

VALIDATION OF SPOT-5 SATELLITE IMAGERY FOR GEOLOGICAL HAZARD IDENTIFICATION AND RISK ASSESSMENT FOR LANDSLIDES, MUD AND DEBRIS FLOWS IN MATAGALPA, NICARAGUA

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ABSTRACT:

This analysis addresses the suitability and potential for the use of high-resolution SPOT-5 remote imagery for geological hazard identification and risk assessment in Matagalpa, Nicaragua. SPOT-5 products are complementary tools in the process of risk analysis and in combination with digital elevation models (DEMs) are particularly helpful for determining large, kilometer-sized hazardous phenomena for watersheds. At Matagalpa, a pseudo-color 2.5 m SPOT-5 image draped over a DEM for 3D simulation is tailored for mapping landslide scarps and recent debris flow deposits at scales up to 1:25'000, but is inappropriate for identifying mud flow events. In contrast, the input of SPOT-5 derived products to hazard susceptibility mapping is limited, since among the prime factors controlling terrain instability (slope, geology, hydrography), only information about geological lineaments can be recovered. A few second-order risk factors, such as barren soils and deforested areas can be extrapolated from SPOT-5 land cover and change detection maps. For vulnerability issues, SPOT-5 images are a relevant source of spatial information on threatened elements (settlements, road infrastructure), if there are neither quality, nor current maps of the area available.

1. INTRODUCTION

After the devastating damage from Hurricane Mitch in late October 1998, the region and city of Matagalpa (Fig. 1), Nicaragua, was in need of considerable humanitarian relief and aid for reconstruction. Due to the lack of appropriate Geographic Information System (GIS) and Resource Centers, immediate assistance to the victims and their resettlements were carried out based on poorly informed decisions that have increased the pressure on weak municipal services, such as water supply and road maintenance, and resulted in deeper vulnerability to disaster risk. In order to address the situation, the Municipality of Matagalpa has requested financial and technical assistance to the Canton of Geneva, Switzerland that in the context of the United Nations Strategy for Disaster Reduction (ISDR) sponsored the UNOSAT assistance for the establishment of the Geographic Information Centre for the watershed of the Rio Grande of Matagalpa (CIGMAT), as a key resource for further geological and hydrological risk assessment, and integration of risk management in urban and rural planning. UNOSAT is a service of the United Nations Institute for Training and Research (UNITAR) implemented by the United Nations Office for Project Services (UNOPS), dedicated to provide satellite imagery and GIS services to humanitarian organizations and local communities in developing countries.

In this context, as partner of the French Space Agency (CNES), Spot Image, the European Space Agency (ESA) and the European Centre for Particle Physics (CERN), UNOSAT accepted to participate in cooperation with CIGMAT to the SPOT-5 validation program by testing in close collaboration with the Laboratory of Geology (GEOLEP) of the Swiss Federal Institute of Technology (EPFL), the suitability and potential of SPOT-5 data in combination with digital elevation

models (DEMs), Synthetic Aperture Radar (SAR) land deformation data, topographic maps and a geological GIS database for natural hazard mapping in the Matagalpa area, using (a) a visual and semi-automatic approach for phenomena identification and monitoring, and (b) the multi-risk factor evaluation methodology developed by EPFL/GEOLEP. For end-users that need reliable and cost-effective master plans, this document also presents a critical analysis and review of SPOT-5 imagery for the generation of vulnerability maps.

In the Matagalpa region, no remote sensing data has yet been integrated for monitoring the common geological hazards, such as landslides, mud flows and debris flows. The available geohazard studies, which were undertaken in the post-Mitch period, are grounded on either field observations (Carreño and Barreto, 2000; Havlíček et al., 2002) or aerial photo interpretations (Cannon et al., 2001). Carreño and Barreto (2000), based on a cartographic analysis of the areas affected by Mitch established a hazard susceptibility map as a decision tool for territorial planning. Cannon et al. (2001), in a contribution dedicated to landslide response to Hurricane Mitch rainfall proposed a detailed inventory of the 1998 active mud/debris flows and landslides, including a delimitation of their initiation points and run out areas. Finally, Havlíček et al. (2002) raised a set of three comprehensive 1:50'000 geological maps, corresponding with the Instituto Nicaragüense de Estudios Territoriales (INETER) Matagalpa topographic sheet, and also with our study area (Fig. 1). They produced (a) a geological map of the underlying volcanic units; (b) a geomorphological map, reporting the quaternary formations, the lateritic soils and the peneplanation levels, and; (c) a hazard map, with the delimitation of occurred movement types (landslides, rock falls, mud/debris flows, including phenomena related to Hurricane Mitch), and the location of structural, morphological and tectonic features prone to natural hazards. All the above

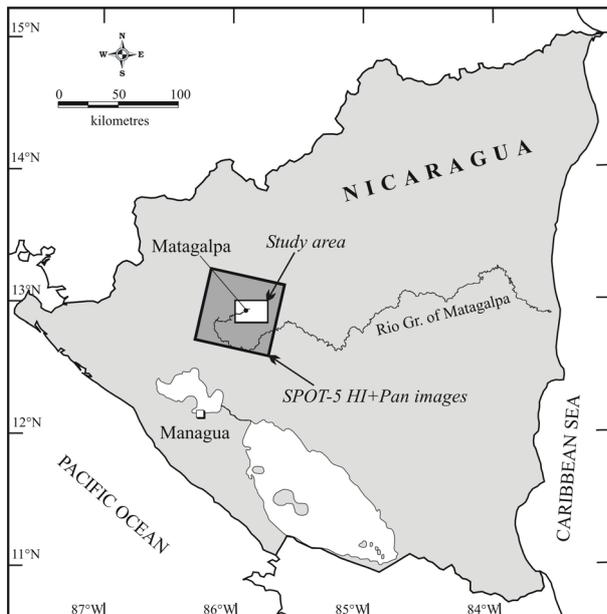


Figure 1. Simplified map of Nicaragua with the location of the SPOT-5 Hi+Pan images. The white frame represents the area of investigation (equal to the Matagalpa INETER 3054-IV topographic sheet).

mentioned maps were used for validating the input of SPOT-5 products for hazard identification and risk assessment.

2. VALIDATION PARAMETERS AND METHODOLOGY

2.1 GIS and RS database

CNES and Spot Image provided UNOSAT with two 60 x 60-km-wide satellite images centered on Matagalpa (Fig. 1), acquired during the dry season (19 April, 2003), with the following specification:

- a level 1A, 2.5 m pixel size SPOT-5 Panchromatic image, and
- a level 1A 4-band, 10 m pixel size SPOT-5 Hi image.

Both images were orthorectified to level 3 using a DEM based on the 3-arc-second SRTM data and 13 Ground Control Points (GCPs) from a Global Positioning System (GPS) field survey. The combination of both images gives a high-resolution 2.5 m 4-band color image.

In addition to SPOT-5 imagery, the project database, built by UNOSAT in cooperation with CIGMAT encompasses the following Remote Sensing (RS) and GIS products:

- a 14-class land cover map, built from an unsupervised classification of the previous SPOT-5 Hi image, field-validated by CIGMAT,
- 1:50'000 INETER topographic sheets (mosaic) covering the Rio Grande of Matagalpa watershed,
- a regional, 90 m pixel size DEM based on the 3-arc-second SRTM mission, covering the upper part of the Rio Grande of Matagalpa watershed,
- a 20 m pixel size DEM rasterized from topographic curves of the 1:50'000 INETER Matagalpa sheet,
- a 100 m pixel size slope map, created from the 20 m DEM product, and a corresponding classified polygon slope map (7 classes in degrees: <5, 5-10, 10-15, 15-25, 25-40, 40-60, >60),
- SAR land deformation maps of the Matagalpa urban

area, processed by UNOSAT partner Gamma RS from a 1997-1999 set of six ERS images,

- a GIS inventory of the water bodies (rivers, lakes, springs), extracted from the INETER maps and the study of Havlíček et al. (2002),
- several 1:50'000 geological vector layers (lateritic soils, landslide deposits, scarps, etc), based on the work of Havlíček et al. (2002), and
- vector layers of the initiation points and run out areas of 1998 active terrain movements (Cannon et al., 2001), covering a 10-km-wide square north of the city of Matagalpa.

All these raster and vector products are in a standard map projection (NUTM 16, WGS 84).

2.2 Hazard definition

In this contribution, we will focus the suitability analysis of SPOT-5 imagery to the most common geological hazards that have occurred or might occur in the Matagalpa region and city. These are landslides, mud flows and debris flows (Carreño and Barreto, 2000; Cannon et al., 2001; Havlíček et al., 2002). According to the nomenclature of Lateltin (1997) and Schneider (2001), landslides are defined as displacements by shearing of compact masses of loose or rock grounds along a failure surface. Mud flows are movements of material mass of polyphasic nature (solid fragments and water) similar to a fluid of variable viscosity. Lastly, debris flows are a mix of solid materials (blocks, gravels, etc.) transported by a viscous fluid (composed of fine sediments, clays and water) under the gravity and which occurs in the drainage network. Whereas mud and debris flows are instantaneous phenomena mainly driven by huge rainfalls (e.g., Hurricane Mitch), landslides are slow movements (from a few mm/y if sub-stabilized to a few cm/y if active) that may last for years, with abrupt accelerating phases that might create along valleys stream blockage and subsequent breaking up (high flood risk, particularly at Matagalpa). Key risk factors, indicating a strong predisposition to terrain movements are, in addition to geology, the presence of water (proximity to river network, soil moisture, and discharge zones) and moderate to steep slopes. Second-order factors that reinforce this susceptibility include faulted zones, barren soils, deforested areas and informal settlements.

2.3 Methodology

There are two ways for assessing geological hazards: (a) by describing occurred and ongoing phenomena (inventory map that reports and represents signs and indicators of terrain movements) and (b) by classifying soil areas according to their predisposition to documented natural hazards (susceptibility map that orders according to three degrees which sectors are potentially risk areas for each natural hazard type).

For the first approach, we tested the visual recognition on SPOT-5 data of morphologies or soils typical of terrain movements (disturbed vegetation, scarps, disturbed drainage, etc.; Dikau, 1999) and their spatial delimitation. The medium for this analysis is a combined Hi+Pan 2.5 m image, processed in pseudo-natural colors and draped over a DEM for 3D visualization. We also evaluated the potential of semi-automatic methods, based on image radiometry, and particularly the use of vegetation indices (NDVI) for generating low- or non-vegetated thematic vector layers (Liu et al., 2002), that are further filtered for extracting possible landslide or debris flow deposits.

For the susceptibility approach, we evaluate the integration of SPOT-5 data to the multi-factor risk methodology developed by

EPFL/GEOLEP in the frame of the CADANAV project (CARTographie des DAngers Naturels du canton de Vaud; Schneider, 2001). This methodology consists of four steps: a) information (DEM, geological and topographic maps, aerial photographs, remote sensing data) management aimed at the set up of classification maps based on risk factors (geology, slopes, hydrographic network distance, water saturation of soils); b) overlap of step 1-created theme maps and spatial analysis of the predisposition, organized in classes, of soils (geotypes) to documented natural hazards; c) validation of predispositions calculated under the former step by comparison with field- or remote-documented geological hazards; and d) validation of potential risk areas (susceptibility map) by comparison with ground observation of active risk areas. In this perspective, we consider the ability to create from SPOT-5-processed products thematic maps (hydrography, barren soils, deforested areas, informal settlements) that can be further class-organized according to the predisposition of their elements to landslides, mud and debris flows.

The final step to undertake in a full risk assessment is to confront the former inventory and susceptibility hazard layers with vulnerability maps to calculate the risk. Vulnerability can be defined as the probable cost of damage the hazard has done or might do to various types of installations. Thus, we look at what threatened elements can be retrieved from SPOT-5 products and how current high-resolution satellite imagery can be beneficial.

3. RESULTS

3.1 Inventory maps

On a pseudo-color SPOT-5 image draped over a DEM for 3D simulation, several features typical of landslides that have actually taken place were visually recognized: a) spreadings at toe, with river diversion; b) slope ruptures created by scarps; c)

deformation of linear features, like roads (Fig. 2). The 2.5 m pixel resolution appears as a significant improvement of SPOT-4 imagery, allowing a more reliable detection and the tracing of the boundaries of the landslides. Our remote sensing-based map shows a good correlation with the field observations collected by Havlíček et al. (2002). The main difference lies in the fact that large-scale sliding structures, such as kilometer-wide slope instabilities are better evaluated using imagery. Some of the detected landslides are presumably still active, as revealed by low-vegetated parcels or barren soils. This suggests that the SPOT-5 product can be used for qualitatively monitoring the landslide activity, although it is unlikely to determine the nature of the movements occurring, i.e. if they are rotational, translational or multiple. Limited time gap and atmospheric perturbations in our SAR interferometric dataset prevented us from corroborating these land deformations.

The inventory work becomes more delicate when dealing with mud and debris flows. Traces of 1998-debris flow deposits have almost completely disappeared, except in lower-gradient valleys such as Waswali, 5 km west of Matagalpa. The later deposits are characterized by large amounts of materials accumulated, channel shapes, and the lack of vegetation. Similarly, mud flow events, launched by Mitch rainfalls and identified on 1998 aerial photographs by Cannon et al. (2001) have not been recognized on the 2003 SPOT-5 image, probably because new vegetation has already covered the devastated areas. Alternatively, mud flow deposits are weakly contrasted so that they can be confused with other geomorphological features. This underlines that, in the Matagalpa region, only an image taken shortly after the damage is suitable for monitoring these phenomena.

From a technical viewpoint, the optimal size for recognition of terrain instability is about 1 sq km. The 3D simulation, with the draping of the pseudo-color image over a DEM, a process that is comparable to a stereographic photo-analysis, greatly

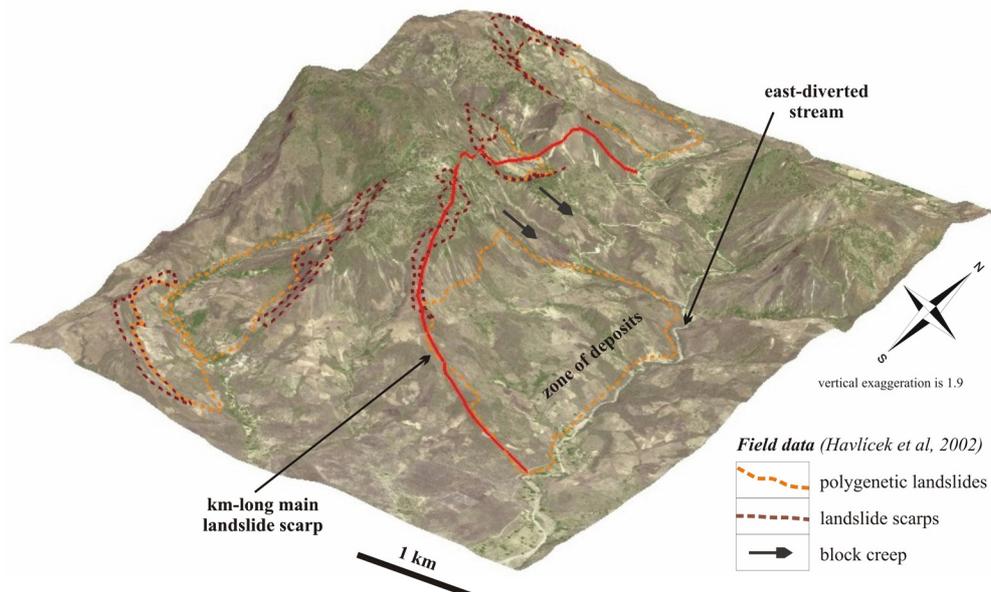


Figure 2. Pseudo-color SPOT-5 image draped over DEM for 3D simulation with the main scarps of large landslides. Typical indicators for landslides are disturbed vegetation and deflection of stream traces at the foot of the zone of deposits. Field data of Havlíček et al. (2002) are reported for comparison.

facilitates the interpretation compared to 2D on screen perception. However, the task should be entrusted to an experienced geologist and followed by a ground validation through a field survey. Another point to stress out is that the geohazard inventory should be regularly updated using multi-temporal images and preferentially after each major rainfall or earthquake (Wunderle, 2002). In tropical zones, like Matagalpa, this action can be seriously hindered because of cloud cover. Benefits of the SPOT-5 mapping tool compared to traditional field or aerial methods include the immediate compatibility with a GIS and the relative quickness of obtaining a global landslide inventory for large areas without accessing all of the area of interest.

Semi-automatic approaches, based on image radiometry remain mainly empirical and their relevance should be assessed from case to case. At Matagalpa, these methods seem not to be appropriate for landslides, because they were recognized on SPOT-5 images more by their morphological features than their reflectances and their deposits are only weakly contrasted. In contrast, debris flow events can presumably be detected using vegetation indexes such as NDVI (Liu et al., 2002). At Matagalpa, their deposits, as poorly vegetated areas have slightly positive NDVI values, comprised between 0.0 and 0.2, similar to the ones of settlements or road infrastructure. The application of a filter, such as a buffer zone along the drainage network allows to reduce this confusion and to sort a low number of candidate areas where debris flows could have been deposited. Such an easy-to-implement method, not functional on its own is supportive in validating visual interpretation.

3.2 Susceptibility maps

The input of a pseudo-color SPOT-5 image and derived land cover classifications to hazard susceptibility mapping appears as restricted, since the prime factors controlling the predisposition of soils to landslides, mud and debris flows, such as geology, terrain slope and hydrography are themes hardly retrievable. Knowing that hill slopes are the most important data for susceptibility issues, a DEM from which a classified slope map can be calculated is a pre-requisite product for this procedure. This slope map should be applied to filter out the output of the thematic layers, so that only areas with moderate slopes (e.g., between 8.5 and 60 degrees, Fig. 3) are kept as soil candidates with predisposition to natural hazards.

In tropical regions, like Matagalpa, the bedrock geology and the quaternary units are mostly masked by the vegetation cover, but the presence of lineaments (surface expression of a basement block boundary or fault) can be easily detected on a pseudo-color SPOT-5 image. The lineaments we traced show quite a similar pattern compared to the published data (faults) of Havlíček et al. (2002). Their detection is very helpful for a susceptibility analysis, since high density lineament areas are considered as prone to landslides, especially when earthquake-induced. In contrast, SPOT-5 imagery despite its resolution is not adapted for delineation of secondary and tertiary hydrographic networks, features that are critical in our methodology.

Attempts were made to extract from land cover classifications thematic information corresponding to second-order risk factors. Annual crop lands, grounds that have properties close to barren soils are potential soil candidates with a predisposition to mud and debris flows. The superimposition of 1998 occurred mud and debris flow events (Cannon et al., 2001) to a slope-filtered SPOT-5 land cover map (Fig. 3) is in broad agreement with this assumption, with 25 percent of the Mitch-related phenomena having actually started from this soil type. Other

mud/debris-flow-favorable land cover classes seem to be agricultural and pasture lands at the external boundaries of forests (Fig. 3) - areas apparently recently deforested. This suggests that land use changes are also a SPOT-5-retrievable parameter to take into consideration for susceptibility mapping, especially when multi-temporal images are available.

3.3 Vulnerability maps

High-resolution SPOT-5 products could be a relevant source of information in the preparation of vulnerability maps, and in particular for spatial data collection of landslide or mud/debris flow-threatened elements. With semi-automatic methods, like

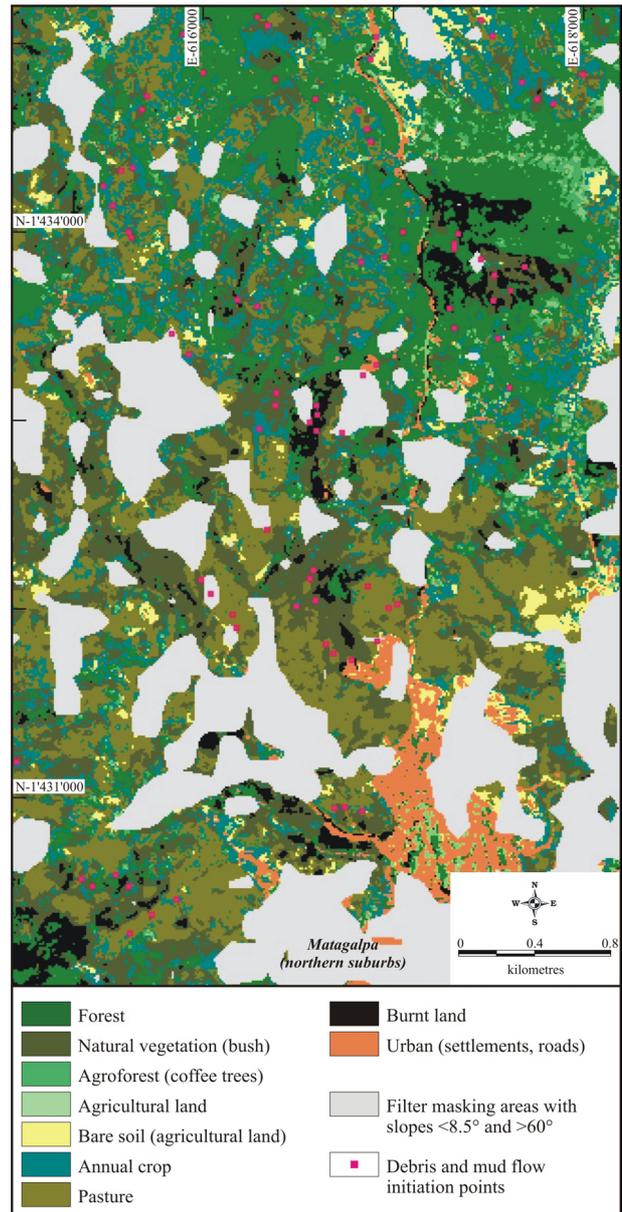


Figure 3. Overlay of the initiation points of 1998-active mud and debris flows (Cannon et al., 2001) on a slope-filtered SPOT-5 land cover map, showing that, north of the city of Matagalpa, annual crop lands and deforested areas (pastures and agricultural lands close to the forest boundaries) are soils with moderate to high predisposition to geohazards.

Table 1. Summary table with benefits and limitations of SPOT-5 derived products for hazard inventory mapping.

<i>Method</i>	<i>Product</i>	<i>Results</i>	<i>Benefits</i>	<i>Limitations</i>
Visual interpretation	SPOT-5 Hi+Pan pseudo-color image draped over a DEM for 3D simulation	Regional inventory and mapping of large landslides and recent mud and debris flows Qualitative monitoring of landslide activity	High spatial resolution, up to 1:25 000 scale Ease of processing for obtaining a GIS layer compared to aerial photographs Potentially quicker than field acquisition (for large areas)	Senior geologist interpreter required Field validation highly recommended Unfavorable weather environment (cloud coverage) Inappropriate for mapping old mud flows
Vegetation index	Filtered NDVI image	Poorly to non-vegetated areas candidates for possible landslide scarps and debris-flow deposits	Support to visual interpretation	Drainage or slope filters necessary to limit confusion with urban areas and road infrastructure Method not functional on its own

Table 2. Summary table with benefits and limitations of SPOT5 derived products for hazard susceptibility mapping.

<i>Method</i>	<i>Product</i>	<i>Results</i>	<i>Benefits</i>	<i>Limitations</i>
Visual interpretation	SPOT-5 Hi+Pan pseudo-color image	Map of geological lineaments (predisposition to earthquake-induced landslides)		Inappropriate for detecting first-order risk factors, such as geological bedrock, quaternary formations and secondary hydrographic network
Unsupervised image classification	Land cover map (SPOT-5 Hi image classification)	Map of annual crop lands, pastures and deforested areas (areas prone to mud/debris flows)	High spatial resolution of land cover data (appropriate for the multi-risk methodology)	Methods for assessing hazard predispositions from land cover data far beyond being operational Classified slope map required as filter Field validation required
Change detection	Land cover maps (SPOT-5 Hi and archive SPOT-4 image classifications)	Map of deforested areas and new settlements (areas prone to terrain instability)	High spatial resolution of land cover change data (appropriate for the multi-risk methodology)	Acquisition of multi-temporal images Field validation required

Table 3. Summary table with benefits and limitations of SPOT5 derived products for vulnerability mapping.

<i>Method</i>	<i>Product</i>	<i>Results</i>	<i>Benefits</i>	<i>Limitations</i>
Unsupervised image classification	Land cover map (SPOT-5 Hi image classification)	Map of urban areas (settlements, isolated buildings, plants and road infrastructure)	Up-to-date information Premium geographic information source if poor map coverage	Significant manual editing work to correct confused land cover classes Field verification highly recommended Combination with socio-economic data required for vulnerability issues Methods for vulnerability definition far beyond being operational

unsupervised land use classification, cartography of settlements, isolated buildings, plants and road infrastructure is feasible, but significant editing work and ground verification, wherever possible, is required to separate confused classes. This tool is particularly helpful if there are neither quality, nor up-to-date maps of the area available.

SPOT-5 collected spatial data on the elements at risk need to be combined with demographic and socio-economic factors and indicators on the economic activities for cost purposes. The resulting cost study is then confronted to expected hazard magnitudes and frequencies for vulnerability definition. However, this method is far beyond being operational for landslide, mud and debris flow events, since little work has been done to assess the potential damages for a given terrain instability (Wunderle, 2002).

4. CONCLUSIONS

SPOT-5 remote imagery is a useful tool for the detection of large landslides and to a lesser extent mud flows and debris flows (Table 1). A pseudo-color 2.5 m SPOT-5 Pan+Hi image draped on a DEM for 3D simulation allows to delimit hazard areas at scales up to 1:25'000 (master plan) and to create a comprehensive inventory map of occurred hazard phenomena, consistent with field observations. The rate of vegetation disturbance yields to some extent a qualitative monitoring of the activity. However, the recognition of hazard characteristics depends to a great extent on the ability and experience of the interpreter. This remote sensing tool, although it does not reach the ground resolution of aerial photography, usefully complements this traditional surveying method. In Matagalpa, semi-automatic approaches, analyzing image radiometry are not suitable for retrieving landslide data. However, vegetation indexes (NDVI), best filtered with the drainage network are helpful for sorting out areas with debris flow deposits.

For hazard susceptibility maps (Table 2), integration of SPOT-5 products is less straightforward, since the derived thematic information has to be filtered with slope classifications. At Matagalpa, among the prime risk factors that indicates a predisposition to landslides, only the information about geological lineaments can be visually recovered from the pseudo-color SPOT-5 image. Additional data, such as barren soils and deforested areas can be extrapolated from land use and change detection maps.

The contribution of SPOT-5 products for vulnerability purposes (Table 3) is relevant where poor map coverage is available or when up-to-date information is required. Land cover maps, after demanding editing work and field validation are helpful for mapping threatened elements such as settlements, buildings, plants and road infrastructure. The later information must nevertheless be combined with socio-economic data of the elements at risk to assess their actual vulnerability.

In conclusion, SPOT-5 products are a complementary tool in the process of risk analysis (hazard inventory, second-order risk factors and vulnerable elements), which is tailored for mapping large (kilometer-wide) hazardous phenomena at the watershed scale. To fully take advantage of its potential, it needs to be integrated as part of a GIS, together with other relevant information, such as DEMs and geological and hydrographic maps. However, a field survey remains essential for validating SPOT-5 derived landslide inventories and land cover classifications. Most of limitations observed with SPOT-5 could probably be overcome with infra-metric resolution capabilities in optical bands and metric resolution radar C-band.

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