10

Remote sensing and geographic information systems for natural disaster management

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ABSTRACT

Natural disasters are extreme events within the Earth's system that result in death or injury to humans, and damage or loss of valuable goods, such as buildings, communication systems, agricultural land, forests, natural environment etc. Disasters can have a purely natural origin, or they can be induced or aggravated by human activity. The economic losses due to natural disasters have shown an increase with a factor of eight over the past four decades, caused by the increased vulnerability of the global society due to population growth, urbanization, poor urban planning, as well as an increase in the number of weather-related disasters.

The activities on natural disaster reduction in the past decade, which was designated by the UN as the 'International Decade for Natural Disaster Reduction', have not led to a reduction in these increasing losses. In future even more work has to be done in disaster management. Natural disaster management requires a large amount of multi-temporal spatial data. Satellite remote sensing is the ideal tool for disaster management, since it offers information over large areas, and at short time intervals. Although it can be utilized in the various phases of disaster management, such as prevention, preparedness, relief, and reconstruction, in practice remote sensing is mostly used for warning and monitoring. During the last decades, remote sensing has become an operational tool in the disaster preparedness and warning phases for cyclones, droughts and floods. The use of remote sensing data is not possible without a proper tool to handle the large amounts of data and combine it with data coming from other sources, such as maps or measurement stations. Therefore, together with the growth of the remote sensing applications, Geographic Information Systems (GIS) have become important for disaster management. This chapter gives a review of the use of remote sensing and GIS for a number of major disaster types.

10.1 INTRODUCTION

Natural disasters are extreme events within the Earth's system (lithosphere, hydrosphere, biosphere or atmosphere) which differ substantially from the mean, resulting in death or injury to humans, and damage or loss of 'goods', such as buildings, communication systems, agricultural land, forest, natural environment.

The impact of a natural disaster may be rapid, as in the case of earthquakes, or slow as in the case of drought.

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 populated area, and brings damage, loss or destruction to the socio-economic system (Alexander 1993). Natural disasters occur in many parts of the world, although each type of disaster is restricted to certain regions. Figure 10.1 gives an indication of the geographical distribution of a number of major hazards, such as earthquakes, volcanoes, tropical storms and cyclones. As can be seen from this figure, earthquakes and volcanoes, for example, are concentrated mainly on the Earth's plate boundaries.

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

- 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 caused by human activities (such as atmospheric pollution, industrial chemical accidents, major armed conflicts, nuclear accidents, oil spills); and
- Human-induced disasters are natural disasters that are accelerated/aggravated by human influence.

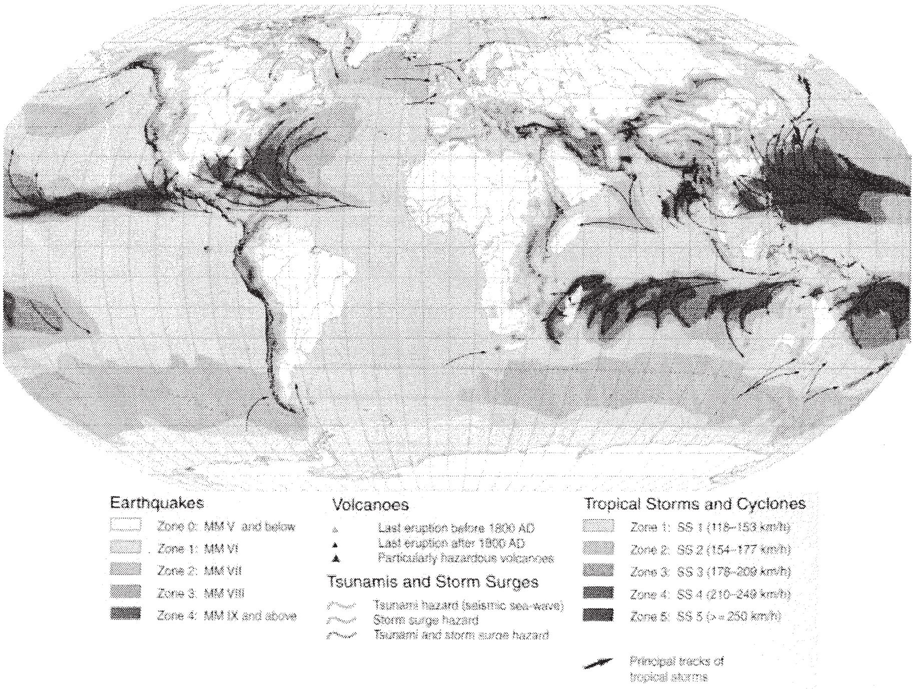

Figure 10.1: World map of natural disasters (Source: Munich Re. 1998).

In Table 10.1, various disasters are classified in a gradual scale between purely natural and purely human-made. 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, or removal of vegetation.

Table 10.1: Classification of disaster in a gradual scale between purely natural and purely human-made.

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	Landslides Subsidence Erosion Desertification Coal fires Coastal erosion Greenhouse effect Sea level 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

Another subdivision relates to the main controlling factors leading to a disaster. These may be meteorological (too much or too little rainfall, high wind-speed), geomorphological/geological (resulting from anomalies 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 (See Table 10.2).

The impact of natural disasters to the global environment is becoming more severe over time. The reported number of disasters has dramatically increased, as well as the cost to the global economy and the number of people affected (see Table 10.3 and Figure 10.2).

Earthquakes result in the largest amount of losses. Of the total losses it accounts for 35 per cent, ahead of floods (29 per cent), windstorms (29 per cent) and others (7 per cent). Earthquake is also the main cause in terms of the number of fatalities (48 per cent), followed by windstorms (44 per cent) and floods (8 per cent), (Munich Re. 2001).

The 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 of factors responsible for this, which can be subdivided into 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.

Table 10.2: Classification of disasters according to the main controlling factor.

Meteorological	**Geomorphological/ Geological**	**Ecological**	**Technological**	**Global environmental**	**Extra terrestrial**
Drought Dust storm Flood Lightning Windstorm Thunderstorm Hailstorm Tornado Cyclone/ Hurricane	Earthquake Tsunami Volcanic eruption Landslide 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 Sea level rise El Niño Ozone depletion	Asteroid impact Aurora borealis

Table 10.3: Statistics of great natural disasters for the last five decades (source: Munich Re 2001).

	Decade 1950 –1959 US $ billion	**Decade 1960 – 1969 US $ billion**	**Decade 1970 – 1979 US $ billion**	**Decade 1980 – 1989 US $ billion**	**Decade 1990 – 1999 US $ billion**	**Last 10 years 1991 – 2000 US $ billion**	**Factor Last 10: 60s**
Number of large disasters	20	27	47	63	89	84	3.1
Economic losses	40.7	73.1	131.5	204.2	629.2	591.0	8.1
Insured losses	0	7.0	12.0	25.5	118.8	104.4	14.9

Depending on the expected growth rates, the world population is estimated to be between 7 and 10 billion by the year 2050 (UNPD 1999).

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. Rapidly growing mega-cities mostly occupy marginal land that is more susceptible to disasters.

Another 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 10.2 shows the distribution of economic and insured losses due to natural disasters during the last 4 decades.

It is also 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.

However, it is not only the increased exposure of the population to hazards that can explain the increase in natural disasters. The frequency of destructive events related to atmospheric extremes (such as floods, drought, cyclones, and landslides) is increasing. 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, these data indicate that climate change is negatively related with the occurrence of natural disasters.

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 per cent of the disaster-related casualties occur in less developed countries, where more than 4,200 million people live. Economic losses attributable to natural hazards in less developed countries may represent as much as 10 per cent of their gross national product (Munich Re. 1998). In industrialized countries, where warning-systems are more sophisticated, it is more feasible to predict the occurrence of certain natural phenomena, and to carry out mass evacuations. The application of building codes and restrictive zoning also accounts for a lower number of casualties in developed countries.

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 was designated the 'International Decade for Natural Disaster Reduction' (IDNDR) by the general assembly of the United Nations. However, now that we are at 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.

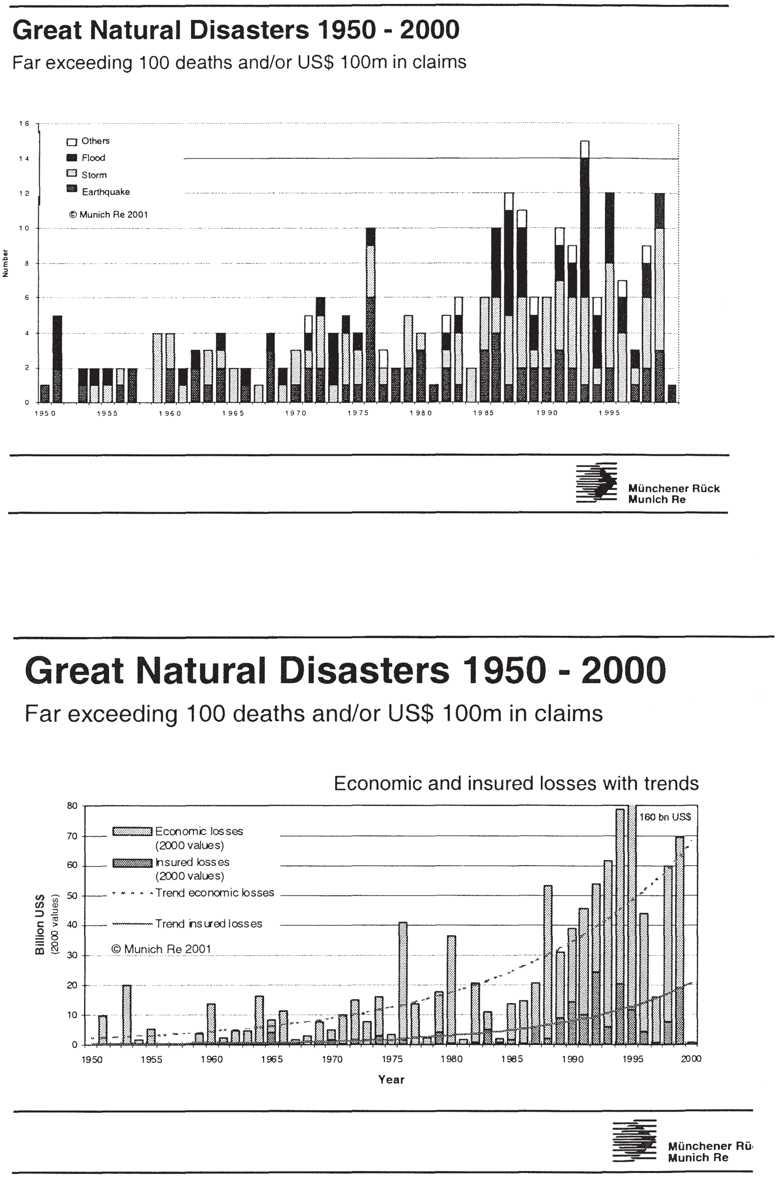

Figure 10.2: Above: number of large natural disasters per year for the period 1950–2000. Below: economic and insured losses due to natural disasters, with trends (Source: Munich Re. 2001).

10.2 DISASTER MANAGEMENT

One way of dealing with natural hazards is to ignore them. In many parts of the world, neither the population nor the authorities choose to take the danger of natural hazards seriously. The complacency may be due to the last major destructive event having happened in the distant past, or people may have moved in the area recently, without having knowledge about potential hazards. Alternatively, the risk due to natural hazards is often taken for granted, given the many dangers and problems confronted by people. Cynical authorities may ignore hazards, because the media exposure and ensuing donor assistance after a disaster has much more impact on voters than the investment of funds for disaster mitigation. To effectively mitigate disasters a complete strategy for disaster management is required, which is also referred to as the disaster management cycle (see Figure 10.3).

Disaster management consists of two phases that take place before a disaster occurs, ***disaster prevention*** and ***disaster preparedness***, and three phases that happen after the occurrence of a disaster, ***disaster relief***, ***rehabilitation*** and ***reconstruction*** (UNDRO 1991). Disaster management is represented here as a cycle, since the occurrence of a disaster will eventually influence the way society is preparing for the next one.

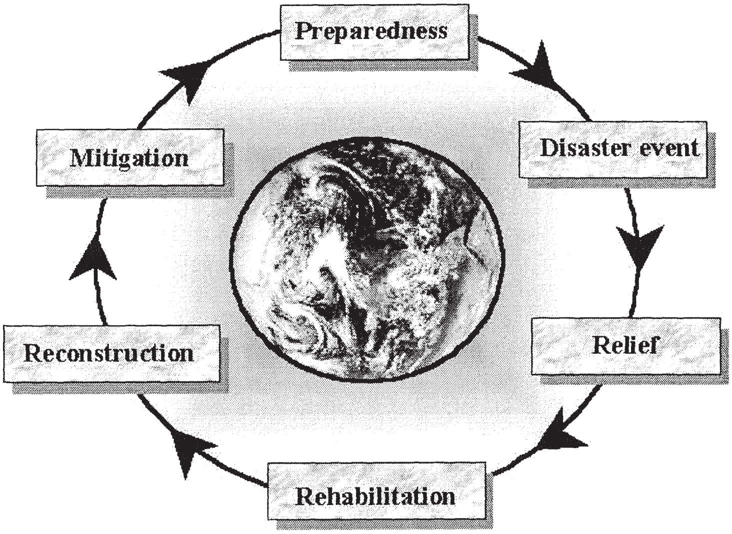

Figure 10.3: The disaster management cycle.

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 the population or the distribution of the losses. The following activities form part of disaster prevention:

- Disaster preparedness involves all preparatory activities prior to a disaster, so that people can be evacuated, protected or rescued as soon as possible.
- Disaster relief involves the provision of emergency relief and assistance when it is needed and the maintenance of public order and safety.
- Rehabilitation and reconstruction refer to the provision of support during and after a disaster, so that community functions quickly recover.

For more information about disaster management the reader is referred to the following websites:

- The US Federal Emergency Management Agency (FEMA):. The Global Emergency Management System is an online, searchable database containing links to websites in a variety of categories that are related in some way to emergency management. http://www.fema.gov/
- The Office of Foreign Disaster Assistance of the United States Agency for International Development (OFDA/USAID). OFDA also sponsors development of early warning system technology and in-country and international training programs designed to strengthen the ability of foreign governments to rely on their own resources. http://www.info.usaid.gov/ofda/
- The Disaster Preparedness and Emergency Response Association, International (DERA) was founded in 1962 to assist communities world wide in disaster preparedness, response and recovery, and to serve as a professional association linking professionals, volunteers, and organizations active in all phases of emergency preparedness and management. http://www.disasters.org/deralink.html
- Relief Web: a project of the United Nations Office for the Co-ordination of Humanitarian Affairs (OCHA) http://www.reliefweb.int/w/rwb.nsf

10.3 REMOTE SENSING AND GIS: TOOLS IN DISASTER MANAGEMENT

10.3.1 Introduction

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. Many types of information that are needed in natural disaster management have an important spatial component such as maps, aerial photography, satellite imagery, GPS data, rainfall data, etc. Many of these data have different projection and co-ordinate systems, and need to be brought to a common map-basis, in order to superimpose them.

Remote sensing and GIS provide a historical database from which hazard maps may be generated, indicating which areas are potentially dangerous. 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. As many types of disasters, such as floods, drought, cyclones and volcanic eruptions will have certain precursors, satellite remote sensing may detect the early stages of these events as anomalies in a time-series.

When a disaster occurs, the speed of information collection from air and space borne platforms and the possibility of information dissemination with a corresponding swiftness make it possible to monitor the occurrence of the disaster. Simultaneously, GIS may be used to plan evacuation routes, design centres for emergency operations, and integrate satellite data with other relevant data.

In the disaster relief phase, GIS is extremely useful in combination with Global Positioning Systems (GPS) for search and rescue operations. Remote sensing can assist in damage assessment and aftermath monitoring, providing a quantitative base for relief operations.

In the disaster rehabilitation phase, GIS can organize the damage information and the post-disaster census information, as well as sites for reconstruction. Remote sensing updates databases used for the reconstruction of an area.

The volume of data required for disaster management, particularly in the context of integrated development planning, is clearly 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. After that all reports should be combined to derive a reconstruction zoning within a relatively short time. GIS may model various hazard and risk scenarios for the future development of an area.

10.3.2 Application levels at different scales

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. Information on natural hazards 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). Geoinformation can play a role at the following levels:

10.3.2.1 National level

At a national level, GIS and remote sensing can provide useful information, and create disaster awareness with politicians and the public, encouraging the establishment of disaster management organization(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. 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.).

An example of this application level for the area affected by Hurricane Mitch in 1998 can be found at: http://cindi.usgs.gov/events/mitch/atlas/index.html

10.3.2.2 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 may constrain 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, environmental and population and infrastructural information can be collected at a larger scale than the national level. Thus, GIS can be utilized for analyses at this scale, although the 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) should be made.
- Preparation of hazard mitigation projects to reduce risk on currently occupied land.
- Guidance on land use and intensity (OAS/DRDE 1990).

10.3.2.3 Medium level

At this level GIS can be used for the prefeasibility study of development projects, at an inter-municipal or district level. For example for the determination of hazard zones in areas with large engineering structures, roads and urbanization plans. The areas to be investigated will have an area of a few hundreds of square kilometres and a considerably 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 utilized extensively. For example, landslide inventories can be combined with other data (geology, slope, land use) using statistical methods to provide hazard susceptibility maps (van Westen 1993).

10.3.2.4 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 are 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 (Terlien *et al.* 1995).

10.3.2.5 Site-investigation scale (> 1:2,000)

At the 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 (such as retaining walls and checkdams). Typical mapping scales are 1:2,000 or larger. Nearly all of the data are 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 (Terlien 1996).

Although the selection of the scale of analysis is usually determined by the intended application of the mapping results, the choice of 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. See also Cova (1999) for an overview of the use of GIS in emergency management.

10.4 EXAMPLES OF THE USE OF GIS AND REMOTE SENSING IN HAZARD ASSESSMENT

10.4.1 Floods

Different types of flooding (e.g. river floods, flash floods, dam-break floods or coastal floods) have different characteristics with respect to the time of occurrence, the magnitude, frequency, duration, flow velocity and the areal extent. Many factors play a role in the occurrence of flooding, such as the intensity and duration of rainfall, snowmelt, deforestation, land use practices, sedimentation in riverbeds, and natural or man has-made obstructions.

Satellite data have been successfully and operationally used in most phases of flood disaster management (CEOS/IGOS 1999). Multi-channel and multi-sensor data sources from meteorological satellites are used for evaluation, interpretation, validation, and assimilation of numerical weather prediction models to assess hydrological and hydro-geological risks (Barrett 1996). Earth observation satellites can be used in many phases of disaster prevention, by mapping geomorphologic elements, historical events and sequential inundation phases, including duration, depth of inundation, and direction of current.

One approach to flood hazard zonation relies on geomorphological analysis of the landforms and the fluvial system, supported wherever possible by information on (past) floods and detailed topographic information. The procedure can be summarized as follows:

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

Figure 10.4 shows flood hazard zonation of an area in Bangladesh on reconnaissance (small) scale based on a geomorphological approach to flood hazard mapping using a series of NOAA AVHRR images and a GIS (Asaduzaman *et al.* 1995).

For the prediction of floods, NOAA AVHRR images, combined with radar data, are used to estimate precipitation intensity, amount, and coverage, measure moisture and winds, and to determine ground effects such as the surface soil wetness (Scofield and Achutuni 1996). Quantitative precipitation estimates (QPE) and forecasts (QPF) use satellite data as one source of information to facilitate flood forecasts in order to provide early warnings of flood hazard to communities.

Earth observation satellites are also used extensively in the phases of preparedness/warning and response/monitoring. The use of optical sensors for flood mapping is limited by cloud cover often present during a flood event. Synthetic Aperture Radar (SAR) from ERS and RADARSAT have been proven very useful for mapping flood inundation areas, due to their bad weather capability. In India, ERS-SAR has been used successfully in flood monitoring since 1993, and Radarsat since 1998 (Chakraborti 1999). A standard procedure is used in which speckle is removed with medium filtering techniques, and a piece-wise linear stretching. Colour composites are generated using SAR data during floods and pre-flood SAR images.

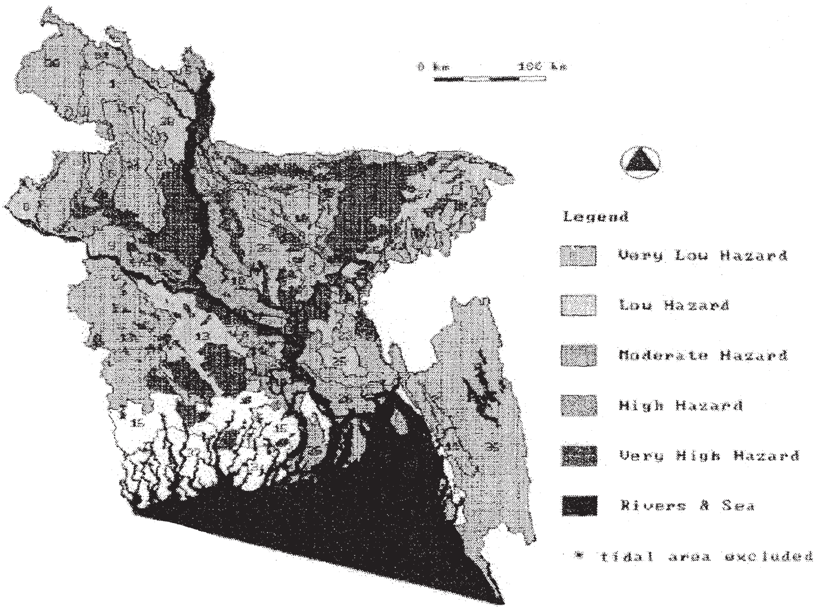

Figure 10.4: Flood hazard zonation map of an area in Bangladesh: results of a reclassification operation using flood frequencies assigned to geomorphological terrain units (Asaduzzaman, 1994)).

For the disaster relief operations, the application of current satellite systems is still limited, due to their poor spatial resolution and problems with cloud cover. Hopefully, higher resolution satellites will improve this (Chapter 3). At a local scale, a large number of hydrological and hydraulic factors can be integrated with high spatial resolution imagery using GIS, especially the generation of detailed topographic information using high precision digital elevation models derived from geodetic surveys, aerial photography, SPOT, LiDAR (Light detection And Ranging) or SAR (Corr 1983). These data are used in two and three dimensional finite element models for the prediction of floods in river channels and floodplains (Gee *et al.* 1990).

10.4.2 Earthquakes

The areas affected by earthquakes are generally large, 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, soil types, depth to the water table, topography, and construction types of buildings.

In earthquake hazard mapping two different approaches are to be distinguished, each with a characteristic order of magnitude of map scale (Hays 1980). Small scale (regional) *seismic macro zonation* at scales 1:5,000,000 to 1:50,000 show the likelihood of occurrence and magnitude and the expected recurrence interval of earthquake events in countries or (sub)continents. Large scale (local) *seismic micro zonation* at scales of 1:50-25,000 to 1:10,000 that indicate the magnitude and probability of the various effects of seismic waves at the terrain surface, including ground shaking, surface faulting, tsunamis, landslides and soil liquefaction.

Satellite remote sensing has no major operational role in earthquake disaster management. In the phase of disaster prevention satellite remote sensing can play a role in the mapping of lineaments and faults, the study of the tectonic setting of an area, and neotectonic studies (Drury 1987). Visible and infra-red imagery with spatial resolutions of 5–20 m are generally used.

Satellite Laser Ranging (SLR) and Very Long Base Baseline Interferometry (VLBI) have been used for the monitoring of crustal movement near active faults (see also section 10.4.3). In the measurement of fault displacements GPS have become very important. An increasingly popular remote sensing application is the mapping of earthquake deformation fields using SAR interferometry (InSAR) (Massonet *et al.* 1994, 1996). It allows for a better understanding of fault mechanisms and strain. However, although some spectacular results have been reported, the technique still has a number of problems making routine application difficult.

There are no generally accepted operational methods for predicting earthquakes. Although there is some mention of observable precursors for earthquakes in the literature, such as variations in the electric field or thermal anomalies, they are heavily disputed.

In the phase of disaster relief, satellite remote sensing can at the moment only play a role in the identification of large associated features (such as landslides), which can be mapped by medium detailed imagery such as SPOT and IRS. Structural damage to buildings cannot be observed with the poor resolution of the current systems. The Near Real Time capability for the assessment of damage and the location of possible victims has now become more possible with the availability of the first civilian optical high resolution imagery (IKONOS), though this will only make a difference if adequate temporal resolution, swath-coverage and ready access to the data can be achieved (CEOS/ IGOS 1999).

Unlike remote sensing, the use of GIS in earthquake disaster management is much more prominent. GIS is used in all phases of disaster management. In the prevention phase the large amount of geological, geophysical and geotechnical data are integrated to derive at earthquake response characteristics of soil and the buildings on it.

The use of GIS for earthquake response is even more important. Emergency managers should have adequate knowledge about the extent of the damage shortly after the earthquake. This requires both detailed digital information about the situation before the disaster occurs (for example, about population, buildings infrastructure and utilities), as well as damage assessment models (Emmi and Horton 1995). Also on a longer time frame, damage databases are important for the insurance industry and for the recovery and rehabilitation phase (see Figure 10.5).

Tsunamis are sea waves due to large-scale sudden movement of the ocean floor during earthquakes. They travel at very high speeds in deep ocean waters (up to 900 km/hour), with a long distance (as much as 500 km) between wave crest, and very low heights (around 1 m until the waves approach shallow water. At coastlines, the 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. 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.

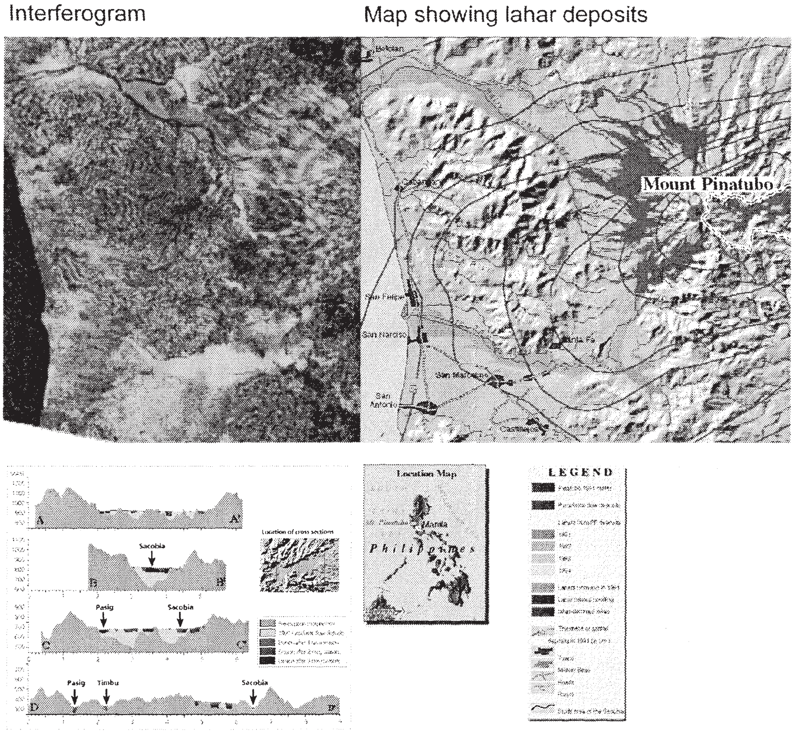

Figure 10.5: Left: Interferogram of Mt Pinatubo generated using a tandem pair of ERS images. Right: map showing main deposits related to the 1991 eruption (ash fall, pyroclastic flows) as well as the extension of lahar.

In the Pacific there is an operational Tsunami Warning System (TWS), in the Pacific Warning Center at Honolulu, Hawaii. It consists of 62 tide stations, and 77 seismic stations in 24 countries surrounding the Pacific ocean. The tsunami warnings are effective on a one-hour basis over the Pacific, and 10 minutes on a regional scale. For local tsunamis, systems with a shorter response time are being tested.

10.4.3 Volcanic eruptions

The areas affected by volcanic eruptions are generally small, and restricted to well known regions and may be densely populated. Volcanic eruptions can lead to a 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 impact air-traffic and the weather. Satellite remote sensing has become operational in some of the phases of volcanic disaster management, specifically in the monitoring of ash clouds. The major applications of remote sensing in volcanic hazard assessment are: 1) monitoring volcanic activity and 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).

Earth observation satellites can be used in the phase of disaster prevention in the mapping of the distribution and type of volcanic deposits. 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 (gas and smoke emission), seismic tremors, and surface deformation (bulging).

For the (detailed to semi-detailed) mapping of volcanic landforms and deposits, the conventional interpretation of stereo aerial photographs is still the most used technique. 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 lava flows.

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 (such as urban development). Topographic measurements, and especially the change in topography, are very important for the prediction of volcanic eruptions. Synthetic Aperture Radar (SAR) sensors can provide valuable data that describes the topography. Measurement of ground deformation may eventually be achieved using SAR interferometry.

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.

Hot areas, for example lavas, fumaroles and hot pyroclastic flows, can be mapped and enhanced using Thematic Mapper data. Landsat B and 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 (Rothery *et al.* 1988; Frances and Rothery 1987; Oppenheimer 1991). Uehara *et al.* (1992) used airborne MSS (1.5 m resolution) to study the thermal distribution of Unzendake volcano in Japan to monitor the lava domes causing pyroclastic flows when collapsed.

Volcanic clouds may be detected by sensors that measure absorption by gases in the cloud such as TOMS (Krueger *et al.* 1994), by infrared sensors such as NOAA AVHRR (Wen and Rose 1994), by comprehensive sensors on meteorological satellites, and by microwave or radar sensors. Remote sensing has become an indispensable part of the global system of detection and tracking of the airborne products of explosive volcanic eruptions via a network of Volcanic Ash Advisory Centers (VAACs) and Meteorological Watch Offices (MWOs). Satellite data provide critical information on current ash cloud coverage, height, movement, and mass as input to aviation SIGnificant METerological (SIGMET) advisories and forecast trajectory dispersion models (CEOS/IGOS 1999).

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. The energy line concept (Malin and Sheridan 1983) was applied by Kesseler (1995) to model pyroclastic flows, using an energy cone in 3-D. The cone is modelled and compared with a digital elevation model in order to find the potentially affected area. For evaluating the hazard to pyroclastic falls, Kesseler (1995) applied a ballistic model in GIS. Carey and Sparks (1986) presented quantitative models of fallout and dispersal of tephra from volcanic eruption columns. Macedonio *et al.* (1988), and Armeti and Macedonio (1988) made computer simulations for the 79AD Plinian Fall of Mt Vesuvius, and the 1980 tephra transport from Mt St Helens, respectively.

The rapidly changing geomorphology of the watersheds before, during and three consecutive years after the eruption of Mt Pinatubo was investigated by Daag and Van Westen (1996). To quantify the volumes of pyroclastic flow material and the yearly erosion, five digital elevation models were made, and analyzed using a GIS.

Examples of lava flow modelling can be found in Wadge *et al.* (1994). An accurate method is known as the *cellular automata method* (Barca *et al.* 1994). 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 characterized 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 cell can be modelled. Promising results were obtained for the Etna lava flows from 1991-1993. Cellular automata is an example of an inductive-empirical technique, using the taxonomic sheme presented in Chapter 2.

However, although the physical modelling of volcanic processes seems to be a promising and powerful tool, the methods are still in an investigation phase. The results of these models need to be further integrated in a real hazard mitigation project.

10.4.4 Landslides

Individual landslides are generally small in area, but often frequent, in certain mountainous regions. Landslides occur in a large variety of forms, depending on the type of movement (slide, topple, flow, fall, spread), the speed of movement (mm/year - m/sec), the material involved (rock, debris, soil), and the triggering mechanism (earthquake, rainfall, human interaction).

In the phase of disaster prevention, satellite imagery can be used for two purposes: landslide inventory and the mapping of factors related to the occurrence of landslides, such as lithology, geomorphological setting, faults, land use, vegetation and slope. For landslide inventory, mapping the size of the landslide features in relation to the ground resolution of the remote sensing data is very important. A typical landslide of 40000 m^2, for example, corresponds to 20 x 20 pixels on a SPOT Pan image and 10 x 10 pixels on SPOT multispectral images. This would be sufficient to identify a landslide that has a high contrast, with respect to its surroundings (e.g. bare scarps within vegetated terrain), but it is insufficient for a proper analysis of the elements pertaining to the failure to establish characteristics and type of landslide. Imagery with sufficient spatial resolution and stereo capability (SPOT, IRS) can be used to make a general inventory of the past landslides. However, they are mostly not detailed enought to map all landslides. As a consequence, aerial photo-interpretation remains essential.

It is believed that the best airphoto-scale for the interpretation of landslides is between 1:15.000 and 1:25.000 (Rengers *et al.*, 1992); if smaller scales are used, a landslide may only be recognized if size and contrast are sufficiently large. It is expected that in future high-resolution imagery, such as IKONOS, might be used for landslide inventory.

Various methods for landslide hazard using GIS can be differentiated (Van Westen 1993). The most straightforward approach to landslide hazard zonation is a *landslide inventory*, based on aerial photo interpretation, ground survey, and/or a database of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale, as points or as isopleths (Wright *et al.* 1974). 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 (Kienholz 1977; Rupke *et al.* 1988; Hansen 1984).

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. In the bivariate statistical method, each factor map (for example slope, geology and land use) is combined with the landslide distribution map, and weight values, based on landslide densities, are calculated for each parameter class (slope class, lithological unit, land use type, etc.). Several statistical methods can be applied to calculate weight values, such as *landslide susceptibility* (Brabb 1984; Van Westen 1993), the *information value method* (Yin and Yan 1988), *weights of evidence modelling Bayesian combination rules, certainty factors, Dempster-Shafer method* and *fuzzy logic* (Chung and Fabbri 1993).

The use of *multivariate statistical* models for landslide hazard zonation has mainly been developed in Italy by Carrara and 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. Also for each of the sampling units the presence or absence of landslides is determined. The resulting matrix is then analysed using multiple regression or discriminant analysis.

Despite problems related to the collection of sufficient and reliable input data, *deterministic models* are increasingly used in hazard analysis at large scales, especially with the aid of GIS, which can handle the large amount of calculations involved when calculating safety factors. This method is usually applied for translational landslides using the infinite slope model. 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 1991; Hammond *et al.* 1992).

10.4.5 Fires

10.4.5.1 Wildfire

The development of a wildland fire depends on three main factors: the fuel (biomass type, condition, moisture etc.), the weather (windspeed, direction, relative humidity, precipitation, temperature) and topography (slope angle, direction, length etc.). Earth observation satellites are used in several phases of fire management such as fuels mapping, risk assessment, detection, monitoring, mapping, burned area recovery, and smoke management.

In the phase of fuel mapping, remote sensing is extensively used to map the vegetation type and vegetation stress. The most frequently used data source for this information is NOAA AVHRR data. Other alternative data sources are ATSR-2; the VEGETATION onboard SPOT 4 as well as the GLI (Global Imager) that will be launched onboard ADEOS-II (CEOS/IGEOS 1999). Existing satellite sensors with wildland fire detection capabilities are under-utilized. They include NOAA-GOES, NOAA-AVHRR, and DMSP-OLS (Robinson 1991).

The TOMS UV aerosol index is used to map the spatial distribution of the UV absorbing aerosols. With the launch of the 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 um 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 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 (Kennedy *et al.* 1994).

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.

Hamilton *et al.* (1989) discuss the usefulness of GIS for wildfire modelling. They integrated data on topography, weather, and vegetation types, to calculate rate of spread and fireline intensity. Vasconcelos and Guertin (1992) developed the FIREMAP model, which uses GIS spread functions for the calculation of the rate of spread, fireline intensity and direction of maximum spread. The main problems in this model relate to the lack of flexibility of GIS spatial operators and the discrete time nature of the simulations. In order to allow for the modelling of temporal changes in weather and fire conditions, Vasconcels *et al.* (1994) propose the use of distributed discrete event simulation (DEVS) for the spatial dynamic modelling of wildfires.

10.4.5.2 Coal fires

Apart from forest and bush fires, coal fires are one of the largest contributors to CO_2 emissions. In 1992 the CO_2 emission was estimated to be 2–3 per cent 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 proven to be very useful. The detection of underground coal fires is limited by the non-uniform solar heating of the terrain. To remove these effects, a DEM can be 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).

10.4.6 Cyclones

Tropical cyclones are intense cyclonic storms which form over warm tropical oceans and threaten lives and property primarily in coastal locations of the tropics, subtropics, and eastern continents in mid-latitudes (World Meteorological Organisation 1995). The term 'tropical cyclones' is often used as a general term for all intensities and locations, including hurricanes, typhoons, tropical storms, tropical depressions, and tropical cyclones. Approximately 80–100 tropical cyclones occur globally in an average year, and their location, season, intensity, and tracks are well documented (WMO 1993).

The following hazards are normally associated with tropical cyclones: strong winds, high ocean waves, flash floods and landslides due to extreme rainfall amounts, and storm surges (which are coastal flooding at the landfall point of the cyclone). In flat areas, the storm surge may reach kilometres far inland and cause considerable loss of life and property damage. The World Meteorological Organisation organizes and co-ordinates tropical cyclone warning centres, in which geostationary satellite imagery is the primary tool for tracking tropical cyclones and estimating intensities. Additional conventional observations, aircraft reconnaissance and numerical model analysis and forecasting, are required for reliable warnings.

Information on the location of the tropical cyclone centres and the way they move can be obtained from weather satellites. The cyclone intensity is estimated using pattern analysis techniques and cloud top temperature information (Dvorak 1984). High-quality animated satellite imagery is used on computer workstations, and objective IR techniques have been developed (CEOS/IGEOS, 1999). Radar images can also provide tracking and intensity information. Doppler radars have been used in locations where tropical cyclones occur.

GIS based emergency systems for cyclone emergency management are used extensively in the south east United States. These provide information including the expected storm surges, which are based on the track and intensity forecast along with a knowledge of the local ocean floor and coastline topography. For evacuation planning, actual evacuation, search and rescue operations and damage assessment, the detailed information stored in the GIS is indispensable.

10.4.7 Environmental hazards

Satellite remote sensing is increasingly being used for mitigation of various environmental hazards. For coastal areas, the accurate location, identification and monitoring of coral reefs, seagrass beds, mangroves, salt marshes, 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, fisheries etc. Large resolution multispectral imagery can be used for small-scale mapping of wetlands, beaches, submerged vegetation, urbanization, storm damage, and general coastal morphology.

Remote sensing can 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.

Remote sensing has been used very successfully to detect illegal oilspills by ships on the open sea. In order to be able to prove these illegal acts, it should be possible to trace the ships leaving behind an oil plume, within a short time period.

For this purpose airborne radar systems have been used, but with the disadvantage that only a very limited level of coverage (both spatial and temporal) could be obtained.

Using satellite based SAR, it is possible to detect oil slicks in a wide range of environmental conditions, day and night, at a considerable reduction in cost compared to conventional techniques. At present, satellite SAR data are used within limited areas due to mission constraints on the attainable revisit and spatial coverage. Results from the current exploitation of the data indicate, however, that a greater reliance on satellite data will develop with the new generation of SAR instruments such as the ENVISAT ASAR and Radarsat-2.

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.

As one of the purely human-made disasters, landmines may be the most widespread, lethal, and long-lasting form of pollution we have yet encountered. At present, about 10 million anti-personnel mines per year have been produced. The production costs of an anti-personnel mine are between 3 to 30 US dollars. The cost to remove a mine is about 300 to 1000 US dollars. In order to accelerate the mine clearance process new demining methods are urgently required. The military has developed remote sensing techniques to detect minefields. Since the need for humanitarian demining has increased, many of these sensors and techniques are now also available to detect minefields from commercially available platforms and sensors. Attempts have been made to detect minefields by combining the results of several airborne remote sensing sensors which are used on test fields. The sensors used cover the optical, infra-red (thermal) or microwave (radar) region of the electro-magnetic spectrum. (http://www.itc.nl/ags/research/posters/minefields_general.htm).

10.5 CONCLUSIONS

The decade of the 1990s, designated as the International Decade for Disaster Reduction, has not resulted in a reduction of the losses due to natural disasters. On the contrary, statistics show a rapid increase, both related to an increasing vulnerability of a large part of the Earth's population, as well as to an increase in the number of weather related events. However, there has been a commensurate increase in the technological capabilities and tools that can be used in disaster management. Some of these tools deal with the collection and management of spatial data, such as remote sensing and GIS. Although no satellite was specifically designed to be used in disaster mitigation, most have demonstrated their usefulness in disaster prevention, preparedness and relief.

For several types of disasters, the use of Earth observation techniques has become operational in the warning and monitoring phases for cyclones, drought, and to a lesser extend floods. The operational applications mainly use imagery with low spatial resolution, coming from meteorological satellites or NOAA-type satellite.

For many weather related disasters, obtaining cloud-free images for damage assessment is often impossible. For some types of disasters, such as floods, debris flows or oil spills, SAR is a proven solution. For other types of disasters (e.g. landslides, earthquakes) detailed optical images should be used.

In the phase of disaster relief, satellite remote sensing can only play a role in the identification for large (affected) areas. For example, structural damage to buildings cannot be observed with the poor resolution of the current systems. Near Real Time damage become theoretically possible with the availability of the first civilian optical high-resolution imagery (IKONOS), though this will only make a difference if adequate temporal resolution, swath-coverage and ready access to the data can be achieved. The temporal resolution provided by individual satellites, especially considering cloud cover, will not be sufficient, and high-resolution imagery will not become operational in damage mapping unless multiple satellites are used. This capability is of prime concern to relief agencies requiring near-real time imagery to locate possible victims and structures at risk, and also to map any changes to access that may have occurred. In most cases, the availability of GIS databases, containing information about elements at risk, if combined with less detailed images showing the extent of the area affected, will allow for a rapid assessment of the number of persons and buildings affected.

In view of the limitations inherent to the data collection and analysis techniques and the restrictions imposed by the scale of mapping, especially the phase of hazard assessment within the disaster management cycle will always retain a certain degree of subjectivity. This does not necessarily imply inaccuracy. The objectivity, and certainly the reproducibility, of the assessment can be considerably improved by the interpretation of sequential imagery, a quantitative description of the factors considered, as well as defined analytical procedures and decision rules. The most important aspect however remains the experience of the analyst, both with regard to various factors involved in hazard surveys, as well as in the specific conditions of the study area. Due to the difficulty of formalizing expert rules, the use of expert systems in hazard assessment is still not advanced (Pearson *et al.* 1991).

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