REMOTE SENSING AND GIS TECHNOLOGIES AS TOOLS TO SUPPORT SUSTAINABLE MANAGEMENT OF AREAS DEVASTATED BY LANDSLIDES

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(Received 7 June 2001; accepted 23 April 2002)

Abstract. IKONOS panchromatic images from a single year were used to characterise the effects of an extreme rainstorm event on six mountain catchment areas in Venezuela. Image registrations were accomplished using topographic base maps at 1 : 5000 scale giving a mapping accuracy between 37 and 40 m. It was used an 8-bit channel for correction, rectification, filteration and tone enhancements.

Landsliding was discerned in the affected watersheds using morphometric criteria, including the shape of the slope failure and its position, exposure bedrock in the scar and deposition of debris down-slope. This study is restricted to the impact analysis of the distribution of landslide erosion scars and the depositional processes on the valley floor. Remote sensing data were combined into a geographic information system (GIS) with planimetric data, contour lines, hydrology and vegetation types to evaluate the distribution of the scars and their effects on the highly populated areas located on the alluvial fans. Hillslope mass wasting induced mass movements, logging and increased the mud and silt in floodwaters affecting settlement down-slope.

Key words: Debris flows, IKONOS imagery, GIS, landslides, natural disasters, remote sensing, sustainability

1. Introduction

Landsliding involving bedrock hillslope erosion could be caused by rising pore water pressure induced by extreme rainstorms. Precipitation triggers the transport capacity of the fluvial system and sediment transfer at the mountain front resulting on gravity-driven land flows called debris flows. They are fast moving mass of water and material composed of sand, gravel and cobbles. As a result, sediments are discharged in pulses caused by storm events and disturbance by logging accentuates landsliding effects in areas with high population levels, resource utilisation and disturbance levels. They typically include trees, cars, small buildings and other anthropogenic material (Dudley and Fischenich, 1998; Douglas et al., 1999; Hovius et al., 2000).

The effects of landsliding on hillslope areas was lived by the people of La Guaira in the northern central coast of Venezuela, during December 1999 when torrential floods swept away several urban developed areas that had modified the natural

Environment, Development and Sustainability **4:** 221–229, 2002.

course of rivers. Settlements were built on hill slopes exposed to rivers and torrents. An unusually wet period of two weeks occurred along 300 km along the coast which resulted in mudslides, debris flows and flash floods causing loss of human lives and severe damage to infrastructure. Between the 4th and 13th of December precipitation records were low, with an accumulated record of 88.5 mm. However, by the 14th it was registered as 120 mm, the 15th as 380.7 mm and the 16th as 410.4 mm. The total accumulated precipitation registered by the 16th was 911.1 mm, which is the equivalent to the annual average. In other words, it rained in one day what was supposed to have rained over one year (Hernandez, 2000).

The assessment and mitigation of natural and man-made disasters represent a controversial issue in Latin America and the Caribbean. Developing countries are more vulnerable to suffer from the potential of such disasters, considering the tropical climate and varied land forms coupled with informal and disorganised human settlements located in areas of high natural risk (Mora-Castro, 2000). Though it is impossible to neutralise the damaging effects of such events, it could be feasible to minimise the potential risks by developing prevention strategies or preparedness plans. However, such planning is scarcely developed in Venezuela.

After the meteorological events occurred in December 1999, actions were taken during and following the disaster by international organisations and local private and public institutions. However, there is an urgent need for a coherent integration between data providers and the authorities to implement corresponding damage mitigation. It is time to use the information gathered in order to be prepared for next floods, by engaging in analysis and obtaining knowledge of the conditions that derived the formation of such phenomena. Spatial information technologies provide support in pre-disaster preparedness plans, in-disaster response, monitoring activities and post-disaster assessment and recovery.

In this context, the aim of this paper is to explore the value of high-resolution space-borne satellite images for post-disaster evaluation and damage assessment to the specific incident occurred in Venezuela. It also addresses the use of a GIS for a site-specific slope analysis of landslide behaviour, vegetation types and human settlement data for mapping and damage assessment. The advancement of remote sensing and geographic information systems (GIS) technologies has brought to the public new tools that facilitate the creation of sustainable development plans based on spatial variables.

2. Product and data resolution requirements

Today there are at least a dozen earth observation satellites currently collecting data useful for natural disaster mapping including floods and landslides. These provide great capabilities by offering high spatial resolution, up to 1 m, and short periods to revisit the same spot on earth, since their orbits are either polar or sun synchronous. The satellite image data have a spatial resolution ranging from 5.0 m to 1.1 km and panchromatic and multi-spectral wavebands.

For coastal environments there is an urgent need to develop effective monitoring programmes in response to the pressures and damages created by humans over the environment due to their social, political and economic activities. Spectral and spatial analysis could be modelled over time in order to establish baseline patterns to understand resource allocation and utilisation (Douglas et al., 1999; Phinn et al., 2000; Dai et al., 2001). Their analysis will define usage zones that can both save lives and delicate ecosystems. The problem is that human development reasons will always have preferance over any other, creating chaos and imbalance between the different elements, balance that at one time or another will be regained.

There are several types of data products that are useful for disaster management and decision-making. The types and complexity of data products depend on the type and the stage of the disaster (preparedness, mitigation, monitoring, assessment or recovery operations). Disaster response requires rapid damage assessment, to support relief operations once the disaster has occurred. Rehabilitation and reconstruction requires knowledge of current state and location of infrastructure and land use, as well as the damage quantification (Bertazzi, 2000)

Commercially available space-borne digital imagery with 1-m resolution, advanced image processing software programs coupled with multi-layer spatial relational data base management systems, have become the basic tools to create information required to manage the environment at landscape scale. In this context, the 1-m resolution panchromatic images collected by the IKONOS satellite, from Space Imaging were selected to be the best choice. Higher spatial resolution permits the discrimination of smaller units of material on the earth's surface (Roy & Agarwal, 2001). The integration of the digital image and the derived data into a GIS for modelling purposes provided the information for precise mapping of the disaster affected area (Allan, 2001).

3. Study area

The study area is located to the north of El Avila Mountain in Vargas State (Figure 1) ranging from latitude 10°37′39″N to 10°35′45″N and longitude 60°54′44″W to 60°48′39″W. The area is characterised as a faulted-block mountain with abundant schist, gneiss, marble, meta-granite and metamorphic sandstone. It has a pair of fault groups developed in different directions, which have increased weathering effect. Side slopes are in poor stability due to the steep inclinations (Urbani, 2000). The altitude steeply ascends from sea level up to 2200 m at the top of El Avila Mountain, within only 6–9 km from the beach to the top. Vegetation types have been described as evergreen and secondary forest, grasslands, shrubs and cultivated crops. The mountain range comprises steep gradients at the top, valleys and alluvial fans along the seaboard occupied by residential areas, hamlets and other types of infrastructure. Land use varies from agricultural settlements located in Galipan town at 2000 m above the sea level and the disorganised and highly populated urban settlements scattered on the fans at the Avila piedmont. The total population has

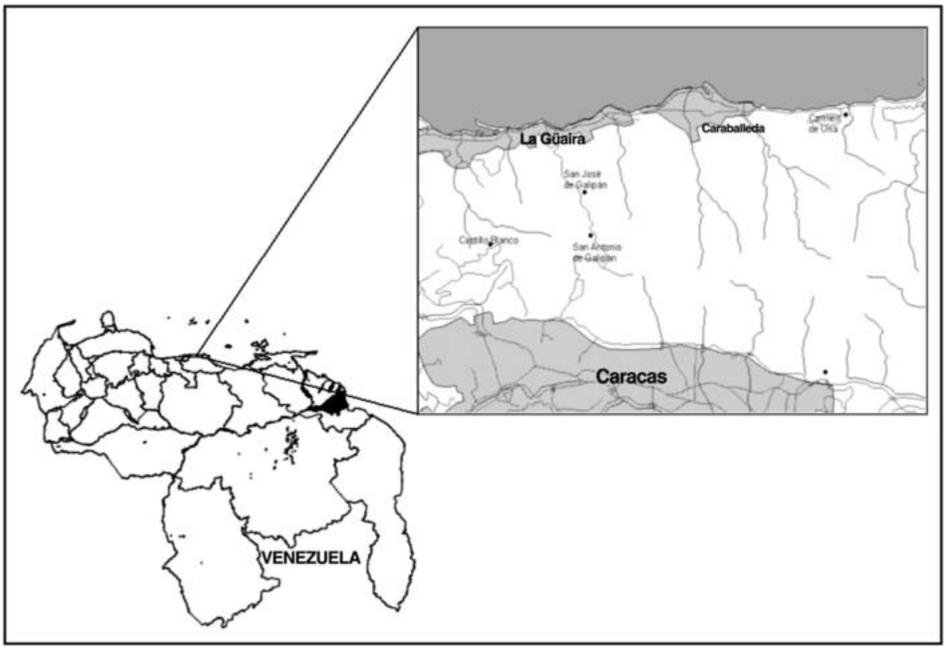

Figure 1. Location of the study area.

been estimated between 300,000 and 400,000, dependent mainly on the local and international tourism, which has been severely affected by the floods and landslides.

The area was first occupied by Spaniard conquerors during the colonisation period. Diego de Osorio founded the city of La Guaira on 29 June 1589. This coastal city was of utmost importance since it was centrally located within a mountain range that served as a natural fortress. Forts were built with heavy artillery to devise ships long before they reach the port to control smuggling activities and shy away pirates. This port was utilised to export many goods to Europe, and today serves as the country's most important port and has an International Airport. The settlers of this period established farmlands with extensive properties to grow mainly coffee, tobacco and cocoa trees. In the 1700s, commerce began to grow and demanded the construction of many facilities like roads, churches, hospitals, a trading company, etc. Several natural disasters have hit this area in the last 200 years, including an earthquake and similar floods, but no extensive damage was done since the rivers had not being affected by humans.

4. Data processing and analysis

Data processing was accomplished using two different software tools, ImageWorks by PCI Geomatics, of Canada, to process the IKONOS data and ArcInfo a GIS by Environmental Systems Research Institute (ESRI), Redlands, California, for modelling purposes and mapping.

IKONOS imagery was acquired on the 29 December 1999 eight days after the disaster and was obtained from the supplier, Space Imaging, before the satellite was even available for commercial purposes (22 January 2000). One of the pre-processing steps involved georeferencing the imagery data set to UTM topographic base maps at 1 : 5000 scale. It uses an 8-bit channel, instead of a 16-bit one for geo-correcting, geometric rectification, tone enhancements and adjustments before analysis.

A land movement consists of an erosion scar bounded by a breakaway zone above an area across which transport and deposition of failed material has occurred (Hovuis et al., 2000). Distribution and classification of source areas (scars) and deposition zones were identified on a mosaic built for the whole affected area (Figure 2). It was based on physical parameters as lithology, slope gradient, slope aspect, elevation, vegetation cover and proximity to drainage line. Landslide scars created by land movements, as landslides, rock falls, debris flows and the creation of natural dams by logging were identified and delimited. Recent highly reflective erosion scars were visible on the mosaic for their identification and digitisation.

Rock outcrops and infrastructure were very easily identified in the 1-m resolution panchromatic mosaic due to reflective properties. The brighter tones potentially represent areas of more intense alterations whereas areas of darker tones represent areas of less intense alteration. Planimetric data such as infrastructure, hydrology and vegetation types delineated from aerial photographs dated back to 1991 at 1 : 5000 scale were updated with the IKONOS image, to detect change.

The capabilities of the GIS were employed to interpolate a hydrologically correct surface from contour lines every 20 m and the river basin coverage. A continuous surface grid was generated with a 50 m pixel size. The topographic surface was then used to generate a continuous slope grid expressed as degree values from 0 (sea level) up to 76 degrees at the top of the El Avila Mountain. It was created a perspective view using the triangulated irregular network (TIN) module in ArcInfo (Figure 3) combining the slope grid, the river, infrastructure and the land movement coverage.

5. Results and discussion

The hazards from the torrential rainfalls were different between mountainous and flatter areas along the coast. Property and major infrastructure, such as dams, bridges, transport and electricity services, made up most of the direct damage. In some affected watershed areas, where informal and disorganised human settlings sprung up over the years, different types of mudflows mobilised mixtures of water–solid materials as soon as the natural soils were wet enough. The hillslope mass wasting accentuated the logging effect and downstream settlements were swept under and destroyed. The damage was estimated at $3.2 billion and at between 19,000 and 20,000 lives were lost (Herrera et al., 2000; USGS, 2001).

Different types of *flows,* at an instant of time were observed after the extraordinary precipitation in such a short period of time. Most of the hillslope mass wasting was

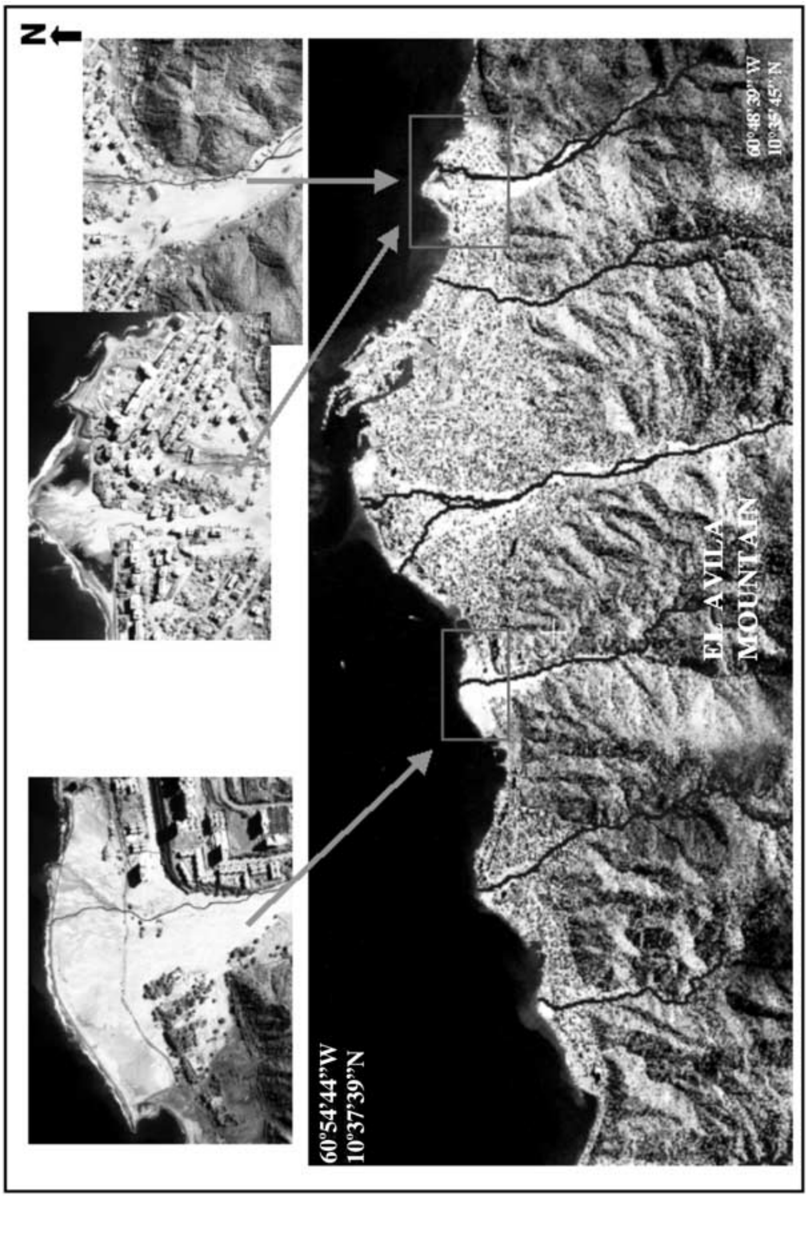

Figure 2. Section of the IKONOS image showing the six watersheds used for modelling purposes. Subsections enclosed in the squares are showed in detail at the top of the figure.

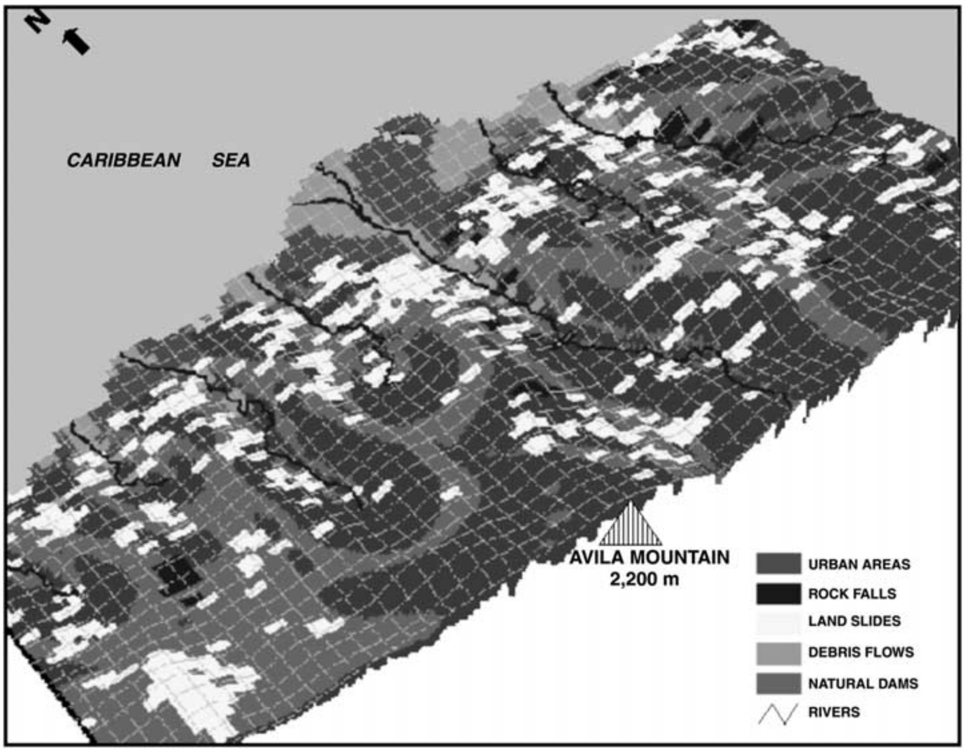

Figure 3. Model sustainability output combining the slope model and the coverages: hydrology, infrastructure, and land mass movements. The land masses considered were: rock falls, landslides, debris flows and natural dams.

fluxed out of the mountain front, and was deposited on the alluvial fans at the end of the mountain–valley system. The post-impact analysis of the distribution of land movements, gave a coarse and poorly sorted sediments, massive rocks, logs and debris deposited on the alluvial fan lodged against houses, buildings and other obstacles. The sediment yield in that time exceeded the annual sediment load in several previous years.

High slopes over 60% at the top of the mountain facilitated the release of gravity potential of loose deposits, trees and the confluence of rainstorm runoffs. Debris flows generated from debris slides or by extreme forms of stream flow erosion were the most destructive flows and pushed the coastline into the sea for about 300 m at the end of the alluvial fans. The major problems occurred where structures and man-made obstruction restricted the flow of water. The volume of transported sediments was basically dependent on the inclination of the riverbed, the concentration of solids and rocks, trees, the rainfall intensity, the size of the watershed and the land cover. Dudley and Fischenich (1998), have noted that the drag–velocity relation was 39% greater when woody debris was present in a riparian ecosystem after debris flow disturbance.

Natural disasters are a dramatic example of people living in conflict with the environment. Disasters such as flows, tornadoes, hurricanes, and the like are simply natural occurrences. They become disasters only when they conflict with people and property (Dunne, 1998). The final view, Figure 3, addresses three related issues:

(1) debris flows occurring in groups and devastating great extents of land concentrated in the lower and northwest facing slopes, in the alluvial fans where towns and hamlets were the main land cover type,
(2) natural dam formation at the end of the alluvial fans due to the inertial impact of sediments, massive rocks, trees detached from steep slopes and stopped by buildings and
(3) the association of the incremental dark tones with the steepest slopes and the landslides and rock falls as the main land movements when slopes are greater than 35 degrees.

6. Summary and concluding comments

The great potential of IKONOS imagery is based on a greater depth of information including high accuracy standards, frequent revisit capability and higher level of resolution than any other commercial imaging satellite. This high-resolution data set allows obtaining information in inaccessible areas where organising ground truth campaigns is difficult or too expensive.

The relevance of space information technology application is more significant in developing countries where there is a need for improving local capacity, education and training, coordination for emergency response in regard to natural disasters like flood hazards. In such areas this sort of tragedy increases the need of creating programmes to inform the people about the risks of building houses in areas that are not the best for this purpose. Also bringing into use modern planning tools that can provide more objectivity to zoning and permitting activities regarding land use. A great extent of the damage was a consequence of the lack of planning of the urban centres that were developed around these high-risk areas.

Striving for sustainability management model is a daunting task, even for those communities that are not disaster-prone. Changing the way we use resources and approach development is a slow-going process that often leads to great frustration. Spatial information technology has a very important and unique role to play in the planing and warning of impending disasters by rising the levels of preparedness of society to minimise the loss of life and damage to productive resources. The ability of this technology to provide basic information in space, time and frequency domains has been proved to be very useful in providing permanent records by mapping, monitoring and managing flow dynamics over time. In the field of floods, where there are many information gaps, the integration of spatial technologies is strongly recommended for the benefit of final users. All of the information derived from this case was put to use by the corresponding government agencies as the basis for the preparation of the reconstruction plans for the affected areas. The new plans have re-established a properly defined urban plan to develop economic, urban, commercial and tourist zones, which form the basis for the sustainable development of that urban and coastal area.

Acknowledgements

The authors wish to thank Space Imaging for the quick image acquisition and delivery for this time-critical analysis. We also want to thank the team involved in the data processing and analysis.

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