Disasters, 2002, 26(2): 140–160

Satellite Remote Sensing as a Tool in Lahar Disaster Management

Norman Kerle
Volcano Remote Sensing Group University of Cambridge

Clive Oppenheimer
Volcano Remote Sensing Group University of Cambridge

At least 40,000 deaths have been attributed to historic lahars (volcanic mudflows). The most recent lahar disaster occurred in 1998 at Casita volcano, Nicaragua, claiming over 2,500 lives. Lahars can cover large areas and be highly destructive, and constitute a challenge for disaster management. With infrastructure affected and access frequently impeded, disaster management can benefit from the synoptic coverage provided by satellite imagery. This potential has been recognised for other types of natural disasters, but limitations are also known. Dedicated satellite constellations for disaster response and management have been proposed as one solution. Here we investigate the utility of currently available and forthcoming optical and radar sensors as tools in lahar disaster management. Applied to the Casita case, we find that imagery available at the time could not have significantly improved disaster response. However, forthcoming satellites, especially radar, will improve the situation, reducing the benefit of dedicated constellations.

Keywords: volcanoes, lahars, Nicaragua, satellites for disaster response.

Introduction

Approximately one-quarter of the world's population currently lives at risk from natural hazards, and economic losses from natural disaster events can exceed US$100 billion annually (Verstappen, 1995; Smith, 2001). Every decade an estimated one million people are killed by natural disasters (Tobias et al., 2000), while annually some 50 events require international aid in response and recovery. We follow the definition of natural disasters as events that result in mortality and damage which exceed the response and recovery capabilities of the affected area, creating the need for outside assistance. The latter aspect underlines the potential for the space technology discussed in this study. Although volcanoes are the cause of only some 2 per cent of all natural disasters (Smith, 2001), their activity has killed more than 220,000 people in the past 200 years. According to Tanguy et al. (1998), of all recorded deaths since 1783 attributed to volcanic activity, close to 40,000 (17 per cent) were caused by volcanic mudflows — or lahars. Scott et al. (2001) put the number of victims from historic lahars in the Western hemisphere alone at 49,000. Nine recorded events have claimed around 1,000 lives or more each.

Published by Blackwell Publishers, Oxford OX4 1JF, UK and 350 Main Street, Malden, MA 02148, USA.

The overall cost of a disaster, both in terms of economic damage and fatalities, depends on how quickly the event is responded to, and how efficiently response activities are managed. This, however, requires a synoptic overview of the affected area in the critical hours following an event, to allow for an orchestrated disaster response. In particular 'adverse public health consequences', that is morbidity and mortality, can be reduced significantly by rapid damage assessment (Garshnek et al., 1998). During a disaster, however, critical lifelines — in particular roads, telecommunication and power supplies — are frequently incapacitated. This leads to limited information from, and impeded access to, the disaster area, consequently hindering an efficient response. Particularly in remote or mountainous terrain, no ground-based survey can provide the comprehensive and timely information required, and aerial reconnaissance may not be possible for logistical or meteorological reasons (Zimmerman, 1991; Luscombe and Hassan, 1993). Satellite remote sensing is seen as a promising tool to provide the necessary intelligence (Alexander, 1991; Zimmerman, 1991).

In this study we investigate the utility of currently operational, non-classified Earth Observation (EO) satellites for lahar disaster management. We consider what information is needed, and which data can be provided by available satellites, both optical and radar, and of high and low spatial resolution. Scientists have frequently noted limitations of satellite technology, chiefly related to low spatial or temporal resolution (detail in the image, and revisit time, respectively), limited utility of optical data in cloudy situations and delays in data availability (Tobias et al., 2000). In recognition of the potential of space-borne sensors, and to overcome some of those limitations, satellite constellations solely dedicated to hazard research and disaster management have been proposed. Given the ever-increasing number of EO satellites, we explore whether such dedicated constellations are indeed necessary, and what organisational improvements may increase the utility of data collected by already-existing and forthcoming governmental and commercial sensors. Data from military satellites have played a role in disaster management in the past. However, since they are not readily available and, therefore, not a predictable source of imagery, they are not further considered here.

The most recent lahar disaster occurred in 1998 at Casita volcano, Nicaragua, when heavy rainfall associated with Hurricane Mitch triggered a small flank collapse, which subsequently transformed into a lahar. Two towns were completely destroyed, and over 2,500 lives lost. After addressing the kinds of information relevant to lahars that satellite technology can provide, we use Casita as an example to test if data from EO satellites operational at the time could have improved the management of that particular disaster.

Lahars as hazards

Among the many volcanic hazards, lahars, also called debris flows or mudflows, assume a unique position in that they can be syn-eruptive, post-eruptive or completely unrelated to eruptive activity. They also occur on the most active of volcanoes, and on ones long extinct. If channelled, they can leave a path of destruction over 200km long; alternatively, they can cover areas of several hundred square kilometres.

A variety of processes can lead to lahar formation. Hot pyroclastic material can melt glacier ice and snow, providing the water subsequently used to mobilise flank materials. Crater lakes or other surface water bodies on a volcano can drain during an eruption or a crater breach, also generating devastating mudflows. Such an event resulted in more than 5,000 fatalities on Kelut (Indonesia) in 1919, and several hundred more in 1966. Similarly, subglacial eruptions can form subglacial lakes that, after an eventual breakout, not only lead to jökulhlaups (breakout floods) but, if sediment entrainment is sufficient, also to lahars. Many lahars are triggered by rainfall. Precipitation may come from an untimely typhoon passing over a volcano (as at Mount Pinatubo in 1991), the annual rainy season, or it may be propagated by volcanic eruptions themselves, when ash particles lead to the nucleation of raindrops. Since lahars are generated by many different agents, and affect inactive volcanoes as much as active ones, they often come unheralded (Scott et al., 2001).

All of the above processes lead directly to lahar formation. A less direct genesis involves transformation of debris avalanches resulting from large volcanic edifice failures (sector collapses; volumes typically >1 km^3) or smaller flank failures. Debris avalanches can lose much of their load during downslope movement and turn into lahars, or even more dilute hyperconcentrated flows (sediment concentrations of 20–60 per cent by volume; Vallance, 2000). Water for those transformations can be provided by entrainment of surface water, but also from released pore water. Hydrothermally altered rocks, common on volcanoes, are particularly efficient in trapping infiltrating rain water because of the impermeability imparted by clay layers, and the large pore space of clay minerals. Infiltrated water accounted for at least 18 per cent of the failure volume of the Casita flank collapse (Scott et al., forthcoming). Conversely, floods can also turn into lahars by eroding colluvium from the volcano's flank, a process known as bulking (Scott, 1988).

It is not always the largest volcanic eruptions that result in the deadliest lahars. While mudflows generated by the powerful Mount St Helens (1980) and Pinatubo (1991) eruptions led to long runout flows and covered hundreds of square kilometres, respectively, neither resulted in the number of fatalities that might have been expected from the vast energy released during both events. Of the 57 people killed during the 1980 Mount St Helens eruption, few fatalities were caused by lahars (K. Scott, pers. comm.), while Pinatubo's lahars killed about 100 (Janda et al., 1997). A much more severe lahar disaster resulted from the minor 1985 eruption of Nevado del Ruiz (Colombia), when the town of Armero was destroyed, with the loss of 23,000 lives. The small eruption of the glacier-capped volcano produced an estimated 2×10^7 cubic metres of meltwater, producing a lahar that travelled over 100km (Rodolfo, 2000). This event demonstrates:

- how the source of a lahar and the affected zones can be quite separated spatially,
- the consequent difficulty of recognising the hazard, and
- the large dimensions of the generated flow.

In addition to immediate casualties, the typically widespread damage of lahars can displace thousands of people (over 50,000 following the 1991 Pinatubo eruption alone; Vallance, 2000) leading to further deaths from famine or disease (Tayag and Punongbayan, 1994).

Volcanic mass movements are distinctly different from non-volcanic ones. This applies to the materials involved, the triggering mechanisms, the transformations occurring during downslope movement and emplacement characteristics. Loose airfall and pyroclastic flow deposits are easily eroded by running water. Hydrothermal alteration can reduce edifice stability, and, in case of flank failure, also provides large amounts of clay, which result in cohesive and highly mobile flows. For that reason lahars tend to cover areas approximately 20 times those of equivalent rock avalanches (Iverson et al., 1998), making them a more substantial hazard. The high sediment concentration results in a consistency similar to wet concrete which, combined with high flow velocities, leads to impact forces as high as 10^4–10^6kg m^{-2} (Rodolfo, 2000). A combination of population growth in many of the countries exposed to volcanic hazards and high fertility of volcanic soil, also continues to put more people in harm's way on the volcanic slopes. Landcover changes induced by anthropogenic activity, such as deforestation, in turn reduce the hydraulic roughness of the flanks, which leads to more severe lahar events (Scott et al., 2001).

Management of natural disasters

Vast resources and efforts have been expended on hazard and disaster research in recent decades. Good progress has been made in understanding and monitoring the hazards that lead to disasters. Droughts are detected in their early stages, allowing the anticipation of famines and forest fires that ensue. Scientists know more about when a volcano will erupt than ever before, and track developing hurricanes and issue warnings with increasing accuracy. Hazard awareness also continues to increase, aided as much by governmental efforts, such as Japan's earthquake awareness and preparation programmes, as by NGOs conducting community work. Yet despite such progress, the number of natural disasters has continued to rise, matched by increasing economic damage. This is primarily a result of increasing accumulation of wealth in hazardous areas, but also a consequence of rising vulnerability (Smith, 2001). Population growth remains high in many developing countries, resulting in stretched resources and an ever-increasing marginalisation of the poorest population fraction. Without access to hazard-related information (or proper education in general), access to resources ranging from suitable building materials to insurance, and simply lack of choice in where to settle, vulnerability is unlikely to decrease on a global scale. Especially in poorer countries, the setback (or reversal) of economic progress following a natural disaster can be significant and lasting, as was demonstrated during the Mozambique floods in 2000, or by Hurricane Mitch's effect on Honduras in 1998 (Glantz and Jamieson, 2000).

Understanding the hazards and reducing vulnerability are the keys to prevent disasters. However, despite such coordinated efforts as the International Decade of Natural Disaster Reduction (IDNDR; the 1990s), connected with some optimistic expectations of a halving of economic damage by the end of the decade, disasters remain a reality. Therefore, in addition to preventive measures, disaster response and management must be improved as well.

Natural disasters typically exceed the capabilities and resources of the affected region or country to deal with the effects, causing them to require outside assistance. This creates opportunities for a more adequate disaster response, as additional means and resources become available (virtual, in the form of expertise, as much as physical, such as food and equipment). Conversely, outside involvement can also create confusion. Disaster response frequently proceeds in an ad hoc fashion, where the

Table 1 Advantages and disadvantages of satellite remote sensing as a disaster management tool. Disadvantages preceded by • will diminish with future satellites; the ones preceded by ✶ are likely to lose relevance as well

Advantages	*Disadvantages*
Synoptic, continuous coverage	• Insufficient spatial and temporal resolution for many applications
Availability of pre-event, reference imagery	• Delayed initial image acquisition, especially for non-pointable sensors
Variety of complimentary sensors (radar and optical, and high and low spatial resolution)	• High cost of imagery
Availability of increasingly sophisticated and easy-to-use software and algorithms	• Low number of operational radar (i.e. all-weather) satellites
Overcomes access problems	✶ Typically slow data dissemination
Increased safety (minimal fieldwork)	✶ Lack of central inventory of available satellites and their current location
Almost unlimited number of sample points (area- rather than location-specific sampling)	✶ Frequent data incompatibility problems
Easy integration of GIS, elevation and map data, to generate imagery-derived map products–IDP	✶ Large image-file size, which makes electronic use/dissemination in the field difficult
Pointable sensors allow acquisition of stereo-images or elevation data	✶ Lack of global coverage by ground receiving stations for some satellites, resulting in incomplete coverage
Visual, yet quantitative data	Limited use of optical sensors in cloudy situations
Images can be archived and reused, to check repeatability of a method, or to test a new theory	Unfamiliarity of disaster managers with satellite imagery and their use
Rapidly increasing sophistication of satellites	Variable equatorial crossing times (and, consequently, variable illumination) of some polar orbiters
More than 20 additional EO satellites scheduled for launch within the next three years	

military, governmental agencies, NGOs, international aid organisations and support groups and foreign experts try to manage the crisis. The situation is exacerbated by a lack of information and reduced access to the site, which prevent a comprehensive damage assessment. Following the Gujarat earthquake in January 2001, it took almost three days even to identify affected remote villages (Louis, 2001). Similarly, the first aerial survey of southern Florida following Hurricane Andrew in 1992 only took place two days later (van der A et al., 1994), demonstrating that this is not a problem only endemic to less-developed countries.

Remote sensing as a tool in disaster management

The Earth is currently being monitored by some 18 (non-classified) optical EO satellites of medium to high spatial resolution (60m or better), and several satellites with low-resolution optical, or radar sensors, all generating a continuous, vast amount of image data (see Figure 1). The potential of satellite technology for hazard assessment, disaster prevention and preparedness, in-disaster response and

Table 2 Proposed or conceptualised satellite constellations dedicated to hazard assessment and disaster management

Constellation name	*Characteristics*	*Reference*
Constellations being built		
Disaster Monitoring Constellation (DMC)	• Built by Surrey Small Satellite Technology Ltd. (SSTL), to be completed in 2003 • 5 optical micro-satellites in polar orbit at 686-kilometre altitude • 36m resolution, capable of visiting the same area once a day • Each satellite is owned by a different country, but imagery is expected to be shared globally in case of a disaster	Sun et al., 2001
COSMO/ SkyMed	• Built by Alenia Spazio, Italy; SAR constellation to be operational by 2005 • Designed primarily for the Mediterranean region, but capable to global service, focusing on sea pollution and coastal monitoring in addition to disaster monitoring • Two separate sun-synchronous orbits at 600km altitude • Four radar satellites (X-Band; 3.2cm); three multi-sensor optical (one high-resolution panchromatic, one medium-resolution multispectral sensor; one medium and one low-resolution hyperspectral sensor)	Galeazzi, 2000; P. Laberinti of Alenia Spazio, pers. comm.
FUEGO (also called FOC – Fire Observation Constellation)	• Designed for forest fire detection and management in southern Europe; operational in 2004 • System allows reliable detection of fires within 20 minutes, providing subsequent fireline and temperature information every 30 minutes • Only covering latitudes up to 47.5° N-S, due to highly inclined obits (135.5°), which allow high temporal resolution coverage with only 10 satellites in two orbit planes	Tobias et al., 2000; Martín-Rico and Gonzalo, 2001
Other proposed constellations		
Global Disaster Observation Satellite System (GDOS)	• Proposed by members of the Society of Japanese Aerospace Companies • Upgraded version of World Environment and Disaster Observation Satellite System (WEDOS) • Constellation should provide all-weather data within 24 hours after an event • 24 sun-synchronous orbiters, supported by six geostationary relay satellites • At least daily revisit at 15m resolution (180km swath) in non-disaster times • All-weather capability at 5m resolution, during disaster at 2 m over a 40km swath • First observation within two hours of disaster, subsequent visits every two hours	Kuroda et al., 1997
Global Emergency Observation, Warning and Relief Network (GEOWARN)	• Proposed by NASA • Six satellites, supported by 30 dedicated aircraft operating out of 20 airbases • Initial use of existing meteorological and commercial observation satellites (SPOT, Landsat etc.), dedicated GEOWARN satellites in final phase	van der A et al., 1994

	• Data processed in semi-autonomous multinational centres (one per continent) • Initial airborne, later space-borne, radar data acquisition • Plans to build a comprehensive GIS, archive all imagery, to improve disaster response • Close cooperation with UNDRO, WMO and FAO	
None	• Lack of timely radar information spawned conceptualisation of SAR network, integrated with existing optical sensors • Four SAR satellites, allowing initial coverage within 12 hours of a disaster (at latitudes above 40 degrees, and with pointable radar sensor) • X-Band radar, with selectable horizontal or vertical polarisation • Spatial resolution of 3m over 40km swath (stripmap mode), or 20m over 120, and 30m over 200km (scansar submodes)	Tobias et al., 2000
None	• Proposed by Alcatel Space Industries • Six X-band SAR satellites in sun-synchronous orbit • 2m spatial resolution over 20km swath (stripmap mode), or 20m over 100km swath (scarsar mode) • From 480km orbit, initial access within 24 hours; 12 satellites required for 12-hour access	Tobias et al., 2000
Other concepts		
None	• Small (250–400kg), inexpensive satellites, with spatial resolution of 10–30m in dense constellation are seen as the key to provide high temporal resolution coverage • Up to 32 satellites are needed for global 30-minute revisits • Data collection by each country to avoid large central database	Iglseder et al., 1995
DisasterSat	• Conceptualisation of what information is necessary and how it can be obtained, also in terms of organisational changes. Options include: system modelled after a proven system such as SPOT (expensive); a new system of small and inexpensive satellites (unproven technology poses risk); establish agreement with commercial companies to pre-empt image acquisition in times of disaster; build a system and lease it to a commercial company for operation, with right to pre-empt image acquisition schedule during a disaster • Revisit-frequency of approximately 16 hours is possible with three satellites in 69º inclination (coverage up to 72° N-S)	Zimmer-man, 1991
None	• Chinese proposal • Six small satellites, including two radar and four optical orbiters (wide-FOV multispectral sensors, two also with infrared, the other two with hyperspectral scanners)	Qi-Zheng and Ming, 2000

management, and post-disaster relief has been emphasised repeatedly (for example, Luscombe and Hassan, 1993; Walter, 1994; Iglseder et al., 1995), and is reflected in over 400 scientific articles on the use of remote sensing in hazard and disaster research between 1972 and 1998 (Showalter, 2001). The advantages of remote-sensing technology listed in Table 1 explain such high expectations. With the ever-increasing number of sensors continuously monitoring the globe, synoptic coverage, either in the optical or microwave (i.e. radar) region (or both) should, in theory, be obtainable relatively quickly after a disaster, and allow a much more informed response to an

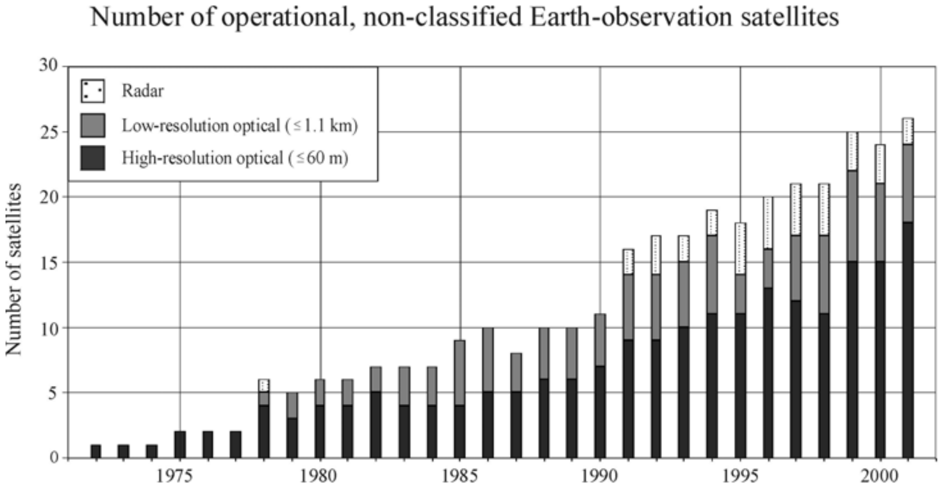

Figure 1 Number of operational, non-classified Earth-observation optical and radar satellites. Graph only includes sensors with spatial resolution of 1.1km or better, as a lower resolution is of limited value in mapping the effects of natural disaster. Satellites on standby are included

event. Additionally, available image archives can provide reference information of the pre-disaster situation. Especially for assessing the situation in more remote places, which are frequently only reached days or even weeks after an event, a detailed inventory of affected settlements and infrastructure may save many lives and speed up recovery. Note, however, that the required information is disaster specific. Following an earthquake, for example, information on the spatial extent and the severity of structural damage is needed, as are data on interrupted lifelines and fires caused by the event. During a flood, measurements of changes in water height over time are as important as the extent of the floodwater itself. In addition, the onset time for different disasters varies greatly, from seconds/minutes (e.g. earthquakes, lahars), to weeks/months (e.g. drought), the latter allowing more time for the acquisition of suitable imagery.

Despite the high potential of the technology, the disadvantages listed in Table 1 explain its continued under-utilisation (e.g. Walter, 1990; San Miguel-Ayanz et al., 2000). Some of those disadvantages indicated, however, have already begun to diminish. Ikonos-2, successfully launched in 1999, and eagerly awaited by the disaster response community, is the first non-classified satellite to provide 1m-resolution optical (panchromatic) imagery at significantly lower cost than previously available data. Several other disadvantages will probably become less relevant as well with future satellites. Because of the varied problems of existing sensors, however, satellite constellations solely dedicated to hazard assessment and disaster management have repeatedly been proposed, most of them including optical and microwave sensors, and characterised by a rapid response time following a disaster, as well as subsequent high temporal and spatial resolution coverage of the scene (see Table 2). Note that some constellations are only theoretical concepts, based on how the 'perfect' array of sensors would have to be shaped, while others are actual practical blueprints, specifying technical details as much as the needed organisational structures. Dedicated satellite constellations have been discussed for more than a decade, yet even with the IDNDR, none has become operational. Currently three systems are actually in the construction

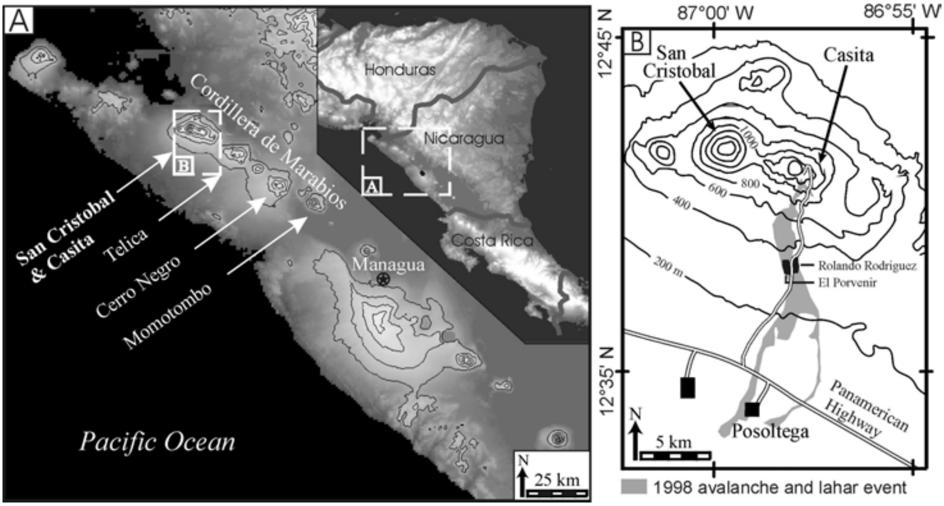

Figure 2 Map showing the location of Casita volcano (A), and the extent of the 1998 debris avalanche and lahar event (B). The destroyed towns are indicated. In the distal runout zone, the flow crossed the Panamerican Highway, destroying several bridges, and causing damage and fatalities in Posoltega

stage, of which Surrey Satellite Technology Ltd's (SSTL) Disaster Management Constellation (DMC), a modest array of five optical, 36m spatial-resolution sensors, is the only one designed for global coverage. COSMO/SkyMed was devised primarily for the Mediterranean region, FUEGO for southern Europe. Given these limitations, a further detailed assessment of the capabilities of currently operating and forthcoming sensors as tools in disaster response and management is useful.

In the following sections we introduce the 1998 Casita lahar disaster, and describe how satellite technology can aid in information collection, and therefore disaster management, by assessing whether image data available at the time could have led to an improved disaster management. The conclusions reached in this study are not strictly limited to the Casita event, nor, indeed, to lahars in general. From a remote-sensing viewpoint, mudflow disasters combine some of the major challenges posed by other disasters, which makes them perhaps the most difficult type of calamity to manage. The extensive destruction caused by lahars is similar to flooding, storm and earthquake damage. In addition, lahars frequently occur unexpectedly (again, similar to earthquakes). Lahars are also either directly associated with clouds (when rainfall-triggered), or occur at volcanic structures where, due to orographic reasons, clouds are common. This necessitates all-weather imaging capabilities.

A ground-based view of the Casita lahar event

In October 1998, Hurricane Mitch devastated large parts of Nicaragua and Honduras. The highest total rainfall was confined to a small area in north-western Nicaragua, the location of Casita volcano within the San Cristobal volcanic complex (Ferraro et al., 1999; see Figure 2). The event occurred at the end of the rainy season (April to October), which had already brought more than 2.2m of rain. An additional 750mm of infiltrating rainwater further increased the instability of a structure weakened by intense hydrothermal activity and deformation (van Wyk de Vries et al., 2000). On 30 October, a small collapse (approximately 1.6 x $10^6 m^3$; Kerle, forthcoming) occurred on the south-western flank, leading to a debris avalanche that descended southwards through an existing gully. The avalanche transformed into a hyperconcentrated flow when the coarse bedload was outrun by the progressively dilute peak wave. This watery flow subsequently entrained colluvium from the lower flanks (i.e. 'bulked'), and, approximately 2.5km from the source, a lahar formed. Closely following the existing topography, the flow spread out to a width of over 1km and, some 6km from the source, arrived at the towns of El Porvenir and Rolando Rodriguez as a wave exceeding 3m in height, killing over 2,500 people. Farther downstream, the flow returned to hyperconcentrated levels, and followed existing riverbeds for more than 25km towards the Pacific Ocean. The flow destroyed several bridges along the Panamerican Highway, and killed several more people in the town of Posoltega. The material deposited by the event shows great variability, ranging from coarse debris avalanche deposits, dominated by cobbles and boulders, to very fine, fluvial deposits in the distal runout area. The actual lahar deposits are characterised by pebbly clasts in a muddy matrix; however, a dense layer of wooden debris dominated the scene.

Despite the heavy rainfall, the Casita flow event occurred unexpectedly. No lahar hazard had been recognised for the volcano's lowlands, and no warning was issued when the flank collapsed. Indeed, the flow arrived at the towns after only 2.5–3 minutes (Scott et al., forthcoming). The event received a slow official response, with Nicaraguan soldiers, hindered by restricted access, only arriving at the disaster scene two days after the event, likely increasing mortality. Since no disaster response plans for such situations existed, crisis management only began some time after the event. For a more detailed description of the flow, its transformations and sedimentology, see Scott et al. (forthcoming), and Kerle and van Wyk de Vries (2001).

Remote sensing applied to lahar disasters

In increasing our understanding of the Casita event, remote-sensing imagery, both air- and space-borne, has been vital. Aerial photographs have allowed structural mapping of the volcano, and the identification of edifice deformation (van Wyk de Vries et al., 2000), to which the 1998 flank collapse has been linked (Kerle and van Wyk de Vries, 2001). Elevation information extracted from pre- and post-event aerial imagery has allowed the calculation of the initial failure volume (Kerle, forthcoming). Lastly, a comprehensive assessment of the Casita flow deposits, its drainage structure and morphology, as well as the damage caused, was carried out, using Advanced Very High Resolution Radiometer (AVHRR) and SPOT data, aerial photos and radar images. In this article, a summary of the findings relevant to disaster management is provided. For the complete study see Kerle et al. (forthcoming).

In a disaster-response situation similar to the one at Casita, information of primary concern is on extent and dimension of the flow, damage to life and infrastructure (including access to the area) and the total number of people potentially affected. In addition, information on the actual nature of the event, the material involved, the source of the flow and the potential of further flows are of interest. The effect of a lahar on infrastructure is radically different from damage induced by flooding. Because of their sediment load, fast-moving lahars easily destroy bridges and settlements. Not a single foundation remained of the houses in the direct path of the Casita flow; indeed, the destroyed towns could initially only be located by GPS. Access to disaster areas can be restricted, especially in long-runout events and high-relief areas. Identifying such problem areas, as well as alternative access, is also critical.

From currently operational satellites, three general types of data are potentially available: low spatial resolution optical; high spatial resolution optical; and Synthetic Aperture Radar (SAR) data. The most significant differences in terms of information content exist between optical and radar. While the energy recorded by optical sensors is a function of the chemical characteristics (the molecular bonds and electronic structure) of the imaged surface materials, radar data are an expression of the physical and electrical properties of the surface illuminated by an active sensor. Optical sensors operate primarily in the part of the electromagnetic spectrum the human eye can perceive, and, therefore, result in images similar to the photographs we are familiar with. In addition, most optical sensors provide information in the near-infrared (NIR), some also in the mid-infrared and thermal parts of the spectrum. Data collected by a SAR sensor depend on the moisture of the ground material, its surface roughness, the incident angle of the radar signal as well as the local incident angle (which depends on the local slope), and polarisation (the orientation of the electric field) of the emitted and received radar signal. Optical and radar data are almost uncorrelated, and have been shown to be complementary (for example, Koopmans and Forero, 1993).

Lahar detection and assessment using optical imagery

In a cloud-free situation, optical data would show clearly the lahar deposition area, as its colour (typically greyish-white to yellow or brown) is usually different from the surrounding area. Whenever lahars destroy healthy vegetation, NIR bands can be used to map those areas, for example using a Normalised Difference Vegetation Index (NDVI) image. This is because of vegetation's high NIR, and low visible reflectance. Standing or running water located in the deposition area would also be detectable in NIR bands, such as Landsat TM's band 4 (0.76–0.90 μm). The larger amount of suspended sediment in running water would be apparent in the optical bands, allowing the detection of flow mobility. Identification of structural damage, as well as restricted access to the site, depends on the sensor's spatial resolution and the dimensions of the features. With sensors covering large areas (wide field-of-view), such as TM or SPOT (Système Probatoire d'Observation de la Terre), with spatial resolutions of 15 and 10m (panchromatic), respectively, damage to individual houses will not be detectable, but large-scale damage will be apparent. Damage quantification is aided by pre-disaster reference imagery, which allows images of change to be produced. Problems may arise with archive images acquired with another sensor, from a different viewing angle or under different illumination and atmospheric conditions, although methods exist to remove some of those effects and allow for an accurate change detection (Mas, 1999). Damage to access roads or individual bridges can often only be inferred from image context, which is facilitated by some knowledge of the area. Infrastructure in high-relief areas is generally more vulnerable to damage by lahars than in flat terrain, where affected zones can usually be bypassed.

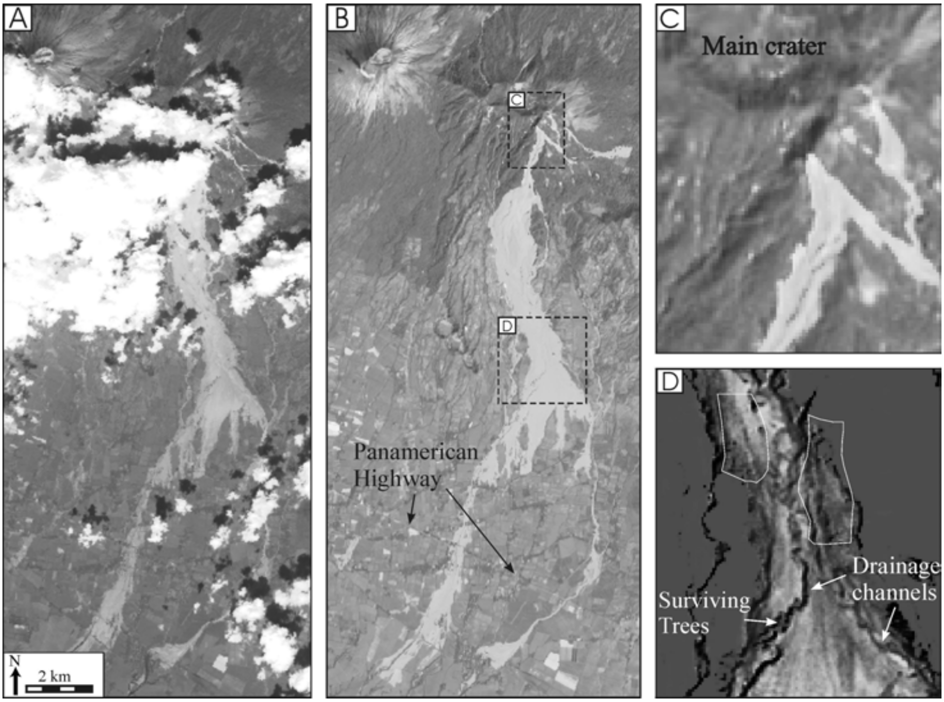

Figure 3 SPOT scenes showing the extent of the Casita lahar deposits. The first post-event scene, acquired on 16 November 1998, is heavily cloud contaminated (A). An image captured on 25 November (26 days after the event) shows good detail on the extent of the flow deposits (B), Casita volcano as the source (C), and drainage structure within the deposits (D). The spatial detail is sufficient to highlight features such as the Panamerican Highway, which was crossed in two places (B), but not enough to show damaged houses or small settlements. No trace remained of the destroyed towns, indicated in (D). Note that the original imagery is multispectral (3 bands for the 25 November image), showing more detail in a false colour composite than is apparent in the greyscale images shown here. For example, surviving vegetation (indicated in (D)), can be identified by its NIR signature

Several researchers have pointed out the limitations of satellite data in mountain hazard applications, related to geometric distortions and scale variation or shadow caused by high relief (for example, Rengers et al., 1992; Buchroithner, 1995). The latter also propagates atmospheric effects, ranging from orographic clouds to differences in atmosphere thickness, which causes problems for atmospheric correction (Buchroithner, 1995). However, Song et al. (2001) showed that operations such as change detection may not require such corrections.

With daily revisits, NOAA's AVHRR (1.1km spatial resolution at nadir) currently is the EO satellite with the highest temporal resolution (apart from low spatial resolution weather satellites). However, because of greatly reduced spatial resolution (detail) away from nadir, occasional night-time imaging, and persistent cloud cover, the

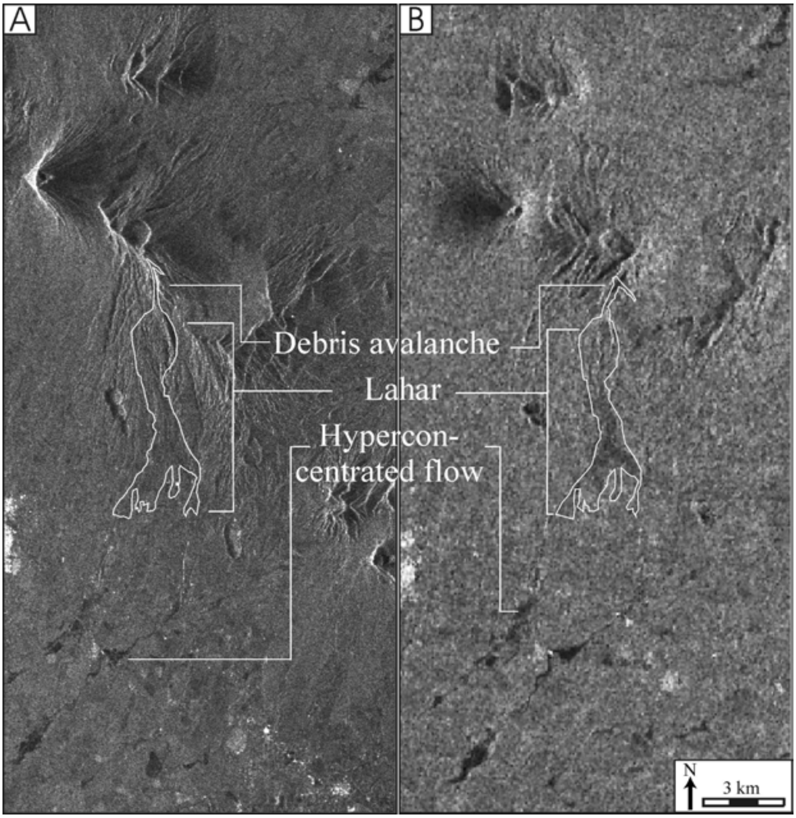

Figure 4 Post-disaster radar images. ERS scene acquired on 20 November 1998 (A), and RADARSAT image of 3 November (B). ERS did not manage to image the main flow deposits (outlined), while the area appears slightly darker than the surroundings in the RADARSAT scene. The distal fine-grained, fluvial deposits left by the hyperconcentrated runout flow appear dark in both images because of specular reflection. See text for discussion. Note the geometric distortion in both images, especially in the summit area

first useful daytime AVHRR image of Casita was only acquired on 13 November, two weeks after the event, and clearly of no operational use (inset in Figure 5). Even if a useful image had been acquired earlier, an analyst without knowledge of the actual flow would probably have been unable to detect it. This is because of the small size of the deposition area (approximately 12km^2) relative to the pixel size, noise from remaining clouds and integration of deposition area and surrounding land, which dilutes the signal contained in a pixel ('mixed pixels'). The image also does not contain enough detail to assess structural damage and reduced access.

Unless especially programmed, SPOT has a nominal revisit time of 26 days. With three satellites in orbit (one on standby), in theory, every place on Earth can be visited daily. This requires a dedicated use of the sensor's pointing capability. Pre-empting existing SPOT acquisition schedules, however, costs up to US$1 million (Zimmerman, 1991), and was not done for the Casita event. The first post-event SPOT scene, heavily cloud-contaminated, was only acquired on 16 November, a cloud-free image was taken on 25 November, 17 and 26 days after the event, respectively (see

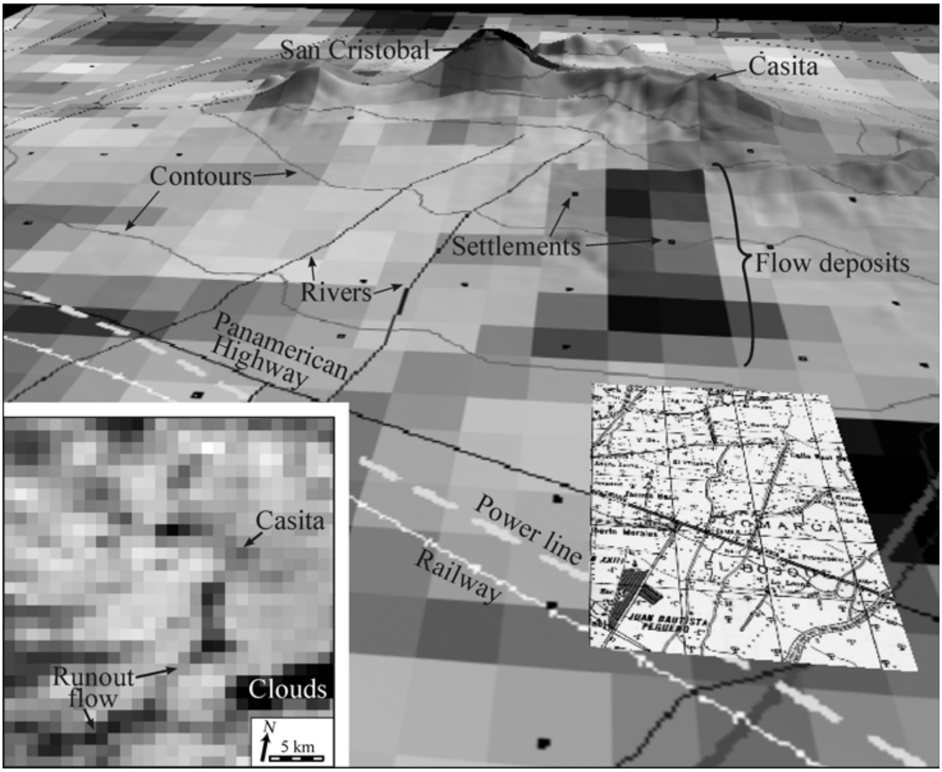

Figure 5 Greyscale reproduction of an enhanced multispectral AVHRR scene acquired on 13 November 1998, showing the Casita flow deposits in relation to lifelines and infrastructure within a GIS environment. Despite the low spatial resolution it is apparent that at least one settlement was affected by the lahar, and that the subsequent runout flow probably crossed the Panamerican Highway. However, because of pixel integration the flow appears wider (2 pixels=2.2km) than it actually is (approximately 1km). Flow identification is also obstructed by clouds and other spectrally similar surfaces. Note that elevation, map (here only included as a subset for illustration purposes) and GIS data greatly facilitate image interpretation; compare with raw image (inset)

Figures 3A, B). As with AVHRR, neither would have been of use as a fast-response tool, and earlier images would probably have suffered from the same cloudiness seen in the AVHRR scenes. The cloud-free, multispectral image (20m resolution) clearly outlines the extent of the flow, its source (Casita volcano) and its internal drainage structure (see Figures 3C, D). Some ambiguity regarding the nature of the flow remains, however. The SPOT image alone does not reveal if the flow resulted from a breached crater lake or similar body of surface water generated by the hurricane's rain, or a flank collapse (see Figure 3C).

Despite the high spatial resolution, direct damage assessment is also difficult. No trace remained of the towns, and therefore, without knowledge of their existence, they would not get classified as destroyed or damaged. Because of the towns' small size, the widespread use of natural construction materials, and trees hiding buildings, even available pre-event reference images may not have revealed them. Similarly, lifelines (for example, power lines) cannot be seen, and damage to the Panamerican Highway can only be inferred from the flow crossing it in two places (see Figure 3B).

Lahar detection and assessment using radar imagery

Based on technical considerations, lahar identification and delineation could be more difficult using radar data. For successful detection, the deposition area would need to have morphological or electrical characteristics that are significantly different from those of the surrounding area. This may not necessarily be the case. Depending on the particle size distribution of the deposited material, which typically ranges from clay fraction to occasional metre-size boulders, the complex return signal may not be distinguishable from the non-affected areas, even if the actual surface material is radically different. Similarly, following a rain-induced lahar, the moisture content of the unaffected land may be as high as that of a freshly drained lahar-deposit, making delineation of the deposits impossible. An analyst's ability to map and characterise the disaster area largely depends on the properties of the specific radar sensor. A change in either incident angle, wavelength or polarisation significantly alters the return signal. In areas with vegetation, a short wavelength (say, ERS or RADARSAT's C-Band (5.6cm)) may be the most useful, as multiple reflections within the canopy (volume scattering) would allow the mapping of unaffected vegetation. Standing water would be the most easily detected feature, appearing dark on an image because of specular (i.e. mirror-like) reflection.

Geometric distortion, inherent in any radar image, can prevent a successful assessment of the disaster scene. The volcanic structure responsible for a lahar can be severely distorted by layover and foreshortening, which, depending on the azimuth of the radar wave, can compress or mask part of the deposition area, as well as the damaged or access-impeded terrain (see Figure 4). The distortion largely depends on the incident angle; for example, smaller angles, such as ERS's 23°, result in more significant layover than JERS's 35°. Radar shadow, where topography essentially blocks the obliquely arriving radar signal, has a similar effect. A further disadvantage of radar is that the number of available sensors is very small (currently only ERS and RADARSAT), compared to the fleet of optical sensors. This has implications for revisit times, and, consequently, image availability in the critical hours after a disaster. The radar sensors on ERS and RADARSAT are also comparatively simple, neither allowing multi-polarisation (combinations of vertical and horizontal) nor multi-wavelength imaging. The most useful property of radar sensors, however, is their all-weather, day-and-night imaging capability.

Despite cloud penetration, the difficulty of lahar deposit detection is apparent in the Casita radar images. In the first post-disaster ERS radar image, taken on 20 November, the deposits are not apparent (Figure 4A), and only indistinct in a RADARSAT image taken on 3 November (Figure 4B). Only the distal runout areas are clear, which appear radar-dark because of the specular reflection of the smooth fluvial deposits. Even if the debris avalanche or lahar deposits differ significantly from the surrounding land (in terms of roughness or electrical properties), it is not recorded by the sensors. Radar was used successfully on Pinatubo's smooth lahars, which appeared dark in images (for example, Chorowicz et al., 1997; Garcia et al., 1997). The difference is, that the Casita lahar is not ash derived, but composed of coarser avalanche material and remobilised colluvium. In addition, the wooden debris greatly increases surface roughness. RADARSAT, despite its identical wavelength to ERS, is more successful at imaging the flow. This is probably due to its higher incident angle (31–46°, compared to ERS's 23°), which has produced better results in imaging similarly rough forest clearcut areas (Yatabe and Leckie, 1995). Even though both images reveal little about the flow deposits, they nevertheless show the absence of lasting flooding as the result of the flow.

Similar to images of change produced with pre- and post-event optical imagery, a coherence image can be produced from radar imagery. The radar signal contains information on both amplitude (back-scatter intensity) and phase. The latter is a function of the time delay between radar wave transmission and return signal reception. If a pre- and post event pair with a sufficiently short baseline (distance between the positions of the sensor during image acquisition) exists, the coherence, or interferometric correlation, can be computed. This reflects physical changes in the observed area, such as lahar deposition. At Casita this technique was not useful, as correlation was lost due to dense vegetation.

Integration of auxiliary datasets

Given that the spatial resolution sets a limit on image detail, damage assessment can benefit considerably from the integration of accurate large-scale maps, digital elevation models (DEM) and Geographic Information System (GIS) data on infrastructure and settlements. All of which information is becoming increasingly available for many countries. In particular GIS data are easily updated and expanded, and can thus be available immediately after an event. For example, Jiang and Cao (1994) reported on a successful real-time, GIS- and radar-based system for airborne flood monitoring. Auxiliary information is useful because smaller features, for example power lines, require imagery with very high spatial resolution to be detectable, while virtual elements, such as administrative boundaries, are not visible at all. Elevation data, especially in form of DEMs, greatly aid image analysis by adding topographic information.

At Casita, all image types used individually showed limitations, which were partially offset by synergistic effects when used in combination with other data. Image analysis and damage assessment at Casita were improved greatly by the use of auxiliary spatial datasets. Figure 5 shows the AVHRR image of 13 November in a GIS setting. Note how the information that is not directly apparent in the image (e.g. on settlements, lifelines, but also on elevation) can be related to the flow. Casita is clearly the source of the event, and at least one settlement was affected. The integration of GIS data also imparts map-like qualities to satellite imagery, making it easier to comprehend for disaster management personnel not trained in image analysis.

Discussion and conclusions

Utility of current remote sensing technology in lahar disaster management

The globe is currently being monitored by some 18 EO satellites of medium to high spatial resolution, providing a continuous stream of image data. The potential of satellite technology in all phases of a disaster has been recognised, yet despite increasingly sophisticated (and easy-to-use) image analysis software, and the introduction of remote sensing in many areas outside academia, the systematic use of remote sensing in disaster management has been slow.

Time is of critical importance, with the value of remote-sensing data diminishing at an exponential rate following a disaster (San Miguel-Ayanz et al., 2000), and any delay aggravating the situation (Luscombe and Hassan, 1993). This is reflected in rapid initial response as a key parameter in proposed dedicated satellite constellations. In several studies it has been argued that initial image acquisition within a few hours of an event is necessary (e.g. Kuroda et al., 1997; Tobias et al., 2000). Currently, however, non-pointable sensors with long revisit times, delays in (and high cost of) custom image acquisition and data dissemination continue to undermine the technology's potential. For example, an emergency image acquisition with RADARSAT requires advance programming, leading to delays of between 31.5 and 58 hours (F. Debroux of Radarsat Intl., pers. comm.).

As demonstrated in the Casita case, the utility of remote-sensing data strongly depends on the disaster type and its onset time. Extensive flooding is arguably the easiest to detect, as standing water is readily imaged with radar, which also disregards cloud cover. With available imaging technology, lahars provide a more serious challenge. The typically rapid, unexpected onset leaves no time for satellite re-programming, while clouds render optical imagery useless. The currently operational radar sensors, not sufficient in number to provide a fast, global response, also have difficulties in imaging lahars rougher than the Pinatubo-type, ash-derived flow deposits. Radar's inability to image damage to infrastructure and lifelines further diminishes its value as an operational tool.

To improve the current situation, the following technical improvements are necessary:

- an increased number of both optical and radar satellites, to ensure complete, global coverage at higher temporal resolution;
- pointability for all sensors to reduce revisit times;
- multi-frequency and -polarisation radar image acquisition;
- better standardisation of data formats; and
- faster (internet-based) data dissemination.

Expectations for the near future

At least 20 additional EO satellites are scheduled for launch within the next three years, most of them characterised by high spatial resolution as well as pointable sensors. Of particular interest for lahar detection are RADARSAT 2, PALSAR and ENVISAT's Advanced Synthetic Aperture Radar (ASAR), all characterised by multi-polarisation and variable incident angles, with RADARSAT 2 providing very high (3m) spatial resolution and three-day revisits. PALSAR will also use a longer wavelength (L-Band; 24cm), which has been found useful for lahar delineation (Mouginis-Mark, 1995; Guo et al., 1997). The new high-resolution benchmark for optical data set by Ikonos-2 will be improved further by Quickbird, which is expected to provide 0.61m (panchromatic) and 2.5m (multispectral) resolution images from early 2002 onwards. Such a level of detail will have profound implications for damage assessment. The expanding fleet of concurrently operating spacecraft will also increase the probability of suitable imagery being available shortly after a disaster, regardless of location and local weather.

An attractive alternative to conventional air- and space-based systems could be 'atmospheric satellites', such as NASA's Helios, which is currently being tested. The solar-powered aircraft is designed for continuous, unmanned operations over many months, and will be able to carry scientific instruments (see http://www.dfrc.nasa.gov/Projects/Erast/helios.html). Four advantages for disaster management are: the low cost of operation compared to satellites; a versatility similar to airplanes (not tied to a specific orbit); flexible operational altitude (up to 30,000m), which allows high-altitude synoptic coverage, as well as high spatial resolution imaging from a lower altitude; and possible operation below high-level clouds.

Of the dedicated satellite constellations, SSTL's DMC is expected to be operational in 2003, while SkyMed/COSMO, with four radar and two optical satellites is expected to fly in 2005 (Galeazzi, 2000; P. Laberinti of Alenia Aerospazio, pers. comm.), and FUEGO in 2004.

Organisational requirements

The use of remote sensing in disaster management is dominated by a single challenge: to establish an efficient information flow from image acquisition to the end user. The process begins with the identification of the need for imagery, and ends with useful information supplied to the disaster response forces in the field in as near real-time as possible. Good progress has been made; For example, the International Charter on Space and Major Disasters, signed by the French, Canadian and European space agencies, provides for rapid image delivery in emergency situations. The US Federal Emergency Management Agency (FEMA), although not capable of in-house image analysis, has set up partnerships with the remote sensing community, which provide imagery-derived map products (IDP). In the absence of suitable conventional satellite imagery, FEMA can also draw on classified data through the National Imagery and Mapping Agency (NIMA; see http://www.fema.gov/library/remotes.pdf). Nevertheless, several substantial problems remain:

- With every additional EO satellite, the probability of coverage of any given place at any time increases. This, however, also requires improved organisation and coordination. No single database allows a real-time overview of the current location and orbit of all (non-classified) EO satellites, which is the prerequisite for a timely disaster response.
- Disaster management frequently proceeds in an uncoordinated fashion. A dedicated image analysis and distribution needs to converge with the efforts of all parties involved in the management in the most efficient way. One possibility is to use established, largely internet-based, information networks, such as Reuter's AlertNet (http://www.alertnet.org) and ReliefWeb (http://www.reliefweb.int), managed by the Office for the Coordination of Humanitarian Affairs.
- The expense of satellite imagery is seen as a challenge, which, together with their unfamiliarity intimidates disaster managers in the field (J. Hall of FEMA, pers. comm.).
- Lastly, the financial benefit of a dedicated satellite system for disaster management is not always clear. Once a disaster has occurred, remote sensing imagery can only help to make response actions more efficient. This may save lives, but does not

necessarily reduce the cost (in economic terms) of a disaster. Using satellite imagery during the crisis management will also not reduce people's vulnerability or prevent future disasters. Satellite technology's strongest potential, therefore, lies in the study of hazards and the monitoring of developing potential disasters. For that, however, no dedicated satellite constellation is needed. FUEGO can be regarded as an exception. Due to the dynamics of forest fires, the high spatial resolution imagery to be provided at 30-minute intervals is essential for efficient fire fighting, any delay results in high cost from lost forest. A cost-benefit analysis has shown the viability of the system (Martín-Rico and Gonzalo, 2001).

From the Casita disaster we can conclude that satellite imagery, even if data had been available, would have been of very limited use in the first days following the disaster. The area was too cloudy to allow useful optical images to be acquired, and neither of the available radar satellites would have provided the information needed by disaster managers. Given the proximity to existing military infrastructure, an airborne survey would have been the most appropriate and useful response.

With new satellites expected to become operational in the near future, the situation will improve considerably in terms of reduced response and revisit times, better spatial and spectral resolution, increased capabilities of the radar sensors, but also increasingly available auxiliary datasets. In addition to the constellations being built, those forthcoming sensors, especially radar, will offer significant opportunities for disaster management. To maximise that potential, however, a dedicated information chain from image acquisition to the disaster managers in the field is necessary.

Acknowledgements

The SPOT scenes and the RADARSAT image were provided by the Nicaraguan government (Instituto Nicaragüense de Estudios Territoriales). The ERS image was acquired with support from the Centre de Recherches Volcanologiques (CRV). NK would like to thank the German Academic Exchange Service (DAAD), Sidney Sussex College and Cambridge University for financial support. The paper was also improved by comments from several anonymous reviewers.

References

Alexander, D. (1991) Information Technology in Real-time for Monitoring and Managing Natural Disasters. *Progress in Physical Geography* 15(3): 238–60.

Buchroithner, M.F. (1995) Problems of Mountain Hazard Mapping Using Spaceborne Remote Sensing Techniques. *Advances in Space Research* 15(11): 57–66.

Chorowicz, J., E. Lopez, F. Garcia, J.F. Parrot, J.P. Rudant and R. Vinluan (1997) Keys to Analyze Active Lahars from Pinatubo on SAR ERS Imagery. *Remote Sensing of Environment* 62(1): 20–29.

Ferraro, R., G. Vicente, M. Ba, A. Gruber, R. Scofield, Q. Li and R. Weldon (1999) Satellite Techniques Yield Insight Into Devastating Rainfall From Hurricane Mitch. *EOS* 80(43): 505–14.

Galeazzi, C. (2000) PRIMA: A New, Competitive Small Satellite Platform. *Acta Astronautica* 46(2-6): 379–88.

Garcia, F., P.J. Delos Reyes and J. Chorowicz (1997) Comparison of SPOT and SAR ERS-1 Data in Mapping of Volcanic Deposits on the Western Flank of Pinatubo Volcano. Paper presented at the Third ERS symposium, Florence, 17–21 March.

Garshnek, V., K. Shinchi and F.M. Burkle (1998) Disaster Assessment and Satellite Communication: on the Threshold of a New Era. *Space Policy* 14(4): 223–7.

Glantz, M. and D. Jamieson (2000) Societal Response to Hurricane Mitch and Intra- Versus Intergenerational Equity Issues: Whose Norms Should Apply? *Risk Analysis* 20(6): 869–82.

Guo, H.D., J.J. Liao, C.L. Wang, C. Wang, T.G. Farr and D.L. Evans (1997) Use of Multifrequency, Multipolarization Shuttle Imaging Radar for Volcano Mapping in the Kunlun Mountains of Western China. *Remote Sensing of Environment* 59(2): 364–74.

Iglseder, H., W. Arensfischer and W. Wolfsberger (1995) Small Satellite Constellations for Disaster Detection and Monitoring. *Advances in Space Research* 15(11): 79–85.

Iverson, R.M., S.P. Schilling and J.W. Vallance (1998) Objective Delineation of Lahar-inundation Hazard Zones. *Geological Society of America Bulletin* 110(8): 972–84.

Janda, R.J., A.S. Daag, P.J. Delos Reyes, C.G. Newhall, T.C. Pierson, R.S. Punongbayan, K.S. Rodolfo, R.U. Solidum and J.V. Umbal (1997) Assessment and Response to Lahar Hazard Around Mount Pinatubo, 1991 to 1993. In C.G. Newhall and R.S. Punongbayan (eds.) *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*. Philippine Institute of Volcanology and Seismology and University of Washington Press, Quezon City and Seattle.

Jiang, J. and S. Cao (1994) Real-time Disaster Monitoring System by Using SAR. Paper presented at Microwave Instrumentation and Satellite Photogrammetry for Remote Sensing of the Earth, Rome, 28–30 September.

Kerle, N. (forthcoming) Volume Estimation of the 1998 Flank Collapse at Casita Volcano, Nicaragua – a Comparison of Photogrammetric and Conventional Techniques. *Earth Surface Processes and Landforms*.

—— , J-L. Froger, C. Oppenheimer and B. van Wyk de Vries (forthcoming) Remote Sensing of the 1998 Mudflow at Casita Volcano, Nicaragua. Submitted to *International Journal of Remote Sensing*.

—— and B. van Wyk de Vries (2001) The 1998 Debris Avalanche at Casita Volcano, Nicaragua – Investigation of Structural Deformation as the Cause of Slope Instability Using Remote Sensing. *Journal of Volcanology and Geothermal Research* 105(1–2): 49–63.

Koopmans, B.N. and G. Forero (1993) Airborne SAR and Landsat MSS as Complementary Information Source for Geological Hazard Mapping. *ISPRS Journal of Photogrammetry and Remote Sensing* 48(6): 28–37.

Kuroda, T., T. Orii and S. Koizumi (1997) Concept of Global Disaster Observation Satellite System (GDOS) and Measures to be Taken for Its Realization. *Acta Astronautica* 41(4–10): 537–49.

Louis, P. (2001) Gujarat: Earthquake and After. *Economic and Political Weekly* 36(11): 908-910.

Luscombe, B.W. and H.M. Hassan (1993) Applying Remote Sensing Technologies to Natural Disaster Risk Management – Implications for Developmental Investments. *Acta Astronautica* 29(10–11): 871–6.

Martín-Rico, C., J. Gonzalo, A. Mariani and W. Leibrandt (2001) The FUEGO System Concept. *Acta Astronautica* 48(1): 45–056.

Mas, J.F. (1999) Monitoring Land-cover Changes: A Comparison of Change Detection Techniques. *International Journal of Remote Sensing* 20(1): 139–52.

Mouginis-Mark, P.J. (1995) Preliminary Observations of Volcanos with the SIR-C Radar. *IEEE Transactions On Geoscience and Remote Sensing* 33(4): 934–41.

Munich Re (2001) Topics – Jahresrückblick Naturkatastrophen 2000. Munich.

Qi-Zheng, H. and L. Ming (2000) Small Satellite Constellation for Disaster and Environmental Monitoring. Paper presented at the Seventh Session of the Asia-Pacific Regional Space Agency Forum (APRSAF-7), Tokyo, 19–22 June.

Rengers, N., R. Soeters and C.J. van Westen (1992) Remote Sensing and GIS Applied to Mountain Hazard Mapping. *Episodes* 15(1): 36–45.

Rodolfo, K.S. (2000) The Hazard from Lahars and Jökulhlaups. In H. Sigurdsson (ed.) *Encyclopedia of Volcanoes*. Academic Press, San Diego.

San Miguel-Ayanz, J., M.M. Verstratete, B. Pinty, J. Meyer-Roux and G. Schmuck (2000) The Use of Existing and Future Remote Sensing Systems in Natural Hazard Management: Specifications and Requirements. In M.M. Verstratete, M. Menenti and J. Peltoniemi (eds.)

Observing Land From Space: Science, Customers and Technology. Kluwer Academic Publishers, Dordrecht.

Scott, K.M. (1988) *Origins, Behaviour, and Sedimentology of Lahars and Lahar-runout Flows in the Toutle-Cowlitz River System*. US Geological Survey Professional Paper 1447-A. US Geological Survey, Washington.

—— , J.L. Macías, J.A. Naranjo, S. Rodríguez and J.P. McGeehin (2001) *Catastrophic Debris Flows Transformed from Landslides in Volcanic Terrains: Mobility, Hazard Assessment, and Mitigation Strategies*. US Geological Survey Professional Paper 1630. US Geological Survey, Washington.

—— , J.W. Vallance, N. Kerle, J.L. Macías, W. Strauch and G. Devóli (forthcoming) Catastrophic, Precipitation-triggered Lahar at Casita Volcano, Nicaragua – Flow Transformations, Flow Bulking, and Future Mitigation Strategies. Submitted to *Geological Society of America Bulletin*.

Showalter, P.S. (2001) Remote Sensing's Use in Disaster Research: A Review. *Disaster Prevention and Management* 10(1): 21–9.

Smith, K. (2001) *Environmental Hazards*. Routledge, London and New York.

Song, C., C.E. Woodcock, K.C. Seto, M.P. Lenney and S.A. Macomber (2001) Classification and Change Detection using Landsat TM Data: When and How to Correct Atmospheric Effects? *Remote Sensing of Environment* 75(2): 230–44.

Sun, W., J.P. Stephens and M.N. Sweeting (2001) Micro-minisatellites for Affordable EO Constellations: RapidEye & DMC. Paper presented at the 3rd IAA Symposium on Small Satellites for Earth Observation, Berlin, 2–6 April.

Tanguy, J.C., C. Ribiere, A. Scarth and W.S. Tjetjep (1998) Victims from Volcanic Eruptions: A Revised Database. *Bulletin of Volcanology* 60(2): 137–44.

Tayag, J.C. and R.S. Punongbayan (1994) Volcanic Disaster Mitigation in the Philippines – Experience From Mt. Pinatubo. *Disasters* 18(1): 1–15.

Tobias, A., W. Leibrandt, J. Fuchs and A. Egurrola (2000) Small Satellites: Enabling Operational Disaster Management Systems. *Acta Astronautica* 46(2–6): 101–09.

Vallance, J.W. (2000) Lahars. In H. Sigurdsson (ed.) *Encyclopedia of Volcanoes*. Academic Press, San Diego.

Van der A, R.J., N. Alexander, C. Atkinson, N. Audet, E. Brouillard, A.P. Bukley, A. Defendini, R.A. Dicke, P.A. Edin, P.C. Fatelnig, J. Figa, R.G. Fuller, R. Jehn, R. Jorgensen, R.K. Olivier, C. Kessler, M. Kimura, E. Maliet, K. Matsuda, K. Matsumoto, N. Mizukoshi, J.C. Morland, A.B. Morodi, L. Nana, W.M. Neubert, M. Oieroset, P.J.K. Olsen, P.U. Osterman, J.M. Pasquet, R. Ravulapalli, P.J. Rebholz, J.L. Rusingizandekwe, T.D. Schaffer, A. Suskind, N. Vanstralen, F. Venet, T. Yvain and U. Zech (1994) GEOWARN – A Possible Global Lifesaver. *Space Policy* 10(2): 143–61.

Van Wyk de Vries, B., N. Kerle and D.N. Petley (2000) Sector Collapse Forming at Casita Volcano, Nicaragua. *Geology* 28(2): 167–70.

Verstappen, H.T. (1995) Aerospace-technology and Natural Disaster Reduction. *Advances in Space Research* 15(11): 3–15.

Walter, L.S. (1990) The Uses of Satellite Technology in Disaster Management. *Disasters* 14(1): 20–35.

—— (1994) Natural Hazard Assessment and Mitigation from Space: The Potential of Remote Sensing to Meet Operational Requirements. Paper presented at Natural Hazard Assessment and Mitigation: the Unique Role of Remote Sensing, London, 8–9 March.

Yatabe, S.M. and D.G. Leckie (1995) Clearcut and Forest-type Discrimination in Satellite SAR Imagery. *Canadian Journal of Remote Sensing* 21(4): 455–67.

Zimmerman, P.D. (1991) The Role of Satellite Remote Sensing in Disaster Relief. *Space Communications* 8(2): 141–52.

Address for correspondence: Norman Kerle, Department of Geography, Remote Sensing Group, University of Cambridge, Cambridge CB2 3EN. E-mail: <<nk220@cam.ac.uk>>