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FORENSIC ANALYSIS OF SHALLOW PRECIPITATION TRIGGERED LAHARS IN 2016 ON CONCEPCIÓN AND MADERAS VOLCANOES, OMETEPE ISLAND, NICARAGUA

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FORENSIC ANALYSIS OF SHALLOW PRECIPITATION TRIGGERED LAHARS IN 2016
ON CONCEPCIÓN AND MADERAS VOLCANOES, OMETEPE ISLAND, NICARAGUA

By
Lindsay R. Ellingson

A THESIS

Submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
In Geological Engineering

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Geological Engineering.

Geological and Mining Engineering and Sciences

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Abstract

Residents of volcanic landscapes are vulnerable to eruptions and earthquakes where volcanism is active and landslides, lahars, and flooding regardless of activity. Ometepe Island is formed from a pair of volcanoes, one active and the other less so, located in Lake Nicaragua. Steep slopes and tropical storms yield frequent surface movement that present potential for large landslide and lahar/mud/debris-flow catastrophes. Climate and land-use changes exacerbate the hazard potential, but land-use changes continue unregulated and the area lacks a sufficient system of weather monitoring to understand variability across the two volcanic edifices over time. Over the 2016 year, weather stations located on Concepción and Maderas volcanoes collected detailed information about the climatic events occurring during that time. During that year, lahar events were observed and mapped. A forensic analysis of the shallow slope failure under observed climatic conditions was performed using the Transient Rainfall Infiltration Grid-Based Regional Slope Model. Analysis of this model allows for its use in forecasting for future large storm events, yielding a better understanding of climatic effects on slope stability.

1. Introduction

Volcanic terrains provide both beauty and inherent danger to landscapes all over the world. Active volcanic complexes are capable of producing lava flows, pyroclastic flows, ash and gas eruptions, regional seismicity, and a variety of secondary hazards. Of those hazards, lahar inundation is one of the most devastating (Schaefer et al., 2017; Schaefer et al., 2016; Schaefer et al., 2015). Whether caused by volcanic eruptions, seismicity, or heavy rain, lahars can cause fatalities and bring overwhelming destruction to infrastructure and agricultural land. In Central America, a region that experiences active volcanism in its most heavily populated regions, lahars have had catastrophic impacts. The region experiences a six-month period of heavy rains, saturating soils on steep slopes--priming them for failure. Anthropogenic factors, such as deforestation for cultivation and grazing pasture, leave slopes barren and more susceptible to failure. Such is the case in Nicaragua, where agriculture and livestock are among the highest contributors to GDP. The island of Ometepe in Lake Nicaragua is an agricultural paradise, with rich volcanic soils and tropical rainforests on the steep slopes of volcanoes that form the island. Lahar hazards have been occurring since the formation of the island, but inhabitants have noted an increase in recent decades likely due to anthropogenic interventions. During the rainy season, the communities surrounding the flanks of the volcanoes suffer annual damage to infrastructure and farm land and less frequently loss of life as a result of lahar inundation. A better understanding of climatic impacts on the volcanic edifices will allow for understanding of rain triggered lahars.

Few models have been created to characterize slope stability on Concepción. A lahar hazard zonation map was created by Vallance (2001) and has been utilized by the local government as an educational tool regarding lahar hazards (see Figure 1). This study was based upon field observations of lahar deposits, empirical models displaying likely lahar propagation using typical lahar volumes occurring at other volcanoes, and experience with hazard zonation at similar

volcanoes. The Vallance (2001) study focused on the geomorphology of the volcano while information about specific soil characteristics, water table levels, and regolith depth were not taken into account. Maderas volcano has not previously been modeled for slope stability.

Figure 1: Predicted lahar paths on Concepción. Field data, records obtained from INETER, and satellite data allowed for the creation of a lahar susceptibility map by Vallance (2001). Lahar magnitudes were estimated by Vallance (2001) using prehistoric deposits and personal accounts of past lahars. An empirical model was used to calibrate limits of lahar inundation for previously observed lahar volumes at other similar volcanoes. High-probability lahars are those occurring at higher frequency and lower volumes and low-probability lahars are those occurring at low frequency and large volumes.

2. Study Objectives

The aim of this study is to incorporate measured climatic data into slope stability analyses in order to understand the mechanisms of shallow, rain-triggered slope failure on Ometepe Island. Models were created using data collected in the study area as well as generally accepted assumptions based on local constraints.

Models necessary to analyze soil-water interactions on the volcanic slopes include terrain, water table depth, regolith depth, soil strength parameters, and hydraulic properties. The instances of slope failure observed during the 2016 year were utilized to test the model inputs for accuracy by carrying out a forensic analysis of each slope failure occurrence. The goal of the forensic analysis was to identify model inputs where certain assumptions affect the viability of the analysis. Based on the model output of locations with high susceptibility of failure, a lahar propagation map was created in order to model the downslope flow extent. Suggestions are made to collect further data in order to create a predictive model of shallow, rain triggered slope failure on the island of Ometepe.

3. Geologic Setting

3.1 *Regional Setting: Central America*

Protruding from Lake Nicaragua, the island of Ometepe is defined by two stratovolcanoes (see inset Figure 1). The active Concepción and its less-active counterpart, Maderas, are two of the 39 Quaternary volcanic centers in the Central American Volcanic Front (CAVF). The CAVF extends from Guatemala to northern Costa Rica and dominates the topography of the Pacific Coast of Central America (Burbach, 1984). The relative volcanic heights of the CAVF are constrained by the topographically low Median Trough and Nicaraguan Depression, two large features that extend through El Salvador and Nicaragua. Subduction of the relatively young Cocos plate beneath the oceanic

and continental crust of the older Caribbean plate drives the formation of the CAVF and the evolution of the Nicaraguan Depression and Median Trench.

Figure 2: Map of Central America with an inset of Lake Nicaragua and the island of Ometepe. Political boundaries are from GADM (2011). Volcanic centers are represented by triangles and the boundary of the Nicaraguan Depression (ND) and Median Trough (MD) is represented by a dashed line.

The rate of subduction is $73-90 \pm 5$ mm/yr with the major component of movement generally parallel to the Middle America Trench (DeMets, 2001). The dip of the subducting slab varies significantly across this tectonic region, ranging from about 32° beneath Costa Rica to about 80° beneath the island of Ometepe (Protte, 1994).

The Central American geographic setting, local climate, and geologic setting expose inhabitants to a wide variety of hazards that are not limited to earthquakes, volcanic eruptions, tsunamis, flooding, landslides, drought, wildfire, and hurricanes. Slope failure can be initiated by most of the aforementioned hazards throughout the region. A majority of the inhabitants of Central America are vulnerable to these hazards, as many agricultural settlements favor the fertile soils and cooler elevations of the CAVF.

3.2 *Regional Setting: Nicaragua*

The Nicaraguan volcanic arc contributes significantly to the volcanism along the CAVF. With 21 Quaternary volcanoes, the country is home to 19 historically active volcanoes (Simkin and Siebert, 1995). The active volcanism in Nicaragua has shaped the landscape of the Pacific Coast, which is home to approximately 70% of the population (INEC, 2005). Several of these volcanoes have experienced late Pleistocene to early Holocene Plinian style eruptions including Concepción, Cosiguina, Apoyo, Masaya, and the Chiltepe Volcanic Complex (Kutterolf et al., 2007). Historic activity has not reached such a degree of devastation, but the threat of future eruptions exists. The quaternary volcanic arc is located within the Nicaraguan depression, a half graben with northwest trending normal faults that varies in width from 40-70 km and extends ~500 km from Costa Rica to the Gulf of Fonseca (Saballos, 2013; Mann, 1990). The origins of the Nicaraguan Depression are not yet fully understood. Early theories presented by McBirney and Williams (1965) suggest three periods in the formation of the Nicaraguan Depression: Miocene convergence, Pliocene extension, and finally transtensional movement from the Pleistocene to the present. This theory has been partially confirmed by data collected in both Lakes Nicaragua and Managua by Funk et al. (2009), which suggests that the major force in the half-graben formation was a period of extension and subsidence. The

area of greatest subsidence exists under Lake Nicaragua and likely results from extension and footwall uplift in the Oligocene to Holocene (Funk et al., 2009).

Volcanism has contributed to a variety of devastating events throughout human history in Nicaragua, but the most catastrophic hazards have been secondary consequences to active volcanism and regional geology. Large seismic events occur most frequently along the Pacific coast, affecting a majority of the population. In 1972, the capital city experienced a moderate to large earthquake that registered at 6.2 on the Richter scale. An estimated 5,000 fatalities and \$400-\$600 million USD in property damages resulted (Kates et al., 1973; Brown, 1973). This event inflamed already precarious political instability in the area, and led to even more devastation through military action and bloodshed lasting at least a decade. Approximately 26 years later, Hurricane Mitch reached the shores of Nicaragua and devastated much of the Pacific coastal region of the country. High intensity precipitation from the hurricane caused flooding and slope failure across the nation. Particularly affected was the northwestern coastal region of the country. Casita Volcano, part of the San Cristobal Volcanic Complex, endured high intensity rainfall for six consecutive days, resulting in flank collapse and over 2,000 fatalities. These two events shed light onto the vulnerability of the nation to potential hazards of equal or greater magnitude.

3.3 *Local Setting: Ometepe*

Ometepe, meaning “two peaks” in the native Nahuatl language of the region, is composed of two quaternary stratovolcanoes, Concepción and Maderas (Scaini et al., 2012). The island is located on the southwestern side of Lake Nicaragua. Due to the prevailing trade winds and the isolated nature of the island, Maderas and Concepción are considered pristine volcanic environments (Borgia and van Wyk de Vries, 2003). The lake-bottom and sediment underlying the island is rich in organics and composed mostly of diatomaceous mud (Funk et al., 2009). This

structurally weak layer of sediment extends down to 1 kilometer beneath the island, forming a soft basal boundary (Borgia and van Wyk de Vries, 2003). Borgia and van Wyk de Vries (1996, 2003) have suggested that volcanic spreading is occurring at both volcanic centers on the island of Ometepe.

Figure 3: Map of faulting on the island of Ometepe. The three large fault zones: San Ramón, Jesús María, and Morrito are represented in Lake Nicaragua. Thrust faults and strike-slip faults are shown on Concepción while normal faulting and a large slump feature are identified on Maderas. Faulting mapped by Saballos (2011) and Funk et al. (2009).

Faulting throughout the Nicaraguan Depression influences the structure of the island significantly. Three large fault zones have been identified through analysis of seismic reflection data carried out by Funk et al. (2009): the San Ramón fault zone, the Jesús María fault zone, and the Morrito fault zone (Figure 2). The largest of these is the 25-km long San Ramón fault zone, which is parallel to the

CAVF and forms a half graben by normal faulting along the lake bottom (Funk et al., 2009). The Morrito fault zone is northeast of Maderas while the Jesús María fault zone is characterized by a bathymetric high point along the western flank of Concepción, known locally as ‘Punta Jesús María’.

The island of Ometepe belongs to the regional department of Rivas, a department that spans from Rio San Juan on the Costa Rican border to the central departments of Granada and Carazo along the Pacific Coast of Nicaragua. The island contains two municipalities, each containing the two largest cities on the island. The municipality of Moyogalpa spans the western most region of Concepción Volcano, extending from the community of La Flor to San Jose del Sur. The municipality of Altagracia extends across the eastern extent of Concepción Volcano and over the entirety of Maderas Volcano. According to the 2005 census data from the *Instituto Nacional de Estadística y Censos*, Altagracia is home to 19,955 inhabitants, while Moyogalpa is inhabited by 9,729. Almost half of Moyogalpa's residents are classified as urban dwellers, while only about 18% of those living in Altagracia reside in urban centers.

3.4 *Local Setting: Concepción*

Concepción is a small stratocone located atop the sediments of Lake Nicaragua with a height of 1610 m above sea level. Exhibiting frequent, mild activity, Concepción displays characteristics of a volcano with a relatively open vent and a shallow magmatic reservoir (Saballos, 2011). Compositionally, Concepción is a clinopyroxene-plagioclase bearing andesitic cone with dacitic pumice deposition at the northern base of the volcano (McBirney and Williams, 1965, van Wyk de Vries, 1993, Borgia and van Wyk de Vries, 2003). Basalts are visible at the lateral vents and around the summit cone (Saballos, 2011). Lower silica content differentiates erupted material at lateral vents from the more silica rich, hydrothermally altered rocks that have been observed on the northwestern

summit zone (Saballos, 2011). This hydrothermally altered material overlies the frequently inundated village of La Flor to the northeast of Moyogalpa.

Concepción has been known to produce pyroclastic units, lahars, and lava flows. A magmatic evolution for the volcano has been proposed by Borgia and van Wyk de Vries (2003). The earliest volcano building phase contained low aluminum, high magnesium basalts and is known as the *Quebrada Grande* phase.

Throughout the progression, lavas evolved to be more silicic in nature with increasing aluminum content (Borgia and van Wyk de Vries, 2003). This steady volcano building phase was interrupted by a plinian style eruption known as *Tierra Blanca*, producing dacitic amphiboles. This catastrophic eruption occurred ~19 ka and products from this eruption can be found in drill cores in the Pacific Ocean (Kutterolf, 2008). Explosivity decreased following *Tierra Blanca* with eruptions ranging from strombolian to sub-plinian (Borgia and van Wyk de Vries, 2003). Larger effusive eruptions occurred in 1957 and 1986, with volcanic explosive indices (VEI) of 2 and 1, respectively (Siebert, 2011). Subsequent eruptions have been small-to-moderate block and ash explosions and have occurred frequently (almost annually), maintaining fresh pyroclastic deposits near the summit (Siebert, 2011).

Literature reports a wide variety of bulk density measurements for Concepción. Initially, values were obtained using Nettleton and Parasnis methods and were observed to be $1439 \pm 67 \text{ kg m}^{-3}$ and $1539 \pm 89 \text{ kg m}^{-3}$, respectively (Nettleton, 1954; Parasnis, 1986). For their theory of edifice spreading, Borgia and van Wyk de Vries (2003) used a value of 2500 kg m^{-3} . Saballos (2011) performed a detailed gravity and global positioning study (GPS) study of Concepción and found a bulk density value of 1764 kg m^{-3} , taking into account a low-gravity anomaly on the upper edifice and a high-gravity anomaly that is lower on the edifice. This relatively low bulk density supports the notion that the edifice is continually spreading and suggests the structural composition of the current cone

is loose and porous. Under the model that Saballos (2011) proposes, the low gravity anomaly is explained by the existence of a low density pyroclastic cone at the summit. There is a visible transition between the high and low gravity anomalies on the flank and it is believed that this transition was produced by the Tierra Blanca eruption (Saballos, 2011). Although these gravity studies did yield a relatively high bulk density value, the GPS evidence did not support the hypothesis of continuous edifice spreading proposed (Saballos, 2011, Borgia and van Wyk de Vries, 2003). Evidence for edifice spreading does exist, such as the existence of extensional faults at the summit and compressional stresses at the base (Borgia, 1994), but Saballos (2011) proposes the idea that spreading may be discontinuous, exhibiting stick-slip behavior. This notion complicates the previous theories, pointing toward a dynamic interplay between volcanic and tectonic processes rather than a simple continual spreading model.

Figure 4: Notable features of Concepción volcano. Towns as well as urban centers are noted. The low density cone identified by Saballos (2011) is shown as a dashed red line.

The low-density cone containing highly mobile pyroclastic material exhibits high permeability. During periods of heavy rainfall this material is easily mobilized, especially during high-intensity storms. Where permeability is lower, antecedent moisture conditions play a large role in lahar propagation because infiltration rates are slow. For Concepción, the highly permeable materials become mobilized and flow rapidly down the flanks with large runout distances in many cases. These shallow flows could affect populations living both near and farther from the flanks of the volcano, especially threatening those communities build atop historic lahar paths.

3.5 *Local Setting: Maderas*

Maderas Volcano is a small asymmetric stratovolcano comprising the southeastern half of Ometepe Island. Maderas exhibited intense activity during the early Quaternary period and is currently considered to be inactive. Since volcano building is no longer the dominant process, weathering and radial spreading caused by the weak underlying lacustrine sediments are driving deformation across the edifice (van Wyk de Vries, 1993). Since eruptive activity slowed over 3,000 years ago, the summit has been reduced from about 1,600 meters above sea level to its current 1,345 meters above sea level (Mathieu, 2010). The summit is relatively flat and contains a small crater lake that is the source for much of the drinking water for the low-lying communities along the flanks. The deformation at the summit is dominated by a 135° dextral-striking transtensional fault zone and a parallel graben structure (Mathieu et al., 2011). This fault zone is an extension of the San Ramon fault zone described by Funk et al. (2009). Faulting features at the summit and at the base of Maderas are consistent with faults found on spreading volcanoes (Delcamp et al., 2008). According to a study by van Wyk de Vries and Borgia (1996), Maderas is considered to be a radially spreading edifice that exhibits faulting throughout. Radial spreading typically results in relaxation of elastic stress throughout the edifice. This decreased stress contributes to a low hazard for flank, sector, or edifice collapse; therefore, it is reasonable to consider only shallow slope failure for the purpose of this study.

Although the collapse hazard is relatively low on Maderas, some features have been identified as potentially hazardous for slope failure. Van Wyk de Vries (1993) identified a slump feature on the southwest sector (Figure 4). Other studies have deemed this feature inactive (van Wyk de Vries, 1993). Its structure can still be identified in aerial imagery and could reactivate in response to seismicity or intense rainfall. Two large gullies follow the boundary of the scarp,

and have been known to feed debris fans at the base of the slope. These low-lying, low-relief fans have experienced frequent instances of slope failure, including a destructive debris flow in 1999 (Kerle and van Wyk de Vries, 2001).

Figure 5: Notable features on Maderas volcano. The extent of forested land is identified as well as the portion of the volcano that has the distinction of ‘National Biosphere Reserve’.

A majority of the volcanic edifice exists under a cloud forest and is covered in thick vegetation. Due to the dense canopy cover on Maderas volcano, the crater zone is perpetually inundated with precipitation, even during the dry season. The flanks of Maderas have been inhabited for thousands of years and are still considered favorable for many agricultural practices. The agricultural boundaries and deforested pastures have been continuously encroaching on forested areas. The collection of firewood also contributes to deforestation on the slopes, as a vast majority of the population on the island cooks with wood

burning stoves. As a result, the local government works to enforce laws to impede deforestation, limiting the cutting of forest to the area below 400 meters above mean sea level (amsl) with hopes of protecting the ancient forest. Lake Nicaragua surface elevation is approximately 32-33 m amsl.

4. Climatic Setting

According to the *Instituto Nicaragüense de Estudios Territoriales* (INETER), Nicaragua experiences a tropical climate with two distinct seasons. These seasons are recognized locally as summer and winter, but are essentially distinguished by their respective amounts of precipitation. During the summer months, from January until early May, little to no precipitation is experienced throughout the country. Temperatures are at their highest nationwide in March and April. The winter months begin abruptly in May, with heavy rains typically falling in May and June, followed by a month long “*canicula*”, or period of high heat and low rates of precipitation. The heaviest rains typically fall in October and are sometimes influenced by hurricane systems that originate in the Caribbean or Eastern Pacific between June and November each year. According to INETER, between 1982 and 2002, 41 tropical cyclones had passed through Nicaragua. All of these storms originated in the Caribbean with the exception of one storm, which originated in the Pacific (Baca, 2001). Humidity is highest (near 100%) during the month of June, while April exhibits the driest air with an average humidity of 62%.

While temperatures vary only slightly throughout the calendar year, there are three distinct climatic zones in Nicaragua: the Pacific Lowlands, the Central Highlands, and the Eastern Lowlands. The lowlands on the Pacific and Caribbean coasts experience the highest temperatures throughout the year, ranging on average from 20-30 Celsius, while the coastal highlands experience much lower temperatures and humidity. The Caribbean lowlands are distinct

from the Pacific lowlands due to the longer duration of the rains resulting from the easterly trade winds from the Caribbean Sea. This climatic variation yields a large range of precipitation averages across the coastal region, from 254-635 cm yearly. The Pacific lowlands receive a fraction of this precipitation, averaging only 102 cm per year in the region. Variations in these weather patterns are caused by local topography, with more isolated climates surrounding the tallest volcanic complexes throughout the Pacific region. Global trends show a marked increase in high intensity events in the recent past (Alexander, 2006). These trends are likely exaggerated in the tropics where droughts during the dry season are longer lasting and the wet season is marked by high-intensity, long-duration precipitation events.

5. History of Lahars

Lahars have occurred throughout history on both Maderas and Concepción volcanoes, but current activity varies greatly between the two edifices. Concepción volcano exhibits frequent activity, replenishing the summit zone with mobile pyroclastic material that is highly permeable with rapid rates of infiltration. Maderas volcano exhibits weathered volcanic material at its surface and is highly deformed. The rates of infiltration on Maderas are much lower due to the presence of clays in the soils. Due to the surface cover and the abundance of surface water on Maderas, lahar activity provoked by precipitation events have different characteristics on each of the edifices.

5.1 *Concepción Volcano*

It is clear in aerial imagery and field observations that Concepción volcano has suffered significant lahar activity, with deep scars cutting into the almost perfectly symmetric cone (see Figure 3). Most of the visible lahar deposits are estimated to have occurred within the past 100 years, with a noted increase in

lahar activity and deposit thickness throughout the past 15 years (Saballos, 2013). It is likely that increased activity in the recent past may be a result of better record keeping. According to local community members, lahar activity on Concepción has become a regular occurrence. Prior to the mid 1900s, lahar occurrences were thought to be unique to Maderas volcano. Imagery depicting the volcano before the 1940s shows minimal erosion, and lahar activity was first recorded in 1957 (Ferrey and Williams, 1971), so it is reasonable to date the initial lahar activity to the mid-19th century. A complete inventory of lahar activity does not exist due to a lack of local resources and government instabilities in the 1970s and 1980s. Following the devastating lahar activity in 1998 triggered by heavy rainfalls from Hurricane Mitch, the national government began to systematically compile information about lahar hazards and have continued to keep somewhat detailed reports on recent activity. The national government has particularly focused on the most active volcanoes along the Nicaraguan Volcanic Front. Most of the recently recorded lahar events have been triggered by high-intensity, prolonged-duration rainfall. Several lahars in 2005 were initiated by seismic activity near the southwest side of the island.

Concepción's edifice contains four major lithostratigraphic units: lacustrine sediments, tephra, lavas, and lahar deposits (Borgia and van Wyk de Vries, 2003). The southwestern side is predominantly tephra deposits due to dominating E-W trade winds, while lava flows and pyroclastic deposits are prevalent on the eastern face (Vallance, 2001). These mechanically weak, welded pyroclastic deposits from frequent block and ash flows are known to become easily mobilized (Seibert et al., 2011). Larger lahar deposits occur where more mobile material is present (see Figure 6). The largest deposits exist near the communities of San José del Sur and Los Ramos on the southwestern side of the volcano.

Figure 6: Concepción Volcano viewed from the northwestern port city of Moyogalpa. Deep scars on the edifice chronicle the frequent lahar activity over the past 60 years.

Reliable records for both Maderas and Concepción volcanoes first appear in the literature during the late 1970s. It is known that lahar activity occurred during the 1957 VEI 2 eruption at Concepción, but little information has been recorded about the specific location of those particular events. Records show activity beginning in San José del Sur, a community on the southern face of Concepción, and the town in closest proximity to the volcano, in 1978 and 1979. Evidence of early lahar activity on the northern sector of the volcano is visible from events in La Flor between 1986 and 1987. San José del Sur experienced lahars presumably resulting from similar precipitation events during that same time. San José del Sur continued to suffer from lahar activity almost annually until 1990, when a large magnitude event occurred. This event seems to have washed out much of the mobile material in the area as lahar activity was not reported for almost another decade. There was relatively minimal lahar activity during most of the 1990's with the exception of a damaging event in La Chirca in March of 1993. Resurgent activity started in 1998 for the community of San Jose del Sur, where a small lahar occurred in December of that year. Another large event

occurred there in January of 2000's, with concurrent events in La Flor on the north side of the volcano. Throughout the early 2000s, San Jose del Sur, La Flor, La Chirca, San Marcos, San Jose del Norte, and Japón experienced simultaneous lahars that are likely attributed to prolonged periods of precipitation during the winter months. The largest magnitude event occurred in San Jose del Sur in October of 2003 where almost 6 km² of area was covered by material deposited as a result of slope failure. A large swarm of seismic activity triggered several lahar events in 2005, affecting the communities of San Jose del Sur, La Flor, San Jose del Norte, La Concepción, La Chirca, and San Marcos. A new series of lahars began in 2008 in the community of Los Ramos, a small town on the south side of Concepción near the isthmus. In 2010, San Jose del Sur was impacted by another large lahar on December 8. The community of La Flor suffered a much smaller event that same day. The three largest lahars experienced in San Jose del Sur (1990, 2003, 2010) are comparable in size to those reported at Mount St. Helens and Mount Hood in 1980 (Major and Voight 1986). Following a lahar in 2008, the communities on the southern flank began to suffer almost annually from damages resulting from mass movement. This annual activity culminated in a large lahar in October 2014 that resulted in the death of a 5-year-old in the community of Los Ramos, severe damage to several communities, and the displacement of dozens of families in the area. According to INETER, the lahars that occurred in 2014 were the largest in magnitude that have been registered on Concepción. These events were triggered by intense rainfall during the first weeks of October, affecting the communities of Los Ramos, La Union, Urbaité, Sintiope, La Chirca, La Flor, and La Concepción (Saballos et al., 2014). Lahars in Los Ramos, Sintiope, and La Chirca occurred again in 2016. Extended periods of heavy rainfall were experienced by both Concepción and Maderas, leading to instances of infrastructure damage and continued degradation of the southernmost slopes of Concepción.

Lahars on Concepción are not solely influenced by volcano-tectonic forces; anthropogenic influences have been known to increase lahar propagation on the lower flanks. Deforestation of the gently sloped flanks began during early settlement of the island. Large portions of the forest were removed in order to cultivate agricultural fields, a practice similar to that on Maderas. Agriculture continues to drive the economy on the island, prolonging the trend of deforestation. During the 19th and 20th centuries large-scale tobacco production augmented the rate of deforestation as wood fueled the ovens that treated the leaves (INIFOM, 2001). Lahar hazards frequently inundate these agricultural areas, significantly affecting the income potential of the island inhabitants.

5.2 *Maderas Volcano*

While the visible scars on Concepción display its storied history of lahar activity, those of Maderas are hidden under thick, lush vegetation and low-lying clouds and fog. The lahars experienced by Maderas are very different from those occurring on Concepción due mostly to a lack of volcanic activity during the period in which the island has been inhabited. Slope instability on Maderas is affected mostly by gravitational spreading and faulting, as the heavy volcanic mass deforms atop weak lacustrine sediments (van Wyk de Vries and Borgia, 1996). Edifice features on the volcano show evidence of past activity, with precarious features that may remobilize in future mass movements. An inactive slump feature has been identified by van Wyk de Vries (1993) near the community of Tichaná (see Figure 4). It is believed that this slump feature has been inactive since the last instances of volcanic activity, but extreme precipitation events or seismic events have the ability to reinitiate movement. Due to a lack of activity on Maderas, the volcano has been mostly overlooked in hazard studies on the island, leaving an incomplete inventory of historic lahars. Large, recent events are remembered by local community members, and several instances have been mentioned in various literature

sources (Kapelanczyk et al., 2012; van Wyk de Vries, 1993; Smithsonian, 1996). Large, historic lahar deposits surround the volcanic flanks in most regions, and contain massive boulders that are evidence of high-energy movement. The largest events in recent history occurred in 1996 and displaced the entire community of El Corozal. Another event occurred there in 1999. Although the most recent lahar activity has not resulted in fatalities, infrastructure damage has significantly impacted local communities. A large mass movement near the summit zone mobilized in October 2015, carrying large trees and sediments to lower lying stream beds, destroying 70 water pipes in the community of Madroñal. Rains in August 2016 remobilized this deposit, which then extended to the communities of Las Cuchillas and Balgüe, destroying water distribution systems as well as infrastructure surrounding a waterfall. In the same month, a small lahar overtopped the San Ramon waterfall, causing damage to a popular touristic destination. These events were believed to have been initiated by long duration rainfall events. Although these events occur less often than those on Concepción, it is important to understand the features and characteristics of these mass movements. Smaller, more frequent slope failures on Maderas shed light onto characteristics of slope instability and can prepare low lying communities for larger magnitude events.

The communities on the base of Maderas volcano are much more rural than those on Concepción and are recipients of notably less institutional response to natural hazards. The majority of land around the base of the volcano is used for agricultural purposes, prompting many farmers to clear ancient forests in order to plant rice, beans, plantain crops, or to make space for grazing pasture. Maderas has been classified as a Natural Biosphere Reserve, and therefore it is illegal to cut trees above a 400-m elevation, but the laws are not enforced and the rate of deforestation has not decreased. Anthropogenic factors may play an increasing role in slope instability in the future, so it is important

that local decision makers understand the benefits that forest cover brings to the lower lying communities.

6. Methodology

Following the fatal lahars in October 2014, it was recognized by the author in consultation with Nicaraguan counterparts, Karla Hypatia and Fernando Mendoza of *Universidad Nacional Agraria*, that climatic data for the region was lacking and might aid in the analysis of slope failure triggered by heavy rains. Beginning in January of 2016, we worked together to foster meteorological data collection on both volcanoes and field observations were carried out in order to map slope failures reported on either edifice. The goals of the field research were to locate and map lahars that are linked to specific precipitation events recorded in each weather station location.

6.1 Field Data Collection

Precipitation data was collected throughout 2016 using a Davis Vantage Pro2 weather station and two Davis Vantage Vue weather stations (Davis Instruments Corporation, Hayward, California). The Davis Vantage Pro2 weather station were equipped with components that measure wind direction and speed, a self-emptying tipping bucket measuring rain in 0.01” increments, and air temperature. A radiation shield enabled accurate temperature and humidity readings and a solar panel provided power to the station. The Davis Vantage Vue stations, located in Altagracia and Los Angeles, were equipped with self-emptying tipping spoons to measure rain in 0.01” increments, anemometers to record wind speeds as low as 2 miles per hour and were wind-tunnel tested to 180 miles per hour. A battery-equipped solar panel provided continuous power to the station. Data was collected on a USB data logger at an interval of 10 minutes.

A local nongovernmental organization (NGO), *Fauna y Flora Internacional*, equipped local farmers on both edifices with rain meters such that they were able to measure precipitation on a daily basis. The crude observations taken by these farmers showed a notable variation in rainfall between Maderas and Concepción volcanoes, as well as regionally on each edifice. Following the recent landslides of 2014, it was decidedly more advantageous to place two of the three stations on Concepción. One station was placed on the northern side of Maderas where landslide events of comparable scale to those of Concepción had more recently occurred (see Figure 7). Each station on Concepción was placed within an accessible distance from the roadway. The station on Maderas was placed higher on the flanks. The orographic effect on Concepción could not be considered due to the fact that each station experienced slightly differing precipitation events and that both stations were placed at approximately 70 meters above sea level. High spatial variability of intense rainfall events have been reported by local farmers and by the local government. Higher rainfall amounts tend to correspond to steeper slopes (Daly et al., 1994). This effect is especially pronounced on Maderas volcano, which receives almost constant precipitation at the summit throughout the entirety of the year. With only one station on the flanks of Maderas, the orographic effect could not be explored quantitatively.

Figure 7: Map of Ometepe Island with locations of weather stations indicated. One weather station was located on the north side of Maderas Volcano in the community of Balgüe (noted as Finca Magdalena on the map). Two stations were located on the eastern and western flanks of Concepción volcano in the communities of Altagracia and Los Angeles, respectively.

Four events of slope failure were observed during the 2016 year, two of which occurred simultaneously on the northeastern and southwestern flanks of Concepción. In three of the four cases, relatively high intensity-duration storm events preceded slope failure. The only observed slope failure on Maderas occurred without a large input from one single storm event but was preceded by

over 800 mm of rainfall. The first event occurred in August and the final three occurred during the month of October, two of which resulted from the same storm. These three storm events were used as intensity and duration input to model the storms on both edifices. Due to the spacing of the weather stations and the lack of quantitative orographic evidence, the Inverse Distance Weighting (IDW) method was used to interpolate intensity values between the stations. The IDW formulas are given as follows:

$$R_j = \frac{\sum_{i=1}^n \frac{R_i}{(h_{ij} + \delta)^\beta}}{\sum_{i=1}^n \left(\frac{1}{h_{ij} + \delta} \right)^\beta}$$

where R_j is the intensity of unknown rainfall (mm/hr); R_i is the rainfall data provided by the three weather stations (mm/hr); n is the number of stations; h_{ij} is the mean distance from the weather station to each point on the grid; β is the power which limits or emphasizes the influence that each station has on local interpolation, and δ is the smoothing factor (Tung, 1983). Typically, β values can range from zero to five. Several studies show that a β value of 2 gives the best results for precipitation data in mountainous regions (Dean and Snyder, 1977; Kruizinger and Yperlaan, 1978; Zhu and Jia, 2004; and Lin and Yu, 2008). The Root Mean Square Error for this interpolation was 0.2756.

Figure 8: Cumulative precipitation for 2016 at three weather stations. Precipitation data was recorded every ten minutes using Davis weather stations. The largest storms occurred in early June, late September, and early October. Lahars are marked with the nearest station to which each occurred. On June 10, 2016, a small lahar occurred near San Lazaro. On August 14, 2016, a lahar occurred at Las Cuchillas on Maderas Volcano. On October 3, 2016, two lahars occurred at La Chirca and at Los Ramos. A final lahar occurred at Sintiope on October 20, 2016.

6.2 *USGS Transient Rainfall Infiltration Grid-Based Regional Slope Model*

Several models have been developed to represent slope failure based on an empirical or probabilistic assessment of slope stability (Smith et al., 2015). For this study, the U.S. Geological Survey (USGS) Transient Rainfall Infiltration and Grid-Based Regional Slope Stability Model (TRIGRS) was utilized to represent slope instability caused by rain infiltration. TRIGRS was developed by Baum et al. (2002) and allows the user to identify both temporal and spatial distributions of slope failure following a specific precipitation event. The model computes the

response in transient pore pressure and factor of safety to rain infiltration, taking into account both subsurface and surface flows. The governing equations used in the model represent one-dimensional vertical flow of water in isotropic, homogeneous material. Slope stability is then computed using a simple infinite-slope model. The relationship between slope stability and the changing pore pressure are computed and yield a cell by cell value for the factor of safety (F_s) for the entire grid. TRIGRS allows computation under variable saturation conditions and horizontal heterogeneity, creating a more realistic model of infiltration and surface runoff. This model, however, cannot account for all of the heterogeneities that exist in real systems due to computational and model-input limitations. For example, soil strength parameters and hydraulic properties can be varied horizontally but not vertically as a simple infinite slope model allows for the simplification of a single, isotropic regolith layer of relatively shallow depth. The depth of the soil layer, therefore, must be sufficiently small when compared to the length of the slope. The assumption of infinite slope does not allow for the consideration of abrupt stratigraphic or morphological discontinuities such as road cuts and scars from recent lahars, thus these important features are not included in the analysis (Baum, 2002). Slope stability is modeled by computing the ratio of basal Coulomb frictional strength to gravitationally induced downslope basal driving stress (Iverson, 2000), known as the factor of safety, F_s . The F_s is calculated at each point on the grid at a depth Z using the steady state equation:

$$F_s = \frac{\tan\phi'}{\tan\delta} + \frac{c' + \psi(Z, t)\gamma_w \tan\phi'}{\gamma_s Z \sin\delta \cos\delta}$$

where c' is soil cohesion, ϕ' is the internal angle of friction of soil, γ_w is the unit weight of water, γ_s is the unit weight of soil, $\Psi(Z, t)$ is the depth and time dependent pressure head, and δ is the slope angle. The pressure head will not exceed that which would result if the water table were at the surface. Under

slope-parallel flow conditions, $\beta = \cos^2 \delta$, and under the hydrostatic conditions, $\beta = 1$. A slow rise in water table is modeled, allowing for partial saturation of the regolith layer over time.

Model inputs include topography (terrain), depth to water table, depth of regolith layer, precipitation, soil strength parameters, and hydraulic properties allowing for single cell variation across the grid. The TRIGRS model allows the water table to rise as infiltration increases while surface runoff is routed to downslope cells.

6.2.1 *Water Table Model*

In the absence of adequate data for the water-table depth, two models were created and evaluated using water-well measurements. The first model operated under the assumption that the water table was a subdued version of topography (Haitjema and Mitchell-Briker, 2005). The water table on the island perimeter is equal to the lake level and experiences high seasonal recharge along the slopes, and thus this assumption is theoretically reasonable and pragmatic, as measured data regarding soil characteristics is lacking. The model for the water table depth was created using the Height Above Nearest Drainage (HAND) tool in ArcGIS. The HAND tool assumes that springs and streams are points of intersection between the land surface and the water table and that between these intersection points, water table depth follows topography. Streams were delineated using satellite imagery and the Total Wetness Index (TWI) in order to identify the locations across the region where the water table intersected with the surface. Field observations of streams on Maderas were necessary where forest conceals most ground surface. Well data provided by INETER was used to assess the relationship between water table and topography yielded by HAND. The water

table depth modeled using HAND showed reasonable agreement with water table depths measured in wells (Coefficient of determination - $R^2=0.52$, $n=32$).

A global dataset provided by Fan et al. (2013) was also considered in the analysis. The dataset was created using thousands of measured data points worldwide and interpolation based on a combination of factors affecting water table depth including terrain, precipitation rates, and soil mechanical characteristics. In some cases, observations of existing wetlands and streams were included in order to constrain the model. The resolution for this dataset was coarse considering the extent of the study area. Consequently, the R^2 value for this model was 0.39. Thus, the water table was likely modeled more accurately by the HAND method. The Fan et al. (2013) model would be more appropriate under conditions where there are few local constraints to the water table depth, areas with little precipitation annually or without much topographic relief.

Figure 9: Linear correlation between two models for water table depth. Figure 9 a. shows the water table depth in meters modeled as a subdued replica of terrain using the Height Above Nearest Drainage

tool in ArcGIS. Figure 9 b. shows the correlation between depth of the water table recorded at 32 wells around Ometepe and the depth of the water table. Figure 9 c. shows the water table depth modeled using a global dataset with a 30-arcsecond resolution. Figure 9 d. shows the correlation between the depth to water table from the same wells and water table depths from a global data set using methods described by Fan et al. (2013).

6.2.2 *Regolith Depth Model*

Several techniques were used to constrain the values for regolith depth, which are unknown in the study area. Sentinel 2 imagery (ESA/Copernicus Sentinel data, 2017: http://www.esa.int/Our_activities/observing_the_earth/copernicus/sentinel-2/data_products) was used to identify surface units on Concepción. Various aerial photos were selected based on clarity and resolution in order to represent seasonal variation in vegetation and geomorphologic changes over time. The tone, texture, landform, topographic expression, slope, drainage patterns, texture of soil, vegetation, mode of weathering and surface features were compared between historical images in order to delineate surface lithologies (Ray, 1960). Lava flows, pyroclastic deposits, lahar deposits, and lacustrine deposits were identified based on observations of these categories and using a geologic map created by van Wyk de Vries (2003). Recent lava flows were identified by their rough, irregular character and distinguishing features such as flow lines. Vegetation on top of the recent lava flow units is generally sparse and immature. Lahar deposits had the appearance of fluvial deposits and were easily identified when comparing between historical images. The most recent lahar deposits were free of surface vegetation. Lacustrine deposits and pyroclastic deposits were more conducive to vegetative growth and were differentiated by slope and texture. Each lithologic unit was given thickness limits based on characteristics of each unit. Since lava flows are relatively young and have not had sufficient time to weather, it is acceptable to assume that the only soils present in these areas have been

deposited on top of the flows, with thickness of soil layers constrained to only a few meters.

Pyroclastic deposits can be more complicated. Much of the edifice is formed by vertical accumulation of pyroclastic material. Along the skirt where this material is more stable, deposit thickness could extend to tens of meters. Even on the steeper slopes near the crater, pyroclastic deposits could be several meters thick and may be interbedded with lava flows. It is beyond the scope of this study to consider such deep seeded failure, so a limit of 2.5 meters was set for the soil thickness at these steeply sloping locations with significant pyroclastic deposition.

A soil map created by Aguirre and Acuña (2009) was used to create polygons of known soil series. Based on Aguirre and Acuña (2009) observations of soil profiles, a depth was assigned to each polygon. Soil depth decreases with increasing slope, thus a regression was performed between mean slope values in each soil series and the specific depth defined for each polygon. An exponential function yielded the best fit relationship between series depth and mean slope for each series:

$$D = 1 + 152.9e^{-0.06S}$$

where D is the soil depth in centimeters and S is the slope at each point along the surface expressed in degrees. The standard deviation for the slope data set was identified to be 9.44 degrees and the confidence interval at 95% was calculated to be 0.00036. The R² value for this relationship was 0.53.

Figure 10: Modeled depth of regolith layer. The model is based on the relationship between average depth and slope for each defined soil series.

6.2.3 *Soil Strength Parameters and Hydraulic Properties*

Soil strength parameters and hydraulic properties considered in the TRIGRS model are cohesion, internal angle of friction, saturated hydraulic conductivity, diffusivity, and van Genuchten parameters. Little is known about the soil strength parameters and hydraulic properties in Nicaragua. Minimum and maximum values for cohesion, internal angle of friction, diffusivity, and hydraulic conductivity were determined based on literature values as well as soil series descriptions from Aguirre and Acuña (2009). These ranges were then used in a Monte Carlo inversion to constrain these characteristics for each soil zone. The values used for soil strength properties and hydraulic parameters are shown in

table 1 with references to the derivation of the ranges. A uniform distribution was used in order to randomly sample points within the specified range. A uniform distribution was selected based on the variation of soil descriptions within each unit and through the depth of each unit. Aguirre and Acuña (2009) descriptions showed enough variation in texture that any other distribution of values may not fully encompass the complexity of each soil series. A matrix of 10,000 combinations of these random values was created to input into the TRIGRS model. Following each run, cells were assigned a value of 1 or 0; 1 in the case of failure and 0 in the case of relative stability. These values were assigned based on the factor of safety values for each iteration of the TRIGRS model. Cells with a $F_s < 1$ were assigned a value of 1, representing failure; while cells with a $F_s > 1$ were assigned a value of zero, representing stability. The simulations were compiled to calculate a probability of failure at each.

Field work was carried out to verify the appropriate ranges of cohesion and internal angle of friction. Soil strength parameters were measured using a shear vane tester (H-4227) and a portable dynamic penetrometer (H-4202AS), both manufactured by Humboldt Mfg, Inc., Elgin, IL. The penetrometer was used according to Standard Penetration Testing standards and was converted to internal angle of friction values. Measurements were taken by driving a standard thick-walled sample tube into the soil by blows from a slide hammer with a determined weight and falling distance (Rogers, 2006). The blows are counted for 3 different measurement intervals and the sum of the number of blows required for the second and third 6 inches of penetration is reported as the “standard penetration resistance” or the “N-value”. This value indicates the relative density of the soil. Correlations between these N-values and internal angle of friction values are indicated by Meyerhoff (1956). Measurements collected using the penetrometer are not particularly precise, but are used to differentiate between soils with high internal friction and soils with low internal friction (Sowers and Hedges, 1966). The lack of resources, steep slopes, and

remote terrain dictated the use of a portable penetrometer. Measured friction values varied between ~30 and 40 degrees across the study area.

The shear vane test is an in-situ geotechnical testing method used to estimate the shear strength of soils. The apparatus consists of a four-blade steel vane attached to a rod that is inserted into undisturbed soil. The vane is rotated and peak torque is measured. Torque develops relative to the peak shear force applied to the apparatus. When the shear force is no longer able to resist rotation of the vane, torque ceases and shear strength can be measured. Table 2 shows the values obtained from field work with data points located on maps of Maderas and Concepción (see Figures 11.a and 11.b). Cohesion values collected for each soil series fell within ranges utilized in the Monte Carlo simulation in all but three cases. Shear strength of immature soils atop lava deposits were much lower than represented by values found in the literature. Shear strength values in the Volcan Maderas soil series and Verticos series were higher than anticipated, suggesting that the soil in these regions either contained units of higher cohesive strength such as clays or were compacted. Friction values measured in the field agreed with values in the literature.

Table 1: Soil strength parameters and hydraulic properties for each soil type in TRIGRS model.

Soil Unit (Aguirre Acuña, 2009)	Hydraulic Conductivity (m/s)		Unit Weight of Soil (kN/m³)	Cohesion (kPa)		Soil-Water Diffusivity (m/s)		Internal Angle of Friction (°)		van Genuchten Parameters		
	min	max		min	max	min	max	min	Max	θ_{res}	θ_{sat}	α
Maderas	10 ⁻⁸	10 ⁻⁶	20.5	18	21	10 ⁻⁸	10 ⁻⁶	27	35	0.01	0.43	0.0083
Vertisoles	10 ⁻¹⁰	10 ⁻⁶	20.5	18	21	10 ⁻⁷	10 ⁻⁶	27	35	0.01	0.43	0.0083
Rock	10 ⁻⁶	10 ⁻⁴	21.5	19	24	10 ⁻⁶	10 ⁻⁵	15	40	0.025	0.403	0.0383
Pyroclastic	10 ⁻⁸	10 ⁻⁶	20.5	18.5	22.5	10 ⁻⁷	10 ⁻⁶	27	40	0.01	0.403	0.0383
Marsh	10 ⁻⁹	10 ⁻⁷	21.5	20	23	10 ⁻⁸	10 ⁻⁶	22	32	0.01	0.52	0.0367
Ometepe	10 ⁻⁹	10 ⁻⁶	21.5	20	23	10 ⁻⁸	10 ⁻⁶	17	35	0.01	0.52	0.0367
Merida	10 ⁻⁹	10 ⁻⁶	21.5	20	23	10 ⁻⁸	10 ⁻⁶	27	35	0.01	0.43	0.0083
Magdalena	10 ⁻¹⁰	10 ⁻⁶	19.5	18	21	10 ⁻⁸	10 ⁻⁶	27	35	0.01	0.43	0.0083
Lava	10 ⁻³	10 ¹	21.5	19	24	10 ⁻⁶	10 ⁻⁵	15	40	0.025	0.403	0.0383
Lahar	10 ⁻¹⁰	10 ⁻⁶	19.5	18	21	10 ⁻⁷	10 ⁻⁶	27	35	0.01	0.403	0.0383
Lacustrine	10 ⁻⁹	10 ⁻⁷	21.5	20	23	10 ⁻⁷	10 ⁻⁶	22	32	0.01	0.52	0.0367

Aluvial	10 ⁻⁵	10 ⁻¹	20.5	18.5	22.5	10 ⁻⁷	10 ⁻⁶	20	30	0.01	0.40	0.038
Scarp	10 ⁻⁵	10 ⁻¹	20.5	18.5	22.5	10 ⁻⁷	10 ⁻⁶	20	30	0.01	0.43	0.008
Crater	10 ⁻⁹	10 ⁻⁶	21.5	20	23	10 ⁻⁸	10 ⁻⁶	17	35	0.01	0.52	0.036
Refrences	Swiss Standard (1999); Peck et al. (1974); Dahlgren et al. (2004)		Swiss Standard (1999); Dahlgren et al. (2004)	Shiozawa and Campbell (1990); Dahlgren et al. (2004)		Carter and Bentley, (1991); Dahlgren et al. (2004)		Peck et al. (1974)		Guber and Pachepsky (2010)		
												7

Table 2: Data points for cohesion and internal angle of friction values obtained in the field.

Data Point	UTM Northing (m)	UTM Easting (m)	Cohesion [kPa]	Internal Angle of Friction
1	662594	1269650	28	<30
2	662594	1269650	25	<30
3	662594	1269644	44	30-35
4	664522	1269007	38	<30
5	664616	1268900	42	<30
6	664382	1268694	30	<30
7	664362	1268549	48	30-35
8	665734	1270497	46	35-40
9	666659	1269757	40	<30
10	667286	1267428	60	30-35
11	666808	1262772	100	<30
12	666413	1262045	166	<30
13	664305	1261149	52	30-35
14	661272	1261118	42	<30
15	657405	1264587	108	30-35
16	657227	1268048	34	<30
17	658608	1269750	46	<30
18	660490	1270575	20	<30
19	660641	1270577	38	<30
20	661494	1270617	26	<30
21	642660	1277446	82	30-35
22	643741	1277434	22	<30
23	643800	1277473	18	<30
24	644508	1277676	58	<30
25	645773	1277440	52	35-40
26	646244	1277288	54	<30
27	646926	1277086	44	35-40
28	645380	1278545	28	<30
29	647029	1279515	30	35-40
30	647684	1279581	34	30-35
31	647825	1279548	20	<30
32	648283	1279555	18	<30
33	649867	1279268	32	30-35
34	651907	1279657	20	<30

Data Point	UTM Northing (m)	UTM Easting (m)	Cohesion [kPa]	Internal Angle of Friction
35	653992	1279032	40	<30
36	654127	1277114	56	30-35
37	655315	1275536	8	<30
38	654364	1274979	12	30-35
39	653304	1273744	8	<30
40	652894	1273560	10	30-35
41	651443	1272427	30	30-35
42	651107	1272077	12	<30
43	650299	1271291	10	<30
44	646907	1272017	12	30-35
45	646447	1270393	30	35-40
46	641073	1272569	50	<30
47	641176	1273404	20	30-35
48	642090	1273998	30	35-40
49	660648	1267742	62	35-40

Figure 11: Soil cohesion and internal angle of friction data points. 11.a: Data points collected on Maderas volcano. 11.b: Data points collected on Concepción volcano.

Soil unit weight was constrained based on literature values (Swiss Standard, 1999; Dahlgren et al., 2004). These values, however, may not represent the fact that volcanoclastic deposits exhibit high water retention, a fact that may significantly increase the unit weight of a particular soil horizon (Frattini et al., 2004). This influence on unit weight of soil should be considered as a possible triggering mechanism in landslide propagation. Soil characteristics were found to be highly variable spatially, making it difficult to represent the entire complex structure. The discontinuous nature of a majority of the study area favors the formation of high pore pressure, especially where pyroclastic deposits are present (Johnson and Sitar, 1990).

van Genuchten parameters are based on the relationship between normalized water content and capillary pressure. These parameters adhere to the following relationship:

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

where θ^* is the normalized water content, θ_s is the saturated water content, and θ_r is the residual water content. Normalized water content is then related to capillary pressure, h_c by the following equation:

$$h_c = \frac{1}{c} \left[\theta^{*\left(-\frac{1}{m}\right)} - 1 \right]^{\frac{1}{n}}$$

where α is a parameter with the dimension of length, and $m = 1 - \frac{1}{n}$. The parameters θ_s , θ_r , and α were based on literature values (Guber and Pachepsky, 2010) for soils with similar characteristics. The parameter α is defined as positive for the unsaturated soil conditions and negative for saturated soil conditions; thus, the values were different based on the month in which each

storm occurred and whether sufficient antecedent rainfall could yield saturated soil conditions.

6.3 *Lahar Propagation*

In order to fully model the phenomena of slope failure, post-failure motion must be considered to understand how slope failure affects communities in low-lying areas. The USGS developed a forecasting tool called *LaharZ* to calculate the proximal hazard zone over three dimensional topography estimates the extent of the distal hazard zone (Schilling, 2014). The design of the program is based on the behavior of 27 well observed lahars and their inundation extent. Iverson et al. (1998) defined the relationship between cross sectional area and volume as well as planimetric area and volume as follows:

$$A = 0.05V^{2/3}$$

$$B = 200V^{2/3}$$

where A is the cross sectional area, B is the planimetric area, and V is the lahar volume. The calibration of the *LaharZ* model is based upon datasets for each of the 27 events, which include deposit area, deposit volume, and cross-sectional areas along the flow path. This model is limited by uncertainties that exist within the small dataset and could benefit from recalibration, it is reasonably accurate for smaller magnitude lahars in predicting runout distances (Woelfl et al., 2014).

The topography for the region was represented by a 10-m digital elevation model (DEM) derived from topographic maps prepared and published by the Defense Mapping Agency in 1984. The surface hydrology was modeled using the flow direction, flow accumulation, and stream delineation based on the digital

elevation grid. These inputs allow for the lahar model to traverse downstream, modeling the inundation potential of a lahar at a specified initiation point. The program allows for the consideration of various lahar volumes. Larger volumes typically yield increased width and length for the planimetric area covered by the inundation.

The Monte Carlo TRIGRS simulation produced relative probabilities of failure for all cells in the study area. Cells with a failure probability of more than 40% were identified and used as initiation points in the LaharZ program. Based on observations of previous lahar activity and literature values, a standard volume of 100,000 m³ was selected for each location (van Wyk de Vries, 2000). Larger volumes were tested but were not realistic in width or runout length when compared to the lahars observed in 2016.

7. Results

The storm event in August 2014 modeled on Maderas volcano with estimated soil strength and hydraulic parameters showed five locations along the slope with factors of safety less than one (see Figure 12). Low factors of safety were also identified at the summit crater-lake, but slope failure in that region would be contained by summit depression. Locations with low factors of safety correspond to locations with shallow water table depth.

Figure 12: Factor of safety for Maderas volcano under estimated parameters. Pixels exhibiting likely instability (factor of safety <1) are shown in red. Insets show zoomed image of locations with low factors of safety.

Table 3: Estimated soil strength and hydraulic parameters for Maderas volcano.

Soil Series	Cohesion (kPa)	Friction Angle	Unit Weight (N/m ³)	Diffusivity (m ² /s)	K _s (m/s)	θ_s	θ_r	α
Magdalena	21	35	19500	10 ⁻⁷	10 ⁻⁸	0.4	0.01	-
Merida	23	35	21500	10 ⁻⁷	10 ⁻⁷	0.4	0.01	-
Volcan Maderas	21	35	20500	10 ⁻⁷	10 ⁻⁷	0.4	0.01	-
Vertical Soils	23	30	21500	10 ⁻⁶	10 ⁻⁷	0.5	0.01	-

The Monte Carlo simulations using statistically derived distributions of values of cohesion, internal angle of friction, diffusivity, and hydraulic conductivity, yielded results similar to those produced in the estimated case. Likely lahar initiation points varied only slightly when compared with the estimated case. The predicted slope failures correlated well with the observed lahars in the August 14 storm event (see Figure 13). The model over predicted failure in two instances where slope failure was not actually observed. The slope failure that occurred near the summit and along the stream feeding into the Las Cuchillas waterfall was represented by high probability of failure under the model conditions. A lahar that was not observed by the author but was reported by park personnel at the San Ramon waterfall during the same time period aligned well with the prediction model (see Figure 14).

Figure 13: Map of modeled slope failure occurrence under August 14th storm event conditions. Six locations exhibit high occurrence of slope failure.

Figure 14: Predicted lahar propagation for the August storm event on Maderas volcano. Lahars that were observed and mapped are marked in yellow while the lahar that was reported and not verified is marked with a blue and white line. The lahar was reported at the San Ramon waterfall trail and was located based on oral descriptions of the lahar alone.

The October 3 storm event, which triggered four lahars on Concepción volcano, was modeled over the steep-sloped region of the volcano (see Figure 15). Seven initiation points were selected based on a threshold of 50% failure over the entire Monte Carlo simulation (see Figure 16). Each of these initiation points existed near the summit zone of the volcano.

Figure 15: Map of modeled failure occurrence under the October 3rd storm event conditions. The compiled results of pixels with a factor of safety less than one shows moderate to high probability of failure in 7 locations on the slopes of Concepción.

Figure 16: Map of predicted lahar propagation on Concepción volcano for the October 3 storm event. Higher instances of failure under the Monte Carlo inversion ($>50\%$ occurrence) are denoted in red. Observed lahar occurrences from the October 3rd storm event are denoted in yellow.

Results were similar for the October 20th storm event (see Figure 17). Higher instances of failure were predicted on the northeastern flanks of the volcano as higher intensity precipitation values were observed in Altagracia during this storm event. The October 20th storm event exhibited instances of failure occurrence on the upper flanks. Seven points were located with a higher likelihood of slope failure under the storm event conditions (see Figure 18).

Figure 17: Map of modeled failure occurrence under the October 20 storm event conditions. Little probability of failure is exhibited on the upper flanks of the volcano whereas ten locations on the lower flanks show higher occurrence of slope failure.

Only one lahar was observed following the October 20th storm event. This lahar followed the channel traversed by the October 3rd lahar event near Los Ramos. This lahar, although small and relatively weak in nature, was predicted by the model. Under the storm conditions observed, locations with a high likelihood of failure according to the model did not experience slope failure on October 20th, 2016 (see figure 18).

Figure 18: Map of predicted lahar propagation under October 20th storm conditions. Initiation points were chosen under high occurrence of failure during

8. Discussion

Overall, the model was able to successfully predict four of the eight lahar initiation locations observed throughout 2016. The model for Maderas volcano seemed to most accurately depict the terrain, water table, regolith depth, and soil properties on the volcano. The models created for Concepción accurately represent soil properties but are affected significantly by the low-density pyroclastic cone covering a majority of the edifice and its interaction with the water table and water infiltration through the highly permeable material.

One of the factors that was not considered in the model was the effect of vegetation cover. On the highly vegetated Maderas volcano, it is most likely that

root cohesion, canopy interception, and evapotranspiration play a role in protecting the edifice from mass movement. The model predicted two more lahars than actually occurred during the August 14th storm. The over predictions could be partially explained by the fact that these important factors were not considered. Further investigation into the characteristic vegetation of the volcano would lead to a more accurate depiction of the slopes of Maderas.

More than any other factor, water table depth influenced the output of the TRIGRS program. Concepción, which exhibits little surface flow, is difficult to model the water table depth. All of the 32 wells with reported water depths exist on the gentle slopes of Maderas and Concepción, and therefore do not give any information about the character of the water table beneath the steep slopes toward the summit zone. The water-table depth model therefore likely does not represent accurately the actual depths on Concepción. The model of the water table as a subdued replica of topography is better suited where surface water exists as each point exhibiting surface flow creates another boundary condition for the model. In the case of Concepción, only the lakeshore and the knowledge from clustered well data can be considered. The abrupt increase in slope on the terrain is not physically replicated by the water table model and therefore the model of the water table beneath the summit zone is unrealistically deep.

The DEM used to represent the terrain on the island is based on 1984 Topography, which predates recent mass movements, especially in the case of Concepción, and therefore does not reflect the present-day terrain accurately. Several instances of slope failure and subsequent mass wasting have occurred on Concepción over the past 60 years, deforming the edifice significantly. The influence of this inaccurate DEM can best be represented by the model's prediction of slope failure in San Jose del Sur. Over the past 20 years, several lahar events have occurred, removing much of the pyroclastic deposit existing in the summit zone. Lahar activity in this region has decreased due likely to the

decreased availability of mobile material in the location of probable lahar initiation.

The influence of soil cohesion in the model was tested by running the model with negligible cohesion values. Slope failure was more likely in these models, especially in locations where the internal angle of friction was less than the slope angle. Results were similar in this regard on both Concepción and Maderas, but more instances of failure were introduced on Maderas by neglecting cohesion. It is clear that cohesion plays a large role in slope stability on the clay rich soils of Maderas.

The simplified soil depth model significantly influenced slope stability-estimates. On the steep slopes of Concepción, the regolith depth is more than likely underestimated as pyroclastic deposits may extend up to tens of meters in depth. Most instances of slope failure on Concepción have occurred at shallow depths, so the model was meant to reflect past behavior without considering deep seated failure. When the soil depth was increased by just one meter, instances of slope failure, especially on the steep slopes, increased significantly. The model for Maderas shows less influence of soil depth as locations of failure remain similar when soil depth was varied.

A more practical use for these susceptibility maps would be in analysis for infrastructure repair. In many cases where infrastructure is damaged as a result of lahar inundation, quick repairs are made and no long term solution is considered. In areas that are particularly susceptible to lahar damage, infrastructure is continually under reparation and is costly for the local government and community members. If stable locations could be qualitatively identified, relocation of aqueducts, roadways, wells, homes, or schools could be considered as a long term solution. Access to basic necessities affects community

quality of life significantly. If long-term solutions were made available, less time would be spent without access to these basic necessities.

Finally, the influence of forest cover and increased deforestation on both edifices could draw attention to the current situation on Maderas volcano. Resources allow for better enforcement on Concepción regarding deforestation, but the regulations on Maderas volcano are not enforced regularly. Currently, the law restricts the cutting of trees above 400 m.a.s.l (see forested area in Figure 5). The impact that vegetation has on slope stability and the consequences of losing that benefit may influence local government to play a larger role in regulation enforcement on Maderas volcano.

9. Future Work

In order to utilize the findings in this model for forecasting purposes, a more detailed analysis of climatic conditions should be carried out on the island of Ometepe. The orographic effect of the two slopes is important in modeling actual patterns in rainfall higher up on the flanks. Weather data should be collected over a longer period of time in order to capture larger magnitude storm events and to better understand their frequency. Once climatic patterns are better understood, TRIGRS modeling could provide a better forecasting tool to identify the location of initiation points for shallow, rain triggered lahars on Ometepe Island.

A detailed study on the characteristic properties of the vegetation on the slopes of both Concepción and Maderas would allow for a better understanding of the interaction between soil and vegetation. Root cohesion, canopy cover, and rates of transpiration and evapotranspiration are important factors to consider when modeling slope stability. These details are important for outreach purposes when farmers consider deforesting an area of tree cover for grazing pasture or

cultivation. An in depth analysis of rates of deforestation over time could contribute to the understanding of patterns of tree removal on the island.

The model could be used in the creation of a shallow rain-triggered lahar susceptibility model under more extreme climatic conditions. These results could be utilized in a variety of ways. An early warning system based on real-time rainfall measurements could be set up, such that when a certain intensity is reached a warning is given for potentially exposed locations. This could allow for rapid evacuation or other actions by the authorities and people living in such areas.

In this study only shallow slope failure was considered based on observations of historic lahars on both edifices. Although there is little evidence of deep slope failures on either Concepción or Maderas, deeper failure landslides, which could result in larger lahars may occur at some point in the future. Shallow landslide producing lahars occur much more frequently than deeper seeded landslides, and will most likely be experienced on Concepción and Maderas more frequently in the near future. This does not rule out the possibility of deep slope failure on either volcano, and that possibility should be explored in future studies.

10. Conclusion

In all but one case where failure was observed in 2016, the TRIGRS Monte Carlo model predicted a high probability of slope failure. These results were obtained using recorded rain storm data and soil strength and hydraulic parameters based on field experience and literature estimates (strength, unit weight, hydraulic conductivity etc.). A 10-m DEM was used to derive slope values, from which soil depths were modeled. The DEM was also used to estimate water table depths. The model over predicts failure on both volcanic edifices, likely due to model sensitivity to water table depth. In the case of the slope failure observed at La Chirca, the model did not predict an increased risk of slope failure. Deformation

and an increase in mobile material available at the point of initiation could factor into the observed failure. The model over-predicted instances of slope failure in each of the three cases. With a better understanding of the influence that vegetative cover plays in slope stability, each of these models could have higher accuracy.

The inclusion of precipitation data in a slope stability analysis accurately depicted the observed failure on the island of Ometepe during the 2016 year. The forensic analysis showed appropriate failure occurrence where slope failure was observed in the field, suggesting the appropriateness of the assumptions made in model creation. These specific observed precipitation events aided in the prediction of failure in locations that have historically suffered from frequent slope failure throughout the past 40 years. Model outputs suggest that the most common type of slope failure occurs following high-intensity, long-duration precipitation events. Although the TRIGRS model seems to appropriately represent the interaction between slope stability and changing pore pressure in response to rainfall, the terrain, water table depth, and regolith depth models could be better calibrated to the study area to obtain better results. LaharZ propagation results also accurately represented runout area of observed lahars during the 2016 year. Our estimation of lahar volumes produced inundation areas that were consistent with the actual areas affected by lahars, which were mapped on aerial imagery and on the ground. This model can therefore appropriately be used in probabilistic analyses of large storm events based on different return periods for storms.

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12. Appendices

12.1 *Appendix A: Weather data for three storm events*

Table 4: Precipitation and intensity data from August 14 event.

		Weather Station Location					
		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
14-Aug	0:10	0.51	2	0	0	0.25	1.5
14-Aug	0:20	0.51	3.8	0.25	0	0.25	2.3
14-Aug	0:30	0.51	3.3	0	0	0.25	2.3
14-Aug	0:40	0.51	3.3	0.76	4.1	0.51	2.3
14-Aug	0:50	0.51	3.8	0.76	8.6	0.51	3.3
14-Aug	1:00	0.76	5.6	0	1.3	0.51	3.8
14-Aug	1:10	0.76	5.8	0.51	3.3	1.02	9.3
14-Aug	1:20	0.51	3.3	0.51	3.3	1.02	10.4
14-Aug	1:30	1.02	10.4	0.25	3.3	0.51	4.8
14-Aug	1:40	0.51	4.8	0.51	2.5	0.51	4.3
14-Aug	1:50	0.51	3.6	0.25	1.8	0.51	4.8
14-Aug	2:00	0.25	2.3	0	1.3	0.51	3.8
14-Aug	2:10	0.25	2.3	0.25	1.3	0.51	3.8
14-Aug	2:20	0.25	1.5	0.25	1	1.02	5.3
14-Aug	2:30	0.25	1.3	0	1	0.25	2.8
14-Aug	2:40	0.25	1.3	0	0	0.25	2.3
14-Aug	2:50	0.25	2.5	0	0	0.25	2.3

		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
14-Aug	3:00	0.25	2.3	0	0	0.25	1.5
14-Aug	3:10	0.76	9.4	0.25	0	0	0
14-Aug	3:20	0	1.5	0	0	0	0
14-Aug	3:30	0.25	1.5	0.76	15.2	0	0
14-Aug	3:40	0	1	0	1	0	0
14-Aug	3:50	0	0	0	0	0	0
14-Aug	4:00	0	0	0	0	0	0
14-Aug	4:10	0	0	0	0	0	0
14-Aug	4:20	0	0	0.51	3.8	0	0
14-Aug	4:30	0	0	0	1	0	0

Table 5: Precipitation and intensity data from October 3rd event.

		Weather Station Location					
		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
2-Oct	19:40	0	0	0.25	0	0	0
2-Oct	19:50	0.25	0	0.25	3.6	1.27	34.8
2-Oct	20:00	0	0	7.62	176.3	1.27	23.4
2-Oct	20:10	0	0	3.05	44.2	4.57	67.3
2-Oct	20:20	0	0	2.29	66.5	0	1.3
2-Oct	20:30	0	0	1.78	86.6	2.29	65.3
2-Oct	20:40	3.05	195.1	8.13	99.6	1.27	45.2
2-Oct	20:50	13.46	185.2	11.43	147.8	0	1.3
2-Oct	21:00	2.54	48	2.03	39.9	0.25	1.3
2-Oct	21:10	0.25	9.7	0	1	0	0

		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
2-Oct	21:20	0	0	0	0	0	0
2-Oct	21:30	0.25	0	0	0	0.25	0
2-Oct	21:40	0	0	0	0	0.25	1.5
2-Oct	21:50	0	0	0	0	0	1.5
2-Oct	22:00	0	0	0.25	0	0.25	1.5
2-Oct	22:10	0	0	0	0	0.25	1.5
2-Oct	22:20	0.25	6.3	0	0	0	0
2-Oct	22:30	0.51	31.8	0	0	0	0
2-Oct	22:40	0	0	0	0	0.25	0
2-Oct	22:50	0.25	0	0	0	0	0
2-Oct	23:00	4.06	57.4	0	0	0	0
2-Oct	23:10	0.51	15.2	0.76	17	0	0
2-Oct	23:20	0	1	0.76	14.7	0	0
2-Oct	23:30	0.25	1	0	1	0	0
2-Oct	23:40	0.25	0	0	0	0	0
2-Oct	23:50	0	0	0.25	0	0	0
3-Oct	0:00	0	0	0.25	1.8	0	0
3-Oct	0:10	0	0	0	1.3	0	0
3-Oct	0:20	0	0	0.51	3	0	0
3-Oct	0:30	0	0	0.25	3	0	0
3-Oct	0:40	0.25	0	0.25	6.9	0	0
3-Oct	0:50	0.25	1.3	0.51	3	0	0
3-Oct	1:00	0	1.3	0	1.3	0	0
3-Oct	1:10	0.25	1.3	0.51	2.3	0	0
3-Oct	1:20	0.25	1.5	0	1.5	0.25	0
3-Oct	1:30	0.25	1.5	0.25	1.5	0	0
3-Oct	1:40	0	1	0	0	0	0
3-Oct	1:50	0.25	1.3	0.25	1	0.25	0
3-Oct	2:00	0.25	1.5	0	0	0	0
3-Oct	2:10	0.25	1.5	0	0	0	0
3-Oct	2:20	0.51	10.9	0	0	0	0
3-Oct	2:30	0	0	0.25	0	0	0
3-Oct	2:40	0	0	0	0	0	0
3-Oct	2:50	0	0	0	0	0.51	19.6
3-Oct	3:00	0	0	0	0	0.51	6.9
3-Oct	3:10	0	0	0.25	0	0	1
3-Oct	3:20	0.25	0	0	0	0	0
3-Oct	3:30	0	0	0	0	0	0

		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
3-Oct	3:40	0	0	0	0	0	0
3-Oct	3:50	0.25	0	0	0	0.51	16
3-Oct	4:00	0	0	1.52	35.1	1.02	21.6
3-Oct	4:10	0	0	0	1.3	0	1
3-Oct	4:20	0.76	19	0.25	0	0	0
3-Oct	4:30	4.32	72.4	0.25	2	0	0
3-Oct	4:40	6.86	71.4	0	0	0	0
3-Oct	4:50	3.81	52.3	0	0	0.51	3
3-Oct	5:00	0.51	8.6	0	0	1.78	61
3-Oct	5:10	2.79	149.4	0	0	0	1
3-Oct	5:20	0	1.3	0	0	0.25	1
3-Oct	5:30	0	0	0.25	0	0	0

Table 6: Precipitation and intensity data from October 20 event.

		Weather Station Location					
		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
19-Oct	21:20	0	0	0.51	11.9	0.25	0
19-Oct	21:30	0	0	2.79	35.6	0.76	6.6
19-Oct	21:40	0.51	79.5	1.78	43.4	0.51	3.8
19-Oct	21:50	0.25	0	1.27	13.7	0.25	2.5
19-Oct	22:00	0.25	0	0.51	6.1	0.25	2.3
19-Oct	22:10	3.56	90.4	1.78	17.5	0.51	2.3
19-Oct	22:20	0.25	84.6	1.27	17.5	0.25	2
19-Oct	22:30	3.05	59.4	0.76	8.1	0.25	2
19-Oct	22:40	0.25	18.8	1.52	14	0.25	1.8
19-Oct	22:50	0	1	4.57	71.4	0.51	3.3
19-Oct	23:00	0	0	5.08	56.6	0.76	7.6
19-Oct	23:10	0.25	0	2.54	26.7	0	1.3
19-Oct	23:20	0	0	2.29	23.1	0.25	1.3
19-Oct	23:30	0	0	1.78	19.8	0.25	1.3
19-Oct	23:40	0	0	0.51	8.1	0	0
19-Oct	23:50	0.51	4.6	0.51	3	0.25	0
20-Oct	0:00	1.27	17.8	0.51	2.8	0.25	1.5
20-Oct	0:10	1.78	21.8	0.25	2.5	0.76	6.9

		Finca Magdalena		Altagracia		Los Angeles	
Date	Time	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)	Precip (mm)	Intensity (mm/hr)
20-Oct	0:20	0.51	5.6	0	1.3	0.76	6.6
20-Oct	0:30	0.51	7.4	0	0	0.76	3.8
20-Oct	0:40	0.25	2.5	0.25	0	0.25	3.8
20-Oct	0:50	0	1.3	0	0	0.51	3
20-Oct	1:00	0.25	1.3	0	0	0.25	3
20-Oct	1:10	0	0	0	0	0.25	0
20-Oct	1:20	0	0	0.25	0	0.25	0
20-Oct	1:30	0	0	1.52	24.1	0.76	7.9
20-Oct	1:40	0	0	1.78	23.1	1.52	16.3
20-Oct	1:50	0	0	0.51	5.1	0.25	5.6
20-Oct	2:00	0	0	1.27	14.2	0	1
20-Oct	2:10	0	0	0.76	9.9	0	0
20-Oct	2:20	0.25	0	0.76	4.6	0	0
20-Oct	2:30	0	0	1.02	8.6	1.02	11.2
20-Oct	2:40	0.25	0	1.02	6.3	8.64	105.9
20-Oct	2:50	0	0	0.51	4.6	10.92	115.3
20-Oct	3:00	0	0	1.02	8.9	0.76	25.4
20-Oct	3:10	0.25	0	1.02	7.1	2.29	19.3
20-Oct	3:20	0	0	0.76	5.8	2.29	17.8
20-Oct	3:30	0	0	0.51	4.8	0.76	12.2
20-Oct	3:40	0	0	0.25	3	0.76	5.1
20-Oct	3:50	0	0	0.25	2	1.02	7.1
20-Oct	4:00	0	0	0.25	2	0.76	10.9
20-Oct	4:10	0.25	0	0.25	1.8	1.78	15.5
20-Oct	4:20	0	0	0	1	2.29	19.6
20-Oct	4:30	0	0	0.25	1	1.27	15.2
20-Oct	4:40	0	0	0.25	0	0.51	5.8
20-Oct	4:50	0.25	0	0	0	0.25	2.8
20-Oct	5:00	0	0	0	0	0.51	3.6
20-Oct	5:10	0	0	0	0	0.76	3.6
20-Oct	5:20	0	0	0	0	0.51	3.8
20-Oct	5:30	0	0	0	0	0.51	4.1
20-Oct	5:40	0	0	0	0	0.51	3.8
20-Oct	5:50	0	0	0	0	0.51	3.3
20-Oct	6:00	0	0	0	0	0.25	2.5
20-Oct	6:10	0	0	0	0	0.51	2.3
20-Oct	6:20	0	0	0	0	0	1.3

Figure 19: Slope grade on Ometepe Island. Relief on Concepción is abrupt whereas Maderas exhibits a more gradual slope.

Figure 20: Soil series on Ometepe. Soil series were defined by Aguirre and Acuña (2009) and were assigned soil strength and hydraulic parameters based on grain size observations and soil descriptions.

Figure 21: Modeled regolith depth with a maximum depth of 1.5 meters. Maximum regolith depth was increased by one meter to test the effect of soil depth on the model.

Figure 22: Water table depth based on HAND model.

Figure 23: Sample grid of precipitation intensity for 10 minute period during the October 20th storm event. Intensity was interpolated using Inverse Distance Weighting.

12.3

Appendix C: Soil Strength and Hydraulic Parameters

Table 7: Estimated values for soil strength and hydraulic parameters for the soil series existing on the slopes of either edifice

Soil Series	Cohesion (kPa)	Friction Angle	Unit Weight (N/m ³)	Diffusivity (m ² /s)	Hydraulic Conductivity (m/s)	θ_s	θ_r	α
Magdalena	21	35	19500	1.00E-07	1.00E-08	0.4	0.01	-0.008
Merida	23	35	21500	1.00E-07	1.00E-07	0.4	0.01	-0.008
Volcan Maderas	21	35	20500	1.00E-07	1.00E-07	0.4	0.01	-0.008
Vertical Soils	23	30	21500	1.00E-06	1.00E-07	0.5	0.01	-0.008
Pyroclastic Deposits	30	30	18000	1.00E-06	1.00E-06	0.5	0.01	-0.037
Lahars	15	35	18000	1.00E-05	1.00E-06	0.5	0.01	-0.037
Lava Flows	60	55	26000	1.00E-07	1.00E-07	0.4	0.01	-0.008
Crater Soils	40	40	20000	1.00E-06	1.00E-06	0.5	0.01	-0.4

12.4 ***Appendix D: Lahar Inventory for Concepción and Maderas Volcanoes***

Table 8: Lahar inventory for historical events on Concepción and Maderas Volcanoes.

Year	Month	Day	Location	Size (Volume, Area, Thickness)
1883	2-5			
1885	10	11		
1912	12			
1957	3-7			
1978	2	4	San Jose del Sur	2.21 km ²
1979	4		San Jose del Sur	
1982	5	20	El Corozal	
1986	2	4	La Flor	1.58 km ²
1986	2	4	San Jose del Sur	4.13 km ²
1987	10	14	La Flor	1.31 km ²
1987	10	14	San Jose del Sur	3.29 km ²
1988	10	18	San Jose del Sur	
1990	1	23	San Jose del Sur	5.73 km ²
1993	3		La Chirca	
1996	9	27	El Corozal	
1998	12	15	San Jose del Sur	0.28 km ²
2000	1	27	San Jose del Sur	4.61 km ²
2000	1	27	La Flor	0.66 km ²
2002	10	28	La Chirca	1.5 m
2002	10	31	La Chirca	0.5 m
2003	10	1	San Jose del Sur	5.94 km ²
2003	10	1	La Flor	0.87 km ²
2003	11	25	San Marcos	1 m
2003	11	25	San Jose del Norte	2 m
2003	11	25	Japon	0.6 m
2004	5	21	La Chirca	
2005	1	31	San Jose del Sur	4.21 km ²
2005	5	18	La Flor	
2005	5	18	San Jose del Norte	2 m
2005	6	29	La Concepción	
2005	6	29	La Chirca	
2005	6	29	La Flor	
2005	6	29	San Marcos	
2008	10	4	Los Ramos	.18 km ²

Year	Month	Day	Location	Size (Volume, Area, Thickness)
2008	10	4	La Union	
2008	12	15	Los Ramos	1.18 km ²
2010	7		Pulman	
2010	7		La Palma	
2010	7		Balgue	
2010	9		El Porvenir	
2010	9		Santa Cruz	
2010	9		La Ciguena	
2010	9		Merida	
2010	9	20	Las Cuchillas	
2010	12	8	San Jose del Sur	5.64 km ²
2010	12	8	La Flor	2.52 km ²
2014	10	8	Los Ramos	1.64 km ²
2014	10	8	La Union	
2014	10	8	Urbaite	
2014	10	8	Sintiope	
2014	10	9	Los Ramos	
2014	10	9	La Union	
2014	10	9	Urbaite	
2014	10	9	Sintiope	
2014	10	9	La Chirca	
2014	10	9	La Flor	
2014	10	9	La Concepción	
2014	10	11	Los Ramos	
2014	10	11	La Chirca	
2014	10	12	Los Ramos	
2014	10	16	Los Ramos	
2014	10	16	Urbaite	
2014	10	16	Sintiope	
2014	10	16	La Chirca	
2014	10	16	La Flor	
2014	10	16	La Concepción	
2014	10	18	Los Ramos	
2014	10	18	La Union	
2014	10	18	Urbaite	
2014	10	18	Sintiope	
2014	10	18	La Chirca	
2014	10	18	La Flor	

Year	Month	Day	Location	Size (Volume, Area, Thickness)
2014	10	18	La Concepción	
2014	10	19	Los Ramos	
2014	10	19	La Union	
2014	10	19	Urbaite	
2014	10	19	Sintiope	
2014	10	19	La Chirca	
2014	10	19	La Flor	
2014	10	19	La Concepción	
2014	10	22	Los Ramos	
2014	10	22	La Union	
2014	10	22	Urbaite	
2014	10	22	Sintiope	
2014	10	22	La Chirca	
2014	10	22	La Flor	
2014	10	22	La Concepción	
2014	10	25	La Chirca	
2014	10	25	La Flor	
2014	10	26	La Chirca	
2014	10	26	La Flor	
2015	10		North Maderas Summit	
2015	10		Madroñal	
2016	5	4	Sintiope	
2016	6	8	San Ramon	
2016	8	14	Las Cuchillas	
2016	10	3	Los Ramos	
2016	10	3	La Chirca	