REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS FOR NATURAL DISASTER MANAGEMENT

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1. Natural Disasters

1.1 Introduction

There are many different definitions of disasters, such as:

- a sudden calamitous event bringing great damage, loss or destruction (Merriam Webster dictionary);
- some rapid, instantaneous or profound impact of the natural environment upon the socio-economic system" (Alexander, 1993)
- an event, concentrated in time and space, which threatens a society or a relatively self-sufficient subdivision of a society with major unwanted consequences as a result of precautions which had hitherto been culturally accepted as unwanted (Turner, 1976).
- an extreme event as any manifestation of the earth's system (lithosphere, hydrosphere, biosphere or atmosphere) which differs substantially from the mean (Alexander, 1993).
- an event that results in death or injury to humans, and damage or loss of valuable good, such as buildings, communication systems, agricultural land, forest, natural environment etc.

It is important to distinguish between the terms disaster and hazard. A potentially damaging phenomenon (hazard), such as an earthquake by itself is not considered a disaster when it occurs in uninhabited areas. It is called a disaster when it occurs in a densely populated area, and results in a large destruction.

Figure 1 gives an indication of the geographical distribution of a number of major hazards, such as earthquakes, volcanoes, tropical storms and cyclones.

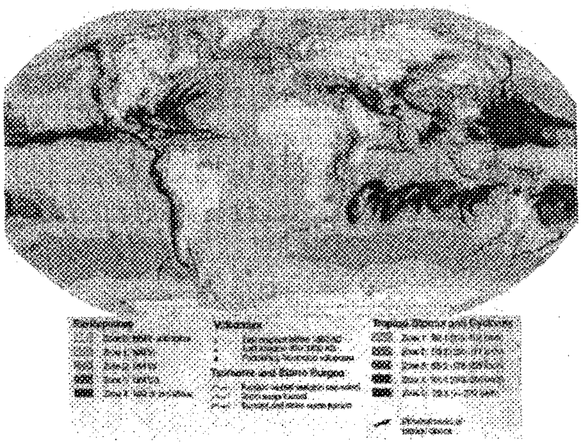

Figure 1: World map of natural disasters (Source: Munich Re., 1998a)

1.2 Disaster Classification

Disasters can be classified in several ways. A possible subdivision is:

- Natural disasters are events which are caused by purely natural phenomena and bring damage to human societies (such as earthquakes, volcanic eruptions, hurricanes)
- Human-made disasters are events which are caused by human activities (such as atmospheric pollution, industrial chemical accidents, major armed conflicts, nuclear accidents, oil spills).
- Human-induced disasters are natural disasters that are accelerated/aggravated by human influence.

In table 1 the various disasters are classified according to this classification, however, by using several classes in-between purely natural, and purely human-made hazards. It is however, always

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Natural	Some human influence	Mixed natural /human influence	Some natural influence	Human
Earthquake Tsunami Volcanic eruption Snow storm / avalanche Glacial lake outburst Lightning Windstorm Thunderstorm Hailstorm Tornado Cyclone/ Hurricane Asteroid impact Aurora borealis	Flood Dust storm Drought El Niño	Landslides Subsidence Erosion Desertification Coal fires Coastal erosion Greenhouse effect Sealevel rise	Crop disease Insect infestation Forest fire Mangrove decline Coral reef decline Acid rain Ozone depletion	Armed conflict Land mines Major (air-, sea-, land-) traffic accidents Nuclear / chemical accidents Oil spill Water / soil / air pollution Groundwater pollution Electrical power breakdown Pesticides

Table 1: Classification of disaster in a gradual scale between purely natural and purely human-made.

difficult to make such classifications. A landslide, for example, may be purely natural, as a result of a heavy rainfall or earthquake, but it may also be human induced, as a result of an oversteepened roadcut.

Another subdivision is related to the main controlling factors leading to a disaster. These may be meteorologically (too much or too little rainfall, high windspeed), geomorphological/geological (resulting from anomaly in the earth's surface or subsurface), ecological (regarding flora and fauna), technological (human made), global environmental (affecting the environment on global scale) and extra terrestrial (from outside earth). See table 2.

Meteorological	Geomorphological/ Geological	Ecological	Technological	Global environmental	Extra terrestrial
DroughtDust storm Flood Lightning Windstorm Thunderstorm HailstormTornado Cyclone/ Hurricane	EarthquakeTsunami Volcanic eruptionLandslide Snow avalanche Glacial lake outburst Subsidence Groundwater pollution Coal fires Coastal erosion	Crop disease Insect infestation Forest fire Mangrove decline Coral reef decline	Armed conflict Land mines Major (air-, sea-, land-)traffic accidents Nuclear / chemical accidents Oil spill Water / soil / air pollution Electrical power breakdown Pesticides	Acid rain Atmospheric pollution Greenhouse effect Sealevel riseEl	Niño Ozone depletion Asteroid impact Aurora borealis

Table 2: Classification of disaster related to the main controlling factors leading to a disaster.

Another useful distinction that can be made between disaster is regarding their duration of impact and the time of forewarning. Some disasters strike within a short period with devastating outcomes (like earthquakes), whilst others have a slow onset period with equally or even more serious repercussions (such as drought). (See table 3)

Also the frequency and type of event can be used to classify disaster types. Frequency can be defined as the number of events with the same magnitude that happen within a given period of time, or how often an event with a given magnitude occurs. The average time between events of the same magnitude, e.g. an earthquake with magnitude 6, is called return period, or recurrence interval. This is also defined as 1 divided by the frequency. In table 3 an indication is given of the average frequency for a number of disaster types.

Magnitude is related to the amount of energy released during the disaster event, or refers to the size of the disaster. Magnitude is indicated using a scale, consisting of classes, related to a logarithmic increase of energy. Examples of this are the Richter scale for earthquake magnitudes, the Volcanic explosivity Index, or the Hurricane Disaster potential scale.

Whereas magnitude refers to the size of the event, the term intensity is used to refer to the damage caused by the event. Intensity is normally indicated by scales, consisting of classes, with arbitrarily defined thresholds, depending on the amount of damage observed. Examples of intensity scales are the Modified Mercalli scale for earthquakes, or the tsunami intensity scale.

Disasters generally follow the magnitude - frequency relation, which means that events with a smaller magnitude happen more often than events with large magnitudes. When the logarithm of the frequency is plotted against magnitude, usually a linear relation can be obtained (see figure 2).

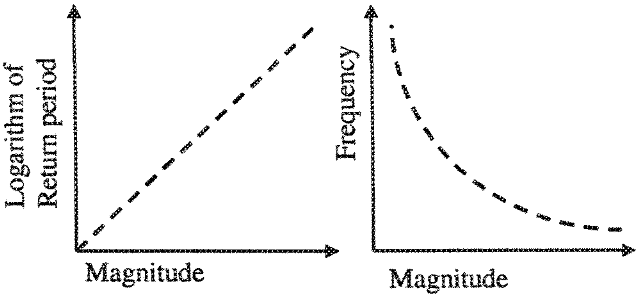

Figure 2: Relationship between Magnitude, frequency and return period.

Magnitude - frequency relations are often not as straightforward as one might think. There are a number of problems involved:

- The establishment of a magnitude -frequency relation for a certain type of hazard in an area is strongly depending on the length of the historical record of events. In many areas the catalogue of earthquake events, for example, is only reliable for the last 50 years or so, during which a seismic network has been operational.

Disaster type	Duration of impact	Length of forewarning	Frequency or type of occurrence
Lightning Snow avalanche Earthquake Tornado Landslide Intense rainstorm Hailstorm Tsunami Flood Subsidence Volcanic eruption Cyclone/ Hurricane Forest fire Coastal erosion Drought Crop disease Desertification	Instant Seconds- minutes Second- minutes Second-hours Second-decades Minutes Minutes Minutes- hours Minutes - days Minutes -decades Minutes-years Hours Hours- Days Hours - decades Days- months Weeks- months Years- Decades	Seconds - hours Seconds - minutes seconds-years Seconds- hoursSeconds- hoursMinutes - hoursMinutes - days Second - years Minutes - weeks Hours - daysSeconds -day sHours Days - weeks Days - months Months - years	Random Seasonal/diurnal ; randomLog- normalSeasonal; negative binomialSeasonal; irregularSeasonal/diurnal; PoissonSeasonal/diurnal; Poisson , gammaRandomSeasonal; Markovian, gamma, log- normalSudden or progressiveIrregularSeasonal / irregularSeasonal / randomSeasonal / irregular ; exponential , gammaSeasonal / irregular ; binomial , gammaSeasonal / irregularProgressive (threshold may be crossed)

Table 3: Classification of disasters by duration of impact, length of forewarning, and frequency or type of occurrence (Alexander, 1993)

- For many types of hazards, there aren't even records available.
- The magnitude - frequency relation often is very complicated, and cannot be described by a simple log-normal distribution. It has to be modelled using different types of distribution functions (Poisson, gamma, binomial, negative binomial, Markovian, gamma, exponential, etc). But they still remain a statistical approximation of reality.
- The above points make it very difficult to make predictions about the frequency of large magnitude events.
- Some types of natural hazards do not have clear magnitude - frequency relations. Whereas for floods, for example, the same area may be hit often by small inundations, and less frequent by larger floods, this cannot be said for landslides, erosion, avalanches or subsidence. Normally an area can become part of a landslide only once. The landslide changes the site conditions (the slope is flattened, material is moved downslope) in such a way that a new landslide at the same place is not likely to happen. In that case the landslide can only be reactivated again.

1.3 Disaster statistics

The impact of natural disasters to the global environment is becoming more and more severe over the last decades. The reported number of disaster has dramatically increased, as well as the cost to the global economy and the number of people affected (see table 4 and 5).

Most fatalities during the last ten years are caused by floods (205,000), often related to windstorms. The cyclone that happened in 1991 in Bangladesh, for example, triggered a huge storm surge that killed 140,000 people. The number of people indicated as affected by drought is rather difficult to compare with the other types of hazards, as drought is a phenomena that affects an area more gradually than the other types of disasters, which are more instantaneously.

The strong increase in losses and people affected by natural disasters is partly due to the developments in communications, as hardly any disaster passes unnoticed by the mass media. But it is also due to the increased exposure of the world's population to natural disasters. There are a number

Disaster type	1960s	1970s	1980-1992
Drought	18,500,000	24,400,000	56,500,000
Flood	5,200,000	15,400,000	63,300,000
Civil strife/conflict	1,100,000	4,800,000	7,600,000
Tropical cyclone	2,500,000	2,800,000	3,320,000
Earthquake	200,000	1,200,000	2,270,000
Other disaster	200,000	500,000	1,000,000
Total	*27,700,000*	*48,300,000*	*131,800,000*

Table 4: Number of people affected per year by disasters (Sources: Wijman, 1984; US Office of foreign Disaster Assistance, 1993)

	Decade 1960 - 1969	Decade 1970 -1979	Decade 1980 - 1989	Last10 years 1988 - 1997	FactorLast 10 : 60s
Number of large disasters	16	29	70	48	3.0
Economic losses	50.4	96.9	153.8	426.7	8.5
Insured losses	6.7	11.3	31.0	93.5	14.0

Table 5: Statistics of great natural disasters for the last four decades (source: Munich Re, 1998b)

of factors responsible for this, which can be subdived in factors leading to a larger risk and factors leading to a higher occurrence of hazardous events. The increased risk is due to the rapid increase of the world population, which has doubled in size from 3 billion in the 1960s to 6 billion in 2000. Depending on the trends, world population is estimated to be between 7 and 10 billion by the year 2050 (see figure 3).

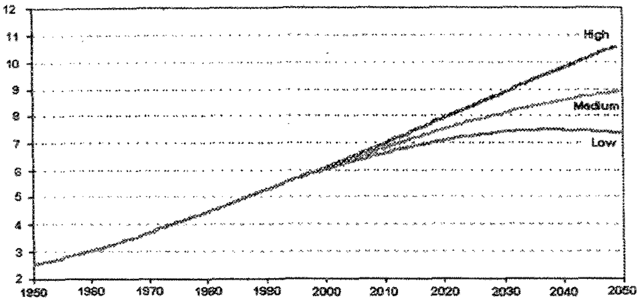

Figure 3. World population size: past estimates and medium-, high- and low fertility variants, 1950-2050 (Source: United Nations Population Division, World Population Prospects: The 1998 Revision, forthcoming)

Another factor related to the population pressure is that areas become settled that were previously avoided due to their susceptibility to natural hazards. Added to this is the important trend of the concentration of people and economic activities in large urban centres, most of which are located in vulnerable coastal areas that are always more subjected to disasters (e.g. Tokyo, San Francisco, Calcutta etc.). Mega-cities with a very rapid growth mostly experience the occupation of marginal land, susceptible to disasters, by the poor newcomers.

A further factor related to the increasing impact of natural disasters has to do with the development of highly sensitive technologies and the growing susceptibility of modern industrial societies to breakdowns in their infrastructure. Figure 4. shows the distribution of economic and insured losses due to natural disasters during the last 4 decades. Some of the best data on natural disaster statistics are collected by the international re-insurance companies that have a direct economic interest in knowing the frequency and magnitude of disasters. It is clear that there is a rapid increase in the insured losses, which are mainly related to losses occurring in developed countries. Windstorms clearly dominate the category of insured losses (US $90 billion), followed by earthquakes (US $ 25 billion). Insured losses to flooding are remarkably less (US $ 10 billion), due to the fact that they are most severe in developing countries with lower insurance density.

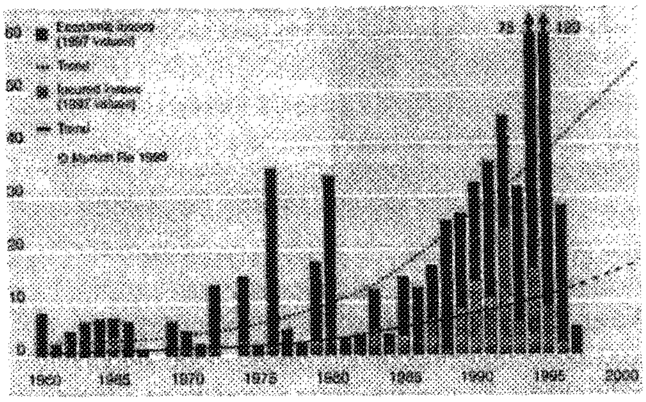

Figure 4: Economic and insured losses due to natural disasters, with trends (Source: Munich Re., 1998b)

However, it is not only the increased exposure of the population to hazards that can explain the increase in natural disasters. There is also a clear trend that the frequency of destructive events, that are related to atmospheric extremes, such as floods, drought, cyclones, and landslides is increasing (see figure 5). During the last 10 years a total of 3,750 windstorms and floods were recorded, accounting for two-thirds of all events. The number of catastrophes due to earthquakes and volcanic activity (about 100 per year) has remained constant (Munich Re., 1998). Although the time-span is still not long enough to indicate it with certainty, it is a clear indication that climate change shows a clear negative trend in relation with the occurrence of natural disaster, which only will be become more severe in the near future. The two "one-hundred" years El Nino events happened during the past 15 years also are believed to be related to this. The total damage due to the 1982-1983 El Nino event were estimated at US $ 10.9 billion, causing 2000 deaths, and the event of 1997 -1998 has surpassed these figures even more.

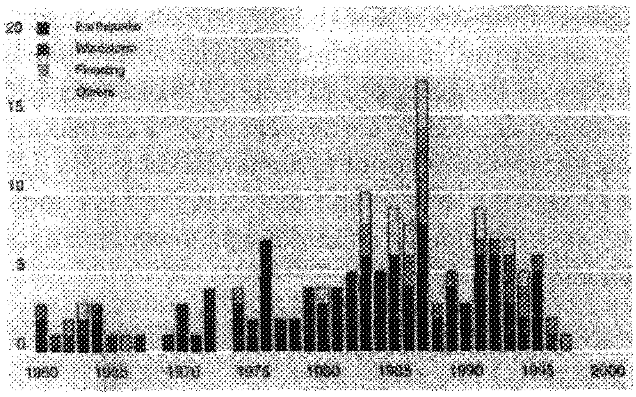

Figure 5: Number of large natural disaster in the period 1960 -1997 (Source: Munich Re., 1998b)

When the impact of disasters is compared per continent (see figure 6, where Australia is not indicated), it can be concluded that Asia and America clearly dominate the various categories, due to the high population figures and the high frequency of events. With economic losses of more than US $ 100 billion, the Kobe earthquake in 1995 remains by far the largest loss of all time.

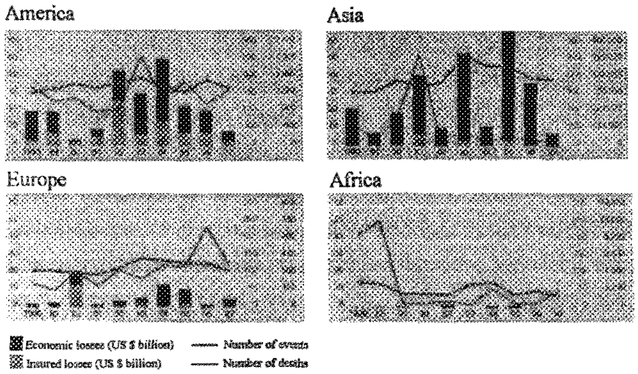

Figure 6: Comparison of disaster statistics for the last 10 years between America, Asia, Europe and Africa (Source: Munich Re., 1998)

There seems to be an inverse relationship between the level of development and loss of human lives in the case of a disaster. About 95 percent of the deaths occur in developing countries, where more than 4.200 million people live. Economic losses attributable to natural hazards in developing countries may represent as much as 10% of gross national product. In industrialised countries, where warning-systems and buildings codes are more sophisticated, it is easier to predict the occurrence of natural phenomena, and to warn people in time. The damages, however, are usually less severe in developing countries, with strictly limited resources. An example of this can be given by comparing the great floods in Bangladesh (1988) which caused the death of 1410 people with the Mississippi flood in the USA in 1993, which only caused about 30 fatalities. However, when we compare the economic losses of the two events, the result are reversed: in Bangladesh a total loss of 1.1 Billion US$ was estimated, while 15.8 Billion US $ in the US.

These statistics illustrate well the importance of hazard mitigation. The International community has become aware of the necessity to increase the work on disaster management. The decade 1990-2000 has been designated the "International Decade for Natural Disaster Reduction" by the general assembly of the United Nations. However, now that we are near the end of the IDNDR, we must conclude that the efforts for reducing the effects for disaster reduction during the last decade have not been sufficient, and have to be enhanced in the next decade.

Information on disasters for each week can be obtained at the following website:
http://www.discovery.com/news/earthalert/earthalert.html

1.4 Disaster Management

One way of dealing with natural hazards is to ignore them. In many areas, neither the people nor the authorities want to take the danger due to natural hazards seriously, due to many different reasons. The last major destructive event might have happened long time ago, and is only remember as a story from the past. People may have moved in the area recently, without having the knowledge on potential hazards. Or it may be that the risk due to natural hazards is taken for granted, given the many dangers and problems confronted with in people's daily lives. Cynical authorities may ignore hazards because the media exposure for their aid supply after the disaster has happened has much more impact on voters than the quit investment of funds for disaster mitigation.

To effectively reduce the impacts of natural disasters a complete strategy for disaster management is required, which is also referred to as the disaster management cycle (see figure 7).

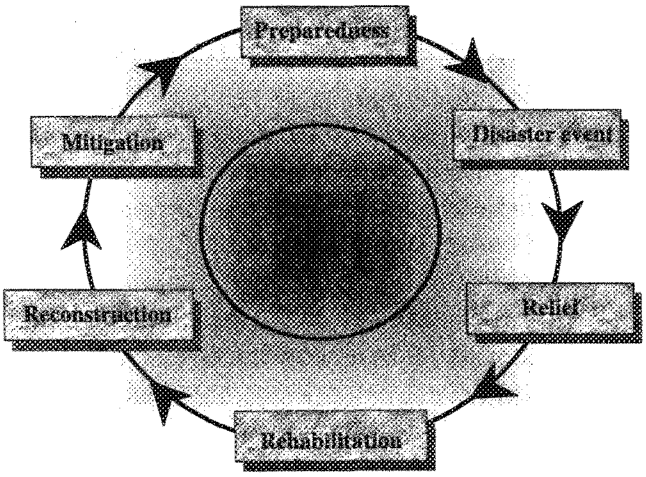

Figure 7: The Disaster Management Cycle

Disaster management consists of two phases that take place before a disaster occurs, disaster prevention and disaster preparedness, a three phases that happen after the occurrence of a disaster, disaster relief, rehabilitation *and* reconstruction.

Disaster management is represented here as a cycle, since the occurrence of a disaster event will eventually influence the way society is preparing for the next one.

Disaster prevention is the planned reduction of risk to human health and safety. This may involve modifying the causes or consequences of the hazard, the vulnerability of population or the distribution of the losses. The following activities form part of hazard mitigation:

- **Hazard assessment:** Determining the type of hazardous phenomena that may affect the area, their frequency and magnitude, and representing on a map which areas are likely to be affected;
- **Vulnerability assessment:** Assessing the degree of loss that these events will cause to population, buildings, infrastructure, economic activities, etc.
- **Risk assessment:** Quantifying the numbers of lives likely to be lost, the number of persons injured, the cost of damage to property and disruption of economic activities caused by the events, and preparation of maps indicating the risk areas.
- **Restrictive zoning:** Implementation of the risk maps in development plans, and development of laws to enforce these plans. Public acquisitions of hazardous areas; removal of unsafe structures; obligatory informing potential buyers of real estate on hazardness of the site; include hazardness in insurance policies of real estate.
- **Protective engineering solutions:** The construction of engineering works to protect the elements at risk from a potentially disastrous event. For example: dikes, floodwalls, slope stabilisation works, erosion control works, cyclone shelters etc
- **Building codes:** The definition of standards for the construction of buildings and infrastructure, so that are able to withstand a disastrous event of a certain magnitude/ intensity. For example: earthquake resistant building codes or the construction of houses on poles in frequently flooded areas.
- **Informing population:** Public information and education on hazards and risks in the area.

Disaster preparedness: All those activities that are intended to be prepared once a disastrous event is going to happen, so that people can be evacuated, protected or rescued as soon as possible. It involves the following activities:

- **Preparation of a disaster plan:** Co-ordination with all emergency services, governmental organisations and the public. Establishing an organisation for emergency operations.

- **Anticipating damage to critical facilities:** Construction of a number of disaster scenarios, in which damage to critical facilities (main roads, hospitals, buildings of emergency organisations, etc.) is anticipated, and the consequences evaluated.
- **Damage inspection, repair, and recovery procedures:** Setting-up procedures for post-disaster damage inspection, and make sure that enough trained personnel are available and that there is a supply of materials to be used in emergency situations.
- **Communications and control centre:** Establish procedures for communication during and after the disaster, with all emergency services, press, and government. Make sure there is enough equipment, and that the equipment will function after the event. Setting up a disaster co-ordination command centre (e.g. Tokyo Metropolitan Disaster Prevention Centre)
- **Disaster training exercises:** Training of personnel of disaster emergency services. Rehearsal of disaster plan with all people involved.
- **Prepare evacuation plans:** Establishing safe sites for disaster shelters, evacuation routes, and the preparation of evacuation maps, in close co-operation with the local population.
- **Informing /training population:** Public information and education on hazards and risks in the area; information about how to prepare for a disaster, and how to react when it happened; information on evacuation procedures.
- **Forecasts/warning/prediction of disasters:** Establishing a natural hazards observatory, a technical centre receiving all kind of scientific data, and whose task it is to do real-time data processing and give forecasts and status reports on disasters to emergency organisations and the public.
- **Monitoring:** Evaluating the development through time of disasters (for example floods)

Disaster relief : The provision of emergency relief and assistance when it is needed and the maintenance of public order and safety. It involves activities, such as:

- **Rapid damage assessment:** Assessment of the severity shortly after the occurrence of a disaster, in order to get a general idea of the scale of the disaster; identify continuing threats to survivors. Later on this is followed by a detailed damage census, during which all damaged buildings will be surveyed.
- **Implementation of disaster response plan:** Starting the disaster co-ordination and command centre; contact and meet with all emergency organisations.
- **Establish communication and infrastructure:** Making sure the basic communication lines for disaster relief co-ordination are working, and establishing main infrastructure (roads, electricity).
- **Search and rescue operations:** Expert personnel, such as medical corps, engineers, police and firemen move in the affected area to search and rescue victims.
- **Evacuation, setting up shelters:** Perform evacuation, on the basis of the evacuation plan, and the current disaster situation; operationalisation of shelters; storage of salvaged properties.
- **Food- and medical supply, disease prevention:** Providing food rations, assuring water supply and sanitation in shelters.
- **Maintaining public order:** Avoiding of looting, making sure no fake-victims arrive from other parts of the country.
- **Mass media coverage:** Arranging logistics for visiting reporters; organisation of press conferences; avoiding of biased news coverage.
- **Co-ordination of international aid:** Making sure that the international financial aid is providing the right materials on the right moment; co-ordination of scientific aid missions.

Rehabilitation and Reconstruction : The provision of support during the aftermath of a disaster, so that community functions can quickly be made to work again. They can be subdivided in the short term Rehabilitation activities and the longer term Reconstruction activities.

- **Repair / Demolition of buildings:** Based on a detailed damage census, structural engineers decide which of the buildings can still be repaired, and which one will have to be demolished.
- **Defining areas of reconstruction:** The areas that have been severely affected by the disaster should be evaluated in detail, to establish the reasons for destruction (due to natural factors, or due to construction type); recommendations should be given whether or not to rebuild in the same area.
- **Reconstruction planning:** Obtaining necessary funds for the reconstruction of the area; return of survivors to the area; planning and construction of improved buildings and infrastructure
- **Improve disaster management plan:** Re-definition of hazard and risk maps; re-definition of building standards:

The reconstruction phase also involves an important aspect of evaluation. The disaster mitigation, preparedness, and relief activities should be critically reviewed. An explanation should be given as to why despite all disaster mitigation efforts, houses that were constructed according to the official building codes, still were collapsed. Or why there were areas affected, that were not indicated in the hazard and risk maps. This will lead to a new phase of adjustment of the disaster mitigation and preparedness plans.

1.5 Hazard, Vulnerability and Risk Mapping

As indicated earlier the assessment of hazard, vulnerability and risk forms a crucial element in disaster mitigation. In this report more emphasis will be given on the various techniques for hazard mapping.

To differentiate between the terms *hazard*, *vulnerability* and *risk*, the following definitions (given by Varnes, 1984) have become generally accepted:

Natural hazard (H): The probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area.

Vulnerability (V): The degree of loss to a given element or set of elements at risk (see below) resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).

Specific risk (Rs): The expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H and V.

Elements at risk (E): The population, properties, economic activities, including public services, etc. at risk in a given area.

Total risk (Rt): The expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon. It is therefore the product of specific risk (Rs) and elements at risk (E): $Rt = (E)*(Rs) = (E)*(H*V)$.

Figure 8: Hazard, vulnerability and risk illustrated using an example of elements at risk (cars, road, people in cars, pipelines) in a landslide area (van Westen, 1993)

Hazards are commonly shown on maps, which display the spatial distribution of hazard classes (hazard zonation). Zonation refers to "the division of the land in 'homogeneous' areas or domains and their ranking according to degrees of actual/potential hazard" (Varnes, 1984). Geohazard zonation requires a detailed knowledge of the geodynamical processes that are or have been active in an area, and on the factors leading to the occurrence of the potentially damaging phenomena. This is considered the task of applied earth scientists, such as geologists, geophysicists, geomorphologists etc.

Vulnerability analysis and the determination of elements at risk requires a detailed knowledge of the population density, engineering characteristics of the infrastructure, and on the value of economic activities. Therefore, the data collection and analysis for these aspects is usually done by specialists from other disciplines, such as urban planning and management, civil engineering, social geography, and economics.

Worked out examples of quantitative risk analysis are still scarce in the literature (Einstein, 1988), because of the difficulties in defining quantitatively both hazard and vulnerability. Hazard analysis is seldomly providing the probability of occurrence of potentially damaging phenomena in a quantitative way. Particularly the time scale is extremely difficult to determine for larger areas, for which the analysis necessarily is more of a qualitative than of a deterministic character. The quantitative determination of probabilities of occurrence requires the quantitative analysis of triggering factors in complex models.

In most cases there is no simple relationship between these triggering factors and the probability of occurrence of geohazards. Therefore, the legend classes used in most hazard maps do only give relative indications, such as high, medium, and low degree of hazard. The tool of GIS provides the possibility to make progress in this field as it allows complex spatial analysis and modelling with large data-sets.

Users of hazard zonation maps are mostly institutions in the public or semi-public sector which are involved in the planning of future landuse, urban and lifeline infrastructure, in the development of renewable and non-renewable natural resources, and in environmental monitoring and management. There still is often a serious gap in the communication between the decision makers in such institutions and the earth scientists working in or for these organisations with the task of hazard assessment. For this reason it is of great importance that any activity for hazard zonation mapping should be preceded by a stage in which the earth scientists and the planners together determine the terms of reference of the mapping activities and such important details as map scale, legend units, etc.

An inherent problem of hazard zonation is the aspect of verification of the produced hazard and risk zonation maps. The resulting maps show anyhow only statistical probabilities for zones in the map area and do now allow for deterministic conclusions about individual sites.

Comprehensive publications or documents on natural hazard assessment, mapping and management with precise methodologies for the different processes are scarce, but presently an increased number of activities are carried out in this field. The readers may be interested in newly appearing publications from many national or international institutions, as the Environment and Climate Program of the European Commission, the Office of Foreign Disaster Assistance of the United States Agency for International Development (OFDA/USAID), the Organisation of American States (OAS), the Overseas Development Administration in London, U.K., the United Nations Disaster Relief Organisation (UNDRO), the United Nations Economic Commission for Latin America (UN/ECLAC), the U.S. Geological Survey, the U.S. Water Resources Council, the World Bank and the World Resources Institute. Also a large number of papers and professional documents is being published by research and educational institutes, by geological surveys, ministries of planning, public works and environmental protection in many other countries in the world.

1.6 RS AND GIS: TOOLS IN DISASTER MANAGEMENT

Mitigation of natural disasters can be successful only when detailed knowledge is obtained about the expected frequency, character, and magnitude of hazardous events in an area. The zonation of hazard must be the basis for any disaster management project and should supply planners and decision makers with adequate and understandable information.

Although, natural disasters have shown in the last decades a drastic increase in magnitude and frequency, it can also be observed that there is a dramatic increase in the technical capabilities to mitigate them. We now have access to information gathering and organising technologies like remote sensing and geographic information systems (GIS), which have proven their usefulness in disaster management.

- First of all, Remote Sensing and GIS provides a data base from which the evidence left behind by disasters that have occurred before can be interpreted, and combined with other information to arrive at hazard maps, indicating which areas are potentially dangerous. Remote sensing data, such as satellite images and aerial photos, allow us to map the variabilities of terrain properties, such as vegetation, water, geology, both in space and time. Satellite images give a synoptic overview and provide very useful environmental information, for a wide range of scales, from entire continents to details of a few metres.
- Secondly, many types of disasters, such as floods, drought, cyclones, volcanic eruptions, etc. will have certain precursors. The satellites can detect the early stages of these events as anomalies in a time series. Images are available at regular short time intervals, and can be used for the prediction of both rapid and slow disasters.
- Then, when a disaster occurs, the speed of information collection from air and space borne platforms and the possibility of information dissemination with a matching swiftness make it possible to monitor the occurrence of the disaster. Many disasters may affect large areas and no other tool than remote sensing would provide a matching spatial coverage. Remote sensing also allows to monitor the event during the time of occurrence while the forces are in full swing. The vantage position of satellites makes it ideal for us to think of, plan for and operationally monitor the event.
- Finally, the impact and departure of the disaster event leaves behind an area of immense devastation. Remote sensing can assist in damage assessment and aftermath monitoring, providing a quantitative base for relief operations.
- After that, it can be used to map the new situation and update the databases used for the reconstruction of an area, and can help to prevent that such a disaster occurs again.

The use of remote sensing has become an integrated, well-developed and successful tool in disaster management in various countries, such as in North America, Europe, Japan, India, and Russia.. These countries have their own earth observation programs, and the requirements for hazard mitigation and monitoring rank high in the planning of new satellites.

Analysis of hazard is a complex task, as many factors can play a role in the occurrence of the disastrous event e.g. an earthquake, or a landslide). The analysis requires a large number of input parameters, and techniques of analysis may be very costly and time-consuming. The increasing availability of computers during the last decades has created opportunities for a more detailed and rapid analysis of natural hazard.

A very powerful tool in the combination of these different types of data are Geographic Information Systems. A geographic information system (GIS) is defined as a "powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes" (Burrough, 1986). Spatial data is data with a geographic component, such as maps, aerial photography, satellite imagery and rainfall data, borehole data etc. GIS allows for the combination of these different kind of data using models.

2. Application of Remote Sensing for Natural Disaster Management

Remote sensing data derived from satellites are excellent tools in the mapping of the spatial distribution of disaster related data within a relatively short period of time. Many different satellite based systems exist nowadays, with different characteristics related to their:

- *Spatial resolution:* the size of the area on the terrain that is covered by the instantaneous field of view of a detector.
- *Temporal resolution:* the revisit time of the satellite for the same part of the earth surface
- *Spectral resolution:* the number and width of the spectral bands recorded.

An overview is presented in figure 9.

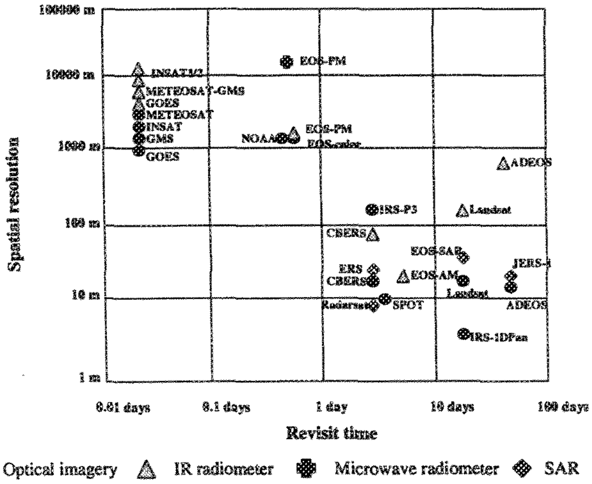

Figure 9: Overview of existing satellite systems that can be used for disaster management. Plotted are the spatial resolution against the revisit time. Partly after ISL (1993).

Besides the use of conventional aerial photographs, which often remain the most useful tools in many types of disaster studies, the application of satellite data has increased enormously over the last decades. After the initial low spatial resolution images of the LANDSAT MSS (60 x 80 metres), LANDSAT is also offering Thematic Mapper images with a spatial resolution of 30 meters (except for the thermal infrared band) and an excellent spectral resolution with 6 bands covering the whole visible and the near and middle infrared part of the spectrum and with one band in the thermal infrared. LANDSAT has an overpass every eighteen days, offering a theoretical temporal resolution of eighteen days, although weather conditions are a serious limiting factor in this respect, as clouds are hampering the acquisition of data from the ground surface. The weakest point of the LANDSAT System is the lack of an adequate stereovision. Theoretically a stereomate of an TM image can be produced with the help of a good digital terrain model (DTM), but this remains a poor compensation as long as very detailed DTM's are not currently available.

The French SPOT satellite is equipped with two sensor systems, covering adjacent paths each one with a 60 kilometres swath width. The sensors have an off-nadir looking capability, offering the possibility for images with good stereoscopic vision. The option for sidewards looking results also in a higher temporal resolution. SPOT is sensing the terrain in a wide panchromatic band and in three narrower spectral bands (green, red and infrared). The spatial resolution in the panchromatic mode is 10 meters, while the three spectral bands have a spatial resolution of 20 meters. The system lacks spectral bands in the middle and far (thermal) infrared. A comparable system to SPOT, although with an even smaller spatial resolution for the panchromatic mode (5.6 meters) is the Indian IRS satellite series (IRS 1B, 1C, 1D, P2, P3) with a variety of sensors which collect information in the optical region with ground resolutions varying from 5 to 188 meters, and revisit times between 5 and 24 days.

Radar satellite images, available from the European ERS, the Canadian Radarsat, and the Japanese JERS, are offering an all weather capability, as the system is cloud penetrating. Theoretically this type of images can yield detailed information on surface roughness and micromorphology, however, the till now applied wavelengths and looking angle have not been very appropriate for the application in mountainous terrain. The first results of the research with radar interferometry are very promising and indicating that detailed terrain models to an accuracy of around one metre can be created, which creates the possibility to monitor slight movements related to landslides, fault-displacements or bulging of volcanic structures.

Remote sensing data should generally be linked or calibrated with other types of data, derived from mapping, measurement networks or sampling points, to derive at parameters which are useful in the study of disasters. The linkage is done in two ways, either via visual interpretation of the image or via classification.

2.1 Characteristics of geological natural disaster types and the role of remote sensing

When we want to describe to usefulness of remote sensing for disaster management, we have to answer a number of questions for each type of disaster (flooding, earthquakes, etc.). These questions can be subdivided into two blocks: how to characterise the disaster (disaster characterisation), and how to observe the features associated with the disaster (disaster observation).

Disaster Characterisation
For each disaster type the following questions need to be answered:

- What is known about their speed of evolution?
- What is their return period?
- What is the area affected?
- What is the nature and extent of damage?
- What is the toll in loss of human life?
- Which forms of preparedness are practical?
- Which forms of mitigation/relief are practised?

Disaster Observation
For each disaster type the following questions need to be answered:

- Which observable features precede the disaster?
- Which observable features accompany the disaster?
- Which observable features can be used to assess the damage?
- In what sense are space observation techniques used in the various phases?
  - Are they main tools or complementary?
  - Are the current techniques adequate?
  - Can these technique be automated?
  - What are the lacks in techniques?
  - What are the requirements of satellite imagery?
  - Spatial resolution, Temporal resolution, Spectral resolution.

In the following paragraphs the answers to these questions will be summarised for a number of different disaster types.

2.2 Flooding

The areas affected by flooding are generally large in size (in the order of 103 - 105 km2). Many different types of flooding exist, with different requirements as to the satellite imagery. In general the following subdivision can be used:

- River floods, which can be seasonal floods related to big rivers, or flash floods in smaller catchments.
- Coastal floods, which can be related to tropical cyclones, or to high tides.

Many factors play a role in the occurrence of flooding, such as the intensity and duration of rainfall, snowmelt, deforestation, poor farming techniques, sedimentation in riverbed, and natural or man made obstructions. In the evaluation of flood hazard, the following parameters should be taken into account: depth of water during flood, the duration of flood, the flow velocity, the rate of rise and decline, and the frequency of occurrence. Satellite data can be used in the phase of disaster prevention, by mapping sequential inundation phases, including duration, depth of inundation, and direction of current. This can be done with automated classification from SPOT, LANDSAT or NOAA images. Furthermore SPOT and LANDSAT TM can be used in the geomorphological mapping of the potential flood area. However, the most crucial data is derived from the calculation of peak discharges and return periods, using data from gauging stations. Radar images (Radarsat, ERS, JERS) have been proven very useful for mapping peak flood inundation areas, especially due to their bad weather capability.

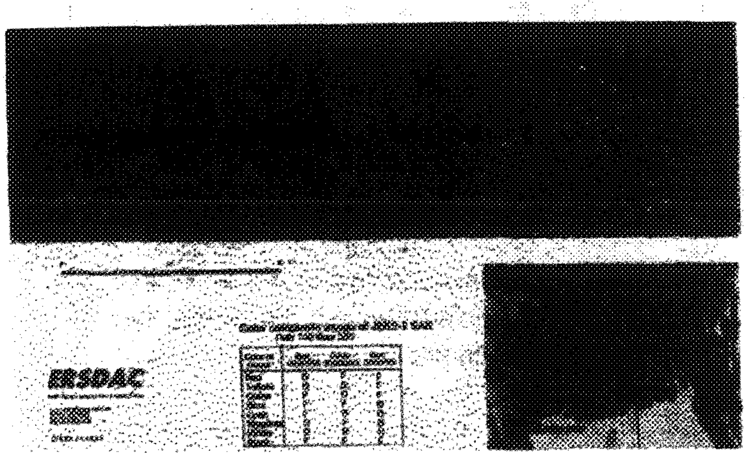

Figure 10: *False colour composite of JERS-1 SAR images providing information on flood inundation areas in Bangladesh (Source: ERSDAC, Japan)*

For the prediction of floods, promising results have been reported recently, on the use of NOAA images, combined with meteorological satellites and radar data, in the calculation of rainfall over large areas. For the monitoring of floods in large catchments, such as in Bangladesh, NOAA images are successfully applied.

For the disaster relief operations, the application of current satellite systems is still limited, due to their poor spatial resolution and the problems with cloud covers. Hopefully, the series of high resolution satellites will improve this.

One-meter pan-sharpened multispectral imagery can be used to measure impervious surfaces, such as roofs, streets, and parking lots. Pervious surfaces, such as tree- and grass-covered areas can also be measured. Applying runoff coefficients to the area of each surface type can provide the best available estimates for non-point source water pollution. By adding parcel boundaries, it is possible to provide estimates of runoff per parcel in order to assess storm sewer fees (Source: earthwatch,1999 http://www.digitalglobe.com/applications/13.html).

Flood boundaries can be measured to within a few meters accuracy in areas without tree cover using submeter multispectral fused imagery. Individual buildings and parcel boundaries can also be identified in order to assess flood vulnerability.

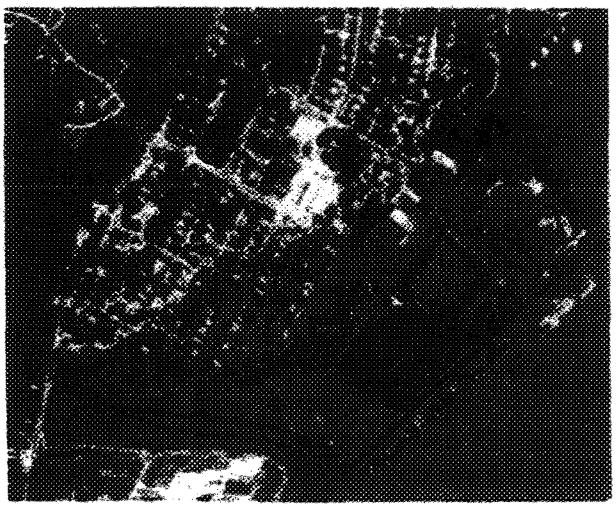

Figure 11: *Four-meter multispectral imagery, sharpened with 1-meter panchromatic, will clearly show flooding outside normal flood line boundaries.*

2.3 Earthquakes

The area affected by earthquakes are generally large (on the order of 102 - 104 km2), but they are restricted to well known regions (plate contacts). Typical recurrence periods vary from decades to centuries. Observable associated features include fault rupture, damage due to ground shaking, liquefaction, landslides, fires and floods. The following aspects play an important role: distance from active faults, geological structure, soiltypes, depth of the watertable, topography, and construction types of buildings.

In the phase of disaster prevention satellite remote sensing can play an important role in the mapping of active faults, using neotectonic studies, with the use of LANDSAT TM/SPOT or radar, and in the measurement of fault displacements, using Satellite Laser Ranging (SLR), Global Positioning System (GPS), or radar interferometry (Figure 12). The most important data for seismic hazard zonation is derived from seismic networks. In seismic microzonation, the use of satellite remote sensing is very limited, as the data is derived from accelerometers, geotechnical mapping, groundwater modelling, and topographic modelling, at large scales.

Earthquakes cannot be predicted with the current state of knowledge, and therefore also satellite remote sensing cannot play a role in the phase of earthquake disaster preparedness.

In the phase of disaster relief, they can only play a role in the identification of large associated features (such as landslides). Structural damage to buildings cannot be observed with the poor resolution of the current systems.

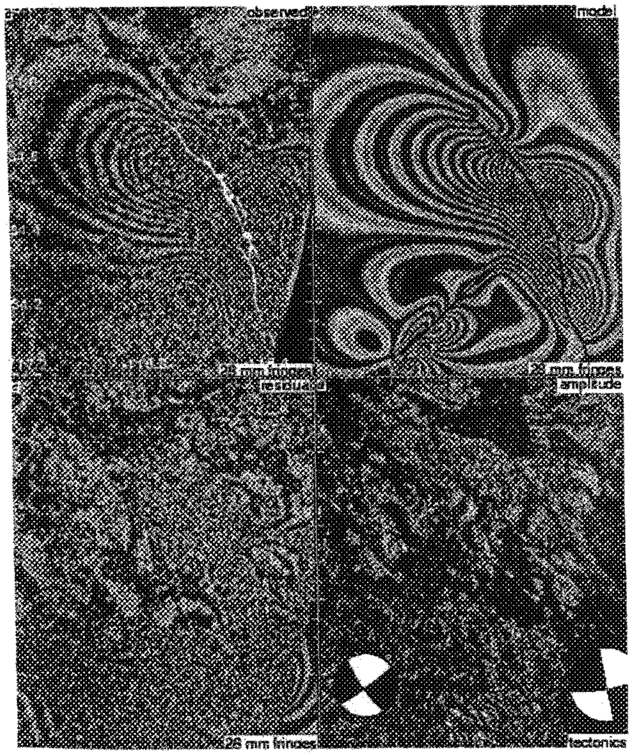

Figure 12. *Landers earthquake. (a) Observed interferogram calculated from ERS-1 SAR images taken before (April 24, 1992) and after (June 18, 1993) the earthquake [Massonnet et al., 1994]. Each fringe in parts a, b and c denotes 28 mm of change in range. The number of fringes increases from zero at the northern edge of the image, where no coseismic displacement is assumed, to at least 20, representing 560 mm in range difference, in the cores of the lobes adjacent to the fault. The asymmetry between the two sides of the fault is due to the curvature of the fault and the geometry of the radar. Black lines denote the surface rupture mapped in the field. The altitude of ambiguity is 220 m. (b) Modeled interferogram with black lines denoting fault patches included in the elastic dislocation model [Feigl et al., 1996]. (c) Residual (observed minus modeled) interferogram. (d) Radar brightness (amplitude) image. (source: http://www.obs-mip.fr/omp/umr5562/groupes/geophy_de_surf/sismo/landers.html)*

2.4 Tsunamis

Tsunamis are sea waves due to large-scale sudden movement of the ocean floor during earthquakes, volcanic eruptions, bombs or man-made explosions. Unknown in the Atlantic ocean since 1918, tsunamis are among the main natural hazards along the coasts of the Pacific. The tsunami waves travel at very high speeds in deep ocean waters, as much as 900 km/hour, with very long distance (as much as 500 km) between wave crest, and very low heights (around one meter) until the waves approach shallow water. There speed decreases and the wave height increases very rapidly, reaching 25 m or even more. The time interval between waves remains unchanged, usually between 15 minutes and one hour. The damages in the coastal zones, not only the shore line, are very high over long distances of hundreds or a thousand kilometres. When tsunamis reach the coastline, the ocean recedes to levels around or lower than the low tide and then rises as a giant destructive wave. Details about tsunami hazard can be found in Heyman et al., OAS/DRDE, 1990.

The tsunami hazard zonation is effectively helped by a geomorphological interpretation of the coastal lowlands, whereby a zonation in terrain units on the base of their height above mean sealevel is the primary objective. Such an interpretation can be executed successfully on satellite imagery. Stereo SPOT images and the landuse pattern as obtained from the interpretation of Landsat TM are the main information sources. The terrain "roughness" is the parameter that influences the depth of inland penetration of a tsunami. Vegetation (e.g. mangrove forest) is one of the most important factors influencing the terrain roughness. Also this observation is obtained from the interpretation of Landsat TM imagery.

2.5 Volcanic Eruptions

The areas affected by volcanic eruptions are generally small (< 100 km2), and restricted to well known regions. The distribution of volcanoes is well known, however, due to missing or very limited historical records, the distribution of active volcanoes is not (especially in developing countries). Many volcanic areas are densely populated. Volcanic eruptions can lead to a large diversity of processes, such as explosion (Krakatau, Mount St. Helens), pyroclastic flow (Mt. Pelee, Pinatubo), lahars (Nevado del Ruiz, Pinatubo), lava flows (Hawaï, Etna), and ashfall (Pinatubo, El Chincon). Volcanic ash clouds can be distributed over large areas, and may have considerable implications for air-traffic and weather conditions. Satellite remote sensing can be used in the phase of disaster preparedness in the mapping of the distribution and type of volcanic deposits, using Landsat TM, SPOT, or Radar. For the determination of the eruptive history other types of data are required, such as morphological analysis, tephra chronology, and lithological composition. Volcanic eruptions occur within minutes to hours, but are mostly preceded by clear precursors, such as fumarolic activity, seismic tremors, and surface deformation (bulging). The thermal band of LANDSAT TM can be used to monitor the thermal characteristics of a volcano, and radar interferometry in the measurement of surface deformation. NOAA-AVHRR data can be used to monitor monitoring lava-flows or ash plumes. Meteosat, GOES or TOMS (Nimbus-7) can be used to monitor the extent of volcanic ash clouds and the SO_2 content.

The development of predictive capabilities to determine when and where volcanic activity could endanger human populations will be aided greatly by EOS observations and models. Improved knowledge of landforms and land use in the vicinity of known volcanoes will help plan for evacuation or disaster relief in active regions. EOS investigators will test the potential for volcano alarm systems based on daily observations from space.

Volcanoes differ from other natural hazards because they are in fixed geographic locations. This is an important advantage for most remote sensing applications because for this application the whole world does not have to be imaged, only the volcanoes and their flanks. This spatial advantage is mitigated by the fact that the timing of eruptions is erratic and long reposes occur. During these repose periods remote sensing is less effective, because little change can be detected. Vegetation covers the slopes of many volcanoes quickly during a repose period, masking the differences in texture, composition and other characteristics which serve to delineate volcanic units at active volcanoes with unvegetated slopes.

The major applications of remote sensing in volcanic hazard assessment are: 1) monitoring volcanic activity & detecting volcanic eruptions , 2) identification of potentially dangerous volcanoes, especially in remote areas and 3) mapping volcanic landforms and deposits (Mouginis-Mark and Francis, 1992).

For the (detailed to semi-detailed) mapping of volcanic landforms and deposits, the conventional interpretation of stereo aerial photographs is still one of the best known techniques. The stereo image does not only give a good view of the different lithologies and the geomorphological characteristics of the volcanic terrain, but it can also be used for delineating possible paths of different kinds of flows.

The wide range of remote sensing systems which are available and can be used in volcanic hazard assessment are characterised by different spectral, spatial and temporal resolutions.

For the monitoring of volcanic activity a high temporal resolution is an advantage. For the identification of different volcanic deposits a high spatial resolution and, to a lesser extent, also a high spectral resolution are more important.

Active volcanoes make spectacular remote sensing targets because a variety of phenomena that are not common in the typical environment at the earth's surface can be found:

Thermal Applications

Hot areas, e.g., lavas, fumaroles and hot pyroclastic flows can be mapped and enhanced using Thematic Mapper data. Actively erupting volcanoes typically have hot areas that can be detected by satellite sensors. Typical maximum temperatures are on the order of 600 to 900 degrees Celcius, and the pattern of thermal anomalies is different on each successive image. The Landsat thematic mapper (TM) provides 30 m ground resolution in six spectral bands (3 visible, 1 near infrared and 2 mid infrared) and 120 m ground resolution in one band (band 6) of thermal infrared.

Band 6 can be used to demonstrate differences in activity which affect larger anomalies such as active block lava flows. For smaller and hotter (>100 C) anomalies the thermal infrared band can be saturated but other infrared bands can be used. Active dome extrusion and fumarolic activity may produce dual band signals (usually bands 5 and 7 of TM) which can be used to retrieve the temperatures of subpixel thermal features, (Rothery et al.,1988) and this subpixel information may be very useful in the interpretation of thermal anomalies (Frances,P. and Rothery D, 1987); (Oppenheimer,C. 1991). Uehara and others (1992), used airborne MSS (1.5m resolution) to study the thermal distribution of Unzendake volcano in Japan to monitor the lava domes causing pyroclastic flows when collapsed.

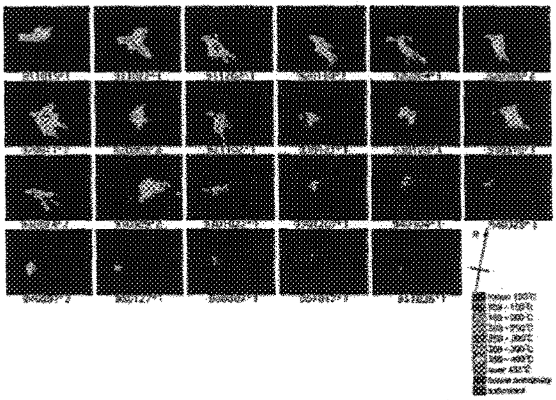

Figure 13: Temperature distribution of Unzen Volcano derived from nighttime Landsat TM band 7 from October 1991 through October 1995.
(source: http://www.gsj.go.jp/~urai/volcano/volce.html)

Measurement of Ash Clouds

Clouds and plumes of volcanic ash and volcanic gases are very different from ordinary meteorological clouds. Volcanic clouds may be detected by sensors that measure absorption by gases in the cloud such as TOMS (Krueger, A. et al, 1994) or TIMS (24) , by infrared sensors such as AVHRR (Wen, S. and Rose, W, 1994) or HIRS which detect particles in semitransparent drifting clouds, by comprehensive sensors such as TM which can detect both opaque and transparent clouds with a resolution of about 30 m, and by microwave or radar sensors such as SSM/I , which can detect only large active eruption columns or very young (<1 hr old) clouds.

Classification of fresh, unvegetated rock surfaces These are found over much of an active volcano and represent the areas covered by recent volcanic materials. They contrast sharply with vegetated terrain that typically occur in nearby nonvolcanic areas. One of the most useful aspects of remote sensing is the ability of the visible and infrared radiation to discriminate between fresh rock and vegetated surfaces. This is useful because vegetation quickly develops on all areas except those disturbed by the volcano or other causes (urban development, etc). Fresh rock surfaces are found on all the active parts of the volcano, and they become vegetated as activity no longer affects certain areas. So the spectral characteristics of volcanoes vary from being very similar to surrounding vegetated areas, to the distinctly different responses of bare rock. Fresh rock surfaces are typically found along the river valleys where active sedimentation is occurring, and can continue for many miles from the volcano, portraying the areas of accelerated sedimentation affected by the volcanic activity.

Topographic Applications

The basic description of the topography of a volcano is one of the most important parts of volcanic hazard evaluations, because most volcanic hazards are controlled by gravity and topography where volcanoes are topographic highs which threaten their lower lying surroundings through gravitational potential energy. At all volcanoes, including those in repose, synthetic aperture radar remote sensors can provide valuable data which describes the topography. Topographic data can be used for the formulation of models predicting which path a pyroclastic flow or lahar or any gravity driven hazard may follow. Measurement of ground deformation may eventually be achieved using remote sensing by synthetic aperture radar (SAR) - airborne or space borne mapping over broad areas. The day and night acquisition capabilities and its cloud penetrability offers no hindrance in data acquisition which are necessary for forecasting events. However due to their low spatial resolution, predicting pyroclastic flows from a collapse of lava dome 100m x 200m seems quite difficult (Okamoto,1993).

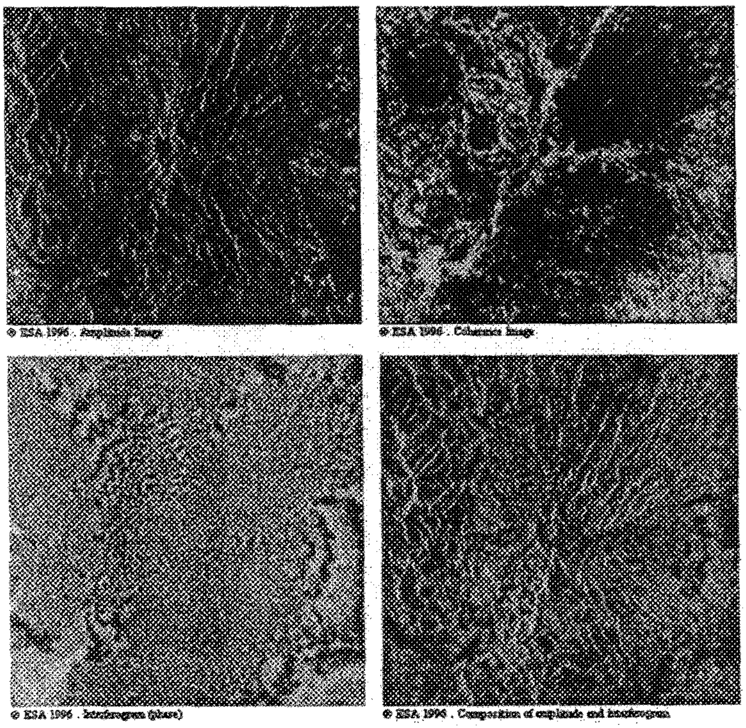
© ESA 1996 . Amplitude Image
© ESA 1996 . Coherence Image
© ESA 1996 . Interferogram (phase)
© ESA 1996 . Composition of amplitude and interferogram

Figure 14 : Interferogram of Mount Pinatubo generated using a tandem pair of ERS images. The amplitude image is shown at the top left, the coherence image top right, and the phase fringes lower left. Over some part of the lahar, high coherence and clear fringes are obtained. In the lower right hand image, the good fringes, representing height contours, are superimposed on the amplitude image.

Each of these four features of the volcanic remote sensing targets is of potential use in hazard mitigation. In addition, repeated topographic surveys to define topographic changes is of critical value.

2.6 Landslides

Individual landslides are generally small (0.001 - 1 km2), but they are very frequent in certain mountain regions. Landslides occur in a large variety, depending on the type of movement (Slide, Flow, Fall), the speed of movement (mm/year - m/sec), the material involved (rock Û soil), and the triggering mechanism (earthquake/rainfall/human interaction).

In the phase of disaster prevention satellite imagery with sufficient spatial resolution and stereo capability (SPOT, IRS) can be used to make an inventory of the past landslides, however, they are mostly not sufficiently detailed to map out all landslides. Aerial photo-interpretation still remains essential. Satellite imagery can also be used to collect data on the relevant parameters involved (soils, geology, slope, geomorphology, landuse, hydrology, rainfall, faults etc.). Digital elevation models can be derived from SPOT or IRS images.

In the phase of disaster preparedness use could be made of the following techniques for the monitoring of landslide movements: ground measurements, photogrammetry, GPS, Radar interferometry. Warning systems for landslides are only operational in a few places in the world, with a vey high density of information (landslide dates as well as daily rainfall should be known in order to establish rainfall thresholds). The use of Meteosat & NOAA for prediction these threshold is being investigated.

The assessment of damage using satellites is only possible if the spatial distribution is very high, or if the individual landslides are large.

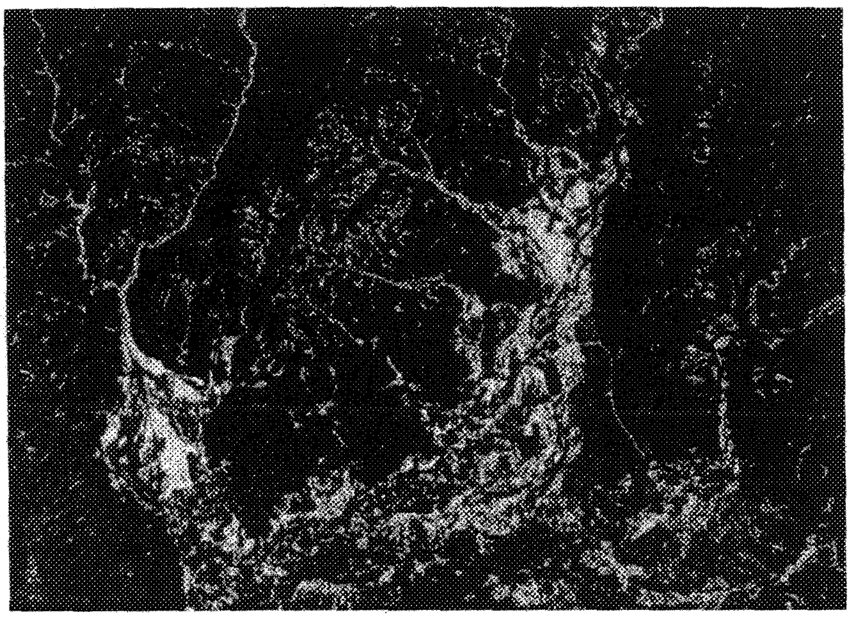

Figure 15 : SPOT false colour composite showing mudslides after major rainstorm event in an area in Thailand.

2.7 WildFires

Due to large-scale human deforestation activities, grassland fires, and naturally occurring wild fires around the world, biomass burning is a major source of greenhouse gases and aerosols. These emission products significantly impact atmospheric chemistry, clouds, and the Earth's radiant energy budget (heat and sunlight) in ways that influence climate on regional and global scales. Also coal fires contribute significantly to the annual CO_2 production.

The most commonly used satellite for monitoring such events are the GOES and AVHRR. The TOMS UV aerosol index is used to map the spatial distribution of the UV absorbing aerosols (*source : http://atmos.uah.edu/~sundar/camerica.html*)
With the recent launch of Tropical Rainfall Measuring Mission (TRMM) program, new remote sensing capabilities now exist to monitor fires, smoke and their impact on the earth-atmosphere system. On the TRMM platform a broadband sensor that measures reflected short-wave radiance in the spectrum between 0.2-4.5 µm called the CERES scanner is used . From the UV part of the electro-magnetic spectrum, all the way to the thermal infrared, a combination of sensors can be used to highlight the different features of the smoke and fire events. Each sensor has its own unique capability. From the spatial, spectral and temporal resolution to the number of overpasses during the day, they can provide useful information on the damage to the ecosystems and the impact of fires on the earth-atmosphere system.

For global fire detection, NOAA-AVHRR images are widely used. AVHRR measures radiation in five spectral channels (0.58-0.68(m, 0.725-1.1(m, 3.55-3.93(m, 10.3-11.3 (m, and 11.5-12.5(m). The mid-infrared channel at 3.7 µm is especially suited to detect fires due to the increased radiant energy from fires as opposed to the background.

For detailed fire assessment Earth observation satellites such as SPOT and Landsat are currently applied to detect and map burned areas by means of images of a vegetation index (NDVI) based on a specific combination of red and near infrared bands, which specially reflects the amount of green vegetation.

Remote sensing images have been widely used to detect fire scars, fire regimes and the regeneration of plant communities. Time series of images are currently used to monitor -through NDVI values- the regeneration process followed by plant communities after forest fires. Regeneration ratios of different plant communities are compared and the effect of other environmental factors on such a process is also studied.

Urban encroachment into natural areas, in conjunction with forest and rangeland fire suppression policies, have increased the frequency and intensity of large-area fires in many portions of the world. Similar to flood events, high spatial resolution imagery can be used before, during, and after a fire to measure fuel potential, access, progress, extent, as well as damage and financial loss.

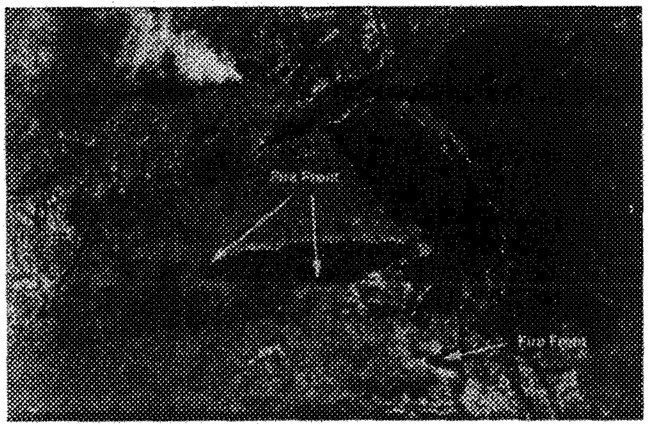

Figure 16: A reduced resolution SPOT image over a site near Collier Bay, Western Australia. Smoke plumes can be seen rising from burning vegetation Zoom-in view of the above image (about 20km by 20km). Black patches are the burnt scar resulting form the bush fire. A few active fires (fire still burning) are also visible (as indicated)
(source: http://www.crisp.nus.edu.sg/)

2.8 Coal fires

Apart from forest and bush fires, coal fires are one of the largest contributors to CO2 emissions. In 1992 the CO2 emission was estimated to be 2-3% of the world's total. Both large underground coal fires occur under natural conditions, as well as in coal mining regions, caused by spontaneous combustion of coal seams.

Remote Sensing has proven to be a reliable technology to detect both surface and underground coal fires. A combination of satellite based sensors and airborne sensors are required to unambiguously detect and locate coal fires. By doing such remote sensing based detection on a regular basis, new fires can be detected at an early stage, when they are easier/cheaper to put out. Also, such routine monitoring is very efficient for evaluating the effectiveness of the fire fighting techniques being employed, and which can be remedied/changed as a result.

Thermal infrared data from satellites, especially from the Landsat-5 channel have been proven to be very useful. In mountain areas,. The detection of underground coal fires is limited by the non-uniform solar heating of the terrain. To remove these effects, a DEM was used for modelling the solar incidence angle. Night-time TM data are more useful for detection, but are not routinely available. On the other hand, due to the low spatial resolution of the TM thermal data (120x120 m) the best night-time TM thermal data can not detect a coal fire less than 50 m even if they have high temperature anomalies. Thus airborne data for detailed detection are still needed.

For the detection and monitoring of coal fires airborne thermal and Landsat TM data have been successfully applied as well as NOAA-AVHRR, ERS1-ATSR and RESURS-01 thermal data (Van Genderen and Haiyan, 1997)

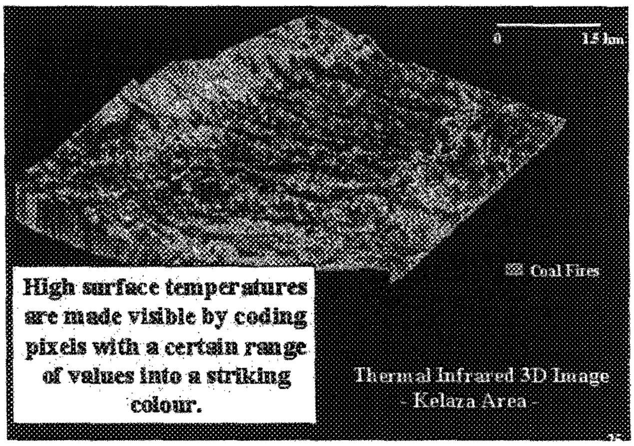

Figure 17:Thermal infrared image of a coal fire area in northern China, shown in 3-D. High surface temperatures are made visible by coding pixels with a certain range of values into a striking colour.
(http://www.itc.nl/ags/data/pdf/posters/graig.pdf)

2.9 Drought and Land degradation

Globally, an estimated 1,965 million ha of land are subject to some kind of degradation. Of this, 1,094 million ha are subject to soil erosion by water, and 549 million ha by soil erosion by wind. An estimated 954 million ha of land are affected by salinity or sodicity or both. (UNEP/ISRIC, 1991). Mulit-temporal Landsat TM, SPOT and IRS imagery has been successfully used for the mapping of eroded lands, salt-affected soils, waterlogged soils, and shifting cultivation areas. Drought warning and monitoring is normally done by measuring the healthiness of vegetation over large areas, using Vegetation Index (VI), which helps in monitoring the photosynthetically active vegetation. A number of vegetation parameters, such as Leaf Area Index (LAI) or biomass, are related with the Vegetation Index. Vegetation needs to be monitored throughout the growing season, and results should be compared with field data, in order to make predictions about the crop yield. The NOAA AVHRR, with a spatial resolution around 1 km2 and revisit time of 12 hours, is the workhorse for drought monitoring and prediction. It is used to generate a time series of Normalised Difference Vegetation Index (NDVI) maps, which is a function of green leaf area and biomass. IRS WiFS sensors on IRS-1C and IRS-1D, with ground reolution of 188 metres, swath of 800 km and revisit time of 5 days is extensively used in India for drought prediction and monitoring (Charkraborti, 1999).

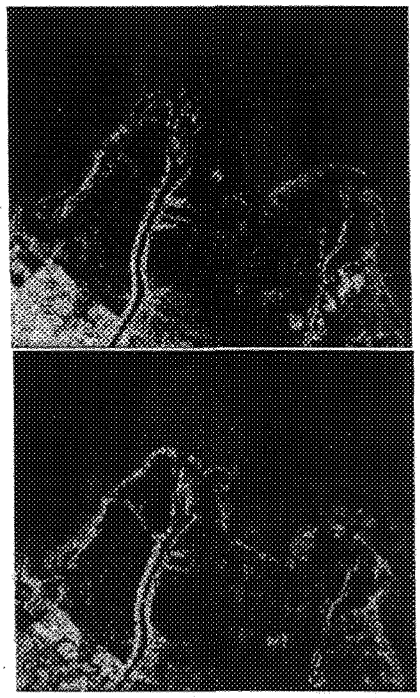

Figure 18: Multitemporal Landsat TM false colour composites showing deltaic growth in the Banten Bay area, Indonesia.

2.10 Coastal Hazards

Multi-temporal remote sensing images are extremely useful in the monitoring of coastal processes, such ad coastal erosion, accumulation, deltaic growth, changes in coral reefs and mangroves. In literature, mostly conventional imagery such as Landsat TM or SPOT is used for this (figure 18)

Accurately locating, identifying, and monitoring coral reefs, seagrass beds, mangroves, salt marshes, chlorophyll, sedimentation, and development activities is greatly facilitated through the use of satellite imagery. Coastal areas can be evaluated for environmental sensitivity and suitability for developing ports, tourist facilities, aquaculture, and fisheries.

Large resolution multispectral imagery can be used for small-scale mapping of wetlands, beaches, submerged vegetation, urbanisation, storm damage, and general coastal morphology. Combined with 1-meter panchromatic imagery, the blue-green band shows water penetration capability. In addition 1-meter imagery shows finer detail, such as sandbars, channels, wave patterns and beach structures

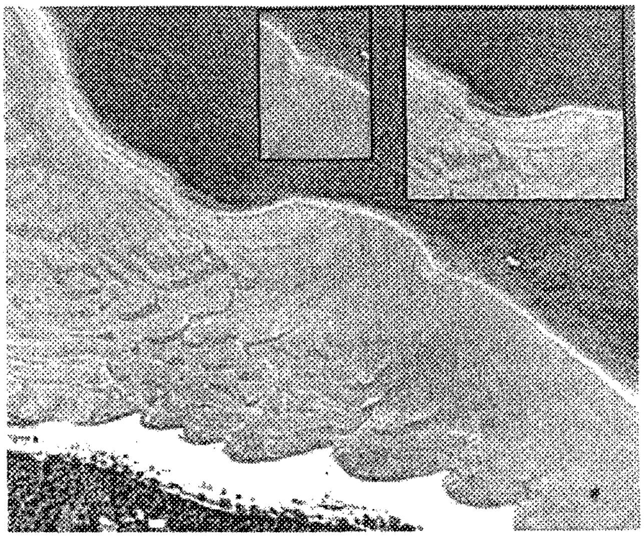

Figure 19: Four-meter multispectral imagery, sharpened with 1-meter panchromatic, (displayed at various zoom levels), will facilitate monitoring coastline conditions and changes. Source: http://www.digitalglobe.com

2.11 Pollution

Hazardous chemical spills:

Surface contamination and effects on the surrounding environment can be detected and monitored with high spatial resolution satellite imagery. Routine monitoring of facilities worldwide that handle or store hazardous chemicals and/ or waste will be possible. Frequent satellite revisits will allow for early detection of contamination events, such as holding tank failures. The satellite imagery can then be used to assess damage and monitor cleanup and recovery .

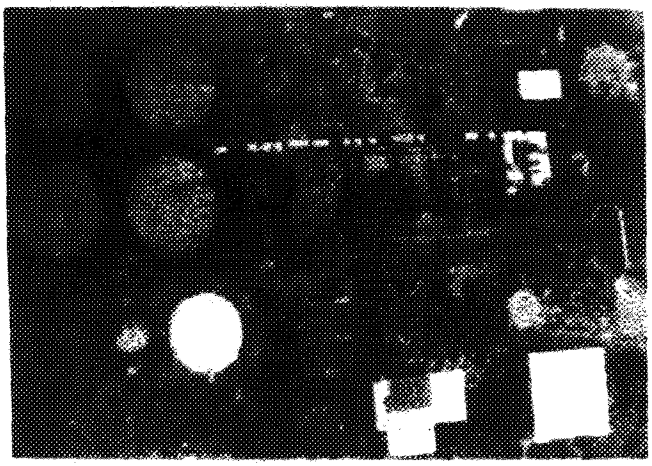

Figure 20 : Four-meter multispectral imagery, sharpened with 1-meter panchromatic, will be capable of showing the effect of contamination due to holding tank failure. (source:http://www.digitalglobe.com/applications/10.html)

Nuclear Accidents

A devastating nuclear accident happened at Chernobyl, Ukraine, on 26 April 1986. This area is near the common borders of Ukraine, Belarus, and Russia (figure 21). The plant lies near the Pripyat River, at the northwest end of a cooling pond. The pond is 12 km long; during normal operation the plant discharges warm water counter clockwise around the pond, taking in cool water near the north end.1 Just northwest of the plant is the city of Pripyat. The smaller town of Chernobyl lies south of the cooling pond.

The 1986 and 1992 images clearly show farm abandonment. Agriculture appears as a collage of bright red (growing crops) and white (highly reflective bare ground). Many of these areas appear a flat tan-green in 1992, indicating natural vegetation which has taken over the abandoned fields. As of 1992, this area remained almost completely abandoned. Among the new features in the 1992 image is a curved white structure north of the Pripyat River. You can see a small amount of water dammed up against it and in the channels behind it. Soon after the accident the Soviets built a series of levees, dams and other structures to prevent contaminated runoff water from entering the rivers and contaminating regional water supplies, especially for the city of Kiev (Frank et al, 1987).

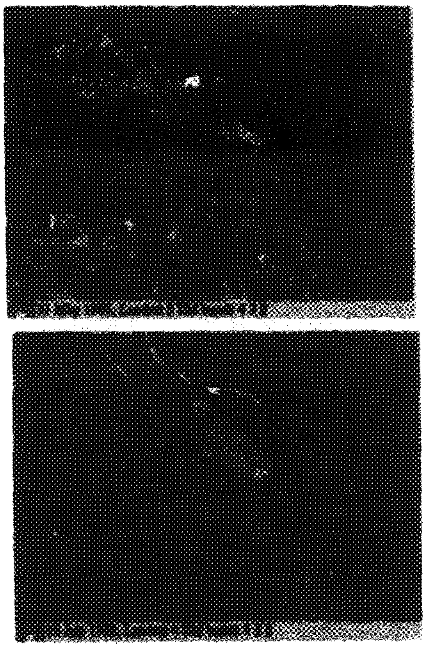

Figure 21: These images show the area around the Chernobyl nuclear power plant approximately one month after the accident, and six years after the accident.

Oil spills in water

Remote sensing can also be used to detect legal and illegal discharges from industrial and municipal facilities into waterways. The surface dimensions of a discharge plume, as well as the source, can be identified and measured if it contains suspended material, such as hydrocarbons, sediments, bubbles, or dye. The effectiveness of containment methods can also be assessed using satellite imagery.

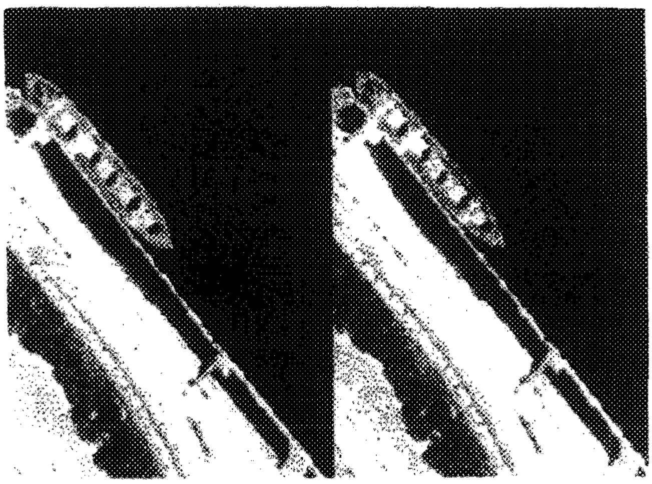

Figure 22:Four-meter multispectral imagery, sharpened with 1-meter panchromatic, will be able to be used to identify and measure the surface dimensions of an oil spill.
(source: http://www.digitalglobe.com/applications/11.html)

Also radar images have been used successfully in the detection of illegal oil spills at sea, which clearly show a different response then water (figure 23)

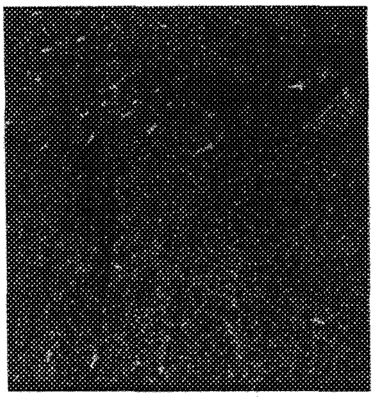

Figure 23: *This figure illustrates a case of oil spill near Singapore in August 1996. A ship near the lower left corner of the image is seen discharging into the sea a plume of oil pollution 5 km in length. With this ERS SAR image acquired by the CRISP receiving station, together with other evidence, the guilty parties were convicted in court and fined a total of S$1.25 million. (Source:*

Air pollution

Accidental airborne releases of toxic chemicals can be detected and monitored with satellite imagery. For example, if the plume from an oil tank fire is visible to the naked eye, satellite imagery can measure the extent and dissipation of the airborne release, as well as pinpoint the source and identify potential areas of impact downwind.

Figure 24: Four-meter multispectral imagery, sharpened with 1-meter panchromatic, will be capable of detecting and monitoring various types of airborne pollutants.
(source : http://www.digitalglobe.com/applications/12.html)

TM images have been used to monitor the huge oil fires in Kuwait during the Persian Gulf war. More than 600 oil wells were ignited during the air and ground war of January-February 1991. The last fire was extinguished on 6 November 1991.

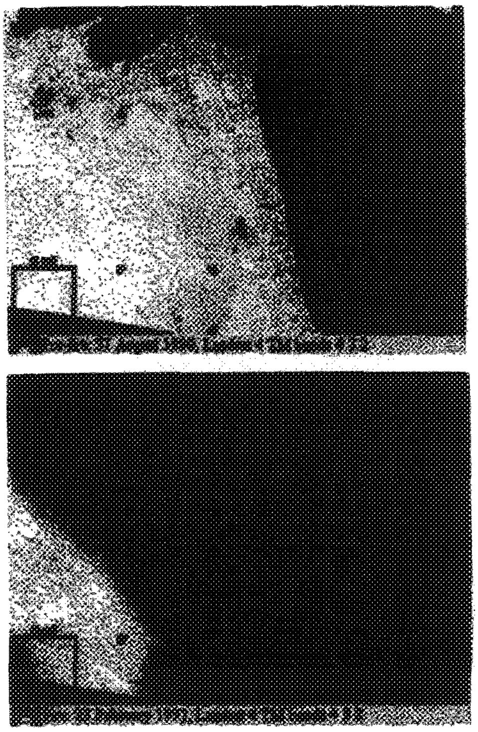

Figure 25: The August 1990 image shows the capital city Kuwait in the upper part of the image. In the February 1991 image the Kuwaiti coastline south of the city is obscured by smoke plumes from burning oil wells. The November 1991 image was acquired after the fires had been extinguished. The results of the oil fires are evident in the black deposits on the land surface, particularly south of Kuwait City (Williams, 1991).
http://edcwww.cr.usgs.gov/earthshots/slow/Kuwait/Kuwait

2.12 Future Satellites for Disaster Management

Within the coming years a wide range of satellites is planned for launching that can have an important

Country	Program	Scheduled Date	Instrument Type	Resolution(m)			Remarks
				P	M	R	
Russia	Kosmos/KVR-1000	1987	Camera	2-3			
India	IRS-1C	1996	P/M	5.8	20		
Canada	Radarsat	1996	R			9	
Japan	ADEOS-1	1997	P	8	16		Lost in 1997
US	TRW Lewis	1997	P/M	5	4		Lost in 1997
US	EarlyBird	1997	P/M	3	15		Lost in 1997
Russia	RESURS-01#4	1997	M			34-525	
NASA/NASDA	TRMM	1997	M/R			2000	
US	GDE	1998	P	1			
India	IRS-1D	1997	P/M	5.8	24, 70		
France	Spot 4	1998	P/M	10	20		
USA/Japan	ADEOS-2	1999	P	8	16		
USA/NOAA	Landsat-7	1999	M		30		
USA/SpaceImaging/EOSAT	Ikonos-1	1999	P/M	1	4		
Ukraine	Sich2/Okean-O#1	1999	R			25	
China-Brazil	CBERS 1	1999					
USA/SpaceImaging/EOSAT	Ikonos-2	1999	P/M	1	4		
USA/Japan	EOS AM-1/Terra	1999	M		15-90		
Europe	ENVISAT	1999	R			30	
USA commercial	Orbview-3	1999	P/M	1	4		
USA, NASA	NMP/EO-1	1999	H		10		315 bands
USA/Commercial	Quickbird	1999	P/M	0.8	4		
USA/Israel	EROS A	1999	P	1.5			
Russia	RESURS-01#5	1998	M		30		
USA/Israel	EROS B	1999	P	1			
India	IRS-P5 (Cartosat)	1999	P/M	2.5			
Argentina	SAC-C	1999	M		35		
India	IRS-P6 (Resourcesat)	2000	P/M	10	23		
USA commercial	Resource21	2000	P	10			
Australia	Aries-1	2000	H				100 bands
US	Orbview-4	2000	P/M/H	1	4		280 bands
China-Brazil	CBERS 2	2002	M		20		
USA NASA	EOS-PM-1	2000	M		250		
Canada	Radarsat 2	2000	R				
Russia	Gemma_Nika_Kuban	2000	Camera		2-5		
USA	Radar1	2001	R			1	
China-Brazil	CBERS 3	2002	P	3			
France	Spot5	2002	P/M	5	10,20		
Japan	ALOS	2003	P/M/R	2.5	10	10	
US	EOS AM-2 /L-8	2004	P/M	10	30		
France	SPOT 5B	2004	P/M	5	10		

Table 6: Overview of recently launched and planned earth observation satellites (sources: several internet sites). Instrument Type: M: Multispectral only , P/M: Panchromatic and Multispectral , P: Panchromatic Only, R: Radar

contribution to disaster management (see table 6).

- One of the important new developments will be the availability within the coming years of satellites with a very high spatial resolution up to 1meter. Currently the IRS-1D satellite has the highest spatial resolution with a panchromatic sensor of 5.6 meters. Several satellites with a 1 meter spatial resolution are planned for 1999 (EarthWatch-Quickbird, Ikonos-1, Orbview-3). High resolution imagery could be used for damage assessment after a disaster. If used in GIS in conjunction with vector data -- such as parcel layers, street names and address ranges -- it is possible to precisely determine which properties suffered the most damage and assess the decrease in value as a result and calculate the affected area. From the outlined polygon, parcel (property) coverage could be overlain to determine which specific properties have been damaged (See figure 26)

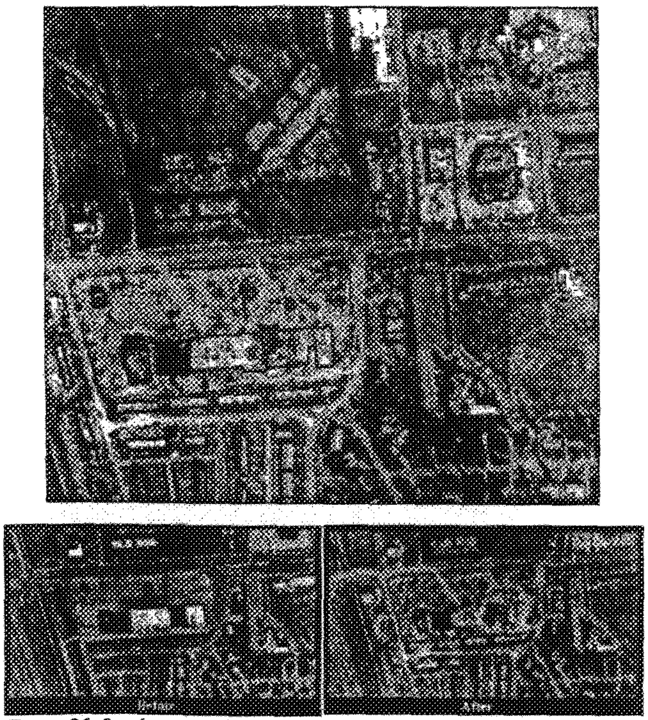

Figure 26: In this one-meter imagery, the buildings with structural damage have been outlined in red. These outlines, or footprints, have been extracted from the pre-tornado image to demonstrate the extent of destruction to buildings.
(Source: http://www.spaceimage.com/home/apps/disaster/post3.html)

- Tropical Rainfall Measuring Mission (TRMM) is NASA's first mission dedicated to observing and understanding the tropical rainfall and how this rainfall affects the global climate. It is a joint mission with the National Space Development Agency of Japan. The primary instruments for measuring precipitation are the Precipitation Radar, the TRMM Microwave Imager, and the Visible and Infrared Scanner. Additionally, TRMM will carry the Lightning Imaging Sensor and CERES (Clouds and the Earth's Radiant Energy System). The system has successfully been applied to measure rainfall amounts during Hurricane Mitch (1998).

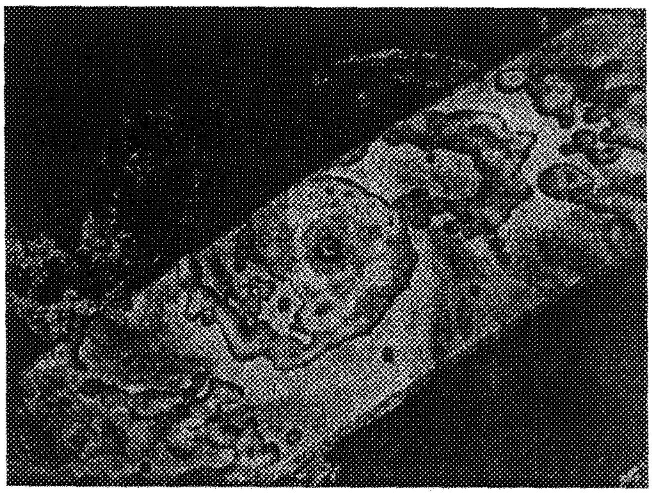

Figure 27: Image derived from TRMM data showing rainfall distribution pattern during Hurricane Mitch (October 1998. Source: http://trmm.gsfc.nasa.gov/latest.html)

- Mission to Planet Earth (MTPE) is NASA's contribution to the U.S. Global Change Research Program (USGCRP), which in turn is embedded within the larger international global change research effort. The Earth Observing System (EOS) is the core of the ambitious MTPE Program. Even though the broader goals of EOS have been scaled back over the years in response to fiscal and other external factors, the program will yield more information on Earth system processes than has ever been achieved previously. Instruments on follow-on spacecraft can and will be changed with technology advances and evolving observational requirements.

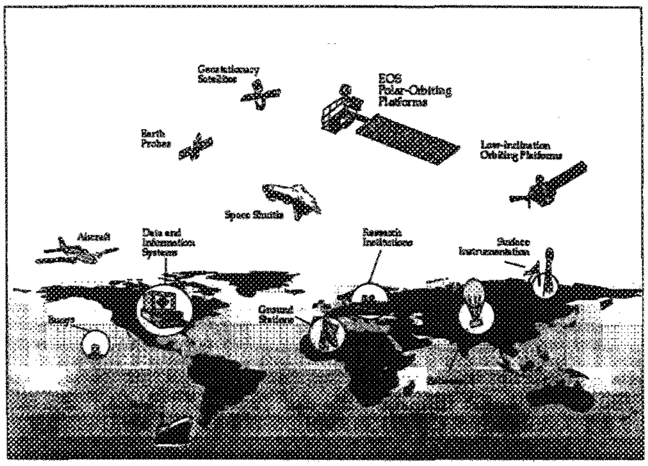

Figure 28: NASA's Mission to planet earth program
(source: http://eospso.gsfc.nasa.gov/sci_strategy/chapter1.html)

The MTPE Program employs a space- and surface-based measurement strategy to provide the scientific basis to address global change. Scientific priorities having been determined and the strategy for addressing them developed, implementation requires launching several suites of instruments into orbit--each designed to accomplish a critical portion of the mission:

- **EOS-AM Series**--Measurement of the diurnal properties of clouds and radiative fluxes and aerosols requires observations in morning and afternoon Sun-synchronous orbits, as well as the inclined orbits provided by TRMM and the EOS-AERO series. In addition, a group of instruments on the morning spacecraft will address issues related to land-atmosphere exchanges of energy, carbon, and water--a task that AVHRR and Landsat address now only qualitatively. The instrument complement will obtain information about the physical and radiative properties of clouds (ASTER, CERES, MISR, MODIS); air-land and air-sea exchanges of energy, carbon, and water (ASTER, MISR, MODIS); total column measurements of methane (MOPITT); and the role of volcanoes in the climate system (ASTER, MISR, MODIS). The U.S. provides CERES, MISR, and MODIS; Canada provides MOPITT; and Japan provides ASTER.
- **EOS-PM Series**--This series' afternoon crossing time will enhance collection of meteorological data by the atmospheric sounders onboard. The instrument complement will provide information on cloud formation, precipitation, and radiative properties through AIRS, AMSU, CERES, MHS/AMSU-B, and MODIS. In concert with vector wind stress measurements from a scatterometer (e.g., SeaWinds on ADEOS II), AIRS/AMSU/MHS, MIMR, and MODIS will provide data for global-scale studies of air-sea fluxes of energy, moisture, and momentum. In addition, AIRS, MIMR, and MODIS will contribute to studies of sea-ice extent and heat exchange with the atmosphere. Flight of this platform during the operational lifetime of TRMM will allow assessment of the utility and accuracy of precipitation estimates, with MIMR and MODIS mapping the extent and properties of snow and its role in the climate and hydrological systems. The U.S. provides AIRS, AMSU, CERES, and MODIS; the United Kingdom provides MHS/AMSU-B; and ESA provides MIMR.
- **EOS-COLOR Satellite**-- Observations of the oceans' color and productivity, with a specific focus on understanding the oceans' role in the global carbon cycle.
- **EOS-AERO Series**-- To optimise collection of occultation data in the equatorial and mid-latitude regions.
- **EOS-ALT Series**-- Investigation of ocean circulation and ice sheets (relevant to sea-level changes) requires accurate altimeter measurements.
- **EOS-CHEM Series**-- Measurements of solar energy flux, solar ultraviolet radiation, and atmospheric temperature, aerosols, and gases.

3. GIS Applications in Natural Disaster Management

3.1 Introduction

Many types of information needed in natural disaster management have an important spatial component. Spatial data, used in GIS, are data with a geographic component, such as maps, aerial photography, satellite imagery, GPS data, rainfall data, borehole data etc. Many of these data will have a different projection and co-ordinate system, and need to be brought to a common map-basis, in order to superimpose them. GIS allows for the combination of these different kinds of spatial data, with non spatial, attribute data, and use them as useful information in the various stages of disaster management, for example:

- In the disaster prevention phase, GIS is used to manage the large volumes of data needed for the hazard and risk assessment;
- In the disaster preparedness phase it is a tool for the planning of evacuation routes, for the design of centres for emergency operations, and for integration of satellite data with other relevant data in the design of disaster warning systems;
- In the disaster relief phase, GIS is extremely useful in combination with Global Positioning Systems (GPS) in search and rescue operations in areas that have been devastated and where it is difficult to orientate
- In the disaster rehabilitation phase GIS is used to organise the damage information and the post-disaster census information, and in the evaluation of sites for reconstruction

The volume of data needed for disaster management, particularly in the context of integrated development planning, clearly is too much to be handled by manual methods in a timely and effective way. For example, the post disaster damage reports on buildings in an earthquake stricken city, may be thousands. Each one will need to be evaluated separately in order to decide if the building has suffered irreparable damage or not. After that all reports should be combined to derive at a reconstruction zoning within a relatively small period of time.

One of the main advantages of the use of the powerful combination techniques of a GIS, is the evaluation of several hazard and risk scenarios, that can be used in the decision-making about the future development of an area, and the optimum way to protect it from natural disasters.

The data required for disaster management is coming from different scientific disciplines, and should be integrated. Data integration is one of the strongest points of GIS. In general the following types of data are required:

- Data on the disastrous phenomena (e.g. landslides, floods, earthquakes), their location, frequency , magnitude etc.
- Data on the environment in which the disastrous events might take place: topography, geology, geomorphology, soils, hydrology, land use, vegetation etc.
- Data on the elements that might be destroyed if the event takes place: infrastructure, settlements, population, socio-economic data etc.

3.2 GIS for Different Application Levels

The amount and type of data that has to be stored in a GIS for disaster management depends very much on the level of application, or the scale of the management project.

Natural hazards information should be included routinely in development planning and investment project preparation. Development and investment projects should include a cost/benefit analysis of investing in hazard mitigation measures, and weigh them against the losses that are likely to occur if these measures are not taken (OAS/DRDE, 1990). GIS can play a role at the following levels:

- **National Level**

At a national level, GIS can provide useful information, and create disaster awareness with politicians and the public, so that on a national level decisions are taken on the establishment of (a) disaster management organisation(s). At such a general level, the objective is to give an inventory of disasters and the areas affected or threatened for an entire country. The detail will be low, as the assessment is mostly done on the basis of general applicable rules. Mapping scales will be in the order of 1:1,000,000 or smaller. The following types of information should be indicated:

- Hazard-free regions suitable for development;
- Regions with severe hazards where most development should be avoided;
- Hazardous regions where development already has taken place and where measures are needed to reduce the vulnerability;
- Regions where more hazard investigations are required.
- National scale information is also required for those disasters that affect an entire country (drought, major hurricanes, floods etc.) In figure 29 an example of such information is given from Hurricane Mitch in 1998, which affected large parts of Honduras, Guatemala, El Salvador and Nicaragua.

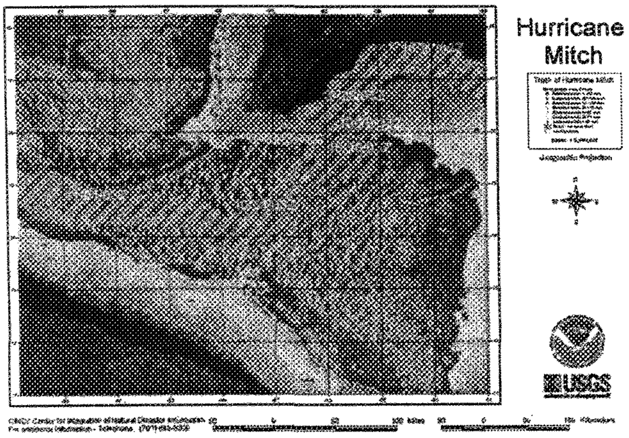

Figure 29: Example of hazard information on national / or even international level. The track of Hurricane Mitch in October-November 1998, affected large parts of central America. A GIS data base was constructed by the U.S. Geological Survey's Centre for Integration of Natural Disaster Information (CINDI) together with other governmental and private industry partners.

(source: http://www.cindi.usgs.gov\events\mitch\cent_amer.html)

- **Regional Level**

At regional levels the use of GIS for disaster management is intended for planners in the early phases of regional development projects or large engineering projects. It is used to investigate where hazards can be a constraint on the development of rural, urban or infrastructural projects. The areas to be investigated are large, generally several thousands of square kilometres, and the required detail of the input data is still rather low. Typical mapping scales for this level are between 1:100,000 and 1:1,000,000. Synoptic earth observation is the main source of information at this level, forming the basis for hazard assessment. Apart from the actual hazard information, also environmental and population and infrastructural information can be collected at a larger detail than the national level. Therefore, the GIS can be utilised more for analysis at this scale, although the type of analysis will mostly be qualitative, due to the lack of detailed information.

Some examples of GIS applications at the regional level are:

- Identification of investment projects and preparation of project profiles showing where hazard mitigation measures (flood protection, earthquake resistant structures) must be taken into account in the design.
- Preparation of hazard mitigation projects to reduce risk on currently occupied land.
- Guidance on land use and intensity (OAS/ DRDE, 1990)

- **Medium Level**

At this level GIS can be used for the prefeasibility study of development projects, at a inter-municipal or district level. For example for the determination of hazard zones in areas with large engineering structures, roads and urbanisation plans. The areas to be investigated will have an extend of a few hundreds of square kilometres and a considerable higher detail is required at this scale. Typical mapping scales are in the order of 1:25,000-1:100,000. Slope information at this scale is sufficiently detailed to generate Digital Elevation Models, and derivative products such as slope maps. GIS analysis capabilities for hazard zonation can be utilised extensively. For example, landslide inventories can be combined with other data (geology, slope, land use) using statistical methods to provide hazard susceptibility maps.

The detail should be such that adjacent slopes in the same lithology are evaluated separately and may obtain different hazard scores, depending on characteristics, such as slope angle or form and type of land use. Within the same terrain unit distinctions should be made between different slope segments.

- **Local level (1:5,000 - 1:15,000)**

The level of application is typically that of a municipality. The use of GIS at this level is intended for planners to formulate projects at feasibility levels. But it is also used to generate hazard and risk map for existing settlements and cities, and in the planning of disaster preparedness and disaster relief activities.
Typical mapping scales are 1:5,000 - 1:25,000. The detail of information will be high, including for example cadastral information. The hazard data is more quantitative, derived from laboratory testing of materials and in-field measurements. Also the hazard assessment techniques will be more quantitative and based on deterministic/ probabilistic models.
This scale is also meant to evaluate the variability of a safety factor as function of variable slope conditions or under influence of triggering factors, such as rainfall and seismicity. The size of area under study is in the order of several tenths of square kilometres and the hazard classes on such maps should be absolute, indicating the probability of occurrence for mapping units, with areas down to one hectare or less.

- **Site-investigation scale (> 1:2,000)**
  At site-investigation scale GIS is used in the planning and design of engineering structures (buildings bridges, roads etc), and in detailed engineering measures to mitigate natural hazards (retaining walls, checkdams etc). Typical mapping scale are 1:2,000 or larger. Nearly all of the data is of a quantitative nature. GIS is basically used for the data management, and not for data analysis, since mostly external deterministic models are used for that. Also 3-D GIS can be of great use at this level.

Although the selection of the scale of analysis is usually determined by the intended application of the mapping results, the choice of a analysis technique remains open. This choice depends on the type of problem, the availability of data, the availability of financial resources, the time available for the investigation, as well as the professional experience of the experts involved in the survey.
In the remainder of this section we will concentrate on the application of GIS for hazard assessment. For a treatment of other phases of disaster management, the reader is referred to Cova (1999).

3.3 Hazard Assessment: General Aspects

Geohazard zoning can be defined as the mapping of areas with the equal probability of occurrence of a particular geohazard within a specified period of time (Varnes, 1984). The hazard zonation consists mostly of two different aspects:

- The susceptibility or the vulnerability of the terrain for a particular type of geologic hazard. The susceptibility of the terrain expresses the likelihood that such a phenomenon occurs under the given terrain conditions or parameters, while the vulnerability of the terrain expresses the probable reaction of the terrain, given certain parameters or terrain conditions, on a hazardous event.
- The determination of the probability that a triggering event occurs. The probability of occurrence is mostly evaluated by calculating the probability of triggering events, such as major rainfall events, the recurrence frequency of earthquakes with a certain magnitude, the recurrence of exceptional high water discharges, etc.

It is important to realise that the calculation of the probability of a hazard to occur is more complicated for certain hazard (landslides, avalanches) than for other geohazards (earthquakes, floods). Since there are not always simple relationships between the occurrence of a particular hazard (e.g. landslide) and the related triggering event. Also the scarcity of reliable historic data is a complicating factor in the establishment relations between triggering events and terrain vulnerability in particular and in geohazard zonation in general.

The joint analysis of the terrain parameters defining the vulnerability of the system and the complex of factors defining the spatial variation in the intensity of the triggering factor, has gained enormously by the introduction of Geographic Information Systems. GIS proved to be the ideal tool for the joint analysis of parameters with a high degree of spatial variability.

Hazard assessment methods can be classified in different ways:

- **Direct mapping** methodology is the experience driven applied geomorphological approach, where the earth scientist evaluates the direct relationship between the hazard and the environmental setting (geomorphological, geological, hydrological) during the survey at the site of the hazard event. A hazard classification is made on the basis of the expert opinion. GIS is generally not used as analysis tool, but merely as data management tool.
- **Indirect mapping** methodology, which consists of the mapping of a large amount of parameters and the (statistical or deterministic) analysis of all these possible contributing factors in relation to the occurrence of the hazard phenomena. Based on the results of this analysis predictions for future hazards are made. GIS is extensively used in this method in a number of standardized (automated) analysis.

  Another useful division in techniques for assessment of slope instability hazard is given by Hartlen and Viberg (1988), who differentiate between relative hazard and absolute hazard assessment techniques.
- **The relative hazard** assessment techniques differentiate the likelihood of occurrence of hazard events for different areas on the map, without giving exact values.
- **Absolute hazard** maps display an absolute value for the hazard, such as a factor of safety or a probability of occurrence.

A third classification of hazard assessment techniques is (Carrara, 1983; Hartlen and Viberg, 1988):

- **White box models**, based on physical models (slope stability and hydrological models), also referred to as deterministic models;
- **Black box models**, not based on physical models but on statistical analysis;
- **Grey box models**, based partly on physical models and partly on statistics.

Many types of hazards (landslides, debris flows, pyroclastic flow, lava flows, snow avalanches etc.) involve the effect of gravity. The component of gravitational acceleration parallel to the slope of the local surface is the key factor in determining the state of slope stability and flow under gravity on that slope (Wadge, 1988). Detailed topographic information can be obtained from a Digital Elevation Model (DEM). The use of DEMs in a GIS offers potentials for studying the problems of slope instability and gravity flow kinematics.

Many of the processes should be studied by evaluating their motion, and the extend to which they reach (runout distance) in contrary to studying their stability, as is the case in landslide studies. As a consequence, their exist two types of models: static models and dynamic models. Many processes, such a debris flows, floods, pyroclastic flows and lava flows require dynamic models.

Raster-based locational information is the obvious choice of data for a system concerned with gravity flows based on DEMs.

Traditionally, Geographic Information Systems are used to overly information on a pixel by pixel basis: called map overlay. However, dynamic models require so called neighbourhood operations, which allow to evaluate the characteristics of an area surrounding a specified location. These operations make use of a small calculation window (e.g. of 3 by 3 cells) which does the same calculation for every pixel in the map, taking into account the values of its neighbours. For many operations, an iterative procedure is required, in which the calculation window, after finishing the calculation for the last pixel in the last line, will start a reverse operation, for which the input data of the previous run are used. The calculation will be repeated several times until no more changes occur in the map.

3.4 GIS in Volcanic Hazard Assessment

The classical volcanological studies have been conducted along two main streams:

- By using the traditional geological mapping methods, in order to understand the eruptive history of a volcano, determine the extent of the various volcanic deposits, and to define the main eruption types.
- By using geophysical and geochemical methods to identify changes in the activity of a volcano, and analyse precursory evidences of an eruption.

Good overviews exist of the various methods in publications such as the one from Tilling (1989) and Crandell et al (1984). The majority of the traditional volcanological studies resulted in qualitative hazard maps.

In order to determine the hazard of an area, three principal problems have to be solved:

- Where is the most probable zone in which an eruption may occur?
- What is the probability of an eruption within a predefined time period?
- What will be its magnitude and which area will be affected?

The assessment of volcanic hazards using GIS is a relatively new approach. Wadge and Isaacs (1988) used GIS techniques to simulate the effects of a wide variety of eruptions of the Soufriere hills volcano, on Montserrat. A similar approach was used by Kesseler (1995) for two active volcanoes on the island of Vulcano (Italy). They applied the energy line concept (Malin and Sheridan, 1983) to model energy losses due to pyroclastic flows. The height of the collapsing eruption column is the main unknown parameter in this analysis. In three dimensions, the energy line becomes a cone, whose apex is the eruption column vertically above the vent. The cone is modelled and compared with a Digital Elevation Model in order to find the potentially affected area.

This method is appropriate for gravity flows in which the flowing material behaves as cohesionless grains. Real pyroclastic flows may depart form this assumption, due to changes in rheologic behaviour, channelisation of the flow and the fact that the eruption column may not be vertical. Other work on modelling pyroclastic flows can be found in Valentine and Wohletz (1989), and Dobran et al. (1994). Denlinger, 1987, also modelled the generation of ashclouds by pyroclastic flows from the 1980 eruption of Mt. St. Helens.

For evaluating the hazard to pyroclastic falls, Kesseler (1995) applied a ballistic model in GIS, which makes use of the following parameters: (1) ejecting velocity, (2) ejecting angle, (3) the form of the block, and (5) the friction coefficient with respect to the atmosphere (Fudali and Melson, 1970). For different scenarios this model comes down to the application of distance buffers.

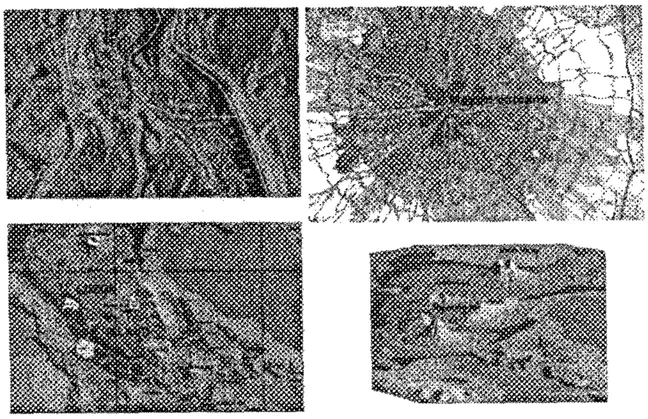

Figure 30: Application of GIS for the creation of a volcanic database for the Mayon volcano, Philippines (source: Daag and Van Westen, 1994)

For the evaluation of potential tephra fall thickness GIS can be used in combination with statistical data on the prevailing wind directions, wind speeds at different altitudes. Carey and Sparks (1986) presented quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Macedonio and others (1988), Armeti and others (1988) made computer simulations for the 79AD Plinian Fall of Mt. Vesuvius, and the 1980 tephra transport Mt. St. Helens, respectively.

According to the method as proposed by Kilburn (1983) the probability of lava inundation is proportional to the probability of an eruption within the catchment within the time period of interest, reduced by the probability that any lava flow from such an eruption will reach that area. It is more direct to estimate probability of inundation by lava flow directly from the frequency of lava flows which have inundated the region of interest in the past (Kauahikaua, 1995). The estimation of the recurrence interval is the most crucial step (Wickman, 1966; Klein, 1982). The method is only applicable if a good historic record of lava flows exist. GIS can be used to map the lava flows from different periods.

An example of deposit and geomorphological maps of the Mayon volcano in the Philippines is shown in figure 30. Deposits were mapped using aerial photos, satellite imagery and ground investigations, and entered in a GIS by digitising. The deposit maps show eruption events from multi-date RS data as well from existing reports. Owing to the general cyclicity of events in terms of recurrence and magnitude of the eruptions, these maps can be used to delineated the general extent of hazards. Note that these are purely deposit maps and extra buffers zones should be considered especially when delineating hazards from flows (lava, pyroclastic and lahar flows) which tend to extend further from the existing deposit maps.

The eruption of the Pinatubo Volcano on June 15 1991 deposited approximately 5 to 7 km3 of pyroclastic materials. The pyroclastic flow deposits affected eight major watersheds around the volcano and radically altered the hydrological regimes, leading to unprecedented amounts of erosion and sediment delivery in the form of destructive lahars. The rapidly changing geomorphology of the watersheds before, during and 3 consecutive years after the eruption was investigated by Daag and Van Westen (1994). To quantify the volumes of pyroclastic flow material and the yearly erosion, five digital elevation models (DEM) were made, and analysed using a geographic information system (GIS).

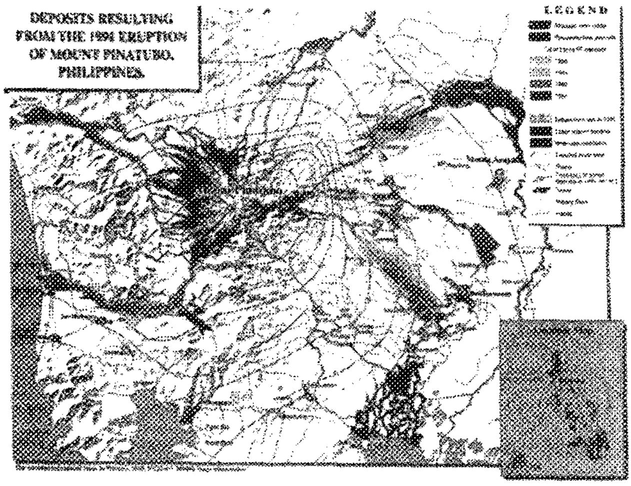

Figure 31: GIS generated map of the hazards associated with the eruption of Mount Pinatubo. Indicated are the isopachs of ash thickness, the location of pyroclastic flow deposits (red), and lahar deposited during 4 consecutive years (Source: Daag and Van Westen, 1994)

The development of a lava flow depends on many factors, such as the volume and continuity of the eruption, the rheological characteristics of the magma and the surface topography (Hulme, 1974; Dobran et al., 1990). The use of computational methods for the solution of differential equations regarding lava flows is very difficult, considering the particular complexities arising, when lava, while solidifying during emplacement, may range rheologically from approximately Newtonian liquids to brittle solids.

Several approaches have been made to model lave flows quantitatively.

Examples of lava flow modelling can be found in Ishihara et al (1989), Young and Wadge (1990), Wadge et al (1994), Macedonio and Pareschi (1992) and Gomez (1995).

For indicating potential dangerous areas for lava flows, Kesseler (1995) used simple combination rules in GIS to identify areas that may be subjected to lava flows. As factors he used the distance from the potential eruption point, the slope of the terrain (classified in classes below 5 degrees, between 5 and 15 and above 15 degrees), and the slope direction.

Gomez (1996) used a model of maximum slope angle for the determination of lava flows. In this simplified model it is assumed that the topography is the most important parameter in the determination of potential lava flow areas. From the pixel, representing the eruption point, it is assumed that the lava flow can move in the direction of any of its 8 neighbouring pixels. The probability that a lava flow will move to a neighbouring pixel is considered proportionally to the altitude difference between the central pixel and its neighbour. A Monte Carlo model is applied that calculates lava flow paths many times. The pixels that are traversed most times by the lava flow trajectories are considered as high hazard areas. To avoid that the lava flow extends eternally a maximum length of lava flow was assumed.

A more complex and accurate method is known as the Cellular Automata method (Barca et al., 1993, 1994; Crisci et al., 1996). A Cellular Automata can be considered as a large group of cells with equal dimensions. Each of these cells receives input from its neighbouring cells, and gives output to its neighbours at discrete time intervals. For lava flow modelling, each cell is characterised by specific values (the state) of the following physical parameters: altitude, lava thickness, lava temperature and lava outflow towards neighbouring cells. With this method the interaction of several lava flows in the same can be modelled. Promising results were obtained for the Etna lava flows from 1991-1993.

The application of GIS for the numerical modelling of debrisflows and lahars also presents many difficulties, similarly to lava flow modelling. Few examples exist of such models for volcanic debris flows in literature. For the Pinatubo, lahar modelling was performed using a hydrological model. Most examples of debrisflow models are for debrisflows which are not directly related to volcanic eruptions (for example: Di Gregorio et al, 1994; Hungr, 1995).

However, although the physical modelling of volcanic processes seems to be a promising powerful tool, the methods are still in a investigation phase. The integration of the results in a real hazard mitigation project still needs to be developed .

3.5 GIS in Flood Hazard Assessment

Floodplains and other flood-prone areas are recently analysed by satellite remote sensing techniques, which permit digital and/or photo-optical monitoring and analysis at small-to-intermediate scales and also, with the new satellite images, at large scale. A general overview of methodologies for the preparation of flooding hazard maps is detailed by Deutsch and Wiesnet in OAS/DRDE, 1990.

The example given in figure 32 shows a flood hazard zonation of an area in Bangladesh on reconnaissance (small) scale based on a geomorphological approach to flood hazard mapping using remote sensing and geographical information systems. In this example only the riverine inundation hazard is considered. Assaduzaman et al. (1995).

The geomorphological approach consists on the geomorphological analysis of the landforms and the fluvial system, to be supported wherever possible by information on (past) floods and detailed topographic information. The procedures to be followed can be summarised as follows:

a) detailed geomorphological terrain zoning mapping, emphasising fluvial landforms, such as floodplains, terraces, natural levees, backswamps, etc.
b) mapping of historical floods by remote sensing image interpretation and field verification to define flooded zone outlines and characteristics
c) overlaying of the geomorphological map and the flood map to obtain indications for the susceptibility to flooding for each geomorphological unit
d) improving the predicting capacities of the method by combination of geomorphological, hydrological, landuse, and other data.

In Bangladesh a general relationship exists between the micro relief and the landuse. Through the analysis of the landuse, which can be deducted from multi temporal satellite imagery, an idea can be obtained of the micro relief, which in turn governs the flow of the flood water.

The geomorphological, soil, landuse, geological and hydrological data are used as attributes, stored in a data base, which are linked to the geomorphological model. Results of the analysis of the attribute values can be visualised through a reclassified geomorphological map.

The map given in figure32 shows the results of such a reclassification operation using the flood susceptibilities assigned to the geomorphological units. The flood hazard zonation map is a grouping of geomorphic units with similar flood susceptibilities. The tidal and coastal areas are not considered, the depression are all assigned a very high inundation hazard.

The validation of the model was done using flood NOAA AVHRR imagery with known recurrence. The reclassified model, having similar recurrence, is showing a high correlation with the flood situation as shown on the AVHRR imagery.

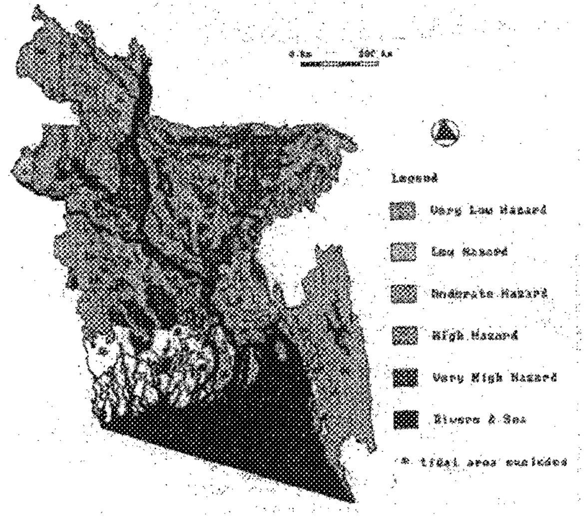

Figure 32: Flood hazard zonation map of an area in Bangladesh: results of a reclassification operation using flood frequencies assigned to geomorphological terrain units. Asaduzzaman et al. (1995)

3.6 GIS in Earthquake Hazard Assessment

In earthquake hazard mapping two different approaches are to be distinguished, each with a characteristic order of magnitude of map scale.

Seismic Macro Zonation

Small scale (regional) seismic macro zonation at scales 1:5,000,000 to 1:50,000, which show the likely hood of occurrence and magnitude (and sometimes also the expected recurrence interval) of earthquake events in (regions of) countries or in (sub)continents.

Figure 33 shows an earthquake occurrence map based on historical and instrumental data for NW Colombia. The map is based on earthquake records since 1566 in a database in which co-ordinates of the epicentres, the depth and the date of occurrence are recorded. Although the map preparation is based on straightforward handling of these data, digital data basing techniques facilitate continuous updating with new earthquake data and facilitate the preparation of maps for which (for different applications) different information filters are used.

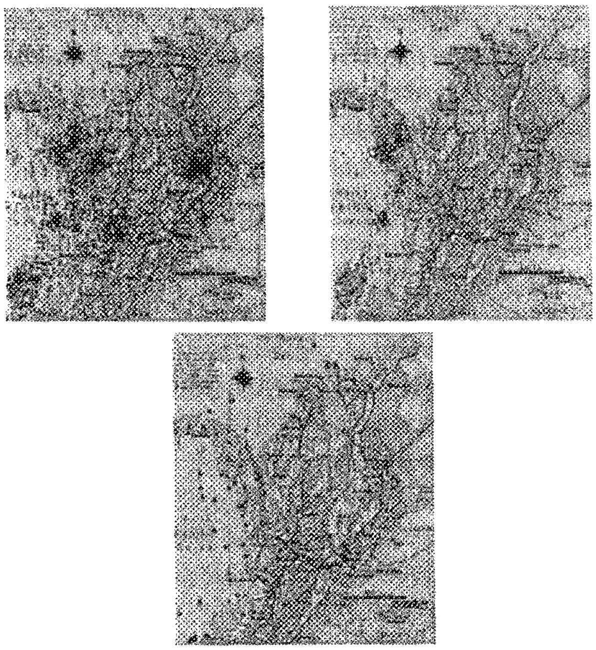

Figure 33: Left: Historical and Instrumental earthquakes from 1566 to 1995, Right and Bottom: Superficial and Intermediate focal depths , right: Ms >6 greater than 6

Seismic Micro Zonation

Large scale (local) seismic micro zonation at scales of 1:50-25,000 to 1:10,000. Seismic micro-hazard assessment is derived from the estimation of the various effects of seismic waves at the terrain surface: ground shaking, surface faulting, tsunamis, landslides and soil liquefaction.

A general discussion with a description of the occurring processes and a proposal for a zonation methodology is presented by Heyman et al. in OAS/DRDE, 1990.

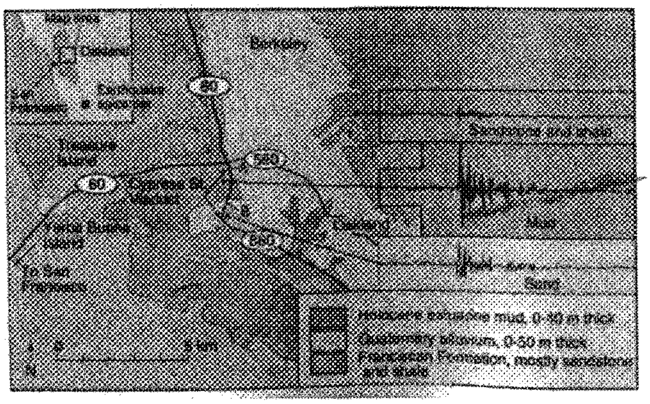

Figure 34: Map of Eastern San Francisco Bay region showing surface geology and seismograms revelaing the relative amplitude of waves passing through different material
(source: USGS Earthquake Reduction Program")

Ground shaking, a principal cause of the collapse of structures, is a ground motion or vibration caused by the different seismic wave fronts during an earthquake. First, the sound wave or P wave and then the shear waves or S waves reach the earth's surface causing damages, particularly by vibrations perpendicular to the S wave from direction. Two more slow low-frequency surface waves fronts follow causing water waves and further building damages. The main ground shaking parameters influencing the damage levels are:

- earthquake Richter magnitude (or Modified Mercalli intensity),
- earthquake duration,
- site conditions, and
- attenuation.

From these parameters some are depending of the fault segment or surface disrupted and its dynamic behaviour during the earthquake (magnitude and duration) as the other depend on the distance to the epicentre and geotechnical or geomorphological conditions in particular sites more or less susceptible to the effects of the earthquake waves (site conditions, attenuation).

Surface faulting is related to faulting during the earthquake or to a new movement induced by the earthquake along pre-existing faults or in new faults created by crust deformations due to the earthquake. Surface faulting can, seriously damage buildings and linear structures or morphological features such as highways, roads, rivers or dams.

Liquefaction is a particular behaviour of unconsolidated saturated fine sands and silts or clays, loosing abruptly their shear strength when the effective stress reduces to zero as the water pressure increases during the deformations induced in the soils by the earthquake waves. Holocene fine sandy soils in alluvial plains or lands recently recovered from the ocean, lakes or rivers, are usually affected by liquefaction during earthquakes of a given magnitude or duration. These type of lands are often intensively irrigated and occupied by cities and villages. The given magnitude to cause soil liquefaction depends on the soil conditions (depth, compaction or relative density, groundwater table level). Also some types of landslides (flows and lateral spreads) result from soil liquefaction.

3.7 Landslide Hazard

In the following sections the various methodological approaches, reviewed by Hansen (1984) , Varnes (1984), and Van Westen (1993) are summarised and illustrated with some examples.

Landslide Inventory

The most straightforward approach to landslide hazard zonation is a landslide inventory, based on aerial photo interpretation, ground survey, and/or a data base of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale or as points (Wieczorek, 1984). 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. They provide information only for the period shortly preceding the date the aerial photos were taken or the fieldwork was conducted. They provide no insight into the temporal changes in mass movement distribution. Many landslides that occurred some time before the photographs were taken may have become undetectable. Therefore a refinement is the construction of landslide activity maps, based on multi-temporal aerial photo interpretation (Canutti et al., 1979). To study the effects of the temporal variation of a factor such as land use, landslide activity maps are indispensable.

Landslide distribution can also be shown in the form of a density map. Wright et al. (1974) presented a method to calculate landslide densities using counting circles. The resulting density values are interpolated and presented by means of landslide isopleths. Although the method does not investigate the relationship between mass movements and causal factors, it is useful in presenting landslide densities quantitatively.

Heuristic Approach

In heuristic methods the expert opinion of the geomorphologist, making the survey, is used to classify the hazard. The mapping of mass movements and their geomorphological setting is the main input factor for hazard determination. Two types of heuristic analysis can be distinguished:

(1) Geomorphological analysis. The basis for this approach was outlined by Kienholz (1977), who developed a method to produce a combined hazard map based on the mapping of "silent witnesses (Stumme Zeugen)". The geomorphological method is also known as the direct mapping method. The hazard is determined directly in the field by the geomorphologist. The process is based on his experience and he is using a reasoning of analogy. The decision rules are therefore difficult to formulate, as they vary from place to place. Examples of this methodology for the appraisal of the susceptibility of the terrain for slope instability are coming especially from Europe, where ample experience exists in geomorphological and engineering geological mapping (Carrara and Merenda,1974; Malgot and Mahr, 1979; Kienholz, 1977, 1978; Kienholz et al., 1983, 1988; Ives and Messerli, 1981; Rupke et al., 1988 and many others, see also Varnes, 1984 and Hansen, 1984). The French programme of the 1:25.000 ZERMOS maps (Meneroud and Calvino, 1976) is in this respect the best example, but the reproducibility of the maps is much debated (Antoine, 1977). The same is true for the method used by Brunsden and his collaborators (Brunsden et al, 1975), who are even not giving a hazard zonation in a project related with a road alignment. They are projecting directly the alignment for the best possible road according their assessment for the stability of the slopes.

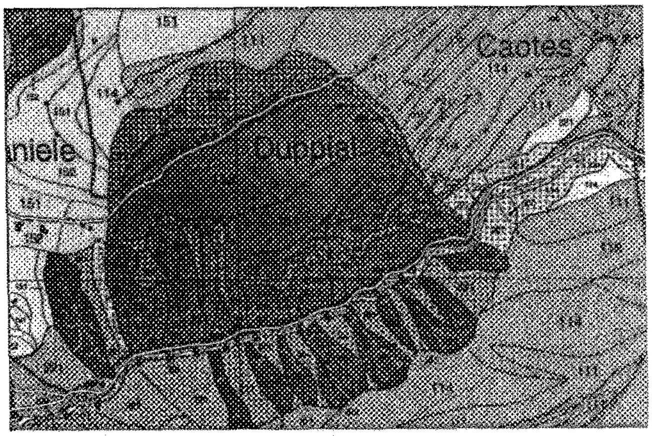

Figure 35: Fragment of a detailed Geomorphological hazard map, prepared using GIS, of an area near Alpago, Belluno, Italy (van Westen et al, 1999)

(2) To overcome the problem of the "hidden rules" in geomorphological mapping, other qualitative methods have been developed based on qualitative map combination. In a qualitative map combination, the earth scientist uses his expert knowledge to assign weight values to series of parameter maps. The terrain conditions are summated according to these weights, leading to

hazard values, which can be grouped into hazard classes. Stevenson (1977) developed an empirical hazard rating system for an area in Tasmania. On the basis of his expert knowledge on the causal factors of slope instability, he assigned weighting values to different classes in a number of parameter maps. This method of qualitative map combination has become very popular in slope instability zonation. The problem with this method is that the exact weighting of the various parameter maps is often based on insufficient field knowledge of the important factors, which will lead to unacceptable generalisations.

Statistical Approach

In statistical landslide hazard analysis, the combinations of factors that have led to landslides in the past, are determined statistically and quantitative predictions are made for landslide free areas with similar conditions. Two different statistical approaches are used in landslide hazard analysis:

(1) Bivariate statistical analysis. In this method, 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). The first example of such an analysis was given by Brabb et al. (1972), who performed a simple combination of a landslide distribution map with a lithological map and a slope map. Several statistical methods can be applied to calculate weight values, such as landslide susceptibility (Brabb, 1984; Van Westen, 1993), the information value method (Yin and Yan, 1988; Kobashi and Suzuki, 1988), weights of evidence modelling (Spiegelhalter, 1986), Bayesian combination rules, certainty factors, Dempster-Shafer method and fuzzy logic (Chung and Fabbri, 1993).

(2) The use of multivariate statistical models for landslide hazard zonation has mainly been developed in Italy by Carrara (1983, 1988) and his colleagues (Carrara et al, 1990, 1991, 1992). In their applications, all relevant factors are sampled either on a large 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 analysed using multiple regression or discriminant analysis. With these techniques, good results can be expected in homogeneous zones or areas with a small variation in typology of slope instability processes, as shown in the work of Jones et al. (1961) on mass movements in terrace deposits. When applying complex statistics, as done by Carrara and his collaborators, Neuland (1976) or Kobashi and Suzuki (1988), a subdivision according to the type of landslide should be made as well, and therefore, large data sets are needed to obtain reliable results. This implies that the use of complex statistics asks for a laborious effort in collecting large amounts of data, without making use of selective criteria based on professional experience.

Deterministic Approach

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis over larger areas, especially with the aid of geographic information systems, which can handle the large amount of calculations involved when calculating safety factors over large areas. 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. The advantage of these "white box models" is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors). The main problem with these method is the high degree of oversimplification. This method is usually applied for translational landslides using the infinite slope model (Ward et al., 1982). The methods generally require the use of groundwater simulation models (Okimura and Kawatani, 1986). Stochastic methods are sometimes used for selection of input parameters (Mulder and van Asch, 1988; Mulder, 1991; Hammond et al., 1992).

Not all methods for landslide hazard zonation are equally applicable at each scale of analysis. Some require very detailed input data, which can only be collected for small areas at the expense of a lot of efforts and costs. Therefore a selection has to be made of the most useful types of analysis for each of the mapping scales, maintaining an adequate cost / benefit ratio.

Evaluating the methodological approaches and the literature on slope instability hazard zonation practices, it appears that the applied geomorphological or direct mapping methods intends to establish, based on a scientific and professional oriented reasoning, the real causes for slope instability. However, considering the scale of slope failures and the complexity of the causes which are leading to slope instability, the direct mapping methods have to be executed on large scales and therefore a practical hierarchical set up is difficult to implement. The combination of a geomorphological analysis and the application of weights to the contributing parameters, as used for example by Kienholz (1977, 1978), improves the objectivity and reproducibility. This is particularly the case when the weights are based on the degree of contribution of the parameter to slope instability, established by simple statistics.

3.8 Accuracy and Objectivity of Hazard 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 hazard free and hazard prone areas.

The evaluation of the accuracy of a hazard 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. One of the most frequently used methods for checking the accuracy of hazard maps is the combination of the final hazard map with the pattern of historical events. This method can be refined if multitemporal hazardous event distribution maps are available. The hazard prediction, based on an older distribution map, can then be checked with a younger distribution. Also 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. The accuracy of a hazard prediction is depending on a large number of factors, among which the most important ones are:

(1) The accuracy of the models that were used;
(2) The accuracy of the input data;
(3) The experience of the earth scientists involved;
(4) The size of the study area;

Many of these factors are interrelated. The size of the study area determines to a large degree what kind of data can be collected at which density, and what kind of analysis technique can be applied .

Related to the problem of assessing the accuracy of hazard maps is the question of objectivity. The terms objective and subjective are used to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgement of the earth scientist in charge of the hazard study.

Objectivity in the assessment of hazard does not necessarily result in an accurate hazard map, for example if a very simple, but verifiable, model was used, or if only a few parameters are taken into account. On the other hand, subjective studies, such as detailed geomorphological analysis, may result in very accurate hazard maps, when made by experienced geomorphologists. However, such a good, but subjective assessment has a relative value, as the reproducibility will be low. This means that the same evaluation made by another expert will probably yield other results, which can have clearly undesirable legal effects.

The degree of objectivity of a hazard study depends on the techniques used in data collection and the methods used in data analysis. The use of objective analysis techniques, such as statistical analysis or deterministic analysis, may still lead to subjective results, depending on the amount of subjectivity which is required for creating the parameter maps. Studies on the degree of subjectivity, considering the interpretation of large scale photographs (1:10.000) by a group of twelve photo-interpreters, several of them with considerable experience and some with local knowledge, have shown that the differences between interpretations can be large. These findings coincide with similar investigations on the subjectivity of photo-interpretation in slope instability mapping (Fookes et al., 1991; Carrara et al., 1992).

Many of the input maps used in hazard analysis are based on image-interpretation and will therefore contain a large degree of subjectivity. Also for factors which are obtained by means of precise measurements (such as soil strength) the degree of subjectivity of the resulting parameter maps may be high, as the point-wise data has to be linked with a material map, made by photo-interpretation and fieldwork.

In view of the limitations inherent to the data collection and analysis techniques and the restrictions imposed by the scale of mapping, a hazard survey will always retain a certain degree of subjectivity. This does not necessarily imply an inaccuracy. The objectivity and certainly the reproducibility of the assessment can considerably be improved by the interpretation of sequential imagery, the use of clear, if possible, quantitative description of the factors considered, as well as well defined analytical procedures and decision rules, which are applied to come to the hazard assessment. The most important aspect however remains the experience of the interpreter, both with regard to various factors involved in slope instability hazard surveys, as well as in the specific conditions of the study area.

REFERENCES

Alexander, D. 1993. Natural disasters. UCL Press Ltd., University College London. 632 pp.

Armeti, P. and Macedonio,G. (1988). A numerical Model for Simulation of Tephra Transport and Deposition: Applications to May 18, 1980, Mt. St. Helens Eruption. Journal of Geophysical Research, Vol. 93, No. B6, pp. 6463-6476, .Asaduzzaman, A.T.M., N.C. Kingma and B.H.P. Maathuis, 1995.
A geomorphic approach to flood hazard assessment and zonation in Bangladesh, using Remote Sensing and Geographical Information Systems.

Baez, E.E., Beltran, L.B. and Gonzalez, G. (1988)
Inventory of mass movements observed in the Colombian road network during 1986
Technical report ID-UN-018A.
Research program on landslides in the Colombian road network
Ministry of Public Works. Bogotá. 68 pp.

Barberi, F., Macedonio, M., Pareschi, M.T. and Santacroce, R. (1990). Mapping the tephra fallout risk: an example from Vesuvius, Italy. Nature 344, pp. 142-144.

Barberi,F., Carapezza, M.L., Macedonio, G. and Massone, S. (1995). Hazard map of Mount Etna based on past activity and numerical simulation. Per. Mineral. 64, pp. 87-88

Barca, D, Crisci, G.M., Di Gregorio and S., Nicoletta, F. P. (1993). Cellular automata methods for modelling lava flow: simulation of the 1986-1987 etnean eruption. in: Kilburn, C. and Luongo, G. (eds): Active Lavas. UCL Press London. pp. 283-301

Barca, D, Crisci, G.M., Di Gregorio S. and, Nicoletta, F.P. (1994). Cellular automata methods for modelling lava flow: a method and examples of the Etnean eruptions. Transport theory and statistical physics, 23 (1-3), pp. 195-232.

Bernknopf, R.L., Campbell, R.H., Brookshire, D.S. and Shapiro, C.D. (1988) A probabilistic approach to landslide hazard mapping in Cincinatti, Ohio, with applications for economic evaluation.Bulletin International Association of Engineering Geologists, Vol. 25, No.1, pp. 39-56.

Bonham-Carter, G.F., Agterberg, F.P., Wright, D.F. (1990) Weights of evidence modelling: a new approach to mapping mineral potential.Geological Survey of Canada Paper 8-9. Agterberg, F.P. and Bonham-Carter, G.F. (eds). Ottawa, Canada, pp.171-183.

Brabb, E.E. (1984) Innovative approaches to landslide hazard and risk mapping. Proceedings 4th International Symposium on Landslides, Toronto, Canada, Vol. 1, pp 307-324.

Brabb, E.E., Pampeyan, E.H., and Bonilla, M.G. (1972). Landslide susceptibility in San Mateo County, California, US Geological Survey Miscellaneous field Studies Map. MF360, scale 1:62,500.

Brabb, E.E., Guzzetti, F., Mark, R. and Simpson, R.W. (1989) The extent of landsliding in northern New Mexico and similar semi-arid regions In: Landslides in a semi-arid environment. Sadler and Morton (eds). Publications of the Inland Geological Society, Vol. 2, pp. 163-173.

Brass, A., Wadge, G. and Reading, A.J. (1989) Designing a Geographical Information System for the prediction of landsliding potential in the West Indies.Proceedings Economic Geology and Geotechnics of Active Tectonic Regions, University College, London, 3-7 April, 1989, 13 pp.

Burrough, P.A. (1986) Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford 194 pp.

Capecchi,F. and Focardi, P. (1988) Rainfall and landslides: Research into a critical precipitation coefficient in an area of Italy. Proceedings 5th International Symposium on Landslides, Lausanne, Switzerland, Vol. 2, pp. 1131-1136.

Carey, S. and Sparks, R.S.J. (1986). Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Bull. Volcanol. 48, pp 109-125.

Carrara, A. (1983) Multivariate models for landslide hazard evaluation Mathematical Geology, 15, No. 3, pp. 403-427.

Carrara, A. (1988) Landslide hazard mapping by statistical methods. A "black box" approach.Workshop on Natural Disasters in European Mediterranean Countries, Perugia, Italy, pp 205-224.

Carrara, A. (1992) Landslide hazard assessment Proceedings 1er Simposio Internacional sobre Sensores Remotos y Sistemas de Informacion Geografica (SIG) para el estudio de Riesgos Naturales, Bogotá, Colombia, pp. 329-355.

Carrara, A., Pugliese Carratelli, E. and Merenda, L. (1977) Computer-based data bank and statistical analysis of slope instability phenomena. Zeitschrift f?r Geomorphologie N.F., Vol.21, No 2, pp. 187-222.

Carrara, A., Cardinali, M. and Guzzetti, F. (1992) Uncertainty in assessing landslide hazard and risk. ITC-Journal 1992-2, pp. 172-183.

Carrara, A., Catalano, E., Sorriso Valvo, M., Reali, C. and Osso, I. (1978) Digital terrain analysis for land evaluation. Geologia Applicata e Idrogeologia, Vol. XIII, pp. 69-127.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. and Reichenbach, P. (1990) Geographical Information Systems and multivariate models in landslide hazard evaluation. ALPS 90 Alpine Landslide Practical Seminar. 6th International Conference and Field Workshop on Landslides. Aug. 31-Sept.12, 1990, Milano, Italy. pp. 17-28.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. and Reichenbach, P. (1991) GIS techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landforms, Vol. 16, No. 5, pp. 427- 445.

Choubey, V.D. and Litoria, P.K. (1990) Terrain classification and land hazard mapping in Kalsi-Chakrata area (Garhwal Hinalaya), India. ITC-Journal 1990-1, pp. 58-66.

Chowdury, R.N. (1978) Slope analysis. Developments in geotechnical engineering, vol 22. Elsevier, Amsterdam, 423 pp.

Cova, T.J. (1999) GIS in Emergency management. In: Geographical Information Systems, management and Applications. Longley, P.A., Goodchild, M.F. Maguire, D.J., and Rhind, D.V.

Crandell, D.R., Booth, B., Kusumadinata, K., Shimozuru, D., Walker, G.P.L. and Westercamp, D. (eds) (1984) .Source-book for volcanic hazards zonation. UNESCO, 97 pp

Crisci, G.M., Di gregorio, S., Pindara, O., and Ranieri, G.A., (1986). Lava flow simulation by a discrete cellular model. International Journal of Modeling Simulations, Vol.6, No.4.pp 137-140.

Crisci, G.M., Di Francia, A., Di Gregorio, S., Nicoletta, F., Rongo, R. and Spataro, W. (1996) Simulation of 1991-1992 Etna lava flows by the cellular model SCIARA-2. Computational Science and Engineering.

Crozier, M.J. (1986) Landslides: causes, consequences & environment Croom Helm, London, England, 245 pp.

Denlinger,R. (1987). A Model for Generation of ash Clouds by Pyroclastic Flows, with Application to the 1980 Eruptions of Mt. St. Helens, Washington. Journal of Geophysical Research, Vol. 92, No.B10, September 1987, pp. 10,284-10,298.

Di Gregorio, S., Nicoletta, F.P, Rongo, R. Sorriso-Valvo, M., Spataro, W. (1994). A two dimensional cellular automata model for landslide simulation. Proceedings of 6th Joint EPS-APS International Conference on Physics Computing "PC94" Lugano, Switzerland. pp. 523-526.

Dobran, F., Barberi, F. and Casarosa, C. (1990). Modelling of volcanological processes and simulation of volcanic eruptions. CNR Gruppo Naz. Volcanol.Italia. Repport VSG90-01, 85 pp.

Dobran, F., Neri, A. and Todesco, M. (1994). Assessing the pyroclastic flow hazard at Vesuvius. Nature 367, pp. 551-554.

Einstein, H.H (1988) Special lecture: Landslide risk assessment procedure Proceedings 5th International Symposium on Landslides, Lausanne, Switzerland, 1988, Vol.2, pp. 1075-1090.

Feigl, K. L., and E. Dupré, RNGCHN: a program to calculate displacement components from dislocations in an elastic half-space with applications for modeling geodetic measurements of crustal deformation, Computers and Geosciences, in press, 1996.

Fournier D'Albe, E.M. (1976) Natural disasters. Bulletin International Association of Engineering Geologists, Vol. 14., p. 187. Fournier d'Albe (1979). Objectives of volcanic monitoring and prediction. Jour. Geol. Soc. London 136, pp 321-326. Francis, P. and Rothery, D. (1987). Using the Landsat Thematic Mapper to detect and monitor volcanic activity. Geology 15, pp. 614-617. Frank G. Sadowski and Steven J. Covington, 1987, Processing and analysis of commercial satellite image data of the nuclear accident near Chernobyl, U.S.S.R.: Washington, USGS Survey Bulletin 1785, 19 p., p. 10.

Gardner, T.W., Conners Sasowski, K. and Day, R.L. (1990) Automatic extraction of geomorphometric properties from digitial elevation data. Zeitschrift f?r Geomorphologie N.F. Suppl. Band 60. pp 57-68.

Gomez Fernandez, F. (1996). Desarollo de una metodologia para el analisis del riesgo volcanico en el marco de un sistema de informacion geografica. PhD thesis Universidad Complutense de Madrid. 255 pp.

Graham, J. (1984) Methods of stability analysis. In: Slope Instability. D. Brunsden and D.B. Prior (eds), Wiley & Sons, New York, pp. 171-215.

Hammond, C.J., Prellwitz, R.W. and Miller, S.M. (1992) Landslide hazard assessment using Monte Carlo simulation Proceedings 6th International Symposium on Landslides, Christchurch, New Zealand, Vol 2, pp 959-964.

Hansen, A. (1984) Landslide Hazard Analysis. In: Slope Instability. In: Slope Instability. D. Brunsden and D.B. Prior (eds), Wiley & Sons, New York, pp. 523-602.

Hartlén, J. and Viberg, L. (1988) General report: Evaluation of landslide hazard Proceedings 5th International Symposium on Landslides, Lausanne, Switzerland, Vol. 2, pp. 1037-1057.

Hossli, R., EOS, Transactions, American Geophysical Union, Vol. 73. No. 48, December 1, 1992, pp. 521-522.

Huma, I. and Radulescu (1978) Automatic production of thematic maps of slope instability. Bulletin International Association of Engineering Geologists, No 17, pp. 95-99.

Hungr, A. (1995). A model for the runout analysis of rapid debris flow slides, debris flows and avalanches. Can. Geotech. J. 32, pp. 610-623

IAEG, (1976) Engineering geological maps. A guide to their preparation. International Association of Engineering Geologists. The UNESCO press, Paris. 79 pp.

Ishihara, K., Iguchi, M. and Kamo, K. (1989). Numerical simulation of lava flows on some volcanos in Japan. in Fink, J. (ed): IAVCEI Proc. in Volcanology, Vol. 2. Springer Verlag. ISL 1993. Global Emergency Observation and Warning. International Space Univeristy, Design Project Report. Hunstville, Alabama, USA. 211 pp.

Kauahikaua, J., Margriter, S. and Moore, R.B. (1995). GIS-aided volcanic hazard analysis for the Hawaii geothermal project environmental impact statement. In: Carrara, A. and

Guzzetti, F. (eds.) Geographical Information Systems in assessing natural hazards. Kluwer. pp 235-258

Keefer, K. et al. (1987) Real-Time Landslide Warning During Heavy Rainfall. Science 238, pp. 921-925.

Kesseler, M. (1995). Modelisation et cartographie de l'area volcanique de Vulcano (Iles Eoliennes, Italie) par un Systeme d'Information Georeferee. Publications du Departement de Geologie et Paleontologie. Universite de Geneve. pp. 1-72.

Kienholz, H. (1977) Kombinierte Geomorphologische Gefahrenkarte 1:10.000 von Grindelwald. Geographica Bernensia G4, Geographisches Institut Universit?t, Bern, Switzerland.

Kilburn, C.R.J. (1983) Studies of lava flow development. In: Tazieff, H. and Sabroux J.C. (eds.) Forecasting Volcanic Events. Elsevier. pp 83-98.

Kingsbury, P.A., Hastie, W.J. and Harrington, A.J. (1992) Regional landslip hazard assessment using a Geographical Information System. Proceedings 6th International Symposium on Landslides, Christchurch, New Zealand, Vol 2, pp. 995-999.

Krueger, A. et al. (1994). Volcanic hazard detection with the Total Ozone Mapping Spectrometer (TOMS), U.S. Geol. Surv. Bulletin, 2047, pp. 367-372.

Macedonio, P.L. (1982). Modelling lava flow hazard. In: Barberi, F. Casale, R. and Fantechi, R. (eds). The mitigation of volcanic hazards. Proceedings of a course for the European Commission, pp 89-95

Macedonio,G., Pareschi,M.,T., and Santacroce,R. (1988). A Numerical Simulation of the Plinian Fall Phase of the 79AD Eruption of Vesuvius. Journal of Geophysical Research, Vol. 93. No. B12, Pages 14,817-14,827.

Macedonio, G. and Pareschi, M.T. (1992). Numerical simulation of some lahars from Mount St. Helens. Jour. Volcanol. Geotherm. Res. 54, pp 65-80.

Malin, M.C. and Sheridan, M.F. (1982). Computer-assisted mapping of Pyroclastic Surges. Science, 217, pp 637-639.

Mani,P. and Gerber, B. (1992) Geographische Informationssysteme in der Anlyse von Naturgefahren. Proceedings INTERPRAEVENT 1992, Bern, Switzerland, Band 3, pp 97-108.

Massonnet, D., K. L. Feigl, M. Rossi, and F. Adragna, Radar interferometric mapping of deformation in the year after the Landers earthquake, Nature, 369, 227-230, 1994.

Melekestsev, I.V., Braitseva, O.A., and Ponomareva, V.V. (1989). Prediction of Volcanic Hazards on the Basis of the Study of Dynamics of Volcanic Activity, Kamchatka. In Volcanic Hazards - Assessment and Monitoring. IAVCEI Proceedings in Volcanology 1. John H. Latter - Editor. Springer-Verlag Berlin Heidelberg.

Mouginis-Mark, P.J. and Francis, P.W. (1992). Satellite observations of active volcanoes: prospects for the 1990s. Episodes, Vol. 15, No 1. pp 46-55.

Mulder, H.F.H.M. (1991) Assessment of landslide hazard. Nederlandse Geografische Studies. PhD thesis University of Utrecht. 150p.

Mulder, H.F.H.M. and Asch, T.W.J. van (1988) A stochastical approach to landslide hazard determination in a forested area. Proceeding 5th International Symposium on Landslides, Lausanne, Switzerland, Vol. 2., pp.1207-1210

Munich Reinsurence Company (1998) Wolrd Map of Natural Hazards. Munich Reinsurance Company, Munich, Germany, 55 pp. Munich Reinsurance Company (1998) Annual Review of natural catastrophes 1997. Munich Reinsurance Company, Munich, Germany , 19 pp.

Murphy, W. and Vita-Finzi, C. (1991) Landslides and seismicity: an application of remote sensing. Proceedings 8th Thematic Conference on Geological Remote Sensing (ERIM), Denver, Colorado, USA, Vol. 2, pp 771-784.

Neuland, H. (1976) A prediction model for landslips. Catena, 3, pp. 215-230.

Newman, E.B., Paradis, A.R. and Brabb, E.E. (1978) Feasibility and cost of using a computer to prepare landslide susceptibility maps of the San Fransico Bay Region, California. US Geological Survey Bulletin 1443, 29 pp.

Niemann, K.O. and Howes, D.E. (1991) Applicability of digital terrain models for slope stability assessment. ITC-Journal 1991-3, pp. 127-137. OAS/DRDE (1990). Disaster , Planning and Development: Managing Natural hazards to reduce Loss. Department of Regional Development and Environment. Organization of American States. Washington, USA. 80 pp

Okamoto, K., (1993). Observation of volcano by airborne imaging radar. Proceedings of the workshop on Volcanic Disaster Prevention. March 8-12, 1993. Palo Alto, California, USA.

Okimura, T. and Kawatani, T. (1986) Mapping of the potential surface-failure sites on granite mountain slopes. In: International Geomorphology. Gardiner (ed). Part 1, John Wiley & Sons, pp.121-138.

Oppenheimer, C. (1991), Lava flow cooling estimated from Landsat Thematic Mapper infrared data; The Lonquimay eruption (Chile, 1989), J. Geophys.res., 96, pp. 21865-21878.

Pearson, E., Wadge, G. and Wislocki, A.P. (1991) An integrated expert system/GIS approach to modelling and mapping natural hazards. Proceedings European conference on GIS (EGIS), session 26, pp. 763-771.

Radbruch-Hall, D.H., Edwards, K. and Batson, R.M. (1979). Experimental engineering geological maps of the conterminous United States prepared using computer techniques. Bulletin International Association of Engineering Geologists, No. 19, pp. 358-363.

Realmunto, V. et al. (1994). The use of multispectral thermal infrared image data to estimate the sulfur dioxide flux from volcanoes: A case study from Mount Etna, Sicily, July 29, 1986. J. Geophys Res., Vol.99, No. B1, pp. 481-488.

Rengers, N. (1992) UNESCO-ITC project on mountain hazard analysis using GIS. Proceedings 1er Simposio Internacional sobre Sensores Remotos y Sistemas de Informacion Geografica (SIG) para el estudio de Riesgos Naturales, Bogotá, Colombia.

Rengers, N., Soeters, R. and Westen, C.J. Van (1992) Remote sensing and GIS applied to mountain hazard mapping. Episodes, Vol.15, No.1, March 1992, pp.36-45.

Rothery , D. et al., (1988), Volcano monitoring using short wavelength infrared dat from satellites, J.Geophys.Res. 93:, pp. 7993-8008

Rupke, J., Cammeraat, E., Seijmonsbergen, A.C. and Westen, C.J.v (1988) Engineering geomorphology of the Widentobel catchment, Appenzell and

Sankt Gallen, Switzerland. A Geomorphological inventory system applied to geotechnical appraisal of slope stability. Engineering Geology 26, pp 33-68.

Scott, W.E., (1989), Volcanic and related hazards, Ch. 2, in Volcanic Hazards, Tilling, R.I., ed., short course in geology, v. 1,pp. 9-23.

Seijmonsbergen, A.C., Van Westen, C.J., and Rupke, J. (ed) (1989)

Geomorphological-, Geotechnical- and Natural Hazard maps of the Hintere Bregenzerwald area (Vorarlberg, Austria) Set of 12 maps + overlays + explanation. Gebr. Borntraeger, Stutgart, Germany.

Siebert, L. (1984), Large volcanic debris avalanches : characteristics of source areas, deposits and associated eruptions. Journal of Volcanology and Geothermal Resources, Vol.22, pp. 163-97.

Soeters, R., Rengers, N. and Van Westen, C.J. (1991) Remote sensing and geographical information systems as applied to mountain hazard analysis and environmental monitoring. Proceedings 8th Thematic Conference on Geologic Remote Sensing (ERIM), April 29-May 2, 1991, Denver, USA, Vol. 2, pp. 1389-1402.

Stakenborg, J.H.T. (1986)Digitizing alpine morphology. A digital terrain model based on a geomorphological map for computer-assisted applied mapping. ITC-Journal 1986-4, pp 299-306.

Stevenson, P.C. (1977) An empirical method for the evaluation of relative landslide risk. Bulletin International Association of Engineering Geologists, No. 16, pp 69-72.

Tilling, R.I., (1989), Volcanic Hazards, short course in geology: v. 1, Washington, D.C., American Geophysical Union, 123 p.

Turner, B.A. (1976) The development of disasters: a sequence model for the analysis of the origin of disaster. Sociological Review 24, pp. 753-774

Uehara, S., Kumagai, T. and Yazaki, S. (1992). Thermal Observations of Unzendake Volcanic Activities Using Airborne MSS. Proceedings: Workshop on Predicting Volcanic Eruptions and Hazard Mitigation Technology. March 3-6, 1992. Science and Technology Agency, Japan.

UNDRO 1991. Mitigating Natural Disasters. Phenomena, Effects and Options. United Nations Disaster Relief Co-ordinator, United Nations, New York. 164 pp.

UNEP/ISRIC (1991) Global Assessment of Soil Degradation (GLASOD), Nairobi, Wageningen. United Nations Population Division, World Population Prospects: The 1998 Revision, forthcoming. Website: http://www.popin.org/pop1998/1.htm

US Foreign Disaster Assistance (1993) Report of Disaster History Database. US Agency for International Development Office of US Foreign Disaster Assistance

Valentine, G.A. and Wohletz, K.H. (1989).- Environmental hazards of pyroclastic flows determined by numerical models. Geology 17, pp. 641-644.

Van Asch, T.W.J, Van Westen, C.J., Blijenberg, H. and Terlien, M. (1992) Quantitative landslide hazard analyses in volcanic ashes of the Chinchina area, Colombia. Proceedings 1er Simposio Internacional sobre Sensores Remotes y Sistemas de Informacion Geografica para el estudio de Riesgos Naturales, Bogotá, Colombia 10-12 march 1992, pp. 433-443.

Van Dijke, J.J. and Van Westen, C.J. (1990) Rockfall hazard: a geomorphological application of neighbourhood analysis with ILWIS. ITC-Journal 1990-1, pp. 40-44.

Van Genderen, J.L. and Guan Haiyan (1997) Environmental monitoring of spontaneous combustion in the North China coalfields. Report EC DG XII-G:I.S.C. Contract Number: Cl1*-CT93-0008. 244 pp.

Van Westen, C.J. (1989) ITC-UNESCO project on G.I.S. for Mountain Hazard Analysis Proceedings First South American Symposium on Landslides, 7-10 August 1989, Paipa, Colombia, pp 214-224.

Van Westen, C.J. and Alzate, J.B. (1990) Mountain hazard analysis using a PC-based GIS Proc. 6th Int. Congr. Int. Assoc. Eng. Geol., Vol. 1, pp. 265-272.

Van Westen, C.J. 1992a Scale Related GIS techniques in the analysis of landslide hazard. Proceedings 1er Simposio Internacional sobre Sensores Remotos y Sistemas de Informacion Geografica (SIG) para el estudio de Riesgos Naturales, Bogotá, Colombia, pp. 484-498.

Van Westen, C.J. 1992b Medium scale hazard analysis using GIS. Proceedings 1er Simposio Internacional sobre Sensores Remotos y Sistemas de Informacion Geografica (SIG) para el estudio de Riesgos Naturales, Bogotá, Colombia, Vol. 2, 15 pp.

Van Westen, C.J. (1993) Application of Geographic Information Systems to Landslide Hazard Zonation. ITC-Publication Number 15, ITC, Enschede, The Netherlands, 245 pp.

Varnes, D.J. (1984) Landslide Hazard Zonation: a review of principles and practice Commission on Landslides of the IAEG, UNESCO, Natural Hazards No 3, 61 pp.

Wadge, G. (1988) The potential of GIS modelling of gravity flows and slope instabilities. Int. J. Geographic Information Systems, Vol. 2, No. 2, pp. 143-152

Wadge, G. and Isaacs, M.C. (1988). Mapping the volcanic hazards from Soufriere Hills Volcano, Montserat, West Indies, using an image processor. Jour.Geol.Soc. London 145, pp. 541-551.

Wadge, G., Young, P.A.V. and McKendrick, I.J. (1994). Mapping lava flow hazards using computer simulation. Jour. of Geophys. Res.99, no. B1, pp. 489-504.

Wen, S. and Rose, W. (1994). Retrieval of particle sizes and masses in volcanic clouds using AVHRR bands 4 and 5, J. Geophys.Res. 99, pp. 5421-5431.

Wickmann, F.E. (1966). - Repose period patterns of volcanoes, I. Volcanic erupotions regarded asrandom phenomena. Ark. Mineral Geol. 4, pp. 291-301

Wijman, A. (1984) Natural disasters: Acts of God or Acts of Man? International Institute for Environment and Development, London. Washington DC, 19984

Williams, Richard, S., Heckman, Joanne, and Schneeberger, J., 1991, Environmental Consequences of the Persian Gulf War, 1990-1991: Remote Sensing Datasets of Kuwait and Environs: National Geographic Society, 48 pp.

Wolfe, E.W., (1992), The 1991 eruptions of Mount Pinatubo, Philippines, Earthquakes and Volcanoes, 23 (1), pp. 5-37.

Wright, R.H., Campbell, R.H. and Nilsen, T.H. (1974) Preparation and use of isopleth maps of landslide deposits. Geology, No.2, pp 483-485.

Yin, K.L. and Yan, T.Z. (1988) Statistical prediction model for slope instability of metamorphosed rocks Proceedings 5th International Symposium on Landslides, Lausanne, Switzerland, Vol. 2, pp 1269-1272.

Young, P and Wadge,G. (1990). FLOWFRONT: Simulation of Lava Flows. Computers and Geosciences. Vol. 16, N. 8., pp. 1171-1191.