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Landslide inventory mapping for calculating potential lahar volume for Canton Buenos Aires on Ilamatepec (Santa Ana) Volcano, Santa Ana, El Salvador

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Resumen

Los deslizamientos de tierra en terreno volcánico son comunes y una de las principales fuentes de material para lahares durante los tiempos de los períodos de actividad no volcánicos. Cuando esta información se conoce y se registra se puede utilizar para la creación de mapas de peligros de lahares. Sin embargo, en volcanes donde hay poco o nada de datos se necesita obtener esta información de una manera diferente. Este documento propone la creación de inventarios de deslizamientos utilizando imágenes de satélite, sistemas de información geográfica (GIS) y reconocimiento de campo aplicando la ecuación de la ley de energía que utiliza el área de deslizamiento de tierra y el volumen para alimentar esa relación empírica. Para este propósito, este artículo trabaja el Volcán de Santa Ana también conocido como Volcán Ilamatepec, en Santa Ana, El Salvador, donde se han registrado muy pocos datos sobre lahares y deslizamientos de tierra. Sin embargo, es un área donde estos procesos ocurren de una forma regular. Dos imágenes de satélite y SIG se utilizaron para la identificación, georreferencia y la creación del inventario de deslizamientos. En el campo, 24 deslizamientos de tierra se midieron y se utilizan para estimar el potencial volumen total de material procedente de todos los deslizamientos de tierra. Este volumen se puede utilizar entonces para seleccionar volúmenes de lahar que más se parecen posibles eventos para el cantón de Buenos Aires y otras comunidades alrededor del volcán de Santa Ana.

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Palabras clave: *Volcán Santa Ana, Inventario de derrumbes, Lahar, Mapeo de campo, SIG*.

Resumo

Deslizamentos de terra em terrenos vulcânicos são comuns e uma das principais fontes de material para lahars durante tempos de períodos de atividade não-vulcânicos. Quando esta informação é conhecida e gravado pode ser utilizado para a criação de mapas de risco lahar. No entanto, em vulcões onde existe pouco ou nenhum dado esta informação tem de ser obtida de uma maneira diferente. Este trabalho propõe a criação de estoques de deslizamento a partir de imagens de satélite e Sistemas de Informação Geográfica (GIS) e fiança campo para aplicar a equação da lei de potência que utiliza áreas de deslizamento eo volume para alimentar e relação empírica. Para o efeito, esta papéis olha para o Volcan Santa Ana também conhecido como Ilamatepec Vulcão em Santa Ana, El Salvador, onde foram registrados muito poucos dados sobre lahars e deslizamentos de terra. No entanto, é uma área em que estes processos ocorrem numa base regular. Duas imagens de satélite e SIG foram utilizados para a identificação, georreferenciamento e criação do inventário deslizamento de terra. No campo, 24 deslizamentos foram medida e usado para estimar o potencial de volume total de material derivado de todos os deslizamentos. Este volume pode ser então utilizado para selecionar volumes lahar que mais se assemelham possíveis eventos para a Canton Buenos Aires e outras comunidades ao redor do vulcão Santa Ana.

Palavras-chave: *Santa Ana Volcano, Desmoronamento Inventory, Lahar, Campo mapeamento, GIS.*

Abstract

Landslides in volcanic terrain are common and one of the main sources for material for lahars during times of non-volcanic activity periods. When this information is known and recorded can be used for the creation of lahar hazard maps. However, in volcanoes where there is little or no data this information needs to be obtained in a different way. This paper proposes the creation of landslide inventories using satellite images and Geographic Information Systems (GIS) and field recognizance to applied the power law equation which uses landslide area and volume to feed and empirical relationship. For this purpose, this papers looks at the Volcan Santa Ana also known as Ilamatepec Volcano in Santa Ana, El Salvador, where very little data on lahars and landslides have been recorded. However, it is an area where these processes occur on a regular basis. Two satellite images and GIS were used for the identification, georerencing and creation of the landslide inventory. In the field, 24 landslides were measure and used to estimate the potential total volume of material derived from all landslides. This volume can be then used to select lahar volumes that most closely

resemble possible events for the Canton Buenos Aires and other communities around the Santa Ana Volcano.

Key words: *Santa Ana Volcano, Landslide Inventory, Lahar, Field Mapping, GIS.*

Introduction

Around the world, lahar susceptibility and identification of hazard zones have been achieved by creating lahar inventories and modeling them using GIS (Washington State Department of Natural Resources, 2006; Herva's and Bobrowsky, 2009; Blahut *et al.*, 2010; Paulín *et al.*, 2014; Paulín *et al.*, 2016).

Studying these landslide as main source for materials, such as boulders of different sizes, soil, pyroclastic deposits and vegetation is essential. These materials can be remobilized with water playing an essential part on the lahar behavior, extent and flow. The techniques to calculate the volume differ depending on where they occur (volcano, plane, hill, etc.), the geometric shape of the initial landslide (conic, elliptical, irregular, etc.) and the method to obtain the volume data (geometry, calculus, etc.) (Froggatt, 1992). It is a difficult task to calculate total volumes of landslides which requires surface and subsurface information, for that reason for large areas affected by landslides an empirical relationship between the geometric shape of the landslide and the volume moved is used to extrapolate their volumes Equation 1 (Paulín *et al.*, 2016; Kalderon-Asael *et al.*, 2008; Guzzetti *et al.*, 2009).

Weathered areas and with recent loose volcanic deposits are classified as high risk for lahars (Nadim *et al.*, 2013). Caldera volcanoes, such as the Santa Ana Volcano (SAV), have the potential to generate landslide and debris flows due to their steep slopes and pyroclastic deposits, as well as the weakening affect of weathering in the volcanic edifice (Paulín *et al.*, 2014). Siebe *et al.*, (1992), Siebe *et al.* (1993) and Capra *et al.* (2002) showed that volcanic activity can generate large lahars along river channels and quebradas, with volumes exceeding $10^5 m^3$ (Capra *et al.*, 2002; Korup *et al.*, 2004). However, these events are uncommon (Capra *et al.*, 2002). Smaller volume lahars, between 10^1 and $10^2 m^3$ (Montgomery and Dietrich, 1994; Pack *et al.*, 2001), are more common during periods of volcanic inactivity and can be dangerous and destructive Figure 2. It is important to create a landslide inventory because those events are one of the main sources of dry materials for lahars (Paulín *et al.*, 2014; Paulín *et al.*, 2016).

Study Area

The Canton Buenos Aires is situated in the northern flank of the Santa Ana (Ilamatepec) Volcano (SAV) (Figure 1). This flank was directly affected by the October 1st, 2005 SAV eruption and presents an ideal set up for the volcanic hazard study. It is important to mention that this area has been affected also by other geological hazards.

For example, they have suffered major earthquakes like the one in 2001 which registered as 7.3 in the Richter scale. The study area is also affected by several tropical storms and hurricanes every year.

In the study area, the Canton Buenos Aires community is an example of a community that has shown and demonstrated a willingness to learn and participate in projects that they viewed as helpful for the community. They demonstrated this by creating an internal government completely and subdivided its Canton in sections independently from local and federal governments. They did this as a way to be more efficient and improve communication among themselves. The way they did it was to divide the Canton in 11 sectors and each sector has its own person, leader, in charge. This group of people selected by their peers is the one in charge of organizing meetings and making decisions concerning the Canton, such as the distribution of water which it is control as there is not an unlimited amount of it. They also use this system to communicate information to the rest of the community in a timely manner instead of having to wait until all the community gets together.

The landslide inventory will help this community by gaining an understanding on the potential lahar volumes that this community can encounter and has actually encountered.

Lahars in Canton Buenos Aires

Lahars in the Canton Buenos Aires are triggered mainly by rain from hurricanes, tropical depressions and storms. For example, Hurricane Stan in October 2005 created several lahars that travel on the East flanks of the volcano killing 6 people (information given by members of DGOA) and destroying part of the town Planes de la Laguna located a few kilometers from the crater.

These lahars where extra voluminous due to the eruption of the volcano the day before which fed the lahars with more loose material from pyroclastic density currents and ash fall. The lahars had boulders of different sizes, soil sediment, trees and water (Menjivar, 2006).

These hot deposits made by the eruption and moved by the hurricane in the form of lahars came down the slopes hot and stayed fuming for several days. Due to this fact residents of the area refer to those lahars as lava flows (as per several conversations with residents in the area throughout the years).

Tropical Depression storms like E12 that occurred in October 2011 triggered hundred of debris flows in the flanks of the volcano and some of them transformed into lahars. Some of those lahars came down to on the north flank of the volcano, where Canton Buenos Aires is located, destroying roads and leaving the community isolated for several days until the residents were able to restore part of the road. This is the road that goes to the main road to Santa Ana and Sonsonate the closest cities, and

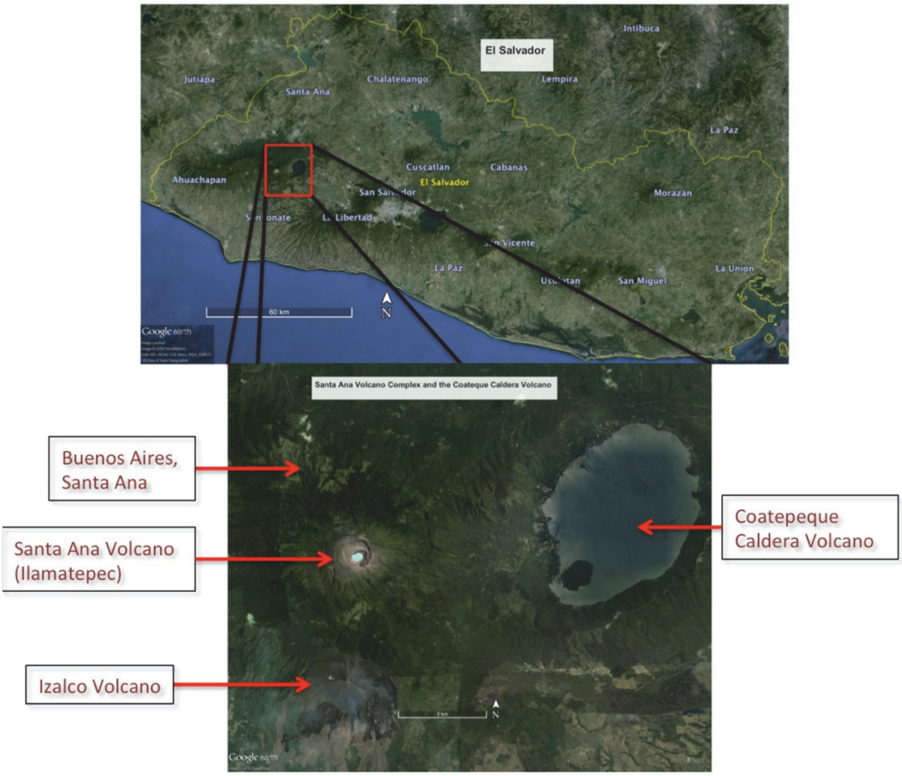

Figure 1. Location of the Coatepeque Caldera Lake. The top image shows the whole El Salvador country with a yellow line indicating its border, and a red box highlighting the location of the Santa Ana Volcano within the country of El Salvador. The bottom image shows the Santa Ana Volcanic field and the Coatepeque Caldera Volcano.

destroying one of the three possible routes for evacuation from a volcanic eruption (see Figure 2).

Those, however, are not the only occurrences of this process in the area as several historical lahar deposits are visible in the area. Lahar deposits vary in thicknesses from a few centimeters to over one meter in several areas around the volcano. In the current hazard map there is note saying that the lahar hazard map for this volcano was done even there was no evidence of this processes in the volcano. The hazard map however identified some of the most probable hazard ravines and run simulations accordantly. The map approximated the events following the 2005 eruption very accurately.

Figure 2. Damages created by lahars during the Hurricane Stan in the East flank of the Santa Ana Volcano in 2005.

However, this hazard maps deals with extreme events and cover only some general areas and it did not take into account past events. Also, it is not clear how the volumes were selected. This paper shows a method to obtain this valuable information for future lahar hazard mapping of the area.

Methods

To find the volumes for the lahar hazard map, a landslide inventory for the SAV was generated. This is a different approach from the map generated by DGOA and USGS.

In the study area, an inventory 447 landslides was mapped from interpretation of satellite images and local field surveys to assess and describe landslide distribution. All landslides were digitized into a geographic information system (GIS), and the spatial geodatabase of landslides was constructed from standardized GIS datasets.

Detailed geometric values of 24 landslides measured during field work defined the landslide area and volume, which were then used to establish an empirical relationship that took the form of a power law with a scaling exponent of $\alpha = 1.1519$. The empirical relationship was used to estimate the potential total volume of material delivered from all landslides in the catchment. The paper shows that landslides here have the potential to deliver 15858 m^3 of sediments to the main stream.

Remote Sensing and GIS Landslide Mapping

The first step in this process was to find two sets of cloud free images of the SAV. This is needed to be able to identify and mapped landslides. Specially giving El Salvador tropical climate, the coffee plantations and vegetation in the flanks of the SAV which make the identification and mapping of landslides nearly impossible in most images.

Using Google Earth these two sets were identified. The first set was from 2003 and the second from 2012 (Figure 4). In the case of the SAV the 2003 images were used as base truth representation of the ground. It allowed to see more clearly differences in the ground and to identify landslides image in the 2012 image.

As one can see in Figure 3, the terrain can change very drastically, and in some areas the distinction between a landslide and manmade changes can be very difficult to identify. Also, the amount of landslides mapped using satellite images are very dependent on when the image was taken. El Salvador does not have a satellite covering all its land on a monthly basis, so images are always dependent on availability, and in some cases the images may be partially or totally cloud cover. It may also happen that the image may not capture any or many landslides as it was the case with the 2003 images. However, one can sometimes find images showing landslide scars from past events as it is the case of the 2012 image.

This image shows the scars from landslides, top image, and how it used to look, bottom image, before the events.

ArcMap was used to georeference both images. Once that was done the images where displayed and used to describe and create the landslide inventory for the SAV flanks.

The 2003 and 2012 SAV Google Earth images were used as based maps to identify (2012 satellite images) areas where landslides have occurred after the tropical storm E-12 passed through that area in 2011. The 2003 set of satellite images were used to check that those areas previously identified in the 2013 set, that they were actual scars and not anthropogenic in nature, like deforestation, coffee or agricultural plantations, roads that may have been abandoned, etc. The combination of the two sets (2003 and 2012) od satellite images helped create the landslide inventory (see Figure 6) of the area of interest and identified areas of interest for the fieldwork mapping (see Figure 5).

Fieldwork Mapping

Once the landslide inventory was created (see Figure 6), several sites where selected for a more detail analysis in the field. 24 landslide (see Figure 5) were selected and visited to be used to calculate the potential total volume of dry material that the landslide can contribute to the lahar. The locations of the landslides were chosen using an accessibility and safety criteria.

This map shows the location of all the landslides measured in the field to be used to calculate the potential total volume (Equation 1) that the landslide can contribute to a lahar.

Due to the topographic characteristics of the SAV, a caldera volcano, it has steep slopes and deep ravines (quebradas) that makes parts of it inaccessible. Also, the country of El Salvador is having internal problems, specially with gangs and assaults that makes the fieldwork harder and unsafe in certain locations (Gomez, 2016). These locations vary in season and sometimes even on a day to day basis. It was for that reason that the decision to select the area to get the landslides from the inventory was given to the local park rangers.

Based on their knowledge of the terrain, and safety places to work 24 landslides were studied and data collected.

After that landslide mapping, field reconnaissance and landslide verification was carried out. In the field, landslide geometry was measured with laser range finder. Soil depths widths, and horizontal and vertical distances at the head scarp, were used to estimate landslide volume of 24 landslides. The measurements of landslide area (A) and volume (V) were used to establish and feed an empirical relationship that took the form of a power law:

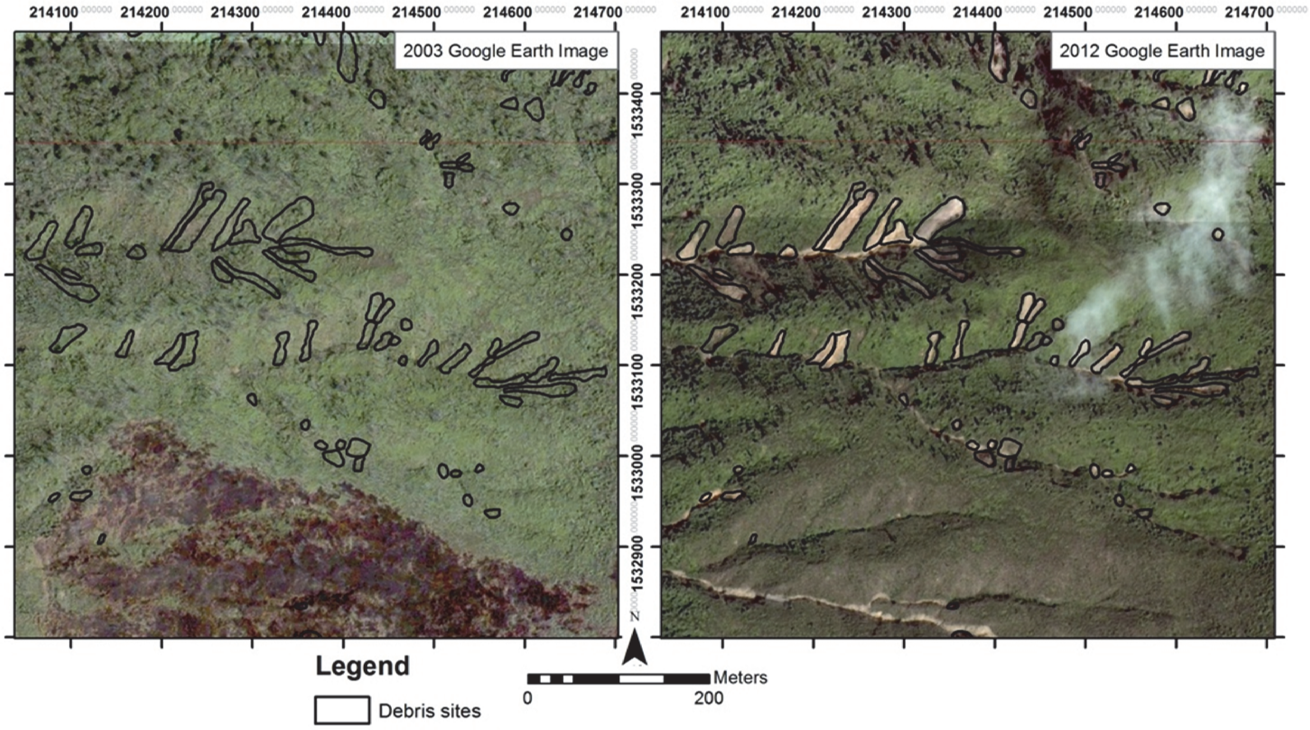

Figure 3. Google Earth close-up where one can appreciate the changes in the landscape. The black outlines indicate where the identified landslide are located in both the 2003 and the 2012 images.

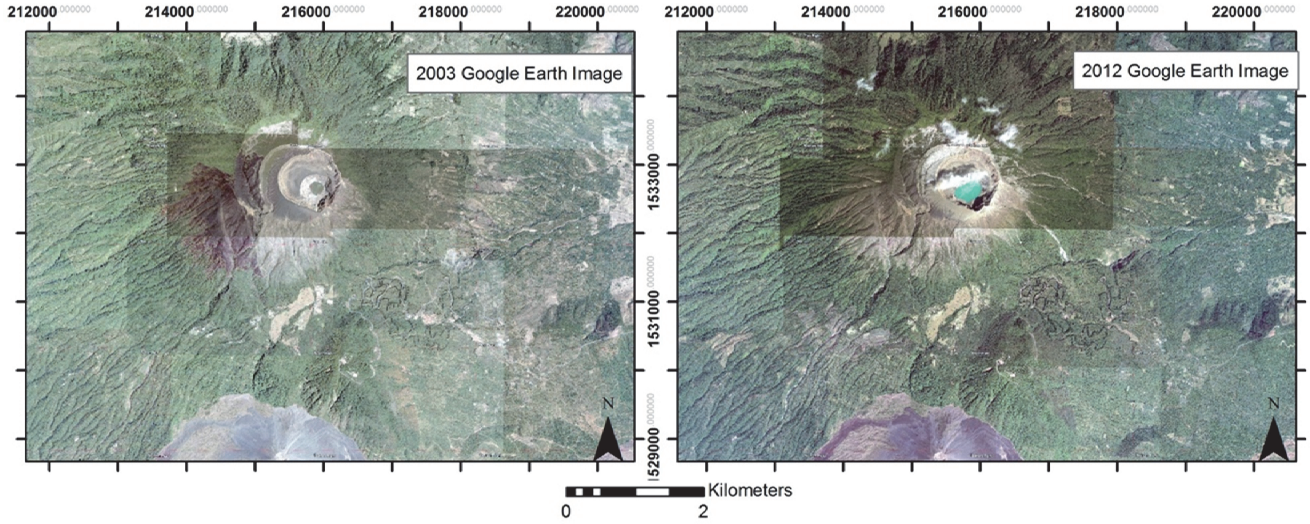

Figure 4. Google Earth images used for the landslide mapping. The 2003 satellite images (left image) was used to make sure that the landslides identify in the 2012 satellite images (right image) were true landslides and not man made features like clearings of forest, agriculture, roads, etc.

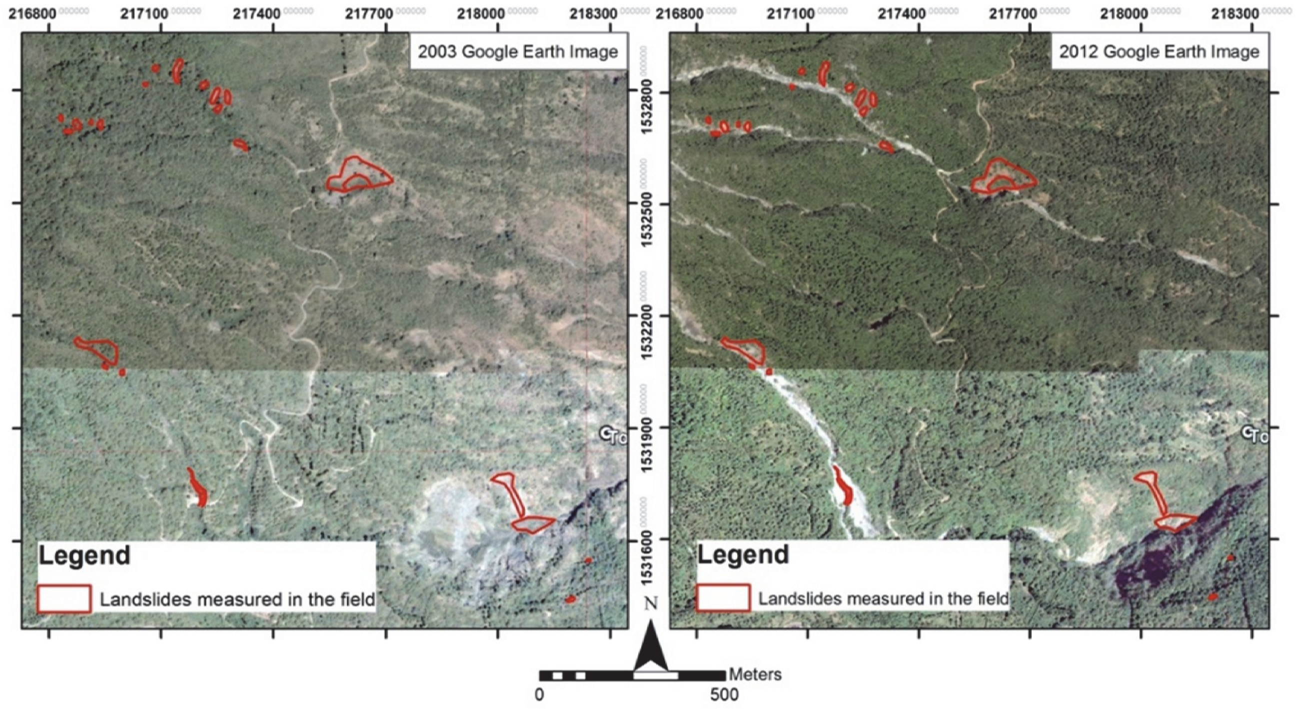

Figure 5. Map of landslides measured in the field overlaid over the 2003 satellite images (left image) and the 2012 satellite images to see differences in the terrain from one year without major landslides (2003) with one with major scaring (2012).

$$V = \epsilon A^{\alpha} \tag{1}$$

This relationship was used to estimate the potential total delivered landslide volume from landslide area obtained by satellite interpretation in the catchment.

Results and Discussion

Remote Sensing and GIS Landslide Mapping

The 2012 images show the aftermath of the Tropical Depression Twelve-E from October 12th, 2011. This storm caused several lahars, debris flows, landslides and damages through out the country of El Salvador (MARN, 2016).

Both set images were imported to ArcMap where they were georeferenced. The next step was to map the landslides by creating polygons around the visible scars and comparing both images to see and identify differences in the identified area.

Using this method 447 landslides were identified and mapped (Figure 6) for the inventory. During field recognizance done in November 2015, 24 landslides (Figure 5) out of those 447 landslides where studied in more detail.

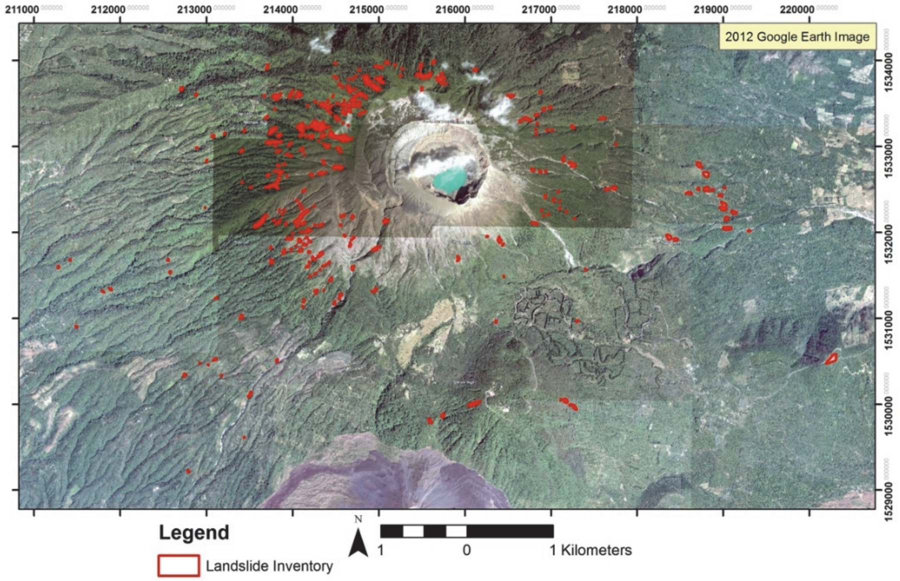

Figure 6. This is the complete landslide inventory, outlined in red, identified using the 2012 satellite images with the 2003 satellite images to collaborate that they were actual landslides.

Table 1
Table of the landslide measured in the field that were used to calculate the potential volumen

Id	*long/tall (m)*	*wide (m)*	*deep (m)*	*X1_area (m^2)*	*Y1_Volume (m^3)*
1	36.00	13.00	3.00	376.00	1,128.00
2	19.50	12.00	4.50	227.00	1,021.50
3	45.00	14.00	3.00	531.00	1,593.00
4	20.00	3.00	3.00	61.00	183.00
5	62.00	10.00	1.00	730.00	730.00
6	14.00	12.00	2.52	143.00	360.36
7	12.00	10.00	1.50	71.00	106.50
9	5.00	6.00	0.50	37.00	18.50
10	18.39	23.00	1.50	343.00	514.50
11	25.00	14.00	2.00	233.00	466.00
12	10.40	3.40	2.00	50.00	100.00
13	27.00	17.00	3.00	364.00	1,092.00
14	10.00	10.00	1.00	107.00	107.00
15	4.00	15.00	2.00	132.00	264.00
16	6.20	74.00	3.00	132.00	396.00
17	6.20	122.00	3.00	348.00	1,044.00
18	3.40	3.50	2.00	105.00	210.00
19	48.00	123.00	4.50	3,524.00	15,858.00
20	6.00	10.00	1.50	90.00	135.00
21	10.40	23.00	5.00	144.00	720.00
22	4.50	9.00	1.50	37.00	55.50
23	120.00	60.00	2.50	2,350.00	5,875.00
24	41.00	114.00	2.00	2,820.00	5,640.00

Table 2
Table with a partial set of data the collected in the field and then used to calculate the potential volume for all 447 landslide

FID	*Area (m^2)*	*Perimeter (m^2)*	*Centroid_X*	*Centroid_Y*	*ShortR (m)*	*LongR (m)*	*VolPowLaw (m^3)*
0	1,088.00	142.00	213,754	1,531,660	12.42	29.64	2,958.64
1	1,122.00	147.00	213,607	1,532,092	11.32	28.92	3,065.40
2	410.00	118.00	214,699	1,531,930	3.67	30.72	961.32
3	418.00	80.00	215,082	1,532,143	8.08	17.38	982.95
4	237.00	59.00	215,060	1,532,131	6.60	12.27	511.30
5	748.00	129.00	215,085	1,532,123	7.59	31.28	1,921.53
6	468.00	103.00	213,562	1,532,077	6.34	24.52	1,119.58
7	201.00	58.00	213,579	1,532,073	5.32	12.12	422.91
8	171.00	50.00	214,200	1,531,487	5.67	9.33	351.07
9	88.00	38.00	214,000	1,531,989	3.25	8.75	163.32
10	544.00	106.00	214,665	1,531,855	6.46	23.61	1,331.49
11	280.00	65.00	212,579	1,531,537	6.95	12.38	619.56
12	255.00	58.00	212,554	1,531,678	8.15	10.52	556.28
13	516.00	138.00	213,660	1,532,145	4.61	33.86	1,252.86
14	287.00	106.00	213,646	1,532,143	1.16	26.60	637.43
15	192.00	127.00	213,652	1,532,143	0.86	32.62	401.18
16	339.00	93.00	213,637	1,532,133	4.61	22.10	772.21
17	568.00	99.00	213,778	1,532,549	7.67	20.39	1,399.37
18	372.00	80.00	213,742	1,532,539	7.25	14.86	859.43
19	168.00	48.00	213,693	1,532,525	5.89	9.08	343.98
20	119.00	41.00	213,715	1,532,527	5.07	8.04	231.22
21	783.00	114.00	213,830	1,532,604	9.03	21.54	2,025.46
22	674.00	107.00	213,815	1,532,526	9.03	23.17	1,704.25
23	468.00	85.00	213,804	1,532,556	8.83	18.29	1,119.58
24	…	…	…	…	…	…	…

Map of the landslide inventory locations around the SAV. This map was used to locate and select 24 of them to create Table 1 to calculate volumes and for the Equation 1.

Fieldwork Mapping

Once the landslide inventory was created (see Figure 6), several sites where selected for a more detail analysis in the field. 24 landslide (see Figure 5) were selected and visited to be used to calculate the potential total volume of dry material that the landslide can contribute to the lahar. The locations of the landslides were chosen using an accessibility and safety criteria.

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Based on their knowledge of the terrain, and safety places to work 24 landslides were studied and data collected. The following table was generated with the field data.

Their geometry, soil depths, widths, and horizontal and vertical distances at the head scarp were measured and used to estimate their volume, see Table 1. After the Table 1 was completed the power law equation (Equation 1) was used to calculate the potential volume of the other 423 landslides, see Table 2 for a sample of the data from the whole inventory.

Conclusions

This project presented and examined the implementation of a cartographic method to create a landslide inventory which is then used to calculate a potential volume for each one of taking advantage of the relationship between area and volume of the landslide as express in the power law. We then used that information to create the lahar hazard map, which required for us to have a volume input. Even though farther study of the lahars in the region is necessary this study is a first step towards the integration of field data into the hazard maps for the SAV, and to support further work in the area. The methodology was adapted from the Washington State Department of Natural Resources (DNR), Forest Practices Division Landslide Hazard Zonation (LHZ) Mapping Protocol (Washington State Department of Natural Resources, 2006). The modification of the protocol was done taking in account the expert knowledge of the area and the used of geospatial data in GIS.

The expert knowledge together with the results from the methodology adapted from DNR, LHZ, will serve as a strong base to implement the model LaharZ and use volume values that correspond within the range of the potential volume calculated from the power law input data. This is important because without this methodology the only other way to choose volumes for lahar hazard maps will be by tried and error, or by guessing volumes by local accounts of past events, or by running simulations until the inundation zone reaches certain areas where lahar deposits have been found.

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