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Visualizing Landslide Hazards: Methods for Empowering Communities in Guatemala Through Hazard Mapping

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VISUALIZING LANDSLIDE HAZARDS: METHODS FOR EMPOWERING COMMUNITIES IN GUATEMALA THROUGH HAZARD MAPPING

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Patrick Burchfiel
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VISUALIZING LANDSLIDE HAZARDS: METHODS FOR EMPOWERING COMMUNITIES IN GUATEMALA THROUGH HAZARD MAPPING

By

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ABSTRACT

VISUALIZING LANDSLIDE HAZARDS: METHODS FOR EMPOWERING COMMUNITIES IN GUATEMALA THROUGH HAZARD MAPPING

by Patrick Burchfiel

Landslides occur at a high frequency throughout the mountainous regions of Guatemala, posing an elevated risk to communities and their infrastructure. A crucial component of the analysis of landslide hazards incorporates the creation of landslide hazard or susceptibility maps. This paper's research objective had two distinct components. The first was to identify practical and effective cartographic visualization methods to deliver map-based hazard information at the community level in Guatemala. Mapping methods were evaluated for their potential effectiveness in visually communicating landslide risks to the isolated rural communities of Lake Atitlan and the town of Santiago Atitlan. The research illustrated the importance of the depiction of relief, imagery, and landmarks in addition to local knowledge of the construction of hazard maps.

The second component analyzed the suitability of SRTM 90-meter resolution DEMs for landslide susceptibility mapping. A SRTM 90-meter resolution DEM of the Sierra de las Minas, Guatemala and corresponding USGS landslide inventories were examined in the ArcMap 10 environment. Spatial analysis revealed that although lower resolution did limit the SRTM DEM's suitability for comprehensive landslide hazard analysis in Guatemala, a potential existed for it to be a useful aid in identifying areas susceptible to large debris flow.

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Introduction

Rainfall-induced landslides pose a significant hazard to the people and infrastructure of Guatemala. Poverty, poorly-regulated development, and a topography predisposed to natural disasters are sparking a growing need for comprehensive landslide hazard analysis throughout Guatemala. Hazard mapping represents a valuable technique for understanding and communicating disaster-related information. Unfortunately, many developing countries do not have the financial means, expertise, or policies in place to generate accurate, natural hazard-related data, and to make the information derived from them readily available to the stakeholders who need hazard data for disaster risk reduction and response planning (Guinau, Pallas, & Vilaplana, 2005). The critical hazard-related information created by these maps rarely acts as an effective communication tool at the community level. Such is the case in Guatemala, where many people are still adversely affected by landslides throughout the rainy season due to vulnerability, poor planning, communication, and lack of hazard analysis.

My research objective is to identify practical cartographic visualization methods for community hazard mapping and investigate the applicability of remote sensing technologies to enhance hazard mapping in developing countries. To accomplish this task, I will examine past visualization approaches and attempt to apply these methods to the geographic context of highland communities in Guatemala. The second half of my research analyzes the applicability of one readily accessible remotely-sensed form of data, Shuttle Radar Topography Mission (SRTM) 90-meter DEMs, in a rainfall-induced landslide hazard analysis. I propose that despite a loss in resolution, the 90-meter resolution DEM is a practical substitute for the more difficult to acquire 10-meter resolution DEMs obtained from topographic maps.

Guatemala

Guatemala is a developing country located in Central America (Figure 1). A mountainous interior dominates central Guatemala's landscape. The mountainous topography gives way to coastal plains along the Pacific Ocean and the Caribbean Sea. Guatemala has a population of approximately 13 million people. Today, the country is one of the most densely populated and impoverished countries in Latin America (The World Bank, 2011). Agriculture accounts for a large proportion of Guatemala's economy and the majority of the country's exports. Guatemala faces a high illiteracy rate and one of the highest malnutrition rates for children under five in the world. Fifty percent of the population lives in rural settings (CIA, 2011).

A combination of geographic, economic, and social factors in Guatemala creates an environment predisposed to high natural disaster vulnerability. The World Bank has designated Guatemala as high-risk to disaster due to the country's economic susceptibility to multiple hazards (The World Bank, 2011). Natural hazards prevalent in Guatemala include earthquakes, volcanic eruptions, floods, storms, landslides, and drought. Of these, over recent years, storms have caused the largest economic damage (The World Bank, 2011). Guatemala is exposed to storms caused by hurricanes making landfall on both the Pacific and Caribbean coasts. Hurricanes Mitch (1998), Stan (2005), and Agatha (2010) brought rains that devastated Guatemala. Guatemala's topography also lends itself to extreme susceptibility to landslides. Vulnerability to all of these hazards is exacerbated by poverty, rapid urbanization, poor planning, lack of building regulations, and informal settlements (The World Bank, 2011).

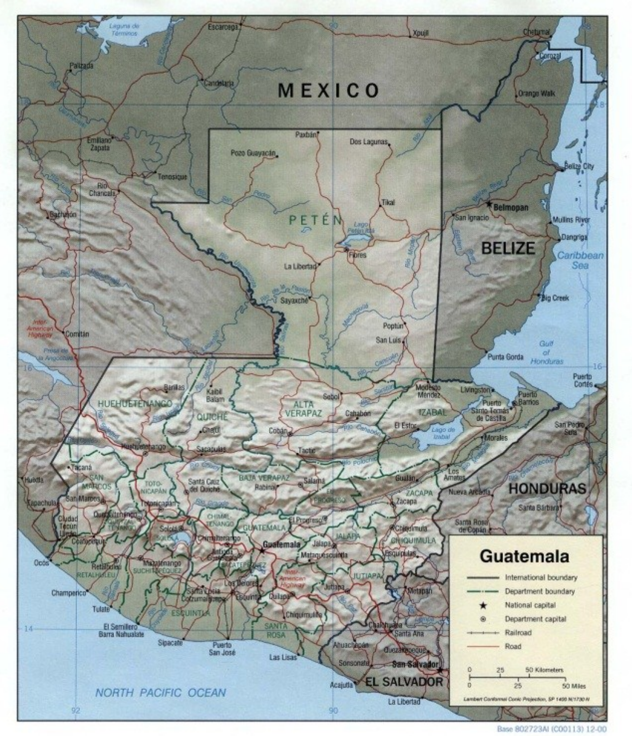

Figure 1. Map of Guatemala (Perry-Castaneda Library Map Collection, 2000). Reprinted with the permission of University of Texas Libraries.

While Guatemala experiences an array of natural hazards, this research will focus on the visualization of precipitation and volcano-induced landslide susceptibility. Landslides in Guatemala typically have a relatively low impact compared to other disasters but occur at a higher frequency, killing people and damaging infrastructure (The World Bank, 2011). Some of the most common and devastating types of landslides in Guatemala are debris flows and lahars (Figure 2). Debris flows can be categorized as fast-moving water saturated landslides (Haapala et al., 2005). The consistency of the debris flows varies with the amount of moisture, dirt, and debris present.

Figure 2. Volcan Santiaguito. Lahar paths along a flank of Volcan Santiaguito (2011). Photograph taken by Patrick Burchfiel.

Lahars are debris flows that usually originate on the slopes of volcanoes and contain volcanic materials. Lahars, composed of volcanic debris, water, mud, and rock, can move quickly down hillsides following extensive rainfall or volcanic activity. Their behavior is characteristic of rain-induced debris flows as they typically flow (and possibly converge) into stream channels and can travel great distances (Haapala et al., 2005; Pallas, 2004). Debris flows progress downslope at great speeds, increasing both in size and destructive power. Guatemala's topography, prevalence of volcanic activity, and intense rainy seasons create an environment vulnerable to both lahars and debris flows. The western highland region of Guatemala has numerous volcanoes and receives large amounts of precipitation from storms originating in the Pacific and Caribbean coastal regions. For the purpose of this paper, the terms *landslide*, *debris flow*, and *lahar* will be used interchangeably.

Guatemala's government has recently made numerous efforts to address disaster risk and response to natural disasters and has identified disaster risk management as a development priority (The World Bank, 2011). This has led to the creation of organizations and programs to deal with the numerous facets of the disaster cycle. Despite recent advancements in Guatemala's disaster risk reduction and response (DRR&R) policies and procedures, natural disasters still cause significant loss of life, damage to infrastructure, and economic woes. Recent disaster events have underscored the government's inability to respond to disasters effectively (The World Bank, 2011).

Many challenges are faced in aiding DRR&R at the local level in Guatemala, especially pertaining to the communication of hazard information to locals. A high percentage of the people still live in rural environments. As mentioned earlier, a high rate of poverty and illiteracy prevails throughout Guatemala.

Figure 3. House in Panabaj. Indigenous family in front of their home located near the sight of the Panabaj landslide (2011). Photograph taken by Patrick Burchfiel.

A large proportion of indigenous Maya populations live throughout the highlands of Guatemala, with unique cultures that need to be taken into consideration during the hazard mapping process. Finally, in addition to the official Spanish language, approximately 23 different Amerindian languages are recognized (and spoken) throughout Guatemala (CIA, 2011).

Hazard Mapping and Local Communities

Hazard maps provide an effective medium for visualizing risk information and bridging communication barriers among varying stakeholders. These maps aid in the assessment, analysis, and mitigation of risks (Dransch, Etter, & Walz, 2005). When fabricating a hazard map, one must keep in mind the purpose of the map, the intended audience, how data will be displayed, and where it will be used (Friedmannova, Konecny, & Stanek, 2007). The creation of effective hazard maps takes into consideration community knowledge through the utilization of participatory mapping methods. These methods aim to involve locals in the mapping process, to reflect local views in governmental policy, and to develop a mutual understanding of surrounding risks (Institute for Ocean Management, 2007).

If constructed appropriately, community-based hazard maps can help bridge the knowledge gap between community members, local governments, non-governmental organizations, and members of the international disaster response and risk reduction community. Mutual collaboration is especially important in Guatemala as there is typically a general mistrust of the government, rooted in the oppressive Guatemalan Civil War (1960-1996) which left more than 100,000 dead and created a large refugee population (CIA, 2011).

Previous research has already indicated the importance of involving local communities in the process of hazard mapping. Cronin et al. (2004) utilized a

Participatory Rural Appraisal (PRA) methodology to bridge the gap between scientific and local knowledge on the highly volcanic island of Vanuatu. A portion of this methodology included the creation of community hazard maps. One major accomplishment of the research was the ability to increase the effectiveness of an island-wide hazard map (Cronin et al., 2004).

Haynes, Barclay, and Pidgeon (2007) were also able to demonstrate the increased effectiveness of hazard maps through the involvement of community knowledge on the island of Montserrat. In July of 1995 the Soufriere Hills volcano began erupting. Cycles of intensified activity led agencies to create numerous hazard maps. A breakdown in the maps' ability to relay risk information was apparent following the deaths of 19 villagers in 1997. In their study, researchers used the results of a survey to determine the most ideal base map visualization for presenting hazard information on the island during a time of increased volcanic activity (Haynes et al., 2007). Although both of the studies mentioned above deal primarily with purely volcanic hazards, the information they provide is very useful when creating debris flow-related hazard maps.

The importance of community-based hazard mapping has already been realized in Central America. Many international and local efforts are already underway to promote related methodologies throughout the region. The United Nations Educational, Scientific and Cultural Organization's (UNESCO) Capacity Building for Natural Disasters Reduction - Regional Action Programme Central America (CBNDR-RAPCA) was created in 1999 to increase local stakeholder's capacity to utilize Geographic Information Science technologies for hazard analysis. The project, which ended in 2004, resulted in the training of numerous disaster management professionals and the creation of a training packet based on case studies in the region (UNESCO, 2004).

Efforts continue to educate local communities in the utilization of hazard maps to identify vulnerabilities and increase communication among stakeholders. In July 2008, approximately 28 community leaders from Guatemala, Honduras, and Nicaragua participated in community hazard map training in Honduras. The training, sponsored by Grassroots Organizations Operating Together in Sisterhood (GROOTS) International, aided the participants in identifying ways to reduce damage caused by disasters through the use of community hazard mapping (Disaster Watch, 2008).

Although an abundance of research regarding community-based hazard mapping is present, a rather limited inquiry regarding effective cartographic visualization techniques to enhance the communication capabilities of these maps persists. Haynes et al. (2007) identified a lack of studies which evaluated how hazard maps are comprehended at the local level. The objective of Haynes et al. (2007) research in Montserrat was to evaluate the effectiveness of hazard maps for conveying risk to local communities and to identify ways in which the maps might be improved. Through community surveys, the researchers were able to determine that the general public in Montserrat had an easier time interpreting aerial photographs and 3-Dimensional (3D) relief maps than contoured topographic maps (which had been previously used as a community outreach hazard map). Locals did not have the geographic knowledge to understand contour lines, thus they were not an effective manner in which to communicate relief.

Photographic-based maps enabled people to utilize their own “mental maps” to help orient themselves and distinguish features on the map (Haynes et al., 2007). Their research provides vital groundwork for understanding the importance of selecting an appropriate base map for presenting hazard data. Furthermore, one can interpret a necessity to incorporate visual landscape cues, such as local landmarks or images, to help residents apply their mental maps. Along with imagery, the representation of relief plays an integral role in helping people correlate mapped data to their perceived surroundings. Vivid relief, such as mountains, provides map users with another tool to access their mental maps (Collier, Forrest, & Pearson, 2003). The depiction of relief takes on added importance in terms of visualizing risk because landslides are heavily terrain dependent.

The research of Cronin et al. (2004) also revealed some crucial information in regards to hazard map visualization techniques. Through their PRA on the island of Ambae, Vanuatu, the researchers identified numerous ways to improve the past hazard mapping methodologies of the island. Geological details were completely removed as villagers had difficulty comprehending them and the role they played in the disaster risk. Multiple hazard processes were confined into three hazard zones. A simplified color scheme was used to label these hazard zones where red was associated with high relative hazard, yellow with medium relative hazard, and green represented with a low hazard area. To display the risk related to lahars, the single highest hazard risk, the drainage networks leading from the volcano were emphasized with red lines. Finally, the amount of text on the map was very limited and was in the local dialect (Cronin et al. 2004).

Cartographic Visualization

The focus of this research is to identify effective visualization techniques for communicating risk associated with volcano and precipitation-induced debris flows at the local level. My research goal was accomplished through an examination of past community-based mapping research and approaches. The methodology will be predominately grounded in a detailed literature review and a comparative study. Common techniques for community mapping will be considered, both in their static and interactive forms (Table 1). For the purpose of this study, *interactive*, will be defined as the local user's ability to manipulate and view data in a GIS environment. Utilizing past research, mapping methods will be evaluated for their potential effectiveness in visually communicating landslide risks to two types of rural communities in Guatemala. Results from the research are intended to assist in the detection of suitable community-level hazard mapping practices for disaster prone communities throughout Guatemala.

Past methods will be compared and applied to rural communities of varying sizes in the Lake Atitlan region. Lake Atitlan, at a surface area of approximately 128 square kilometers, occupies an extinct volcanic caldera (Lake Atitlan, 2011). Rugged topography surrounds the shores of the lake. Three looming stratovolcanoes, San Pedro, Toliman, and Atitlan, are present along the southwestern shores of the lake. Communities along the lake rely on a mixture of agriculture and tourism. This region is especially prone to rainfall-induced landslides due to geographic location, steep terrain, and unregulated development (Figures 4 & 5). Problems have intensified as wealthy outsiders have purchased land, once inhabited by indigenous communities, to cater to tourists or build vacation homes (Little, 2004).

Table 1. Hazard mapping methods.

Method	***Description***
Flat Maps	Dimensional scaled maps in which community members can input local knowledge directly on the map, through superimposed transparencies, or employing a GIS (Rambaldi, Kyem, McCall, & Weiner, 2006). Typically utilizes topographic maps or a GIS to create the base map.
3-Dimensional Modeling	Employs elevation data to create geo-referenced relief models. Solid models comprising terrain data can be provided to communities or created by the stakeholders. Local knowledge is added to model using various techniques. DEMs can be used to create 3-Dimensional Model in a GIS. The finalized map can be either interactive or reproduced on a static flat map.
Photo-Maps	Utilizes remotely sensed data to create base maps. Orthophotos provide accurate, scalable imagery that has been positioned in map coordinates. Community data from transparencies can either be placed directly on the map or digitized (Rambaldi et al., 2006). Imagery can be used in flat maps and 3-Dimensional Modeling to enhance visualization.

Note. Three common mapping methods and their general description.

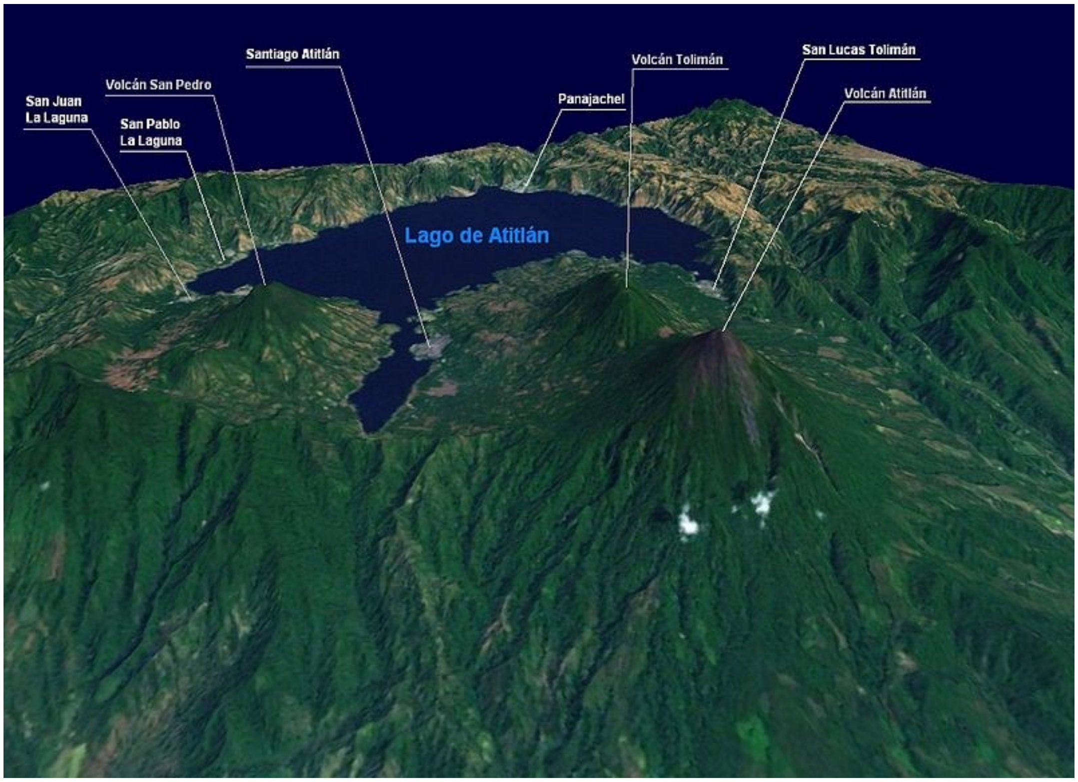

Figure 4. Lake Atitlan. 3D model created from SRTM data illustrating the topography of the Lake Atitlan area (Asybaris01, 2011).

Figure 5. Lake Atitlan debris flows. Debris flows can be seen along the steep cliffs above San Juan La Laguna (2011). Photograph taken by Patrick Burchfiel.

The cartographic visualization analysis is centered on factors such as map production, distribution, versatility, accuracy, and comprehension. Methods for displaying map data are examined to ascertain techniques that facilitate communication among all stakeholders. Examples of these map features include base map selection, scale, representation of relief, use of imagery, symbology, color, and use of text. A hazards map's strategic functionality is to convey details pertaining to areas of risk, location of shelters, gathering points, and evacuation routes. Cartographic visualization is the medium used to communicate these fundamental objectives and should be comprised of both outside specialist data and local community knowledge (Cronin et al., 2004; Haynes, 2007; Rambaldi et al., 2006). The amount of expert and local knowledge will inevitably vary depending on the cartographic visualization techniques employed. Map data will be characterized accordingly during the comparative study.

Comparative Analysis One: Lake Atitlan's Isolated Rural Villages

The first analysis looks at the application of effective hazard mapping methods in the many small, isolated communities in the Lake Atitlan region. Isolated rural communities typically have only a few hundred people, rely heavily on agriculture, and have rudimentary infrastructure. In the Lake Atitlan region, isolated communities can be found along the lakeshore, such as Jaibalito, among the numerous fincas (large farms) that occupy the fertile volcanic slopes, or in other areas with access to agricultural land. These communities tend to be comprised of indigenous Maya who rely mainly on agriculture and tourism activities. A high rate of illiteracy and poverty are found among the isolated rural communities. Implementing interactive GIS hazard mapping solutions in this environment is problematic due to a lack of technological resources and expert knowledge. The analysis will focus on static flat map, photomap, and 3D modeling methods (Figures 6-8).

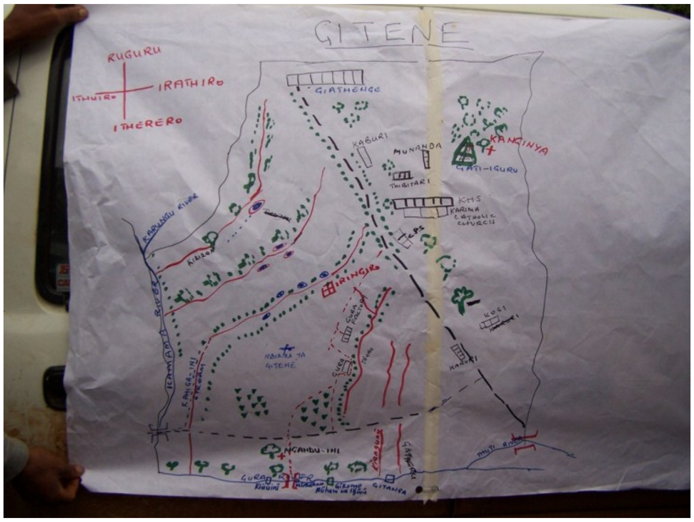

Figure 6. Sketch map. Kenya (Muchemi, n.d.). Photograph taken by Julius Muchemi. Reprinted in accordance with the CTA and IFAD copyright agreement.

Figure 7. Photo-map applications. Women use aerial photos to map their environment, Beqa Island, Fiji Islands (Rambaldi, 2005). Photograph taken by Giacomo Rambaldi. Reprinted with permission from Giacomo Rambaldi.

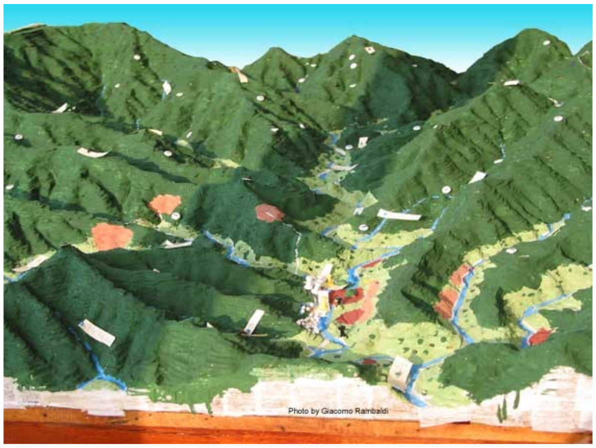

Figure 8. Participatory 3-Dimensional model (Rambaldi, n.d.). Photograph taken by Giacomo Rambaldi. Reprinted with permission from Giacomo Rambaldi.

The use of basic static flat hazard maps is the least resource intensive methodology. Previous research has indicated that comprehension of static flat maps tends to increase with simplification of map features. Expert knowledge can be provided in the form of a geo-referenced, large scale base map. While the depiction of relief is important, contours should be avoided. Use of a DEM visualized with hillshading is a good option, but the cost of acquiring a high enough resolution for a large scale map would most likely prove to be cost prohibitive. Relief can be depicted with a select few elevation points displayed (hilltops, volcanoes, other notable landmarks, etc.). Debris flows tend to follow drainage channels so relevant hydrology should be provided by the expert.

Community meetings enable the locals to input their knowledge into creating the hazard map. This should include known hazards, shelters, meeting locations, paths, drinking water sources, schools, medical clinics, and evacuation routes. Symbology can be created and agreed upon by the community. High illiteracy dictates that text descriptions are kept to a minimum. When text is used, it should be in both the local indigenous language and Spanish. Once the local knowledge input is complete, outside experts can input landslide hazard information (risk zones, safe zones, shelters, and evacuation routes). One can directly place this information on the map, at a sacrifice of accuracy, or in a GIS after the information has been digitized.

3D modeling provides another valuable visualization technique. The base map can be provided either in the format of a foam terrain map based on elevation data or created by the community itself using elevation contour lines. Again, for a large scale mapping project, acquiring high resolution data is cost prohibitive. However, participatory 3D modeling allows the community to construct a terrain model based on locally available topographic maps. The map and map features can be created with locally available resources, which include cardboard, paper, paints, markers, yarn, and pushpins (Gaillard & Maceda, 2009). These 3D modeling methods require slightly more resources than the flat mapping described above but provide a very detailed depiction of relief and enhance community participation. Results from the 3D modeling projects can potentially be digitized for use within a GIS. While 3D models can be very detailed and versatile, they face constraints in terms of permanency. The models themselves can be difficult to update in a timely fashion (especially in terms natural hazard risk factors), are cumbersome to move, and will require general maintenance to increase their lifespan (Muller, Wode, & Wehr, 2003).

The use of scalable photomaps at the small isolated rural community level is restrictive due to the lack of availability of high resolution geo-reference imagery. 1:10000 scale orthophotos can be purchased from the National Geographic Institute of Guatemala (IGN) for approximately 75 US dollars (IGN, 2010). If pertinent data is available, small scale hazard mapping encompassing multiple isolated rural communities can take place using this data. A more important role of imagery is in the use of ground-based photographs to visually enhance the static flat maps discussed earlier.

A local church or community leader's house is a good manner in which to distribute landslide risk information. This eliminates the need to create individual map materials which might be difficult for isolated rural populations to comprehend. Information can be diffused through community meetings utilizing the visualization tools which have been created. Smaller scale mapping projects enable a more regional context, connecting rural communities to the larger infrastructure and addressing land use issues.

Comparative Analysis Two: Santiago Atitlan

The second analysis looks at the potential implications of different hazard mapping methods in the community of Santiago Atitlan. Santiago Atitlan is a town of over 33,000 people located on the southern shores of Lake Atitlan. The town inhabits the flat land at the base of Volcan Toliman and Volcan Atitlan. While the town is larger (and more urbanized) than the other lakeside settlements, the indigenous Maya culture is still relatively intact. Despite the presence of a small middle-income class, the population is predominately poor.

As typical with other regions in Guatemala, the poorest people occupy the areas of land most pre-disposed to debris flow risk; on steep slopes and/or near drainage areas. Agriculture is the main economic activity, and tourism provides a smaller source of income for the community when compared to other lakeside destinations (Santi, Hewitt, VanDine, & Cruz, 2010). Numerous smaller rural villages can be found on the outskirts of Santiago Atitlan, occupying the slopes of the volcanoes. This includes Panabaj (Figures 9 & 10), where an estimated 500 residents were killed from a debris flow that occurred during the torrential rains of Hurricane Stan in 2005 (Norwegian Church Aid, 2006). Recent research has already highlighted the need for debris flow education, awareness, and mitigation in this area (Santi et al., 2010).

Despite the more urban characteristics of Santiago Atitlan, poverty and illiteracy limit the functionality of interactive hazard mapping and visualization techniques. The size of the settlement's population poses challenges to the types of participatory mapping methods that could be implemented.

Figure 9. Panabaj debris flow. One channel of the 2005 landslide can be seen here. Tree tops help illustrate the height of the debris. A part of the village lays buried in the foreground (Ordeman, 2006). Photograph taken by Sharon L. Ordeman. Reprinted with permission from Sharon L. Ordeman.

Figure 10. Panabaj 2011. Volcan Toliman can be seen looming above vacant homes which were destroyed in the 2005 landslide. These homes were built by charity less than a year before the landslide (2011). Photograph taken by Patrick Burchfiel.

Conversely, the size of Santiago Atitlan means there is potential for more mapping resources, including access to GIS data and remotely sensed imagery. A town of this size would greatly benefit from multiple forms of hazard mapping, in which community members could participate at varying capacities.

A large scale hazard mapping project should be aimed towards the residents of the township proper. This includes the more densely populated urban center and the less densely populated incorporated land at the very base of the volcanoes. A static flat hazard map is one effective method for developing a landslide hazard map at large scale. The use of 3D modeling is plausible, but faces numerous constraints due to the high population of the community (with varying interests), and the lack of relief variation at a large scale. Remote sensing at a high enough resolution to be visually effective for a large scale hazard map is cost prohibitive and difficult to obtain. As the town proper of Santiago Atitlan occupies a relatively flat portion of land near the lake, the depiction of relief in improving cartographic visualization becomes less pronounced. Map readers are able to rely more on buildings, roads, watersheds, and land boundaries to orient themselves.

Community members can be provided a geo-rectified base map with street, landmark buildings, and drainage layers already displayed. Through community meetings or the implementation of a committee representing the community, map features are checked for accuracy, local knowledge map features inputted, and a symbology agreed upon. Information is digitized into a GIS and expert risk information depicted. The incorporation of a DEM and landmark photographs have the potential to then enhance the visualization of map features.

A smaller scale hazard mapping project that identifies landslide vulnerability may also be extremely beneficial to Santiago Atitlan and the surrounding small rural communities. A smaller scale sacrifices some map details (such as all individual houses, footpaths, etc.) but incorporates landslide hazard mapping for multiple communities and topologies. At a smaller scale, the use of 3D modeling and photo-maps becomes more effective and practical. An expert-generated 3D model from a DEM provides an optimal platform for community representatives from numerous villages to input their local knowledge. Expert creation of the physical model has the potential to be more costly (anywhere from a couple of thousand dollars to over ten thousand dollars) but alleviates complications that might be encountered with having multiple communities constructing a model. Expert-designed 3D models would also allow for a more accurate input of landslide hazards.

A smaller scale landslide hazard mapping project also suggests that stakeholders have access to a wider selection of remote sensing data. Previous research has suggested that 1:5,000 scale imagery is optimal for community photo-mapping projects (Mather, Boer, Gurung, & Roche, 1998). While obtaining this scale of imagery might be difficult throughout Guatemala, 1:10,000 scale orthophotos are more readily available (IGN, 2010). Incorporating this imagery into either a photo-map or as a background layer to a static flat map aids visualization of relief, networks, and landmarks. Distribution of landslide hazard maps created for the Santiago Atitlan vicinity would include displays at central community meeting areas (public buildings, schools, churches, etc.). Furthermore, areas found to be particularly vulnerable to landslide hazards could be the focus of distribution of basic hazard flat maps and other educational resources.

Employing Practical Remote Sensing Solutions

Geographic Information Science Applications

Geographic information science technologies play a vital role in landslide hazard analysis and the creation of hazard maps. Technological advancements are allowing for more accurate quantitative analysis, enhancing hazard visualization abilities, and increasing accessibility to data. To aid in mitigating the effect of rainfall-induced landslides, it is necessary to perform a landslide hazard analysis. A crucial part of this analysis is the creation of a landslide susceptibility map. Numerous applications and methodologies have been utilized in the past, taking advantage of remote sensing applications and topographic parameters, to accomplish this task. Data from these geographic analyses are combined in a Geographic Information System (GIS) to create a landslide susceptibility map. Data obtained from digital elevation models (DEMs) and landslide inventory maps are the most valuable in the creation of an accurate landslide susceptibility map (Coe, Godt, Baum, Bucknam, & Michael, 2004; Fabbri, Chung, Cendrero, & Remondo, 2003). As past landslides are the best predictors of future landslides, it is crucial to acquire or produce accurate landslide inventory maps in order to create a landslide susceptibility map (Pine, 2009).

This portion of the thesis consists of multiple components. First, I briefly discuss the establishment of the criteria defining "practicability" in terms of this project. Secondly, I review the methodology utilized by the USGS in their landslide hazard analysis following Hurricane Mitch. Third, the methods of this study to analyze the suitability of 90-m SRTM DEMs for landslide hazard analysis are presented. Finally, results from the study are presented along with conclusions and areas for future research.

To guide this research, one must determine the criteria for “practicability,” pertaining both to the scope of this research project and to non-governmental organization (NGO) stakeholders toward which the research is oriented. Multiple factors are taken into consideration for establishing the standards for a practical methodology. In regards to this project, the criteria focus predominately on data availability, accuracy, resolution, and cost. The nature of disaster response in developing countries dictates that data are easily accessible, relatively inexpensive, and current. Stakeholders, including disaster specialists, emergency services, private businesses, community members, NGOs (development, emergency aid, etc.), and the government, rely on information such as landslide susceptibility maps to make informed decisions regarding disaster risk reduction and response.

Hazard-related data are oftentimes very difficult to acquire in a developing country with high levels of poverty because funding for hazard analysis is limited (Guinau et al., 2005). Furthermore, NGOs can have difficulty accessing relevant spatial data from the government, which means they are left to procure it from private businesses where price becomes a much larger factor. For this reason, the methodology was evaluated on its ability to utilize accessible, inexpensive, and accurate data to produce results in a timely manner. These requirements have led to the selection of SRTM 90-m DEM data for the purposes of this study.

Previous Research and Study Area

Prompted by the widespread damage caused by Hurricane Mitch in October and November 1998, the USGS completed an extensive analysis of landslide hazards in the Sierra de las Minas region of Guatemala. A thorough landslide inventory was created, along with a few landslide susceptibility maps. Two important documents were produced from this study. The first is *Landslides Triggered by Hurricane Mitch in Guatemala-Inventory and Discussion* (Bucknam et al, 2001). The second is "Landslide susceptibility from topography in Guatemala" (Coe et al., 2004).

Hurricane Mitch caused large amounts of rainfall throughout Guatemala from October 27 to November 6, 1998. This event occurred at the end of the rainy season in Guatemala when the soil was already heavily saturated. The study area selected by the USGS is the region between the Polochic River and the Motague River in eastern Guatemala. The majority of this area is comprised of the mountainous region of the Sierra de las Minas which is geographically diverse in terms of geology, geomorphology, microclimate, and vegetation. The area experienced thousands of landslides brought on by the torrential rains of Hurricane Mitch (Bucknam et al., 2001).

The USGS gathered an extensive landslide inventory through the identification of landslides from 1:40,000-scale black and white aerial photographs taken between January 14 and March 6, 2000. Landslides greater than approximately 15 m in width were identified. Photographic interpretation of the landslide scars allowed for the differentiation of Hurricane Mitch landslides from those that had occurred previous to Hurricane Mitch. Exposed earth which appeared bright white in the aerial photographs was indicative of a Hurricane Mitch landslide scar. Older landslide scars that had some vegetation re-growth appeared darker on the photographs. Landslides were registered to 1:50,000-scale topographic maps of Guatemala. In total, more than 11,500 landslides were mapped. These inventory maps displayed more than 95 percent of all landslides larger than 15 meters within the study area (Bucknam et al., 2001).

After compiling a detailed landslide inventory, USGS researchers constructed landslide susceptibility maps for two Guatemalan topographic quadrangles. Due to a lack of available data for the study area, USGS researchers relied on topographic data gathered from a 10-m resolution DEM. The 10-m DEM was generated from the 20-m contours on two 1:50,000-scale quadrangles with elevation values assigned to cells based on their proximity to contour lines (Bucknam et al., 2001). The two data layers identified as the most important components of landslide susceptibility mapping were slope and elevation. Elevation and rainfall were correlated in the study area, as revealed by an analysis of two rain stations in the Sierra de las Minas region. USGS researchers believed reasonable susceptibility mapping accuracy could be accomplished using the above parameters following the landslide mapping research of A. G. Fabbri (Coe et al., 2004). Fabbri et al. (2003) concluded that the most accurate determination of landslide locations is slope, elevation, and aspect. For the purpose of the susceptibility mapping in Guatemala, the topographic feature of aspect was removed from the equation as its influence on landslides in the study area probably had more to do with the direction of Hurricane Mitch (Bucknam et al., 2001).

Landslide susceptibility was estimated using a ratio method of the slope and elevation parameters. This involved the comparison of these parameters present at landslide initiation cells to those present at a random sampling of DEM cells (Coe et al., 2004). A moving count-circle approach was used to combine the parameters of slope and elevation (Savage, Coe, & Sweeney, 2001, Coe et al., 2004). Coe et al. (2001) provides a more detailed description of the moving count-circle approach. This enabled the creation of a susceptibility threshold which indicated that as elevation increased, the minimum slope angle for slope failure decreased. Software was created to convert the ratio grid into a susceptibility map (Coe et al., 2004). The resulting map was deemed accurate because 80 percent of landslide locations fell within the susceptibility zone while maximizing the area that had no susceptibility (Coe et al., 2004). Two important characteristics of the landslides should be noted. First, 96 percent of the landslides occurred between the elevations of 500 meters and 2,500 meters. Second, 96 percent of the mapped landslide initiation points were located on slopes between 16 degrees and 44 degrees (Coe et al., 2004).

To further their landslide hazard investigation, USGS researchers employed a GIS-based simulation of a landslide dam failure. The landslide dam in question is located on the Rio La Lima and was caused by the severe rains of Hurricane Mitch. LAHARZ software was used to run the simulation of varying debris flow volumes (Bucknam et al., 2001). This software was originally developed to estimate debris flow extents from volcanoes (referred to as lahars). LAHARZ is a menu-driven software written in the ArcInfo Macro Language (AML). LAHARZ is capable of calculating probable debris flows given a DEM and multiple debris flow volumes (Schilling, 1998). As a catastrophic landslide dam failure would produce conditions similar to that of lahars, the software was used to reveal hazard zones based on varying debris flow volumes (Bucknam et al., 2001).

Data Acquisition

The SRTM 90-meter resolution DEM was selected for this study due to its global coverage, easy accessibility, and low cost of acquisition. Lower resolution DEMs such as the USGS Global 30 arc-second Elevation Dataset (GTOPO30) have proved to be of insufficient resolution for landslide hazard analysis in Guatemala (Chisolm, 2008). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) produces 30-meter resolution DEMs. A study has indicated that errors in the ASTER DEM can cause complications when used by the LAHARZ software for debris flow analysis because there is the potential for more vertical error (Huggel, Schneider, Miranda, Granados, & Kaab, 2008). While ASTER DEMs were not selected for this research project, their potential value to landslide hazard mapping should not be ignored and provide an opportunity for future research.

Higher resolution DEMs are available from remote sensors, such as IKONOS (1-meter resolution) but at a cost that is typically too expensive for many NGOs operating in developing countries. The process of converting topographic maps to DEMs is another method by which to acquire the essential topographic details for a landslide hazard analysis, but it is very time consuming and requires technical expertise. As mentioned above, these agencies and other stakeholders dealing with humanitarian issues do not necessarily have the capacity or expertise to carry out this type of detailed geographic analyses. For this reason, they rely on resources that are readily available or easy to produce because speed is of great importance during disaster risk reduction and response operations.

The basis for this study was the SRTM 90-meter DEM panel 3N15W090 downloaded through the USGS's EarthExplorer website at no cost. Adjoining panels were downloaded for the purpose of aiding in geo-referencing of the USGS's landslide inventory. Data for Hurricane Mitch landslide locations were available in the form of ArcInfo Export files in the USGS's publication warehouse. This includes initiation points and landslide location polygons formulated from the interpretation of 1:40,000-scale aerial photographs.

Landslide inventory data was added to the DEM layer within ArcMap 10. After a visual inspection of the data, two panels of landslide initiation points and their corresponding landslide polygons were selected (identifiers 22611 and 22612) for further analysis. These panels were selected due to the extensive number of landslides, their varying extent, and the presence of large debris flows. Neither the landslide susceptibility maps created by the USGS following Hurricane Mitch, nor the software that was used to create them was available for the purpose of this study.

Analysis

Given the available data, the exact methodology for creating landslide susceptibility maps could not be replicated using the SRTM 90-meter resolution DEM. One solution to this problem was to use the LAHARZ software to predict debris flow paths on the SRTM 90-meter DEM. Results were to be compared to the landslide polygons obtained from the USGS. I hypothesized that this method would be similar in accuracy in identifying large scale debris flows to the 10-meter resolution DEM. Copies of the “aml” and menu files for the LAHARZ software were downloaded from the Internet along with a description of how to run the program. Despite successfully loading ArcInfo Workstation, the LAHARZ software did not function properly. No menus were displayed and no opportunity to load the DEM data was provided. LAHARZ is menu driven, and without the menus displaying, the software could not be run on the ArcInfo Workstation. The problem is potentially with the “aml” and menu files because their Internet source page is dated 1998, which could indicate outdated, missing, or corrupted data.

Taking into consideration available data and software for this study, the ArcMap 10 environment was selected as the best method for analyzing the SRTM 90-meter DEM. After importing the DEM data, the appropriate landslide polygons and initiation point data were overlaid. From here, ArcMap 10 Spatial Analysis tools were utilized to examine the data and identify any possible relationships. In particular the Flow Accumulation, Watershed, and Slope tools were employed to aid in the analysis. USGS landslide polygons from the Hurricane Mitch Landslide Inventory would be layered with the results to assist in a comparative examination. These methods were founded on the importance of slope, elevation, and drainage networks in landslide hazard analysis studies. The selection was also based on the author’s familiarity with the Spatial Analysis tools in the ArcMap environment.

The landslide vector data obtained from the USGS utilized the North American Datum 1983 Universal Transverse Mercator 15N coordinate system. However, the SRTM 90-m DEM was projected in the World Geodetic System 1984 coordinate system. To keep all of the results consistent, the DEM raster was projected to the landslide vector data coordinate system, North American Datum 1983 Universal Transverse Mercator 15N, using the Project Raster option under the Data Management tools.

To further prepare the DEM for analysis, minor flaws in the elevation model were cleaned up using the Fill tool application. This created a new output raster that was used as the input for creating raster layers depicting elevation, slope, flow direction, watershed, and flow accumulation. Elevation data determined from the DEM were displayed with a typical elevation color ramp set at 500 meter manual breaks. Slope was determined from the 90-meter DEM using a Surface Analysis tool. Manual slope breaks were established to best illustrate slope areas that were prone to failure according to the previous USGS research in Guatemala, which demonstrated that slopes greater than 15 degrees were particularly prone to landslides (Bucknam et al., 2001). Also, landslide susceptibility would increase within these slope zones with an increase in elevation.

A watershed analysis would allow one to ascertain if there was any correlation between the watershed and the location of landslides in the study area. This tool required both a flow direction raster and pour points as inputs. The Flow Direction tool ascertains the downward slope direction for each grid cell in the DEM, indicating the direction water will flow. The watershed analysis was completed using landslide initiation locations as pour points and the flow direction raster.

Flow accumulation was calculated utilizing the flow direction raster. This computation takes into consideration the number of cells that flow “downstream” into a particular cell. Manipulating the data output classes allows for stream-like patterns to appear. Performing a flow accumulation analysis makes it possible for one to identify the drainage patterns of the terrain. This is of great importance, as large rainfall-induced landslides and debris flows have a propensity to travel significant distances and merge with drainage networks (Pallas et al., 2004).

Once the layers of elevation, slope, watershed, and flow accumulation were created, a process of visual interpretation and random sampling was used to test the suitability of the SRTM 90-meter DEM resolution for a landslide hazard analysis. The data obtained from the size of the landslides, and the relation of landslide polygons to flow accumulation, provide the best environment for this analysis. One would expect to find strong correlations between flow accumulation, representing drainage networks, and the locations of medium to large debris flows. Further observations could be made by analyzing landslide locations in relation to elevation, slope, and watershed.

Results from SRTM Analysis

Figure 1 depicts the SRTM 90-meter resolution DEM with elevation breaks set at 500-meter intervals and provides a generalized topographic overview of the study area. The landslide polygons are shown in blue. Of particular interest is the identification of the portion of the DEM affected by cloud cover, as indicated by the white pixels in Figure 11 (see page 33). These locations will provide inaccurate data readings in the other data layers and must be avoided in further analysis. An abundance of landslides can be located between the 1,500 and 2,500 meters in the elevation map, which conforms to the findings of Bucknam et al. (2001).

The slope map produced from the SRTM 90-meter DEM can be seen in Figure 12 (see page 34). These results show positive association between landslide initiation points and slopes of 15 degrees or more. These generalized results are similar to those obtained from the USGS's landslide hazard analysis (Bucknam et al. 2001). One can also see the larger landslide polygons track areas of low slope, which can be an indicator of the drainage network. This aids in demonstrating the accuracy of the 90-meter resolution DEM in identifying larger drainage channels where debris flow hazards would exist.

One area of inconsistency stood out in the south-central portion of the study area, characterized by relatively low slope and a high occurrence of landslides (center of Figure 12). As this posed a possible indication of inadequacy of the DEM's resolution, the area was more closely inspected for terrain smoothing. Terrain smoothing could be ruled out, however, as it appeared elevation and aspect were the largest contributors to the increased frequency of landslides. The landslide initiation points that were located in slopes less than 15 degrees tended to conform to elevations between 1,500 meters and 2,500 meters which encountered higher rainfalls, as concluded by Bucknam et al. (2001). Lower slopes caused the majority of these landslide initiation points to have relatively small associated landslide paths (polygons). Furthermore, a generalized higher occurrence of landslides on the south and east facing slopes could be credited to the route of the hurricane (Bucknam et al., 2001). A final analysis to rule out terrain smoothing was completed through the referencing of the Rio Hondo 1:50,000 scale topographic quadrangle which showed the same area of low slope. With additional research, these results may suggest the importance of land cover as a landslide mapping parameter.

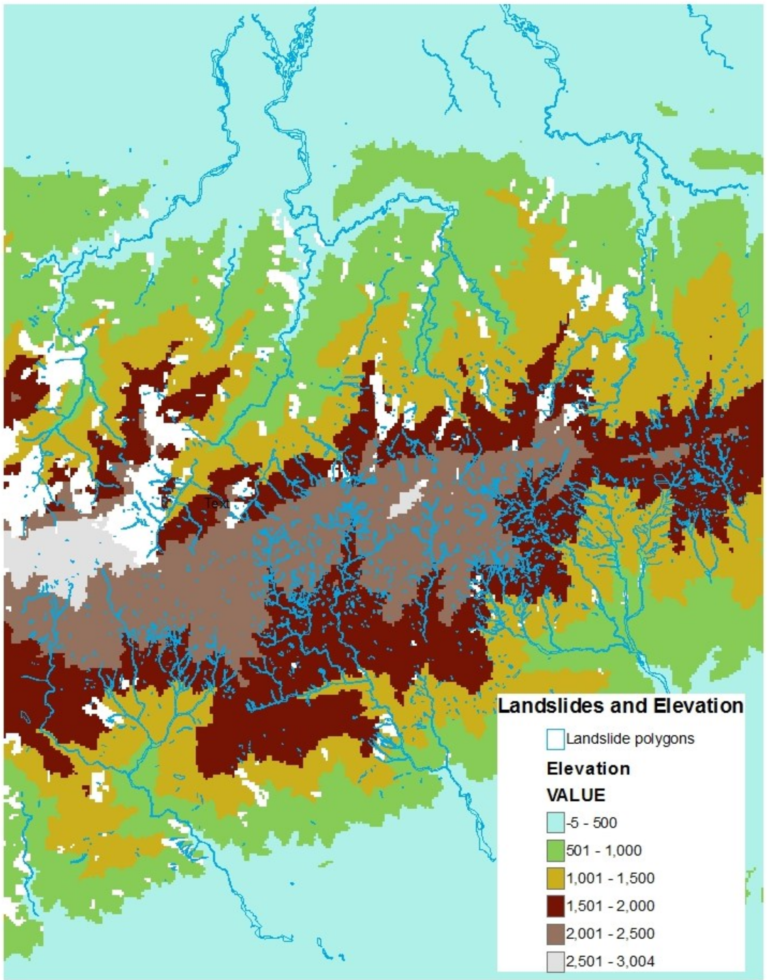

Figure 11. Landslides and elevation. Above is a map depicting the elevation data from the SRTM 90-meter resolution DEM encompassing the study area of the Sierra de las Minas, Guatemala. Hurricane Mitch landslide location polygons acquired from the USGS is shown in blue. White areas on the map indicate portions of the DEM affected by cloud cover.

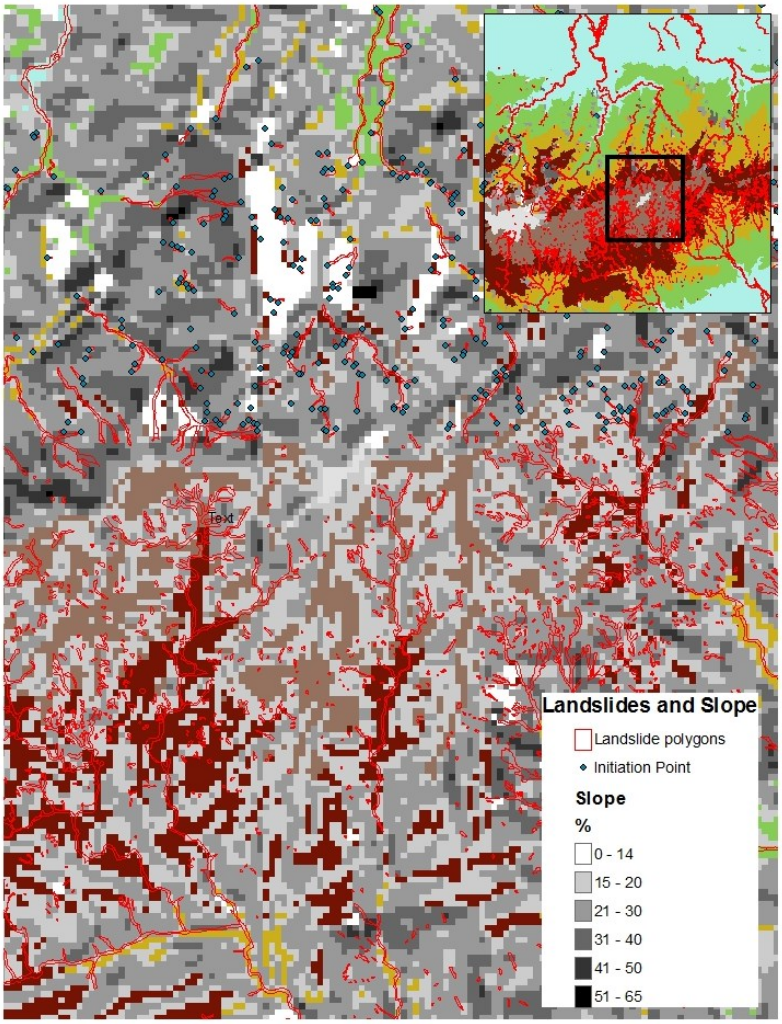

Figure 12. Landslides and slope. Map displaying slope values acquired from the SRTM 90-meter resolution DEM of the Sierra de las Minas. Locations of landslides are identified in red while point symbols represent landslide initiation points. Slope values less than 15 degrees have been set to no color, and their associated elevation data can be viewed.

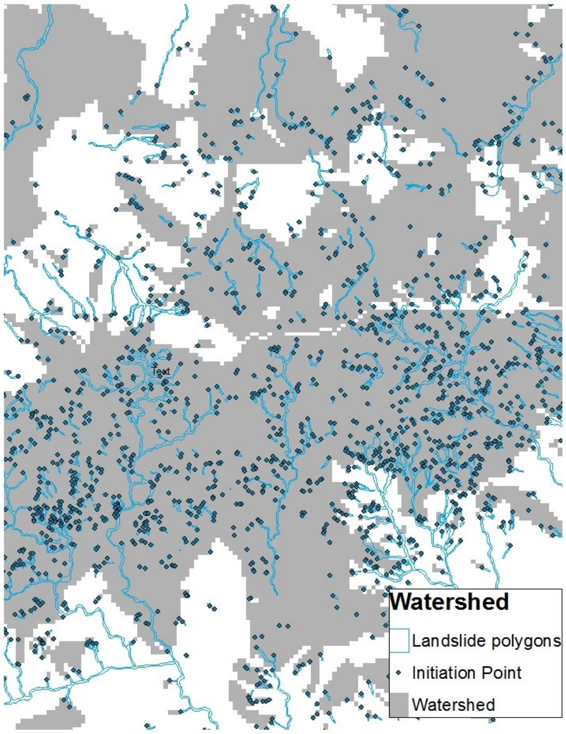

Figure 13. Watershed analysis. Map displaying watershed data utilizing landslide initiation points as pour points. Landslide locations have been over-laid in blue.

The watershed analysis, Figure 13, did not produce any conclusive results that would aid in the evaluation of the SRTM 90-meter DEM resolution's suitability for landslide hazard analysis. Initiation points were used as pour points, and the resulting watershed was displayed, as seen in Figure 13. While the watershed analysis does give one a good representation of the drainage basin, and encompasses areas of high landslide frequency, it does not provide a precise gauge of resolution suitability. Landslide initiation points that are not clustered, such as those in the southern portion of the map (Figure 13), do not necessarily show a positive correlation between initiation point and the associated watershed. This could be seen as an indicator that the 90-meter DEM's resolution is not sufficient, but this would require the use of a 10-meter DEM for comparison. The analysis does, however, provide an additional indicator that terrain smoothing was not occurring in the south-central portion of the study area, for the watershed analysis shows the area as a rather condensed portion of the drainage basin. Watershed irregularities on the north-facing slopes in the eastern portion of the map could possibly be explained by the cloud cover data corruption in that region.

The results from the flow accumulation analysis can be seen in Figure 14 (see page 37). Areas of water accumulation are shown in black and help identify the terrain's drainage system. The flow accumulation layer's class break was established at 1.5 because it gave the viewer a well-defined overview of the drainage pattern. Landslide polygons were over-laid in light blue to illustrate the relationship between the landslides and flow accumulation. Through visual interpretation, a clear relationship between flow accumulation and the landslides could be ascertained. This was especially evident with the larger debris flows that aligned distinctly with the flow accumulation pixels.

As previous research has already established a correlation between drainage systems and debris flows, a positive correlation between flow accumulation and landslide polygons is to be expected (Pallas et al., 2004). This relationship can be seen in Figure 14. Utilizing the Select by Attributes tool, one can determine that the most accurate positive correlation between landslides and flow accumulation pixels, through visual interpretation, occurs with landslide polygons equal to or greater than 1,000 meters in perimeter. This represents only approximately seven percent of the total landslide polygons which could suggest a possible resolution limitation for adequate landslide hazard analysis. Even among the larger debris flows, there appears to be some generalized offset between landslide polygons and the drainage channels. Another indication of a possible resolution constraint with the SRTM 90-meter DEM is the numerous smaller landslide polygons that do not align with flow accumulation pixels.

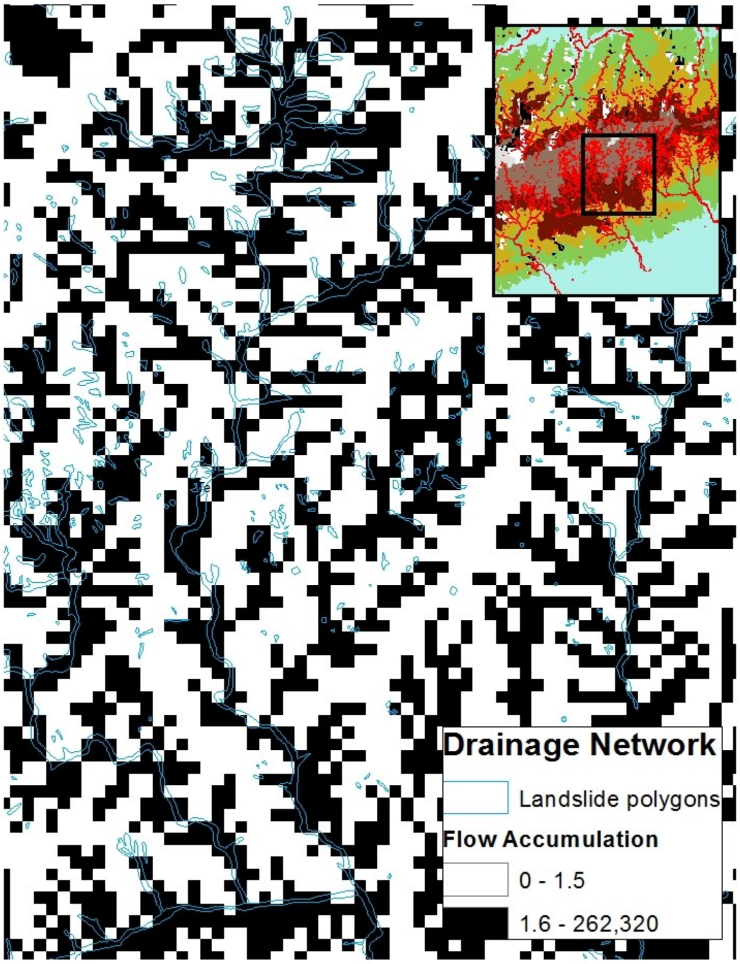

Figure 14. Flow accumulation. Flow accumulation data for the Sierra de las Minas displayed in black and white. The black pixels show areas of water accumulation aiding in the identification of the area's drainage network. Landslide locations are outlined in blue.

To help determine if the flow accumulation results indicate a possible insufficiency with the resolution, analyzing the characteristics of the landslides that do not intersect flow accumulation pixels is necessary. Two separate sets of random samplings of landslide polygons not intersecting flow accumulation pixels were taken. Each set consisted of 50 landslide polygons. Both sets of samples revealed that 84 percent of the landslides that did not intersect flow accumulation pixels were less than 90 meters in total length and less than 45 meters in total width. The remaining landslides tended to have total lengths between 90 meters and 180 meters with total widths between 30 meters and 90 meters.

Conclusion

Evident from the beginning of the research was the importance of incorporating local knowledge into the hazard mapping process. Community involvement aids in the communication from expert to local, which ensures maps are accepted among local stakeholders and empowers community members in the DRR&R process. Utilizing the depiction of relief, imagery, and landmarks in addition to local knowledge not only helps with map comprehension, but supports resident map building processes.

Table 2 generalizes some of the findings from the research and analysis of three common hazard mapping approaches. The socio-economic situation of Guatemala in many ways constrains hazard mapping methods at the community level to static forms. There is no single method or set of methods for enabling practical and efficient cartographic visualization at the local level. Instead, the techniques identified in this thesis provide insight into some of the mapping components necessary to allow sound communication of landslide hazards to local communities.

Remotely-sensed data have the potential to increase accessibility and practicability of landslide hazard analysis. From my research, I concluded that the SRTM 90-m resolution DEM was not a suitable substitute for a 10-m resolution DEM for a comprehensive landslide hazard analysis of the mountainous regions of Guatemala. Resolution was seen as a contributing factor here, because 84 % of the landslides that do not align with flow accumulation pixels are less than 90 m at their longest point. General offsetting between landslide polygons and their associated drainage channels can also be visually interpreted from the mapping results indicating resolution limitations. Further validation of these results might be gathered through the comparative analysis of slope and flow accumulation maps at varying resolutions. Ideally, this would be completed with the original 10-m resolution DEM created by the USGS for its landslide hazard analysis in Guatemala following Hurricane Mitch. At the time of this writing, the DEM utilized by the USGS was not available to the general public, so a test location would have to be selected where one could create slope and flow accumulation maps based on 10-m, 30-m, and finally 90-m resolution DEMs to identify resolution degradation.

Despite the conclusion that the SRTM 90-meter resolution DEM is not an adequate substitute for 10-meter resolution DEM, the results indicate that the SRTM 90-meter resolution DEM may be sufficient for identifying areas susceptible to large debris flows. In general, larger landslide polygons align with the drainage patterns identified by the slope and flow accumulation maps. The initiation point locations tend to support the slope and elevation characteristics established by Bucknam et al. (2001). While larger debris flows may represent only a small portion of the total landslide events that occur following hurricanes, they pose a high risk to settlements and infrastructure due to their destructive force and ability to travel long distances. Although not suitable as a replacement for higher resolution DEMs, the SRTM 90-meter resolution DEM can aid in providing insight into some of the landslide hazards that exist in the mountainous regions of Guatemala until high resolution DEMs of the area are made more readily available to all stakeholders.

Debris flows are an ever-present risk to the people of Guatemala. Hazard mapping is just one of many useful tools in coping with landslide threats. Properly combining community mapping strategies with accessible remotely sensed data stands to increase the resilience of highland communities throughout Guatemala. Stakeholders must realize the limitations of technology, take into account local knowledge, and present data in creative ways to maximize the communicative power of the hazard maps they create.

Table 2. Conclusions.

Method	*Isolated Rural Communities*	*Santiago Atitlan*
Flat Maps	**Pros –** Rapid production; minimal resources required; efficient distribution. **Cons –** Can be difficult to accurately depict relief; challenge for locals to access "mental maps"; user comprehension of map possibly reduced.	**Pros –** Rapid production; minimal resources required; ideal for more urbanized areas lacking relief. **Cons –** Same constraints as listed adjacent; cons are exacerbated at smaller map scales.
3-D Modeling	**Pros –** Community involvement; local knowledge maximized; representation of relief. **Cons –** Field work intensive; potentially resource demanding; permanency.	**Pros –** Effective at smaller scale; community involvement; depiction of hazards as related to relief. **Cons –** Distribution constraints; pros are reduced at a larger scale surface; permanency.
Photo-Maps	**Pros –** Accuracy; efficient distribution, rapid production; depiction of relief and landmarks. **Cons –** Cost prohibitive; limited access to imagery of appropriate resolution.	**Pros –** Efficient distribution; rapid production; accuracy (esp. smaller scale); depiction of relief and landmarks. **Cons –** Constraints are exacerbated at a larger scale; can limit amount of local knowledge input.

Note. Hazard mapping methods as they apply to Lake Atitlan communities.

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