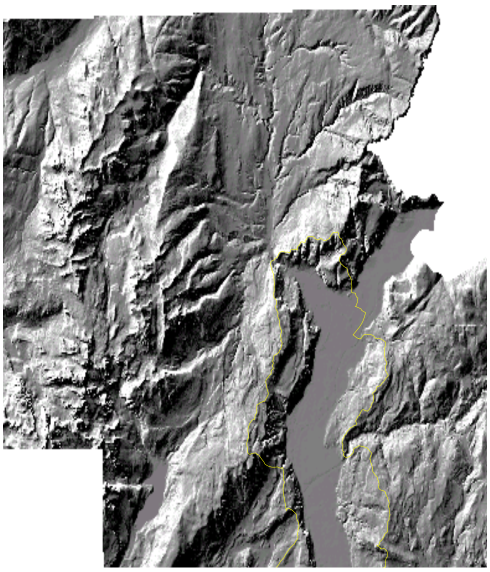


Figure 3.F.7. According to the above given definition, also the Adige valley near Trento can be considered as a "downstream" area. The river Adige, flowing through the flat terrain in the center, is filling in this large Alpine glacial valley with sediments.

The distinction between an upstream and downstream area is useful in the selection of the most appropriate flood hazard assessment techniques. In the upstream area a 1D flow modeling approach is most appropriate because it answers the two questions (how much and when) most efficiently. It uses the prior knowledge of where the water goes: The flow follows the hydrographic network that can easily be derived from the DTM or by digitizing stream networks. All water converges to these flow-paths. In the downstream area this prior knowledge is not available because flood water that has left the river channel may diverge and spread-out over large areas, see figure 3.F.7. In these situations where also the "where" question needs to be addressed, a 2D-waterflow approach is more appropriate.

3.F.3. Flood modeling

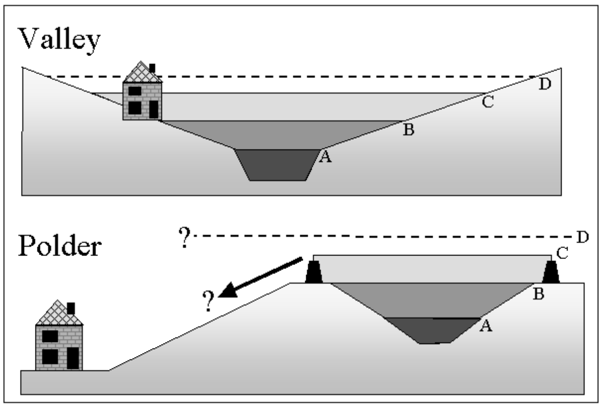


Figure 3.F.8 Morphological differences between upstream and downstream surface topography and its consequences for flood hazard zonation.

Figure 3.F.9: Floods in the lower Mekong area. The flood waters have affected over 200,000 square kilometers (2001). Source: Reuters / Alertnet.

In section 2.2 a flood hazard was defined as the probability that a certain area will be inundated within a given period of time. Thus, traditional flood hazard maps delineate the annual chance of inundation, as shown in the top part of Figure 3.F.8 In this situation there is an inverse relationship between water level and chance of occurrence: the higher the water level the smaller the chance that it happens. In Figure 3.F.8 location A is more hazardous than location D. This is typically an upstream situation.

In the lower part of Figure 3.F.8 the "Polder" situation is depicted, a situation that can be found in all major river delta areas, coastal plains and alluvial plains in the world where the river is flanked by widespread near-flat terrain; a typical downstream situation. In some cases the surrounding terrain lies below the level of the river as a result of different subsidence characteristics between the more sandy deposits in and along the riverbed and the clayey, peaty deposits in the back-swamp areas. Often this difference in height is enhanced by artificial drainage of the back-swamps that leads to further subsidence.

In the "polder" situation there is only a relation between the water level and return period of the flood as long as the river water does not overtop or breach the natural levees (B) or the dikes (C). A traditional hazard map equals the hazard in the whole polder area as the chance that the dikes are overtopped or breached. This approach does not allow the differentiation in degrees of hazard within the alluvial plain (or polder) because it does not consider the propagation of the inundation flow. Clearly, the water level D in the lower part of Figure 3.F.8 is not instantly achieved in the whole flooded alluvial plain or polder. It takes time to fill the bathtub. How much time depends on the flux of water into the area and the characteristics of the terrain, like resistance to overland flow and the presence of obstacles like buildings, embankments, etc. This temporal component is essential for decision-makers because people living in areas that are inundated within hours are more "at risk" than people living further-on that have still days to respond to the hazard. Authorities need to know in advance which people to evacuate first and which roads are still accessible. Traditional flood hazard maps do not provide the right information to develop such evacuation plans. Furthermore they offer no help to planners to analyze the impact of new developments within these areas on possible future inundations. Simulating scenario floods with a 2D flood propagation model can help in these cases. An example of a large alluvial flood is given in figure 3.F.9, a flood that occurred in the Lower Mekong region (Vietnam and Cambodia) in 2001.

Upstream – Downstream relationships

The upstream – downstream distinction makes it easy to connect the two systems. The result of an upstream analysis with a 1D flow model is a hydrograph at the outlet, say the apex of an alluvial fan or delta. This hydrograph can serve as upstream boundary for a 2D flow analysis in the downstream area. Figure 3.F.10 shows an example in Thailand where the downstream consequences of land cover changes in the upstream catchment were estimated. The upstream analysis was carried out with a 1D flow model (LISEM) and the downstream flood propagation modeling was done using a 2D hydraulic model SOBEK (developed by Delft Hydraulics, the Netherlands).

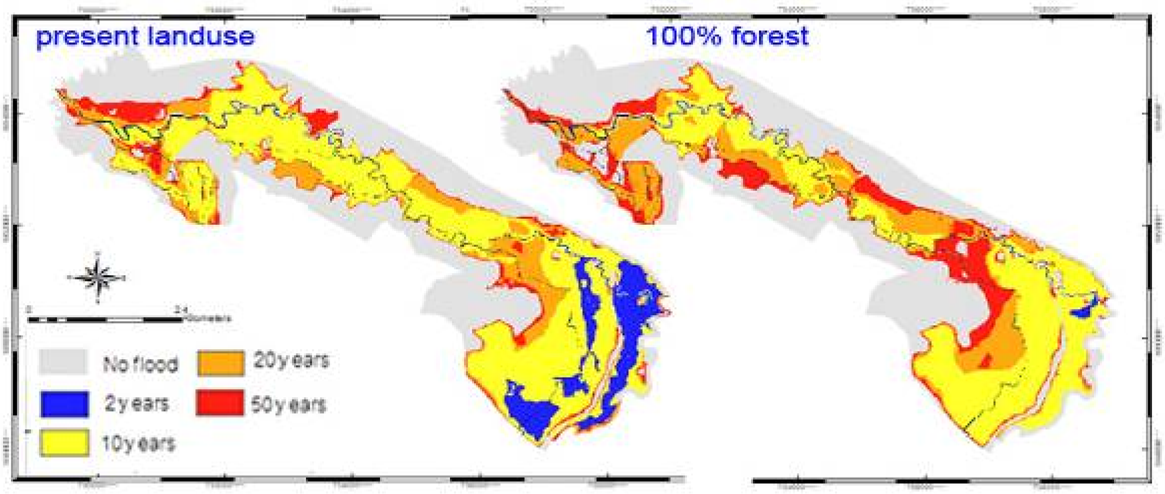


Figure 3.F.10. Two scenarios where the downstream flood consequences are estimated of land cover changes in the upstream area (not on the map). Source: Prachransri, 2007. Case study Thailand, in collaboration with the Land Development Department (LDD).

Flood intensifying factors

The catchment characteristics in the upstream area define for a large part, the peak discharge in the river downstream. Table 3.F.2 gives an overview of several key factors that influence the shape of the hydrograph.

Table 3.F.2

Flood intensifying factors:			
	Catchment Conditions		
		Stable	Area, slope, altitude, shape, geology, soils
		Variable	Vegetation, climate, human action, certain soil properties (infiltration), surface resistance
	Antecedent Conditions		
			Previous rain- and snow fall
	Network and channel conditions		
			Pattern, channel length, stream order, profile & gradient, bifurcation ratio, roughness, human action, (local) storage

The stable catchment conditions define for instance the amount of water that is added to the river network (the area), its velocity (the slope), the form in which the precipitation falls - snow or rain – (altitude), the shape of the hydrograph (shape – see below) and the amount of storage and loss to deeper groundwater (geology and soils). The variable conditions change through the seasons (vegetation, soil moisture conditions) or may change gradual (climate) or abruptly (human action). The surface resistance is strongly related to the vegetation cover that offers resistance to the surface flow of water, and thus affects the flow velocity. The antecedent conditions are strongly related to the previous weather conditions. Antecedent rain affects the soil moisture condition of the soils and the height of the ground water table. Network and channel conditions refer to the specific shape and patterns of the river channels, how they are connected, the river bed conditions in terms of roughness and for instance the presence of local depressions (lakes).

Figure 3.F.11 shows the relationship between the catchment shape (circular or elongated) and the hydrograph response. Rain falling on an elongated catchment (left-hand side) has a diverse range of travel times before it reaches the outlet. Rain falling close to the outlet leaves the area quickly, whereas rain falling in the far end has a much longer travel time. In a circular catchment (right-hand side) this variation in travel times is much smaller and rain falling in different parts of the catchment will reach the outlet nearly simultaneously. In an elongated catchment the diverse range of travel times results in a long, but relatively flat hydrograph, whereas in a circular catchment the hydrograph is much more concentrated with a much higher peak.

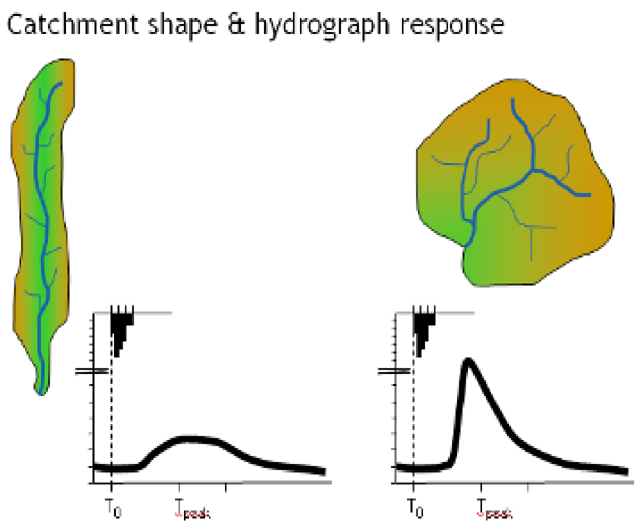


Figure 3.F.11. The effect of the catchment shape on the hydrograph.

3.F.4. Remote sensing and floods

For the analysis of flood events, remote sensing data is indispensible. There are several ways how data, obtained from space-based and airborne sensors, can be used for flood studies. Table 3.F.3 gives an overview; the four categories will be discussed below.

	Medium-Low Resolution	High Resolution	SAR	Other (e.g. LIDAR and SRTM)
Provision of spatial distributed data for modeling				
Validation of model results				
Elements at Risk mapping				
Post disaster rapid response data provision				

Table 3.F.3: Use of remote sensing data for flood hazard assessment (colour code: green = generally very useful, yellow = depends on the situation; white = generally not useful.

Data provision for distributed modeling

Model studies play an important role in gaining a better understanding of the dynamics and behavior of fluvial systems. However most hydrological and hydraulic models are data demanding and require spatial distributed information regarding topography, land cover and soils.

Remote sensing is a key source of data for topography parameterization: traditionally using stereo-photogrammetric methods to get contour maps, but more recently satellite data from e.g. the Space Shuttle Topographic Mission (SRTM), and stereo images from e.g. Aster have become cheap sources of surface elevation data with almost global coverage (see also section 2). Also LIDAR – explained in greater detail in section 2.B.3 – has become an important source of high-accuracy elevation information. Furthermore all kinds of parameters that are important for hydrological modeling are related to the land cover, e.g. interception, evapo-transpiration, surface roughness, etc. Remotely sensed images from satellites and aircrafts are often the only source that can provide this information for large areas at acceptable costs.

Validation of model results

Satellite imagery is not only a useful source of input data for hydrologic models, it also offers good possibilities to validate the output of the models when a flood has occurred. The observed extent of the flood can then be compared with the modeled prediction. Such validation is essential for flood modeling. Although optical remote sensing data could be used to derive the flood extent, it does require cloud-free images and these are not often available during flood events. Radar imagery is more convenient because it is not hindered by cloud cover that frequently accompanies flood events. The radar sensor is very good at distinguishing land and water boundaries because the water reflects almost all the incident microwave radiation away from the sensor, resulting in a black or dark tone for the water covered areas.

Elements at risk mapping

Perhaps the most promising application of RS is its use for elements at risk analysis. In session 4 for of this guide book we will look deeper into its use to identify individual structures. Recognition of the function of these structures is important for the assessment of their vulnerability and their importance and value. Especially for cities that experience fast and uncontrolled expansion into hazardous areas like floodplains, this offers an opportunity to monitor the increasing risks and impacts

Post disaster rapid response data provision

Another important application of remote sensed data is the rapid dissemination of spatial information immediately after a flood event has occurred. The best known system for rapid data availability is the so-called International Charter for Space and Major Disasters, which may be called upon after a major disaster has occurred. The data are provided by Charter partners, such as the German Space Agency (DLR), and UNOSAT who make map products that are made available via the Global Disaster Alert and Coordination System (GDACS, www.gdacs.org), ReliefWeb (www.reliefweb.int) or Reuters' AlertNet (www.alertnet.org).

Task 3.F.4: Internet task (10 min.)
Go to the website of Reliefweb www.reliefweb.int). *Where are currently / recently flood disasters?*

Task: RiskCity exercise 03F1: Flood hazard assessment using flood modeling (3 hours)

Go to the Riskcity exercise 03F1 and carry out the GIS exercise on flood hazard assessment using flood modeling.

Task: RiskCity exercise 03F2: Flood hazard assessment using satellite data (3 hours)

Go to the Riskcity exercise 03F2 and carry out the GIS exercise on flood hazard assessment using satellite images.

Selftest

Self test
In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question: River flood hazard assessment
What are the most important types of <u>output data</u> of a 2-D flood simulation model?
A) Ground water level, surface runoff
B) Water height, soil pollution
C) Water height, flow velocity
D) River discharge, evapotranspiration.

Question: Flood hazard assessment
What are the most important types of input data for a 2-D flood simulation model?
A) Waterheight, flow velocity, flow duration
B) Terrain altitude, surface roughness, river discharge
C) Rainfall, landuse, soils
D) Slope, infiltration capacity, evapotranspiration.

Define the flood risk in a polder area in the Netherlands.
Flood risk scenario's:
Below the level of 2m no dike breaches occur; no flooding.
You have the following data available:

Flood scenario I.: Flood level is **2.0 m** above NAP (Dutch Datum) in the polder. Return period = 100 years:
Flood Scenario II. Flood level is **2.5 m** above NAP in the polder. Return period = 250 years
Flood Scenario III. Flood level is **3.5 m** above NAP in the polder. Return period = 500 years

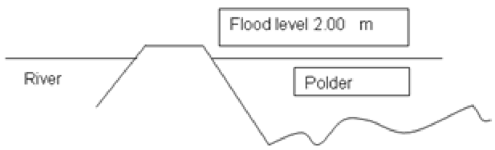
Land use

a	a	c	c
a	a	c	c
r	r	r	r
c	c	h	h

Legend:
a = agriculture
c = company
r = road
h = house

DEM (in meters above NAP)

1.5	1.5	3	3
1.5	1	3.5	3
1	1	2.5	3
1	1	2.5	3



Define the water depth in the polder for scenario's I, II and III, and indicate these in the map below.

Scenario I:

Scenario II :

Scenario III:

Guide book
Choice session 3.C :
Coastal Hazard Assessment

Objectives

After session 3.C you should be able to:

- List the different types of coastal hazards;
- Know about the Coastal Zone Management issues of your own country
- Find data of various coastal hazards to be used for coastal hazard zoning via the internet
- Perform basic GIS and RS modeling for coastal hazard zoning using the ILWIS software

This session contains the following sections and tasks

Section	Topic	Task	Time required		
3.C.1	Introduction to CZM issues	3.C.1 Visit the NOAA Website on Clean & Coastal Resource Management		0.5 h	0.5 h
3.C.2	Rapid Coastal Hazards	3.C.2 Find active cyclones		0.5 h	6.0 h
		3.C.3 Hazard Analysis Cyclones - *Part A*		1.5 h	
		3.C.3 Hazard Analysis Cyclones - *Part B*		2.5 h	
		3.C.4 Poster tsunami		0.3 h	
		3.C.5 News item tsunami Banda Aceh		0.2 h	
		3.C.6 Animations tsunami wave		0.5 h	
		3.C.7 NOAA Interactive tsunami database		0.5 h	
3.C.3	Slow Coastal Hazards	3.C.8 Analysis Enhanced Sea Level Rise		1.0 h	6.5 h
		3.C.9 Reading article subsidence Semarang		1.0 h	
		3.C.10 Modelling land subsidence Semarang		2.0 h	
		3.C.11 Looking at YouTube videos		1.0 h	
		3.C.12 Analysis change Solo River delta		1.5 h	
		Total			**12.5 h**

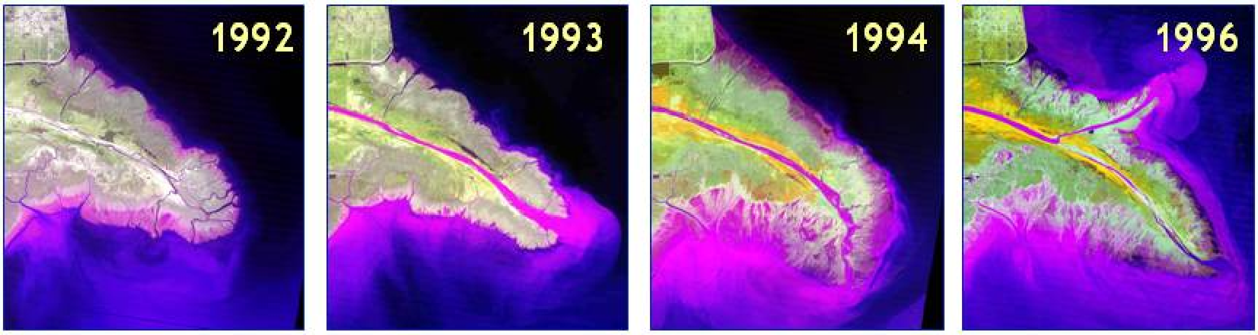
This session ends with a test, and the answers of this should be submitted through Blackboard

3.C.1 Introduction to coastal zone issues

About 70 percent of the world's population lives in the coastal zone. It is the most densely inhabited and industrialized part of almost every coastal country and contributes therefore significantly to the financial well-being of the people living in it.

The high concentration of the population along the coast creates also pressure on its resources. Most megacities in the world are situated in delta areas or at the coasts of estuaries, and suffer from air and water pollution, land subsidence due to groundwater extraction and flooding by the river and the sea. Some cities are very vulnerable to cyclone hazard and enhanced sea level rise due to global warming. Rural coastal areas are dependent on the surrounding lagoons, estuaries, mangrove ecosystems, creeks and inshore waters for their income, food security and well being.

The marine and coastal zones, including their upstream freshwater regions, are presently experiencing degradation in the form of surface and groundwater pollution, such as salt



water intrusion, but also coastal flooding, erosion & accretion, land subsidence as impact from land-based settlements activities; and mining activities of oil and gas.

Figure 3.C.1 Change of the yellow river delta, China in between 1992-2006, Landsat TM & ETM images (band comb. ; 4-5-3 : R –G – B). The suspended sediment in the sea water is shown with a pink colour. The delta is situated close to the Guadong oil field. The exploration area, surrounded by a sea dike is visible in the upper left corner. (Damen, 2006)

The challenge for coastal countries is to use the abundant but depleting coastal and marine environment resources wisely, so that economic development can be achieved without destroying the resource base on which it is founded. Consequently, coastal hazard and risk management has become an important programme for all people living in the coastal zone.

Integrated Coastal Zone Management (ICZM) is a proposed tool achieving sustainable coastal resource use, and one that has been adopted, in principle, by many coastal nations. The concept of integrated management emphasises the importance of coupling the economic, social and environmental dimensions for sustainable coastal resources utilization. Integration of these three pillars of sustainable coastal development starts from the adoption and application of advanced technological tools including geographic information systems (GIS) and change detection using multi-temporal remote sensing imagery (RS) that provide scientific knowledge and analysis and support decision-making for assessment practices and management methods (Figure 3.C.1)

In this Guidance Note examples are given of some of the most common coastal hazards, classified from rapid to relatively slow events. Also the processes are described with are leading to these hazards including examples on their analysis with geographic information systems and multi-temporal aerospace imagery.

Task 3.C.1 Coastal Zone Management (duration 30 minutes)

Visit the NOAA Website on Clean & Coastal Resource Management:

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

http://coastalmanagement.noaa.gov/issues/hazards_activities.html

- Select from the website: *Coastal Issues*.
- Find one or two coastal issues of your interest and compare this with possible plans in your own country.

Example of Integrated Coastal Zone Management in the Netherlands

The Netherlands is famous for its coastal protection with sea dikes at places where the natural defense against marine flooding by dunes is missing. As about half of the country is situated below sea level, it is essential that the national coastal zone management policy is based on a well established hazard analysis. All protection measures are therefore based on a flood hazard zoning of the whole country.

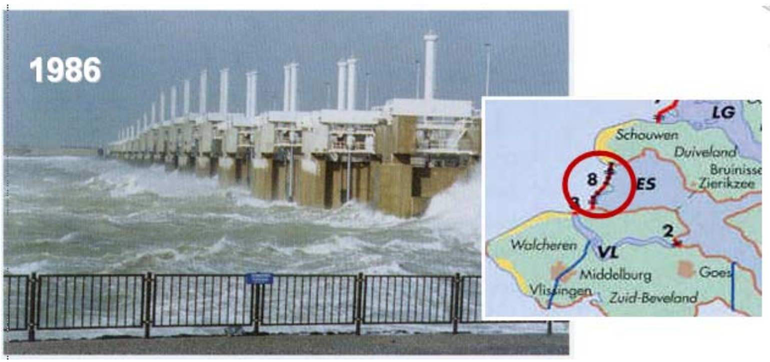


Figure 3.C.2 : Movable sea defense system along the Dutch coast. Delta works, Zeeland (RWS 2009)

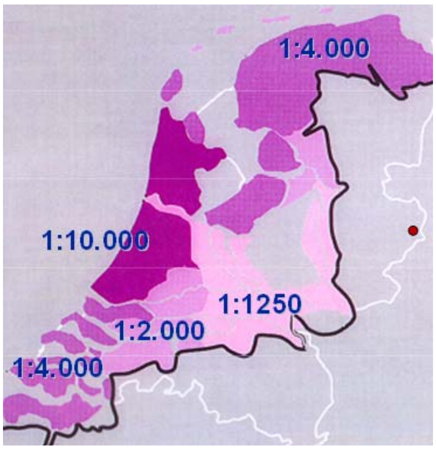


Figure 3.C.3 : Safety standards in respect to flooding in the Netherlands (RWS 1991)

The safety standard for the low lying western part of the coastal area is for instance based on a recurrence interval for sea flooding of once in 10.00 years; at other places this is once in 4.000 years. Inland, in areas of the rivers Rhine and Meuse the standard is 1:1250 or 1:2000 years for river flooding (Figure 3.C.3). The construction of storm surge barriers at the coast (Figure 3.C.2), or sea dikes is based on these safety standards.

In case of, for instance, coastal retreat due to enhanced erosion, mitigating action will be taken well before the "official" 1:10.000 coastline could be crossed. For this purpose, the position of the coastline is being accurately measured at a yearly basis.

In figure 3.C.4 an example if given of a coastal town North of Amsterdam, in which the coastlines for different recurrence intervals are indicated, based on the present erosion rate. This hazard information is used for future urban planning.

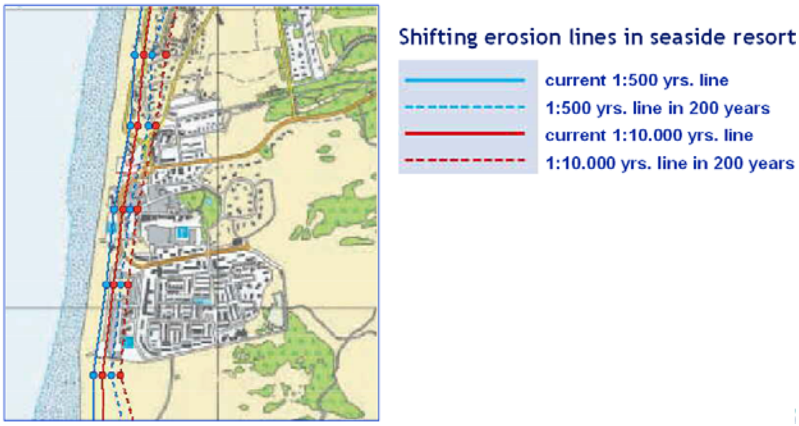


Figure 3.C.4 : Possible future coastlines due to coastal erosion in a coastal town North of Amsterdam, Holland. (RWS, 2002)

Regular suppletion of the sand ("beach nourishment") that has been eroded in front of the coast and along the beach can be a good option to mitigate the erosional process.(Figures 3.C.5&6). To calculate the volumes needed for this suppletion, elevation models are made at an annual base along the entire coast of the Netherlands; this is done by Lidar digital elevation modeling (see also GuideBook Session 2).

Figure 3.C.5 : Basal coastline (1: 4000 years) in red and Lidar DEM (hill-shade) of the same area. The Netherlands (RWS 1996)

Figure 3.C.6 : Beach nourishment along the Dutch coast. (RWS 1996)

3.C.2 Rapid Coastal Hazards

<u>*Cyclone hazards*</u>

The impact by *tropical cyclones* (also known as <u>*hurricanes*</u> or <u>*typhoons*</u>) is caused by tropical revolving storms. Cyclones are low pressure systems around which the air circulates. The storm grows as air spirals inwards, rises and is exhausted on the top by high level winds. Surface air converges at an increasing rate towards the low pressure at the storm center; this is called the "eye" of the cyclone (Figure 3.C.7). This pressure drop might cause the sea level to rise, which – accompanied by very strong winds (over 90 km/hr) gives <u>*storm surges*</u> of 5 m. or more, causing severe damage to agriculture and infrastructure and many casualties. Globally, about 80 cyclones are formed every year. They occur on the South-East coast of the United States, in the Caribbean, Madagascar and Mozambique, India and the Bay of Bengal (Bangladesh), from Thailand to Vietnam, Southern China and Southern Japan, and in Australia (Figure 3.C.8).

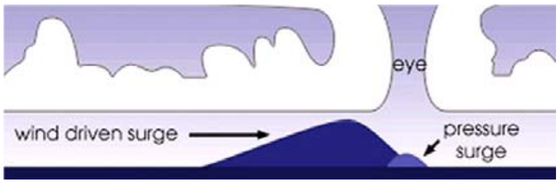


Figure 3.C 7 : Wind driven surge and pressure surge (NOAA-AOML)

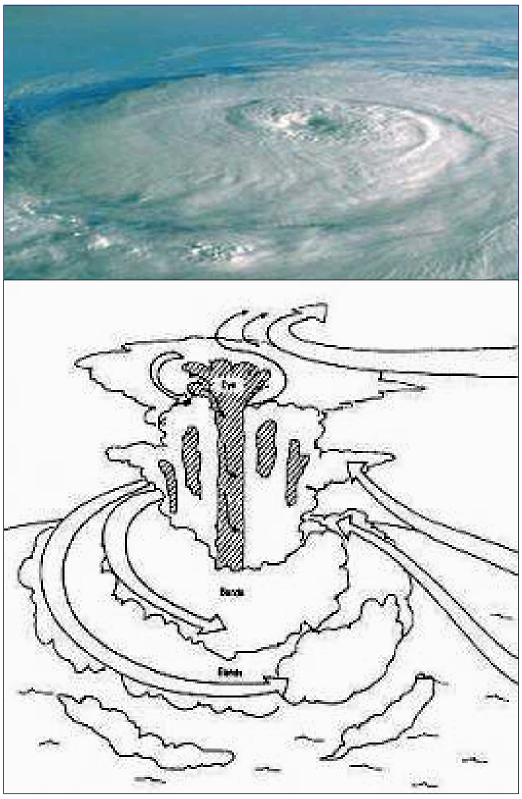


Figure 3.C.7 : Illustration of cyclone's eye and its circulation (UNDRO 1991)

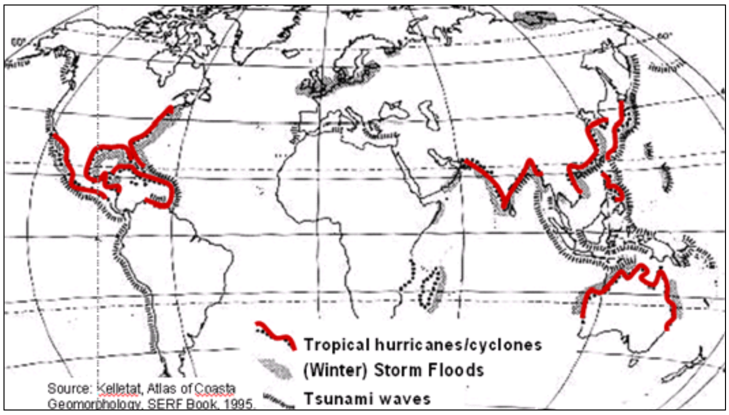


Figure 3.C.8 : Coasts with cyclone hazard (indicated with red lines) – Atlas of coasts (SERF, 1995)

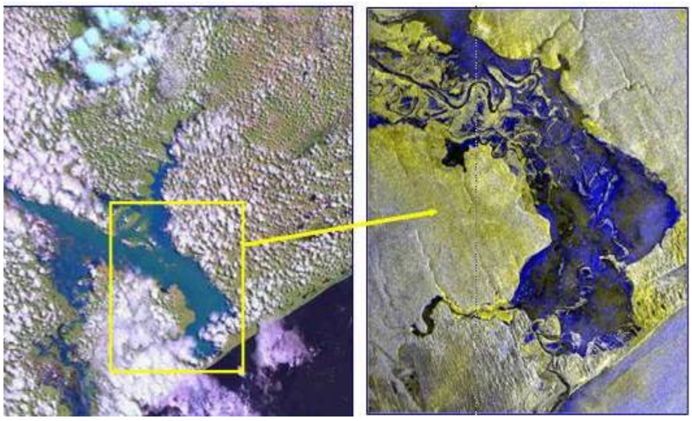


Figure 3.C.9 : Assessment of cyclone flooding using remote sensing. The left image shows the flooding of the March 2000 cyclone event in Mozambique on a Landsat image. The right image shows part of the same flood event on an ERS radar image, on which clouds are not visible. About 800 persons were killed by the event. (NASA Earth Observatory)

Task 3.3.C.2 : Find active cyclones (duration 30 minutes)

On this website of you can follow cyclone tracks and also find historic data. Find data of the possible active cyclone of today:

http://www.solar.ifa.hawaii.edu/Tropical/tropical.

Cyclone hazard analysis of the coast can be based on the frequency of landfall (*Fig. 3.C.11*). For this, historic data can be used on wind speed and surge height (*Fig. 3.C.10*). Other methods of prediction and hazard modelling are based on peak gust wind speeds (*Figures 3.C.12 & 13*)

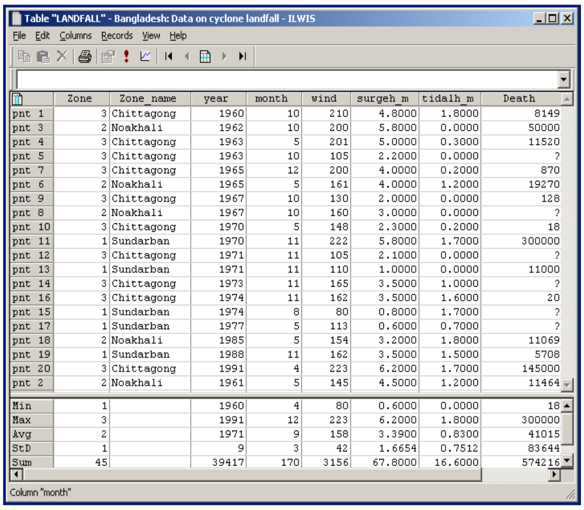


Table "LANDFALL" - Bangladesh: Data on cyclone landfall - ILWIS

	Zone	Zone_name	year	month	wind	surgeh_m	tidalh_m	Death
pnt 1	3	Chittagong	1960	10	210	4.8000	1.8000	8149
pnt 3	2	Noakhali	1962	10	200	5.8000	0.0000	50000
pnt 4	3	Chittagong	1963	5	201	5.0000	0.3000	11520
pnt 5	3	Chittagong	1963	10	105	2.2000	0.0000	?
pnt 7	3	Chittagong	1965	12	200	4.0000	0.2000	870
pnt 6	2	Noakhali	1965	5	161	4.0000	1.2000	19270
pnt 9	3	Chittagong	1967	10	130	2.0000	0.0000	128
pnt 8	2	Noakhali	1967	10	160	3.0000	0.0000	?
pnt 10	3	Chittagong	1970	5	148	2.3000	0.2000	18
pnt 11	1	Sundarban	1970	11	222	5.8000	1.7000	300000
pnt 12	3	Chittagong	1971	11	105	2.1000	0.0000	?
pnt 13	1	Sundarban	1971	11	110	1.0000	0.0000	11000
pnt 14	3	Chittagong	1973	11	165	3.5000	1.0000	?
pnt 16	3	Chittagong	1974	11	162	3.5000	1.6000	20
pnt 15	1	Sundarban	1974	8	80	0.8000	1.7000	?
pnt 17	1	Sundarban	1977	5	113	0.6000	0.7000	?
pnt 18	2	Noakhali	1985	5	154	3.2000	1.8000	11069
pnt 19	1	Sundarban	1988	11	162	3.5000	1.5000	5708
pnt 20	3	Chittagong	1991	4	223	6.2000	1.7000	145000
pnt 2	2	Noakhali	1961	5	145	4.5000	1.2000	11464
Min	1		1960	4	80	0.6000	0.0000	18
Max	3		1991	12	223	6.2000	1.8000	300000
Avg	2		1971	9	158	3.3900	0.8300	41015
StD	1		9	3	42	1.6654	0.7512	83644
Sum	45		39417	170	3156	67.8000	16.6000	574216

Column "month"

Figure 3.C.10: Table of historic cyclone events along the coast of Bangladesh. Columns: data of landfall, surge height in m., tidal height during landfall and number number of casualties (Damen, 2009)

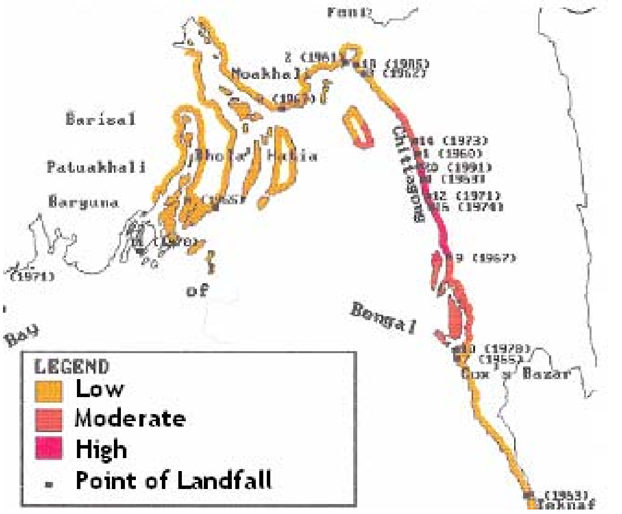


Figure 3.C.11 : Map of cyclone hazard zones along the coast of Bangladesh. Based on the table of historic events in figure 3.3.C.5 (Damen, 2009)

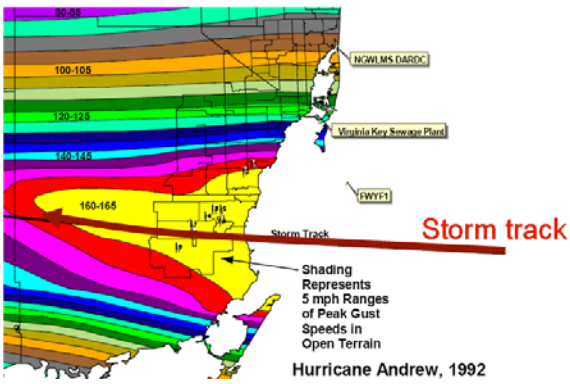


Figure 3.C.12 : Storm track modeling results based on peak gust wind speeds of Hurricane Andrew (1992), East coast US (HAZUS, 2004)

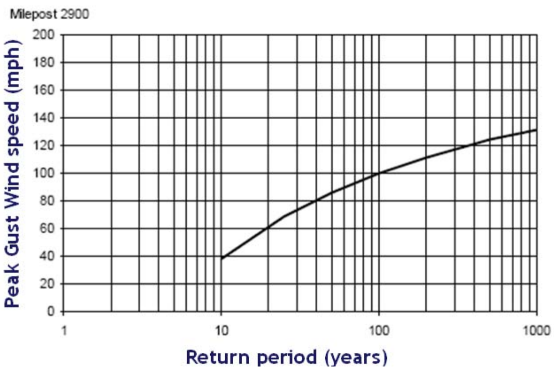


Figure 3.C.13 : Return periods peak gust wind speeds, US coasts (HAZUS, 2004)

Task 3.C.3 : Hazard analysis of cyclones in Bangladesh using ILWIS

Part A : **Analysis of historic cyclone events in Bangladesh (duration 1.5 hour)**

Analysis of cyclone data using Table Calculation on Surge Height, Wind Speed, Number of Casualties, etc. Display of the results in graphs

Part B : **Flood hazard analysis of the Baskhali area for different return periods of the cyclone events (duration 2.5 hour)**

Analysis of the satellite image together with ground photographs of the area; interpolation of elevation point data; cyclone flood modeling for different return period.

Tsunami hazard

Causes of a tsunami

- Displacement along fault line at ocean floor
- Landslides / slumps – submarine or along coastline
- Volcanic eruptions – submarine or along coastline

A *tsunami* is an exceptional disturbance of the sea level caused by an earthquake, landslide or volcanic eruption in and around the oceans. This can generate a sea wave of extreme length and period, travelling outwards in all directions from the source area with speeds up to 500 km/hr. Tsunami waves may attain heights of more than 30 meters by the time they hit the coast (Aceh tsunami December 2004). Several waves may follow each other at intervals of 15 – 45 minutes. (Fig. 3.C.14) In 1883 the explosive eruption of Krakatau volcano in Strait Sunda, Indonesia generated a tsunami run-up of 35 meter

high on the nearby coasts of Java and Sumatra, sweeping away houses and large coral blocks (Fig. 3.C.15). The well known tsunami of December 26, 2004, was caused by an earthquake due to seafloor displacement west of Sumatra.

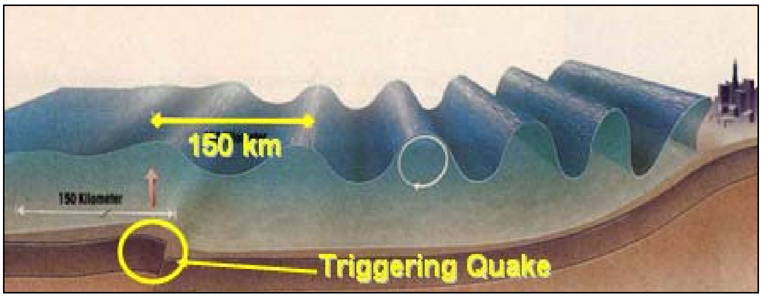


Figure 3.C.14 Tsunami wave triggered by displacement at sea floor

Task 3.C.4 : Poster Tsunami (duration: 15 minutes)

- Study the text and the pictures of the poster made by M. Damen, ITC

Task 3.C.5 : News item tsunami impact Banda Aceh (duration: 10 minutes)

- Look at the shocking news item of the tsunami flood disaster in Banda Aceh, December 2004.

Task 3.C.6 : Animations of tsunami wave propagation and impact in an urban area (duration 30 minutes)

- Observe the different computer animations.

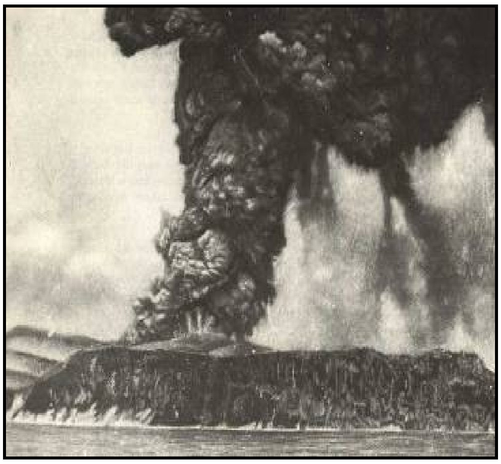


Figure 3.C.15 : Eruption Krakatau volcano, Indonesia in 1883 having caused large tsunami waves along the coasts of Java and Sumatra

Task 3.C.7 : NOAA Interactive tsunami database (duration: 20 – 30 minutes)

WARNING ! High Speed Internet connection needed !

- Visit the interactive web atlas (ARcIMS) of all global tsunami events
- Study the events close to your country

http://www.ngdc.noaa.gov/hazard/tsu_db.shtml

For detailed tsunami hazard analysis, the interpretation of multi-temporal images, in particular the delineation of the hazard zone with the help of elevation data such as Shuttle Radar Topography Mission data (SRTM) or damage assessment with high resolution air-borne and space-borne pre- and post disaster satellite imagery such as IKONOS and Quickbird can be very useful. (Figure 3.C.16)

Figure 3.C.16 : Quick Bird imagery of an island along the coast of Banda Aceh city. Left image: 23 June 2004; right image: 28 December 2004, therefore immediately after the tsunami disaster of 25 December of that year (Image processing: M.Damen)

As both the intensity and probability of the past tsunami events can not always be extracted in sufficient detail from existing databases , the term tsunami susceptibility zoning is preferred , defined as a qualitative rating for the terrain location, intensity and impact of the hazard. In Figure 3.C.17 an example is given of tsunami susceptibility classes in the Aceh area of North Sumatra, Indonesia, based on only a GlobeDEM digital elevation model of the coast (grid cell 1 x 1 km^2). Three classes have been made based on the elevation and width of the lower parts along the coast.

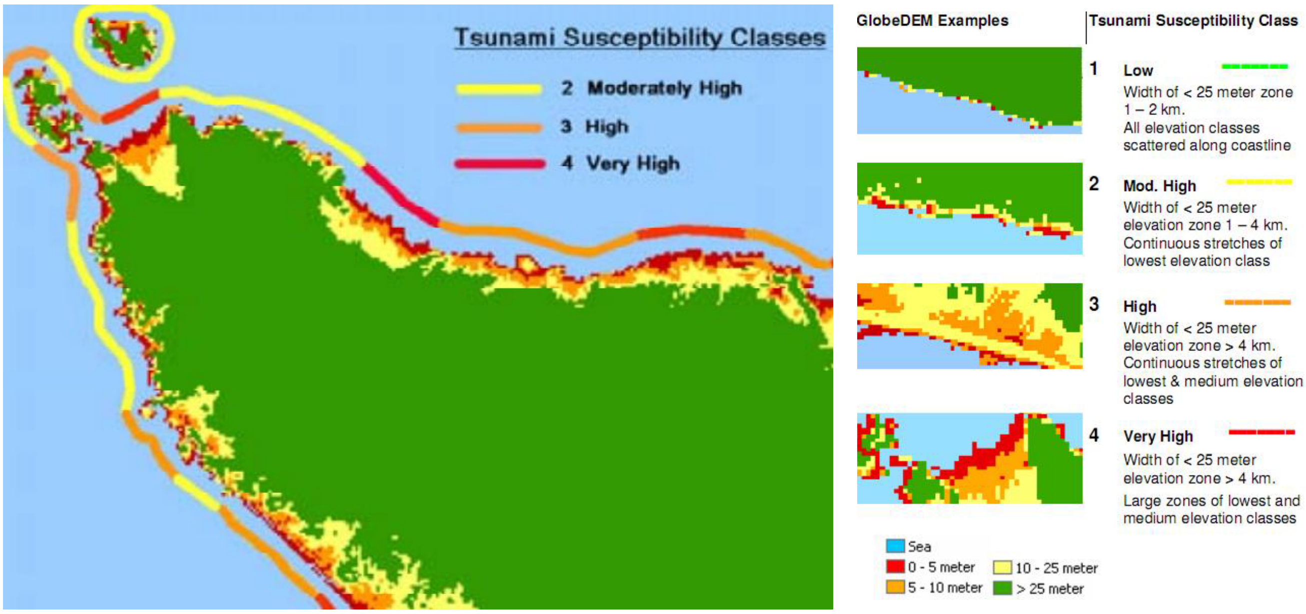


Figure 3.C.17 Semi quantitative Tsunami susceptibility classes of Aceh (North coast of Sumatra, Indonesia) based on a GLOBE DEM elevation model (Damen, 2005).

3.C.4 Slow Coastal Hazards

Enhanced Sea level rise.

Due to global warming and the Greenhouse Effect, the sea level will rise substantially in the near future. The International Panel of Climate Change (IPCC) has developed various scenarios for this (Fig. 3.C.18). In the "Business as Usual" scenario this rise will amount up to 40 cm or even more until the end of this century.

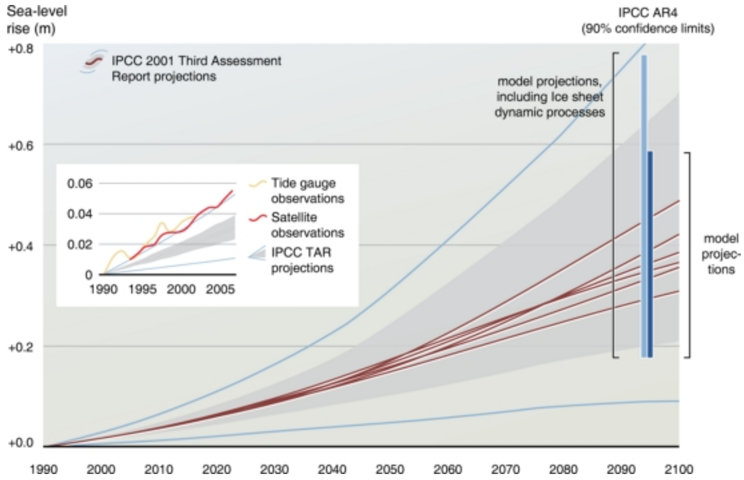


Figure 3.C.18 : Projected Sea Level Rise 21st Century (IPCC, 2009)

The enhanced Sea level rise has to be differentiated from *long term sea-level change.* These changes are so slow, that they are not considered as a hazard. World-wide changes in average sea level are described as *eustatic* to distinguish them from local influences, such as tectonic uplift or land subsidence. Eustatic sea-level changes result from two main causes: (1) changes in the volume of the ocean basins; and (2) changes in the volume of sea water. An example of the last course is sea level rise due to melting of glaciers after the last ice age.

In Holland the effect of eustatic sea level rise has been in particular hazardous due to the land subsidence in the last 1000 years in the peat areas caused by the lowering of the ground water and peat digging (Fig. 3.C.19)

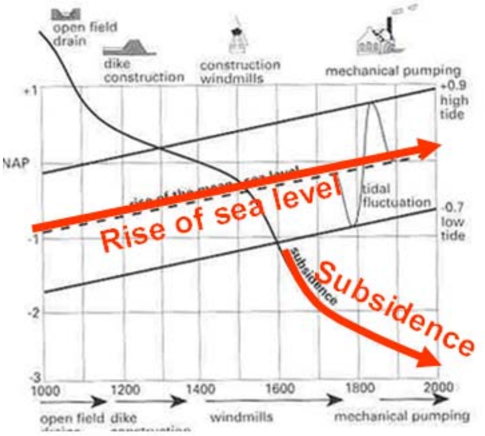


Figure 3.C.19: Land subsidence in Holland in the last 1000 years in the peat area in combination with eustatic rise of sea level (vd Ven 1993)

At other places due to this transgression in the Holocene period (starting 10.300 years Before Present) coastlines has changed rapidly and moved "inland", creating delta's, lagoonal areas with tidal creeks, mudflats and peats as well as beach ridges.

Enhanced Sea Level Rise scenarios for the Netherlands	
Low scenario	20 cm / century
Medium scenario	60 cm / century
High scenario	80 cm / century + 10% extra wind

Consequences:

1. Higher average water levels
2. More frequent storms
3. Larger tidal range

Task 3.C.8 : Hazard analysis of enhanced sea level rise

(duration : 1.0 hour)

- Use of the SRTM elevation model of Java and Bali, Indonesia for the analysis of enhanced sea level rise
- Display of the hazard zones in red, together with the drainage pattern.

Land subsidence

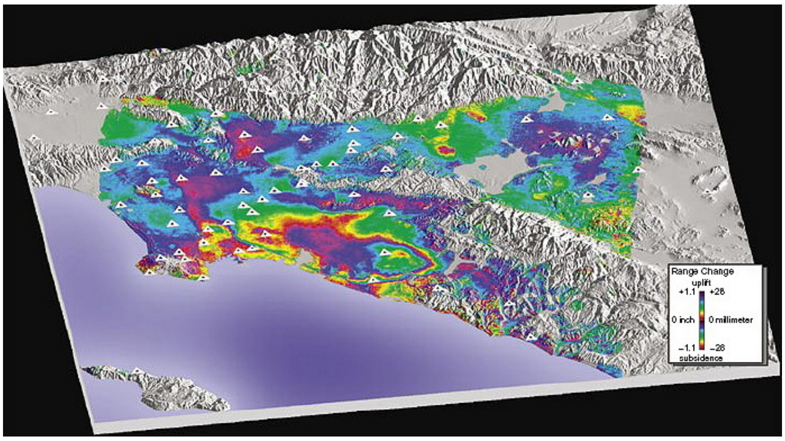


Figure 3.C.20 : Interferogram showing deformation in the Los Angeles Basin, April 1998 - May 1999 (USGS, 2005)

Subsiding coasts can be considered as a severe hazard, especially when they take place in urban areas situated in geologically young and "soft' sedimentary deposits. They can be caused by excessive ground-water extraction through industrial or private wells, as well as decreased discharge of the coastal aquifer.

Subsiding rates up to 15 cm a year or even more might take place. The subsided land is prone to flooding both from the sea and from rivers. A good example is Semarang city, Indonesia with subsidence rates up to 11.5 cm /year (See Figures 3.C.22-A & B).

The subsidence rate itself can only be determined by geo-technical investigations, such as point data. By using Satellite Interferometric Synthetic Aperture Radar (InSAR) technique, using images of different dates, changes in elevation can be measured too (Figure 3.C.20).

Subsiding cities (Rates since recording)	
Tokyo	4.6 m
Shanghai	2.7 m
Houston	2.7 m
Taipei	2.4 m
Bangkok	1.6 m
Semarang	11.5 cm/year

Figure 3.C.21: Rapid land subsidence causes flooding in the industrial area of Semarang, Indonesia (Photo: M. Damen

Task 3.C.9 : Reading article "Monitoring Land Subsidence in Semarang, Indonesia"
(duration: 1 hour)

- Read the article by Aris Marfai and Lorenz King on the "Monitoring Land Subsidence in Semarang, Indonesia"

This is a preparation to task 3.C.10

Task 3.C.10 : Modelling of Land Subsidence & Sea Level Rise in Semarang city, Indonesia
(duration : 2 hours)

- Analyse flooded areas in Semarang due to enhanced sea level rise and subsidence using ILWIS

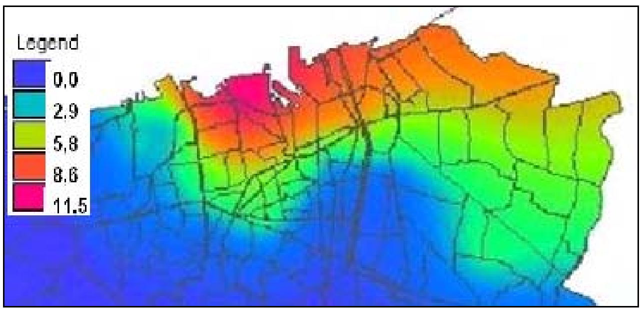


Figure 3.C.22-A : Subsidence rate Semarang city, Indonesia (cm/year). Interpolation from point data. Values in cm/year (M. Damen, 2009)

Figure 3.C.22-B : A Subsidence flooding in the industrial area of Semarang city, Indonesia. Asterbands RGB : 321 (M. Damen, 2009)

Coastal erosion and accretion

Coastal erosion & accretion is basically a natural process, which can becomes a risk to coastal infra-structure or other types of land uses, such as shrimp and fishponds or rice fields. The combined effect of wind-generated waves, tidal waves and currents from rivers, produce a highly variable and complex near-shore hydrodynamic system. Due to the movements of sediment on the sea floor and onshore, offshore and alongshore, the shaping of the coastline is taking place in a dynamic system in a continuous process.

Tides are movements of the ocean water caused by the gravitational effects of the moon and the sun in relation to the earth (Figure 3.C.23). They are very long waves that travel across the ocean and are transmitted into bays, inlets, estuaries and lagoons, causing tidal currents. The cycle produces two high and two low tides in approximately 25 hours. The tides are measured by tide gauges, located mainly at ports.

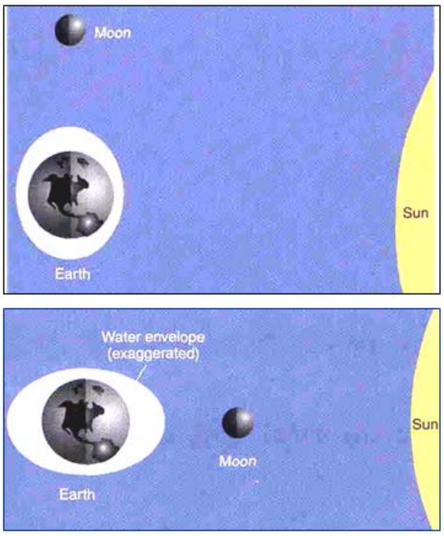


Figure 3.C.23 : Tides – position of moon and sun in relation to earth

Spring tides occur when sun, earth and moon are in alignment; small tides or *neap tides* take place when the sun and the moon are at right angles to the earth.

Tidal currents, produced as tides rise and falls, alternate in direction in coastal waters. The tidal range in mid-ocean is small, about 50 cm. but its height is increased when it reaches the shallow waters of the continental shelf. Low tidal ranges occur most commonly on open coasts and in landlocked seas. The highest tides occur in estuaries or other coasts with convergent shores.

Surface waves generated by wind are – besides tidal waves – the main source of energy along a coast. They form *ocean swells*, which are long, low waves with periods of 10 – 16 seconds. As the move towards the coast the wave crests gain in height steepness, and as they enter shallow water they break to produce a *surf* wave on the beach.

Wave refraction takes place when sea waves approach the coastline in a shallow water environment (see Figure 3.C.24). Ocean swell has a parallel wave crest in deep water, but as the waves move into shallow water they are modified by the frictional effects of the sea floor. The effect of this is that the angle between the swell and the bathymetrical contours diminishes, until they are approximately parallel to each other. The resulting curved patterns of wave crests can be observed from headlands or seen on aerial photographs.

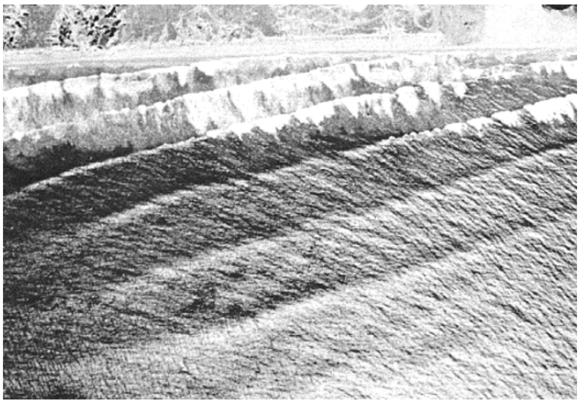


Figure 3.C.24 : Example of wave refraction at a coast. Panchromatic aerial photograph (ITC Photo database)

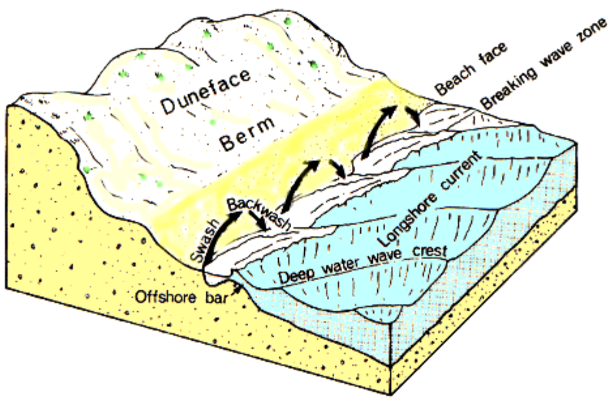


Figure 3.C.25 : Longshore drifting: Swash and backwash along a sandy beach

Even after refraction few waves are parallel to a beach, but approach it at an angle which causes the *swash* to move sediment diagonally up the beach in the direction of the wave approach. The *backwash* will run more directly down the beach so that the sediment undergoes net transport along the beach. The long shore movement of waves and the movement of sediment along the beach together create a *long-shore* or *littoral drift (*see also Figure 3.C.25*).*

On most coasts there are dominant waves from one direction and sediment is transported predominantly in that direction.

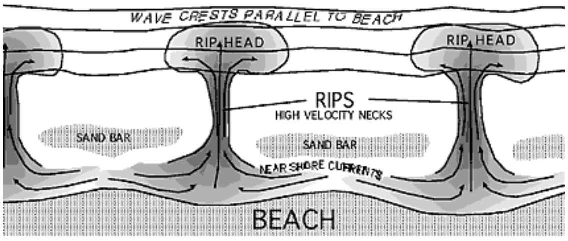


Figure 3.3.C.26 :Rip currents along a sandy beach (Berkely-EDU 2002)

In the near-shore zone water carried onshore by waves is often carried away again by *rip currents*, which may be regularly or irregularly spaced (Figure 3.C.26). Currents are also produced by the discharge from river mouths. River outflow may carry sediments into the sea, maintain or enlarge river outlets or even form *deltas.*

Task 3.C.11 : Look at YouTube videos on Coastal Erosion (duration 1 hour):

- **Longshore drifting (Steve Vetesse):**
  http://oceanica.cofc.edu/an%20educator'sl%20guide%20to%20folly%20beach/guide/process2.htm
- **Longshore drifting :**
  http://www.youtube.com/watch?v=U9EhVa4MmEs&feature=PlayList&p=5F98D2A77B6A176F&playnext=1&playnext_from=PL&index=23

  http://www.youtube.com/watch?v=rCpZYlPqn6E&feature=related
- **The Quite Crisis** – Walney Dog productions:
  http://www.youtube.com/watch?v=5NMF1sqfR3Q
- **Deposition & Erosion** by Liam Sharpe– Cliff formation shown with 365 sequential photographs:

http://www.youtube.com/watch?v=ChEHQUMEkXw&feature=PlayList&p=96730DF14415DE67&playnext=1&playnext_from=PL&index=64

Inventory of spatial datasets required in coastal hazard & risk assessment

Baseline & other thematic data needed for coastal zone management purposes • Topographical maps • Bathymetrical maps • High res. Satellite images (IKONOS, QuickBird) • Elevation data with sufficient accuracy to show minor elevation differences in gentle / flat coastal terrain • Soil & Geomorphological maps • Hydrological maps • Geological maps, with detailed information on the Holocene coastal deposits • Population & infra-structural data of the coastal zone itself • Maps of nature conservation areas	**Data needed for enhanced sea level rise risk analysis** • Local (IPCC) scenarios of sea level rise • (Historic) meteorological data (wind speeds, rainfall, temperature) • Detailed elevation map of the coastal zone for impact modelling • High resolution aerospace data (aerial photographs & satellite imagery) to map (a.o) elements at risk • Database on population & infra structure, including amounts and vulnerabilities • Data on neo-tectonic land movements and other possible causes of land subsidence

Data needed for cyclone risk analysis
• Database of historic events, including gust wind speed, surge height, tidal situation during landfall, # casualties
• Meteorological and tidal data
• Historic cyclone storm tracks
• Detailed elevation model for impact flood assessment / modelling
• High resolution aerospace data (aerial photographs & satellite imagery) to map elements at risk
• Database on population & infra-structure, including numbers and vulnerabilities
• Data on available shelters & evacuation routes
	Data needed for land subsidence risk analysis
	• Multi-date elevation models:
	  o Regional: INSAR Interferogram
	  o Local: detailed DEM (from Lidar, photogrammetry, Diff. GPS surveys)
	  o Point data of subsidence rate
	• Data on surface drainage and subsurface hydrology
	• Lithological and structural data of sub-surface
	• Geological data on neo-tectonic land movements (up and down)
	• High resolution aerospace data (aerial photographs & satellite imagery) to map (a.o.) elements at risk
	• Databases on population & infra structure, including amounts and vulnerabilities

Data needed for tsunami risk analysis • Database of historic events • Detailed coastal terrain elevation for run-up modelling / hazard zone analysis • Bathymetrical maps for tsunami run-in modelling • Geological data on possible triggering locations • High resolution aerospace data (aerial photographs & satellite imagery) to map (a.o.) elements at risk • Database of population & infra-structure, including amounts and vulnerabilities • Data on available shelters / evacuation routes • Warning system	**Data needed for coastal erosion / accretion risk analysis** • Medium to high aerospace imagery of the coastline (aerial photographs, satellite imagery) • Tidal information • Marine data on wave directions, sediment transport, etc. • Discharge data of the river(s) and amounts of suspended sediment, etc. • Maps on coastal geology, geomorphology and soils • High resolution aerspace data to map (a.o.) elements at risk • Database on population & infra structure, including amounts and vulnerabilities

Depositional coastal landforms – the delta as an example

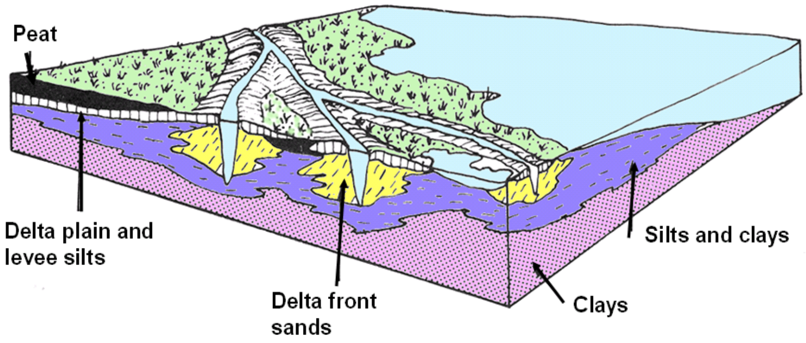
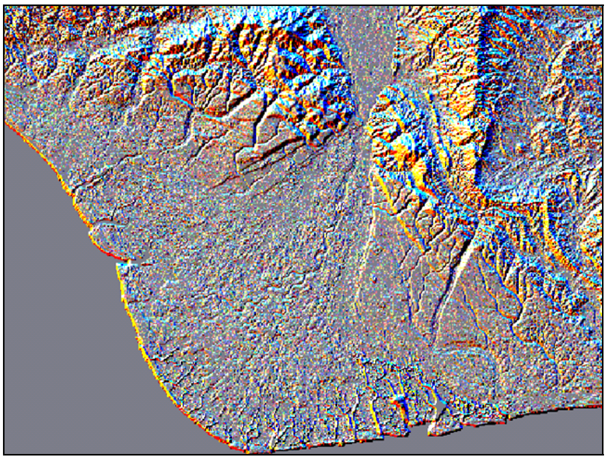


Figure 3.3.C.27 : The delta and its deposits

A *delta* is a low, nearly flat area of land at the mouth of a river where sediment accumulates. (Figure 3.C.27). Deltas may have many shapes with four common shapes widely recognized (Figures 28): (1) *elongated* or *digitate*, like the Mississippi, where alluvium is abundant and the river can built into the sea due to limited wave action, (2) *cuspate*, where wave erosion dominates the distribution of sediment away from the river mouth, (3) *lobate* like the Niger, where the river builds into the sea but wave action is effective in redistributing sediment along coastal barriers and *crenulate*, like the Mekong, where tidal currents produce numerous sandy islands separated by tidal channels along the delta front.



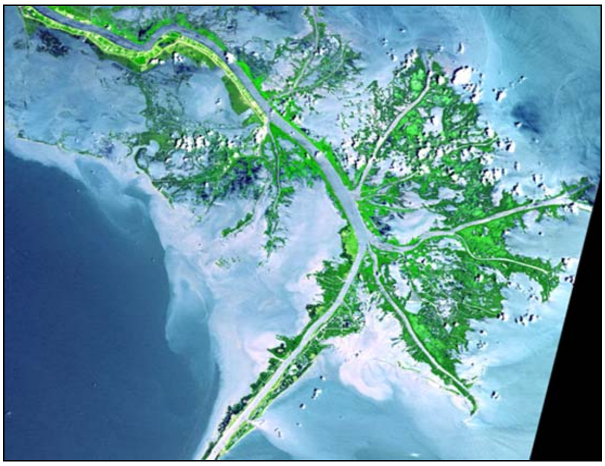


Figure 3.C.28- A : Upper left: Tiber delta -cuspate type Quickbird (Google Earth)

Figure 3.C.28- B : Upper right: Mekong delta – crenulate type Envisat - MERIS

Figure 3.C.28- C : Lower left: Niger delta – Lobate type S RTM elevation data – Color hillshade

Figure 3.C.28- D : Lower right: Mississippi delta – digitate Aster VNIR

Monitoring the Solo river delta, North coast of java, Indonesia

Most of the deltas change the position of the outlet over time. Examples of this are the Mississippi delta where the delta front changes its position several hundred kilometres over the last 5000 years and the Hunaghe or Yellow river delta in China. Below an example of the Solo delta at the North coast of Java, Indonesia (Figure 3.3.C.29).

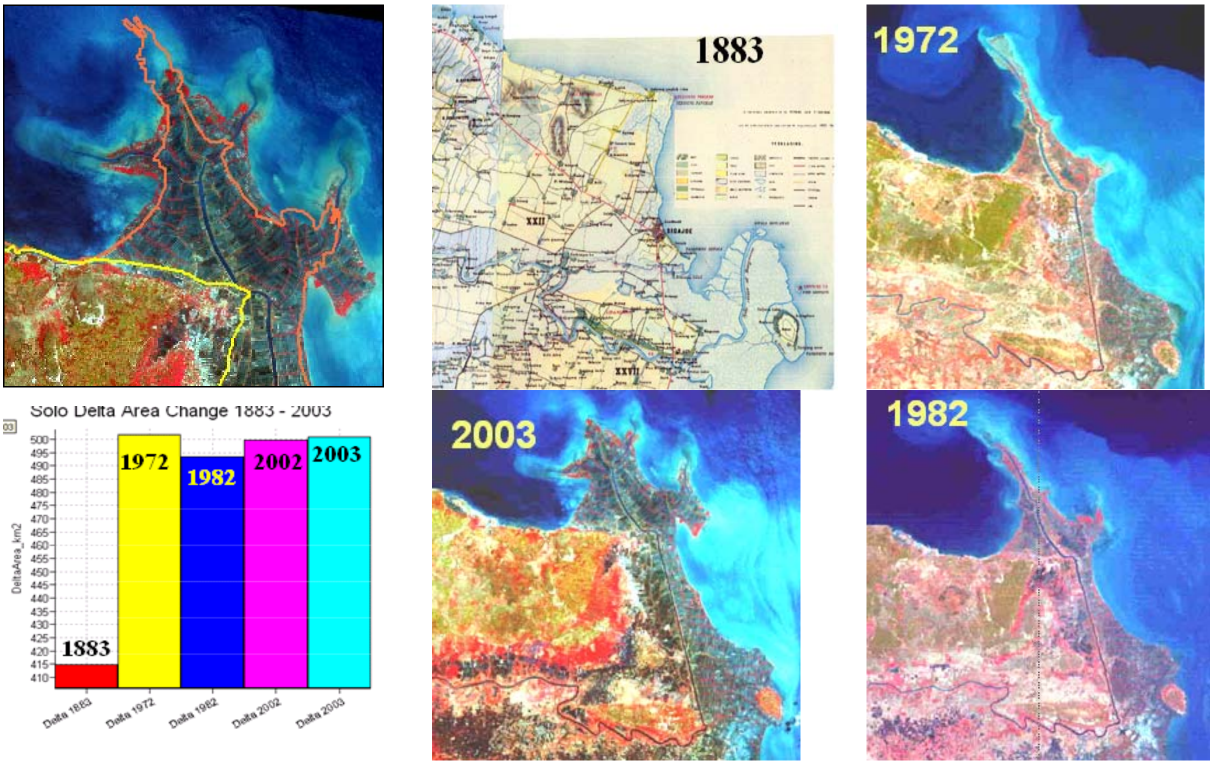


Figure 3.C.29 : Coastline and area change of Solo river delta, Indonesia – 1883: topographical map; 1972: Landsat MSS; 1982: Landsat TM; 2003: Aster VNIR. (M. Damen, 2009)

Task 3.C.12 : Monitoring of the change of the Solo River delta, Java, Indonesia (duration : 1.5 hour)

- Use the provided multi-temporal satellite images and digitized coastlines to analyze the change of the delta, using ILWIS software.

Summary coastal hazard assessment

Coastal hazard analysis and the mitigation of hazards and disasters should be integral part of coastal zone management. Examples are given from the Netherlands, such as the use of multi-temporal Lidar elevation data for the monitoring of the eroding or depositing amounts of sand along the beach.

A subdivision is made between geoinformation methods for the study of slow and rapid coastal hazards. An example of the first type is risk evaluation of cyclones based on statistical analysis of historic events together with GIS modeling of the flood surge impact and the people at risk. Multi-date high resolution remote sensing imagery is shown of Aceh, Indonesia for the analysis of elements at tsunami risk. By using medium resolution elevation data a crude tsunami susceptibility classification of then coastline can be made.

Examples of slow coastal hazards are the study of land subsidence in Semarang city, Indonesia using multi-date elevation models in combination with enhanced sea level rise. Finally some methods are shown on the analysis of of coastal erosion & accretion of delta environments with the use of multi-sensor and multi-date satellite imagery.

Selftest

In order to evaluate whether you have understood the concepts that were presented in this session. Please make the following test, and check the answers in Blackboard.

Question 1:
Mention the three important elements of Integrated Coastal Zone Management.

Question 2:
List some mitigation measures of coastal flooding.

Question 3:
Mention one Remote sensing technique to measure the volumes of sand that might erode or deposit along a sandy beach.

Question 4:
Mention the two most important causes of the sea level to rise due to a cyclone event along the coast.

Question 5:
List at least three causes of a tsunami.

Question 6:
At which places on the earth do the most tsunami events take place? Look for this at the NOAA tsunami database.

Question 7:
Mention at least two causes of the sea level to rise relative to the land area.

Question 8:
What kind of geoinformatics techniques can be applied to measure land subsidence over time?

Question 9:
Explain with a small drawing the process of swash and backwash along a sandy coast.

Question 10:
Mention the four main types of a delta.

Further reading:

- **RWS (2002)** – Towards an Integrated Coastal Zone Policy – Policy Agenda for the Coast - Min. of Transport, Public Works and Water Management, The Hague, The Netherlands
- **Damen & Khan (1985)** Cyclone Hazard in Bangladesh **-** Background information storm surge modeling, ITC
- **Cummins & Leonard (2005)** The boxing day tsunami In Indonesia, Geoscience Australia, Issue 77
- **Marfai, Muh. Aris & King, Lorenz (2007)** Monitoring Land Subsidence in Semarang, Indonesia – Env. Geology 53:651-659
- **Coastal erosion and Accretion –** Document 26 of Sustainable Development of European Coastal Zones. For more documents see: http://www.deduce.eu/results.html

References Coastal hazard Assessment

Berkely-EDU (2002) - Campus News
http://berkeley.edu/news/media/releases/2002/05/23_tides.html

Damen, M. (2003) – Monitoring the change of the Yellow River delta using multi-temporal satellite images, PR China, ITC ILWIS Exercise

Damen, M. (2005) – Geo-information for Tsunami Susceptibility Zoning – Examples from the Coast of Indonesia – Map Asia Congress

Damen, M. (2009) – hazard Analysis of Cyclone Flooding in Bangladesh, ITC ILWIS Exercise

HAZUS (2004) : Multi-hazard Loss Estimation Methodology, FEMA, USA

IPCC (2009) – Projected Sea Level Rise for 21st Century

http://maps.grida.no/go/graphic/projected-sea-level-rise-for-the-21st-century#metainfo

NASA Earth Observatory: http://earthobservatory.nasa.gov/IOTD/view.php?id=524

NOAA-AOML – Atlantic-Oceanographic and Meteorological Laboratory, Hurricane Research division: http://www.aoml.noaa.gov/hrd/tcfaq/C1.html

RWS (1991) – Rising Waters, Impact of the greenhouse effect for the Netherlands (Doc. gwao 90.026). Min. of Transport, Public Works and Water Management, The Hague, The Netherlands

RWS (1996) – Coastline Management – From Coastal monitoring to sand nourishment, Min. of Transport, Public Works and Water Management, The Hague, The Netherlands

RWS (2002) – Towards an Integrated Coastal Zone Policy – Policy Agenda for the Coast - Min. of Transport, Public Works and Water Management, The Hague, The Netherlands

RWS (2009) Delta Works online**:** http://www.deltawerken.com/English/10.html?setlanguage=en

SERF (1995) - Kelletat, Atlas of Coastal Geomorphology, SERF Book

UNDRO (1991) – Mitigating Natural Disasters, Phenomena, Effects and Options. A manual for Policy makers and Planners. Publication within framework IDNDR

Ven, van de, Editor (1993) – Man-made lowlands – History of Water Management and Land Reclamation in the Netherlands – Int. Commission on Irrigation and Drainage. Uitg. Matrijs, Utrecht, Netherlands