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# Precipitation Intensity Required for Landslide Initiation in Rwanda

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Geology Honors Thesis

# Precipitation Intensity Required for Landslide Initiation in Rwanda

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By

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**Abstract**

Rwanda has a high density of landslides, heavy precipitation events and a shortage of resources to study them, making it an excellent candidate for study using satellite-based remote sensing data. To assess landslide hazards countrywide, I first built a landslide inventory of 254 landslides and used a statistical methodology. Using logistic regression on 24 test variables, I determined that slope and population density are statistically most relevant to landslide occurrence in Rwanda. A preliminary predictive hazard map for Rwanda was produced, with an overall predictive accuracy of 79.6%. Second, I worked to define a relationship between precipitation intensity and landslide density for a landslide-prone study area in western Rwanda. In the 1180 $km^2$ study area, I mapped 577 landslides, using CNES/Astrium and WorldView satellite imagery in Google Earth over a study period of 2000 to 2015. One 400 $km^2$ part of the study area has a high landslide density of 1.4 landslides/$km^2$, while another 780 $km^2$ part with identical geology, soils, land-use, and vegetation has a much lower landslide density. To identify possible triggering events for these landslides, I analyzed a 16 year record of TRMM (Tropical Rainfall Measuring Mission) satellite precipitation data. The high landslide density region and the low landslide density region were not notably different in rainfall, as quantified by recurrence interval analysis. A relationship between precipitation and landslide density could therefore not be developed, and the null hypothesis cannot be ruled out. This apparent lack of connection could result from a variety of factors including TRMM grid size, satellite imagery temporal resolution, antecedent soil moisture, or vegetation regrowth rates.

**Approval**

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Dr. Adam Booth, Thesis Advisor Date

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Dr. Martin J. Streck, Department Chair Date

# 1 Introduction

Landslides in the United States cause more than $1 billion in damages and 50 deaths per year (USGS 2014). Globally, figures are much more grave- between 2004 and 2010, 32,322 fatalities from landslides were recorded (Petley 2012). Monitoring, mapping and forecasting of these hazards are less than adequate in many parts of the world. In this study, “landslide” is a general term used for a variety of types of mass movement, including rock and soil falls, topples, slides, and flows. Landslides have a distinctive appearance when viewed from satellite or aerial photographs- the land is deformed and shows evidence of slippage. There is often a clear shape of a head scarp, hummocky slide, and a bulging toe (Ritter et al. 2011). Recent slides are visible as patches of bare earth, where land cover has been disrupted.

Landslide hazards lead to more economic losses and casualties than commonly recognized, due in part to casualties from slope failure being higher in developing nations (Guzetti et al. 1999). Research into rainfall induced landslides is often highly localized and relies on in situ rain gages. Methods based on high resolution spatial and temporal data and adequate ground data do not scale well to regional assessment (Kirschbaum 2009). Rapidly evaluating slope stability in response to storms, over a regional or larger scale is invaluable in a developing nation like Rwanda. Remotely sensed surface and atmospheric data provides an opportunity to assess landslide hazard at a regional scale (Kirschbaum 2012).

## *1.1 Rwanda*

Rwanda is a 26,338 km$^2$ country located in eastern Africa (Figure 1) with a population of approximately 11 million (CIA 2015, NISR 2014). This is the highest population density in mainland Africa (UNEP 2011). Seventy-five percent of the population of Rwanda earns a living from farming, mostly subsistence, and the landscape is ninety percent anthropogenic (eSoko

2015). Rwanda has a nickname of "land of a thousand hills", and the country's steep slopes are prone to landslides (UNEP 2011).

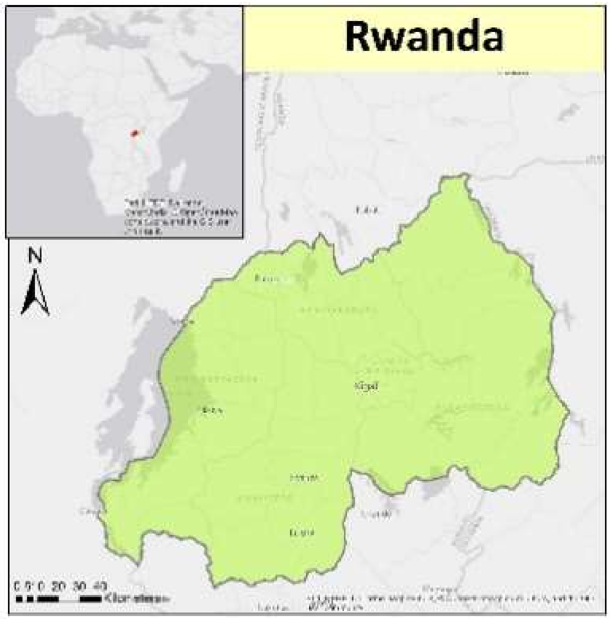


*Figure 1. The country of Rwanda. Rwanda is 26,338 km², about the size of the state of Vermont. It is located in Eastern Africa and has a population of approximately 11 million people*

### *1.2 Causes of landslides*

Material on a hillslope will remain stable as long as the shear stress does not exceed the shear strength of the slope materials (Ritter et al. 2011). When water fully saturates the soil, it pushes the sediment particles apart, which reduces the effective normal stress, and thereby decreases the frictional shear strength, leading to a possible failure surface (Terzaghi 1950). Studies have shown that an increase in pore pressure will initiate or increase the speed of a landslide, and a decrease in pore pressure will slow or stop a landslide (Iverson 2005). Even small differences in soil porosity influence landslide initiation and landslide rates (Iverson et al. 2000; Montgomery et al. 2002). Slope stability analysis is complex and involves many factors, but water plays a key role.

In Rwanda, landslides are often associated with heavy precipitation events and flash floods. Conversely, landslides can cause flood events when the flow of a river is blocked temporarily by a landslide. When this natural dam collapses, large volumes of water can be released without warning, presenting a threat to settlements, people, and agriculture in the valleys (UNEP 2011).

*1.3 Precipitation*

In Rwanda there are two rainy seasons and two dry seasons: one long rainy season in February–May representing 48 percent of annual rainfall, one long dry season from June to mid-September, a second rainy season in September–December representing 30 percent of annual rainfall, and a second short dry season in January–February, representing 22 percent of annual rainfall (UNEP 2011) (Figure 2). Rwanda receives an average of 1,200 mm of precipitation annually, but the annual average ranges from 2,000 mm in the west and north-western highlands to 600 mm in the eastern savannah (UNEP 2011). Available data suggests Rwanda experiences irregular and unpredictable rainfall patterns. Erratic rainfall data is observed in Kigali, one of the few locations where continuous rainfall data is measured. In seasons where excessive rainfall events are observed, they are not evenly spread throughout the season- instead, heavy rain typically falls in less than 3 days, sometimes over just one day (UNEP 2011). Landslides in Rwanda are often associated with heavy precipitation events and flash floods.

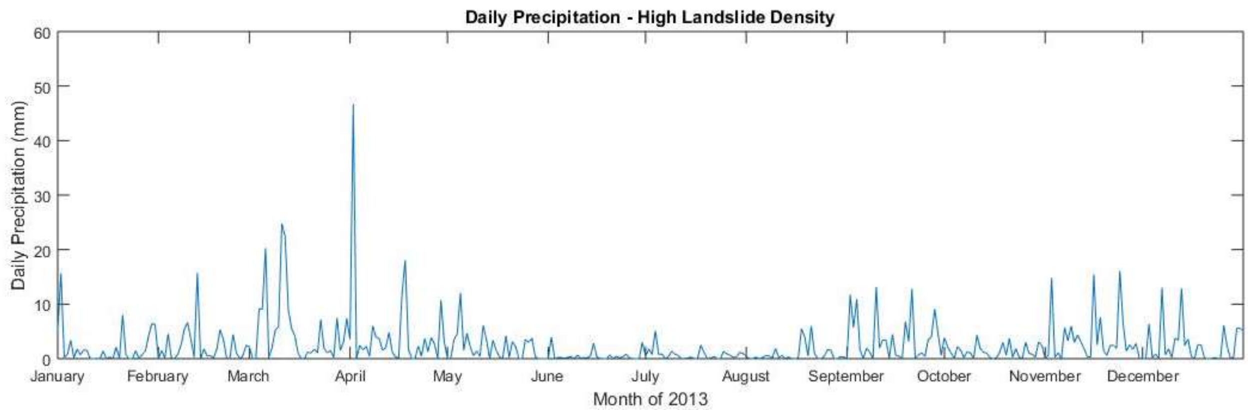


*Figure 2. One year of TRMM data for Rwanda. This year shows the annual pattern of high rainfall in February through May, dry in June to mid-September, briefly rainy again, then dry in January and February.*

In the most thoroughly documented instance, extreme precipitation (over 140 mm in 3 days) in Ruhengeri prefecture resulted in catastrophic debris avalanches, torrents, and earthflows 24 hours later (Byers 1992). This study describes 3 days of heavy rain, a small (4.5 magnitude, located 150 km north in Uganda) earthquake, and then 24 hours later, on a day with low rainfall (1.6 mm), landsliding and debris flows began. The following day, there was heavy rain again, leading to continuing debris flows. It is possible that the earthquake had an adverse effect on slope stability, however, witnesses stated that the landslide activity actually began 24 hours after the small quake. Based on the available data, the landslide event appears to be directly related to soil moisture and infiltration capacity (Byers 1992).

*1.4 Storm Events*

Relative magnitude of a precipitation event can be quantified by calculating a recurrence interval. This is a statistical calculation of the probability that an event will be equaled or exceeded in any given year. For example, recurrence intervals are commonly used in flood hazard analysis in referring to a “100 year flood plain” or a “100-year storm”. This means that there is a 1 in 100 chance that a “100-year storm” will be equaled or exceeded in any given year.

*1.5 Determining Landslide Hazard*

There are many methods to assess landslide hazards, but van Westen et al. (2006), Dai et al. (2002) and others categorize these methods into four general approaches: inventory, heuristic, statistical, and deterministic. A landslide inventory is critical to investigations of where and when landslides have occurred (Kirschbaum et al. 2015). An inventory is often the first step for many of the other landslide susceptibility mapping methodologies (Dai et al. 2002). A heuristic approach uses expert opinions to estimate landslide hazard based on variables. This method may be remote, or based on direct, in-the-field observations (Metternicht et al. 2005). Weighting of variables may be subjective in this method (Dai et al. 2002). A statistical model generally takes the form of bivariate or multivariate statistical analyses of landscape characteristics that have been present in areas where landslides occurred (Metternicht et al. 2005). Statistical analysis estimates future landslide hazard for areas currently free of landslides but with similar conditions to areas with landslides (Dai et al. 2002). This method is used remotely, and requires the collection of large amounts of data. It is considered to be most suitable for landslide hazard prediction at a medium scale (1:25,000 – 1:50,000) (Metternicht et al. 2005). A deterministic approach is based on slope stability analysis, and therefore is best used in small areas, when conditions are fairly uniform across the study area, and the landslide types are known and easy to analyze (Dai et al. 2002). These models often provide the most detailed results, but the data requirements can be prohibitive (Dai et al. 2002).

It is also important to differentiate between "risk" and "hazard". Varnes (1984) defines risk as "the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period". Risk is highly specific, and only practical to assess on a small scale. Hazard, one component of risk, is something to be determined on a larger scale (van Westen 2006). Therefore, this study focused on identifying landslide hazard, not landslide risk.

The global landslide catalog, produced by Kirschbaum et al., (2015), only contains four landslides for the entire country of Rwanda, but a cursory review of Google Earth imagery shows that there are numerous undocumented landslides.

In this thesis I will lay out a methodology for determining study areas and building a landslide inventory. I will describe the statistical methods used to determine which variables are statistically most relevant to landslide hazard in Rwanda, and the satellite data products used for remote sensing. I provide a preliminary hazard map for landslides in Rwanda and an accuracy assessment. I will then investigate the relationship between precipitation and landslide initiation in a specific region of Rwanda with abundant recent landslides, and discuss the implications of my results.

## 2 Study Areas

### *2.1 General Rwanda Landslide Study*

The Area of Interest (AOI) selected was the entire country of Rwanda, plus some of Southern Uganda, to capture landslides close to the border of both countries.

### *2.2 Focused Landslide Study*

To isolate the effects of precipitation on landslides in Rwanda, this study looks at a smaller region of the country. I am looking at two defined locations, one with a high density of landslides, and one with a low density of landslides. Other factors that affect landsliding, such as slope, soil properties, bedrock geology, etc. are relatively constant across these two locations, but precipitation varies. This serves as a natural experiment, and I hypothesized that precipitation was the most important variable that could vary between the two sites. Focusing on a specific region of Rwanda allows for analysis of landslides and precipitation.

The first characteristic I used to identify potential study areas was a high density of landslides. Using the landslide inventory of Rwanda generated in the General Landslide Study, I identified several high density areas. Ideally the area would also have a minimum of two satellite images available within one year, to allow landslides to be dated to the nearest year.

Now that this general region was identified, the AOI needed to be limited to a geologic unit and a soil unit. The soil type and lithology for the majority of high landslide density areas were Umbric Acrisol and metasedimentary, respectively. I produced a map of all areas with this same soil and lithology type to identify an overlap (Figure 3). I further limited the location by considering land cover (Figure 4). The dominant land covers in the region of overlapping soil type and lithology are cropland, grassland, and forest, and I limited landslide mapping to cropland and grassland. Based on these criteria I selected a 400 $km^2$ high landslide density study region, along with a 780 $km^2$ (one TRMM grid square) low landslide density area (Figure 5).

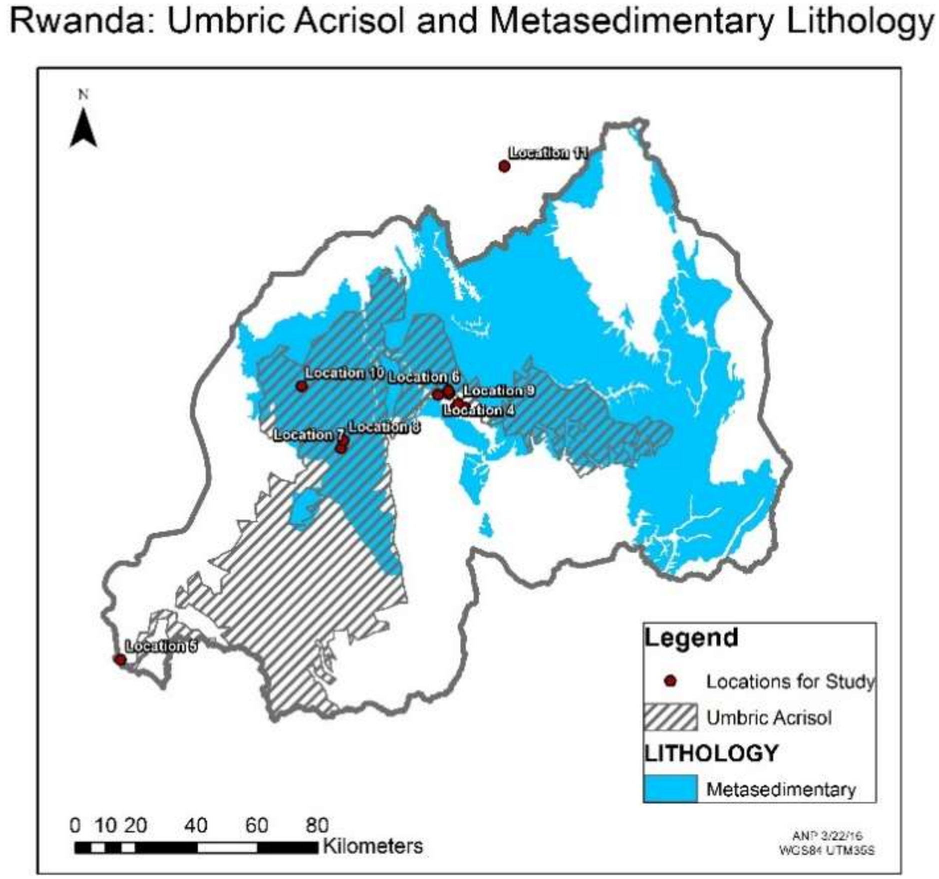


*Figure 3. Map of Umbric Acrisol soils (gray striped area) and Metasedimentary lithology (blue shading) in Rwanda. Red points are areas of high landslide density identified in the General Rwanda Study. This figure demonstrates that most high density areas occur where this soil and lithology type coincide.*

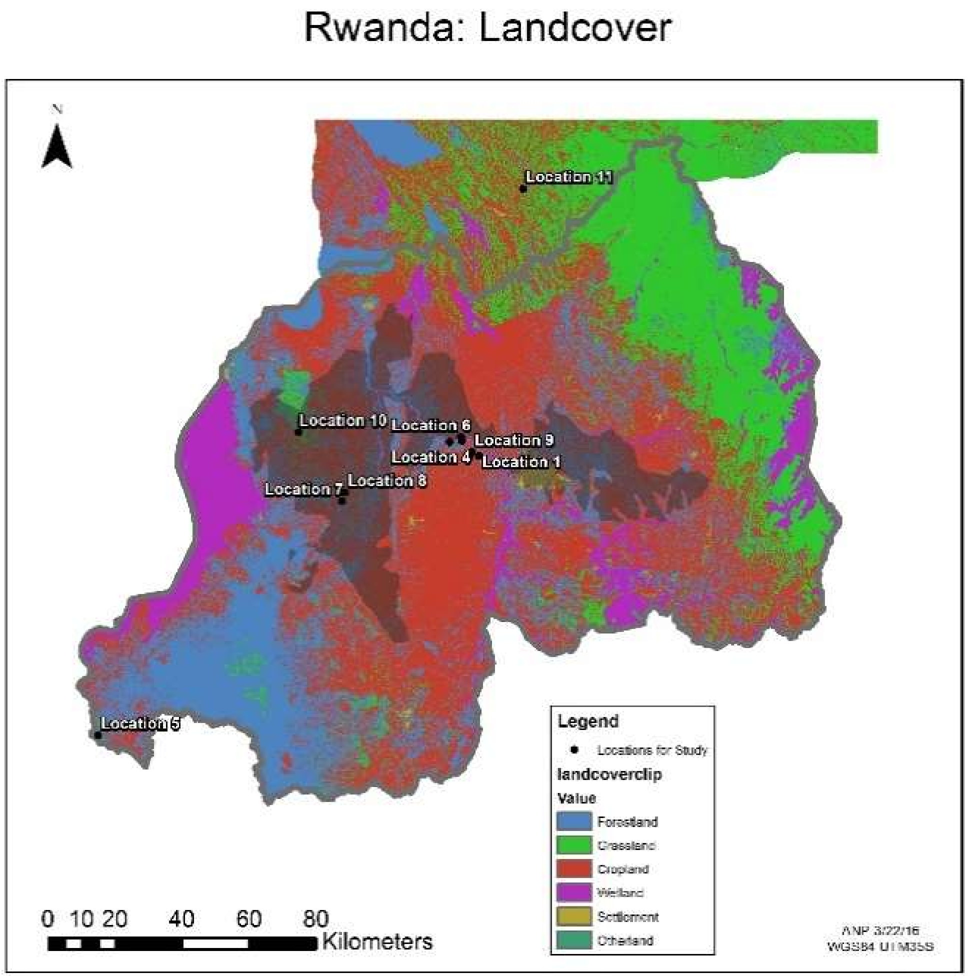


*Figure 4. Map of landcover types in Rwanda. Points represent areas of high landslide density that are possible sites for study. The gray shaded area represents all areas where Umbric Acrisol and metasedimentary lithology overlap (from Figure 3). Landcover types found within this shaded area are grassland, cropland, and forestland. The high landslide density study area was selected from this image.*

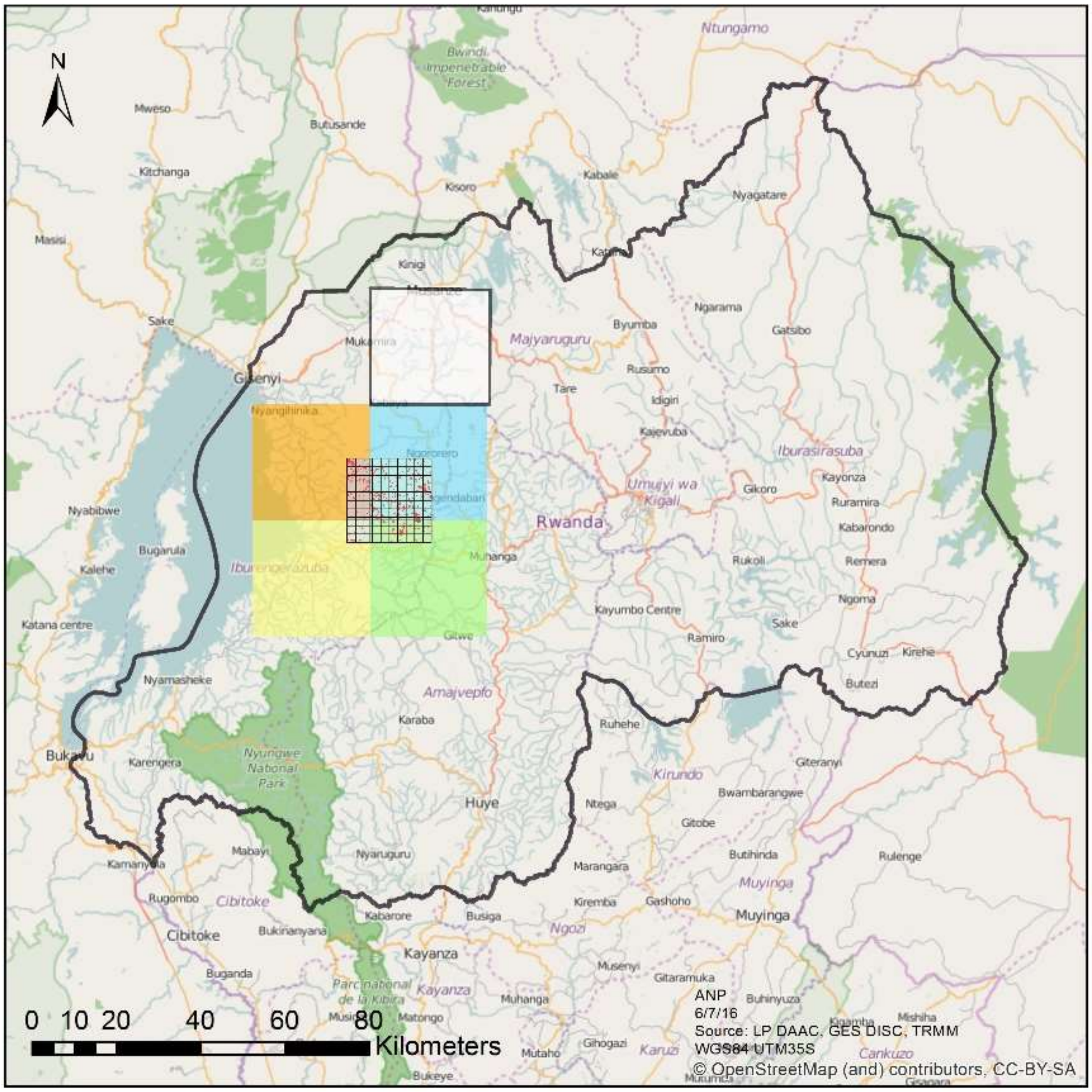


*Figure 5. Overview map of the Focused Study area. Colored squares each represent a 0.25 x 0.25 degree TRMM pixel and the central gridded area shows the study area with landslide polygons in red. The black outlined box shows the low landslide density area.*

## 3 Methods

### *3.1 Remote Sensing Products*

Remote sensing data is invaluable in a developing nation that faces challenges in tracking, cataloging, and predicting the numerous landslides that occur each year. This is not unique to Rwanda- SERVIR (a joint development initiative of the National Aeronautics and

Space Administration (NASA) and the United States Agency for International Development (USAID)) has completed a similar inventory and statistical analysis of landslides in El Salvador, as well as GIS (Global Information System) based hazard mapping in many other regions globally (SERVIR 2015). Remote sensing data makes it possible to study landslides in areas that are costly or otherwise inaccessible, as well as cover large areas.

*3.1.1 Tropical Rainfall Measuring Mission (TRMM)*

The remote sensing satellite TRMM launched in late November 1997, and gathered near-real-time precipitation estimates until April 15, 2015 (GSFC 2016). This mission was flown by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) to improve our quantitative knowledge of the 3D distribution of precipitation in the tropics. The satellite had a passive microwave radiometer, a precipitation radar, and a visible-infrared scanner, among other instruments (GSFC 2016). The product used for this analysis is 3B42 V7 (Daily TRMM and Others Rainfall Estimate). This product has a daily temporal resolution, and is provided on a global 0.25 ° x 0.25 ° grid over the latitude band 50 ° N-S (GSFC 2016). Data is available from January 1, 1998 – May 2, 2015.

*3.1.2 Digital Elevation Model*

Digital elevation models (DEMs) used in this study are constructed using elevation data from stereo aerial photos, digitized contour maps, or global positioning systems (GPS). The NASA Shuttle Radar Topography Mission (SRTM) datasets result from a collaboration between NASA, the National Geospatial Intelligence Agency (NGA), and the German and Italian space agencies. The SRTM instrument was a specially modified radar system that gathered global elevation data over 11 days in 2000. The original SRTM DEM has a spatial resolution of 90 meters (3 arc second), and recently 30 meter (1 arc second) data has been made available

(LPDAAC 2014). Datasets were generated from Shuttle Radar Topography Mission (SRTM) 1-Arc second Digital Elevation Models (DEM). The source for the 90 m DEM is CGIAR, and the 30 m DEM was collected from LPDAAC.

*3.1.3 High-resolution satellite imagery*

Google Earth, as an aggregator of images, was the source for images used to build the landslide catalog for the General Study and the Focused Study. In the study areas, Google Earth provides CNES/Astrium and WorldView satellite imagery.

**3.2 Mapping**

When viewed from satellite images, landslides are visible as regions of bare earth with a rough and hummocky texture. As seen in Figure 6, the color usually contrasts with surrounding vegetation or cultivated land. The slide has a "natural" shape, as opposed to a more rectangular region of land cleared for farming or construction. Human intervention in mapping is important, otherwise farms, mining operations, and even flocks of sheep can be inadvertently identified as landslides.

*Figure 6. Examples of two recent landslides in the study area shown in WorldView/Google Earth satellite imagery. The color of the bare earth and the texture of the landslide scar stands out in contrast to the surrounding farmland or other ground cover.*

*3.2.1 General Study Mapping*

The first step in a statistical approach to estimating relative landslide hazard is gathering enough points representing landslide locations to produce a meaningful analysis. First, existing catalogs were consulted. Feldman and Byxbe (2014) produced a catalog for Rwanda and Uganda using an automated process to identify environmental and spectral characteristics indicative of landslides. Fifty-two points from this catalog were included in this study. The Global Landslide Catalog (GLC) was consulted next.  The GLC methodology is to compile information from newspaper reports, published articles, aerial photographs, and other sources (Kirschbaum et al. 2015). The catalog contains 5741 points, but only 4 points in Rwanda. Additionally, GLC landslides can be cataloged as a point with a several kilometer radius of accuracy based on a news report rather than a visual sighting. Because of this methodology, these points were not usable in this study as they couldn't be matched to an exact point on a satellite image.

The inventory of landslides for Rwanda was built using visual interpretation of high resolution remote sensing images from 2000–2015. 2000 was chosen as the start year because at the time of this study, Google Earth contained no images for Rwanda before that date. As the spectral characteristics of landslides can be similar to other objects, like exposed rocks, roads, and settlements, a visual interpretation method is preferable to a fully automated information extraction method (Xu 2015). Of the 254 total points, the remaining 202 were selected this way (Ballard, 2015).

For logistic regression purposes (section 3.3.2) I generated not-landslide points within the AOI, semi-randomly. Based on the work of Dai et al. (2003) and Koutsias et al. (1998), the sampling size for this set was approximately the same as the landslide points set. I produced these points by importing the Google Earth kml file for the landslide inventory into ArcMap, building a 2km buffer around each landslide point, and erasing study area contained in that buffer layer. Using the tool “Create Random Points” I created points over the remaining area of the AOI. These points then had to be imported into Google Earth and visually inspected; I discarded any points located within landslides, bodies of water, and cloudy or otherwise obscured areas. The first 253 of the remaining not-landslide points were retained.

*3.2.2 Focused Study Mapping*

For this study, I mapped all landslides that could be recognized at an eye altitude of approximately 1830 meters from the currently available satellite images, starting from my existing landslide inventory of Rwanda and adding additional points by locating patches of exposed soil in landslide scars and runout tracks (Figure 6). Similar to the General Study (Section 3.2.1) I built this inventory using visual interpretation of high resolution remote sensing images. To ensure no regions of the study area were overlooked, I used a grid overlay on the study area. I outlined each landslide with a polygon so that the area could be calculated (Figure 7) (see section 4.2 below).


*Figure 7. Example of polygons marking landslides in Google Earth. Each area identified as a landslide scar is outlined with a polygon to approximate the shape and area covered by the slide. Largest landslide is about 181 meters across, and 170 meters top to bottom*

## 3.3 Analysis

### *3.3.1 General Study*

I completed a general study of landslide hazards in Rwanda in August 2015, with the assistance of SERVIR, a joint development initiative of the National Aeronautics and Space Administration (NASA) and the United States Agency for International Development (USAID). This study focused on the development of a landslide inventory and a statistical methodology for assessing landslide hazards. Using logistic regression on 23 test variables (Table 1) and a sample of over 254 landslides, I determined which variables were statistically most relevant to landslide occurrence in Rwanda.

I derived thirteen of the variables from SRTM (Shuttle Radar Topography Mission-generated DEMs (Digital Elevation Models) and tested them at both 30 meter and 90-meter resolution. The source for the 90 meter DEM is CGIAR, and the 30 meter DEM was collected from LPDAAC. As most previous research would have been completed with a 90 meter DEM, both 30 meter and 90 meter were used in this study to see if 30 meter data universally provided a superior regression result. Potentially influential variable ideas were drawn from the literature review, including Dai and Lee (2002), Dai et al. (2002), van Westen (2006), and Anderson (2012). All datasets were projected to WGS84 UTM35S.

The remaining 10 variables were collected from sources such as the Regional Centre for Mapping of Resources for Development (RCMRD), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), the Consultative Group for International Agricultural Research (CGIAR), and the Rwandan government. All datasets were projected to WGS84 UTM35S (Ballard 2015).

*3.3.2 Logistic regression*

Logistic regression is useful for finding the relationship between a list of independent variables and a binary dependent variable (Dai and Lee 2002). In this case the dependent variable is presence of a landslide (0 = no, 1 = yes) and the independent variables are the variables selected and researched for each landslide point (Table 1). A Logistic Regression method pairs well with a geospatial (GIS) methodology. A statistical method, combined with landslide inventory maps, may provide the best risk assessment for the available input data over larger areas (van Westen 2006).

The logistic regression test will show which variable is the most significant for predicting landslides in Rwanda. A statistical approach is based on the assumption that landslides are likely to occur under the same conditions as those which the occurred in the recent past (vanWesten et al. 2006).

The general form of a logistic regression equation is

$$Y = Ax_1 + Bx_2 + Cx_3 + \cdots Zx_n \, , \tag{1}$$

where $x_1$, $x_2$, $x_3$, … $x_n$ are the collected variable values for each landslide, and A, B, C … Z are the coefficients calculated for all landslide points.

*Table 1. Twenty-Three variables used for Logistic Regression.*

| | |
|---|---|
| 30 year rainfall | Land Cover |
| Aspect* | Lithology |
| Curvature(overall)* | Population Density |
| Curvature (plan)* | Slope* |
| Curvature(profile)* | Soil Moisture |
| Distance from Populated Area | Soil Type |
| Distance to Fault | Sediment Power Index* |
| Distance to Road | Sediment Transport Index* |
| Drainage Density* | Surface Roughness* |
| Earthquake Hazard (PGA) | Topographic Wetness Index* |
| Elevation* | Vertical Distance to Drainage* |
| Horizontal Distance to Drainage* | |

*Note: Thirteen variables with * are SRTM DEM derived and were tested at both 30 meter and 90 meter resolution.*

I collected values for each variable for each landslide point using Multi Values to Points and Spatial Join tools in ArcMap. Values were compiled in Excel, then imported into the statistics program for logistic regression testing.

The logistic regression calculations were produced using the statistics program MYSTAT, a student version of SYSTAT. This program was chosen for its graphical user interface and low cost (free). First, a correlation check is performed. A “Pearson’s product moment correlation coefficient” method was used. Correlation is calculated by dividing the covariance of two variables by the product of their standard deviations (SYSTAT 2007). Any variables with correlations of 0.5 or higher are not run in combination with each other.

Using MYSTAT, I tested all variables, one at a time. A binary dependent variable called "Landslide", with a value of 0 for no landslide and 1 for yes, landslide, was tested along with a constant and each of the 23 independent variables. This compares the performance, and informs future decisions of which variables to pair. Next, variables are run in pairs of two. Again, a binary dependent variable is set equal to the constant and independent variables, and coefficients are calculated. The metrics I used to measure statistical significance are Akaike Information Criterion (AIC), p-value, McFadden's Rho-squared, and Area under the Receiver Operating Characteristic (ROC Curve). McFadden's Rho-squared was used as the main indicator of quality, and remaining metrics were used to break any "ties".

The coefficients for the variables with the best statistical significance were inserted into Equation 1 to produce the model for landslide hazard. Coefficients represent the change in logit of each unit change in predictor (SYSTAT 2007).

I produced a hazard map using the coefficients for the variables selected from the Logistic Regression. The layers for the variables selected as "best" (highest McFadden's Rho-squared) were opened in ArcMap, and converted to raster files. I used the tool "Raster Calculator" to build a new layer using the model found in the logistic regression. In order to create a map with values for each pixel ranging from 0 to 1, the values must be normalized, using the equation

$$\frac{e^{[logistic\ regression\ model]}}{1+e^{[logistic\ regression\ model]}} \qquad (2)$$

This transformation is more thoroughly described by Peng et al (2002) in Anderson (2012). A pixel value of 0 means low hazard, and 1 means very high hazard. "Low" "Medium" and "High" categories were assigned evenly to resulting values.

*3.3.3 Accuracy Test*

A logistic regression model is of little use without a metric for its accuracy. To this end, thirty percent of all points, landslide and not-landslide, were selected randomly and withheld from the logistic regression tests. This set is the “reference set”. These points were not used in the logistic regression test; instead I used them to assess the accuracy of the model built using the remaining 70%- the “response set”. The 152 points in the reference set and the hazard map were opened in ArcMap, and the “Extract Values to Points” tool was used to check the calculated hazard value for each point. Values of 0.5 and greater were considered to be landslides, and values less than 0.5 were considered to be non-landslides.

*3.3.4 Focused Landslide Study*

I downloaded TRMM precipitation data from REVERB for all dates available (1/1/1998–5/2/2015). TRMM data is provided as binary files containing data from 50 N to 50 S latitude. I developed a MATLAB script to interpret the TRMM files and pull out specifically the data for my study area (Appendix). Since the high landslide density area spans 4 different TRMM grid squares, I pulled data for each pixel and combined it using a weighted average (Figure 5). I designed the script to combine the thousands of individual daily files into one array, calculated the recurrence interval and exceedance probability of storms with a given total precipitation amount, and generated time series and recurrence interval plots.

To produce a recurrence interval, each precipitation value must be given a rank, in order from largest to smallest. If n represents the number of measurements, the formula is

$$recurrance\ interval = 100 * \frac{rank}{n+1}\ . \tag{3}$$

The formula for exceedance probability is

$$exceedance\ probability = \frac{n+1}{rank}\ . \tag{4}$$

The nearby TRMM grid square with a low density of landslides, but otherwise similar to the main study area was identified for comparison. I ran the script to generate time series and storm recurrence interval plots for this region as well. ArcGIS was used to calculate area of each slide, and total landslide density for the study area.

## 4 Results and Discussion

### *4.1 General Study Results*

The pair of variables that significantly predicted locations of slope failures was slope (calculated with a 30-meter resolution SRTM DEM) and population density (2002). In general, the 30 meter DEM variables consistently performed better than the 90 meter DEM variables. The slope and population density pair have a McFadden's $R^2$ of 0.388. McFadden's $R^2$ ranges from 0 to 1, with a higher value indicating more significant results. A McFadden's $R^2$ value between 0.2 and 0.4 is very satisfactory (SYSTAT 2007). The logistic regression equation found for these two variables was

$$Y = -4.639061 + (10.030704 * Slope30) + (0.003977 * PopDen). \qquad (5)$$

I used the "reference set" of points to assess the accuracy of the model built using the "response set". There were more false positives than false negatives, which means most error is on the side of over-predicting landslides. The overall accuracy, determined by cross-validation, was 79.6% (Table 2).

| | | Predicted | | Total | Correctly Classified |
|---|---|---|---|---|---|
| | | Yes | No | | |
| Observed | Yes | 67 | 12 | 79 | **84.8%** |
| | No | 19 | 54 | 73 | **74.0%** |
| Total | | 86 | 66 | 152 | |
| Overall | | | | | **79.6%** |

*Table 2. Accuracy assessment for hazard map built using slope and population density (Piller 2015). Values in table are the total number of landslides in each category.*

I produced a preliminary predictive hazard map for Rwanda using equation (5) (Figure 8). Although population is represented in the hazard map, this does not become an assessment of risk to population or property. Population density is included in the map because it was a significant result in the logistic regression, which suggests that some aspect of human presence is related to landslide occurrence in Rwanda. The map shows a high hazard in the area surrounding Kigali, which is the area that has the highest population density in Rwanda. The western part of the country that shows a high hazard is near the Albertine rift of the Great Rift Valley.

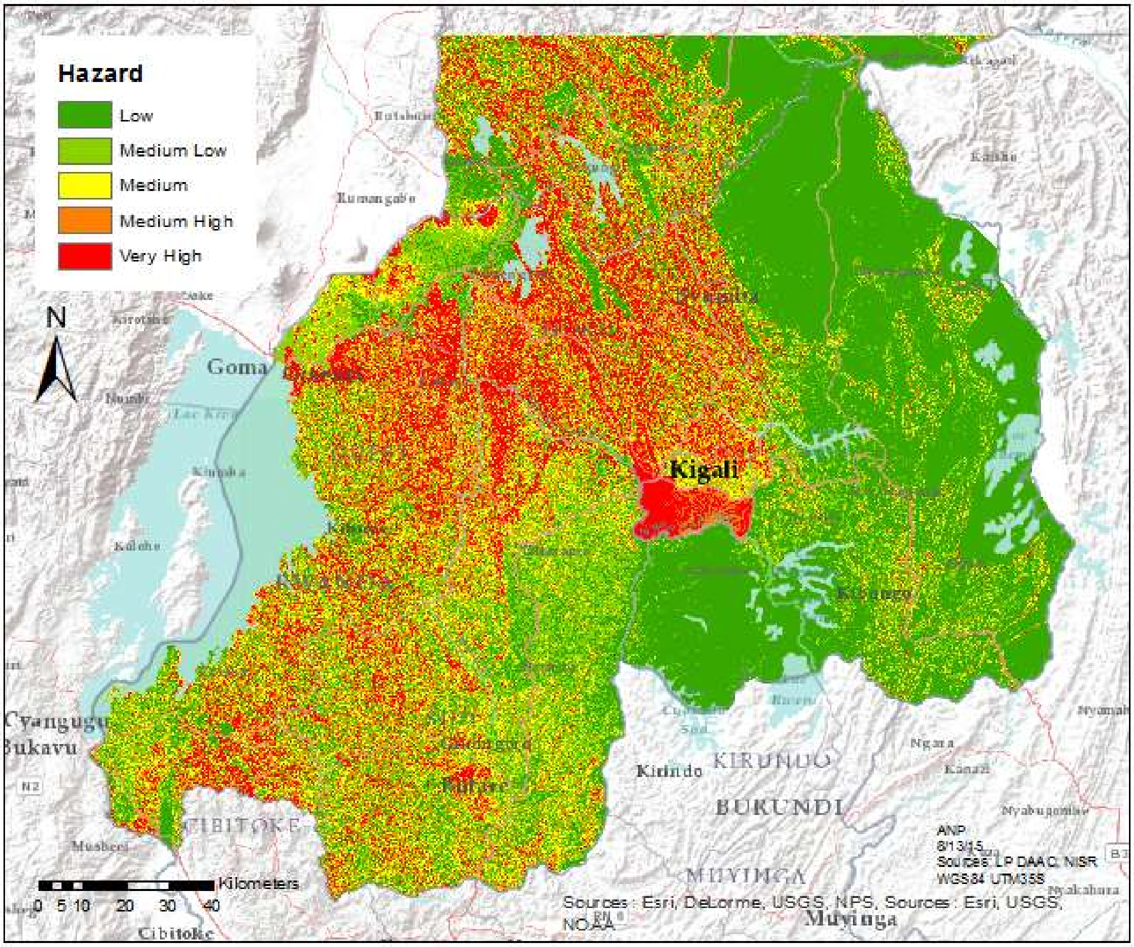


*Figure 8. Landslide Hazard Map for Rwanda, based on slope and population density (Piller 2015).*

### *4.1.2 General Study Discussion*

This hazard map, in the context of Rwanda's topography, seems reasonable. The areas marked as a very high hazard are in fact on steep hillsides or mountain tops. The larger green areas are flat plateaus. With a flat enough slope, sediment transport is minimal and can't really be considered a "landslide". It is not unexpected that slope would be found as a crucial variable in landslide prediction.

Human impact is significant, and also not entirely unexpected, as 90% of the country's landscape is anthropogenic. Much of this is farming, but small-scale mining is also impacting the environment through river bank ripping and landslides (Dusková 2014).

One large high hazard area is found in the area of Kigali, the capital city of Rwanda. The city has a high population, and it is difficult to observe landslides as they are quickly cleaned up, but large numbers of landslides are reported in this area, so it is reasonable to see this area marked as a high hazard.

There is a difference in data granularity between the two variables used to produce this hazard map (Figure 9). Population density was calculated per district, a relatively large political unit. Data is available to calculate this variable by smaller units, called cells, but it is unclear if this would lead to any change in accuracy of the hazard map without analyzing the calculated coefficients provided by the logistic regression tests.  Slope is at a 30 meter resolution, which is still much higher than population density, but using population cells will improve the overall granularity of the hazard map.

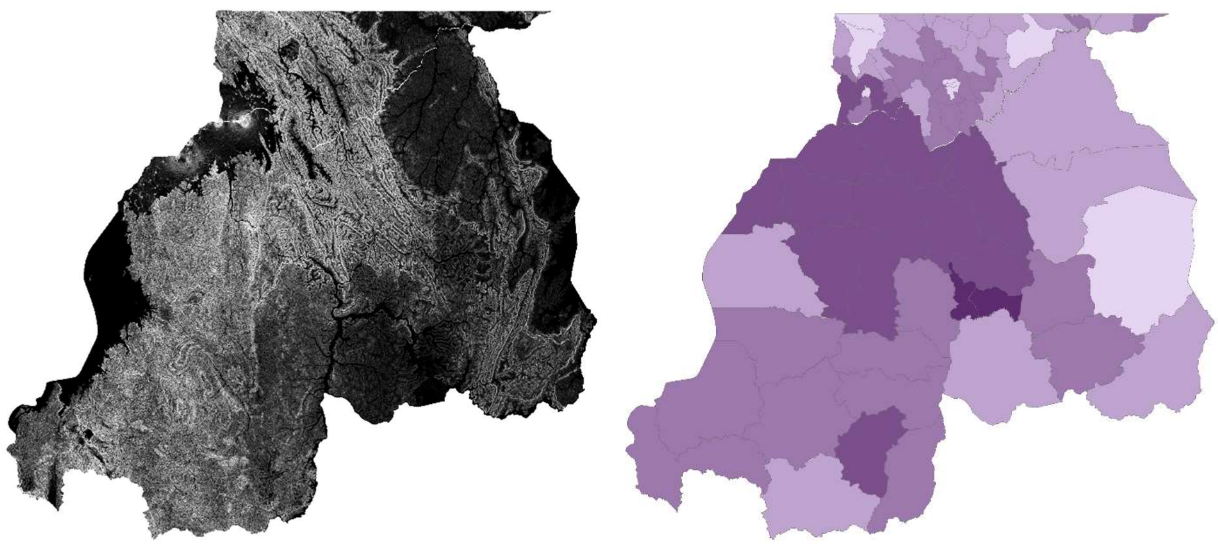

*Figure 9. Granularity Differences between Slope 30 meter (left) and Population Density 30 meter (right)*

Another spatial imprecision in this study may exist between the landslide points created in Google Earth and their respective locations on the DEM layers. Although all layers were projected to the same coordinate system, no analysis was performed to check the accuracy of locations. If possible, a coregistration process to ensure the layers were aligned would have helped. Another method to avoid error would be to use a 3 square sampling method when collecting the DEM-derived variable data- where the neighboring pixels around each landslide point are also sampled and averaged into the final value.

A solution to this would be crowd-sourcing the data collection. If a landslide reporting phone app or call-in number was made available to the public, GPS locations and times of landslides could be collected as they are observed. Another way to achieve this could be scraping social media, like Twitter, for references to landslides in Rwanda.

A statistical methodology does have some unique limitations. There is a tendency to simplify the factors of landslides, by only choosing variables that can be relatively easily mapped or derived from a DEM (van Westen 2006). In this study, 50+ variables were initially considered, but that list was narrowed due to keep the project within time constraints. Variables removed were duplicates by different names, variables that may have an unclear link to landslides, and variables that would be difficult to acquire or calculate data for. This leads to some bias in variable selection.

Another limitation is assuming that all landslides occur under the same combination of conditions throughout the study area (van Westen 2006). This is a tradeoff between doing a time consuming but highly specific set of studies and providing an estimate for a larger region. In this study, this limitation is offset by the relatively small area of Rwanda. Any detrimental error is checked for in the accuracy assessment step.

Lastly, precipitation is an important variable, but not appropriately addressed in this general study. Therefore, this was examined in the more focused landslide study.

*4.2 Focused Study Discussion*

TRMM data for 16 years plotted as a time series indicated a yearly pattern of intense precipitation events (Figure 11). Precipitation ranged from zero up to a maximum of approximately 68 mm/day in 2010 in the low landslide density part of the study area. The time series clearly show the seasonal pattern of rainfall with two broad rainy periods each year separated by periods of no or low precipitation (Figure 10). The time series for the low landslide density pixel has its five highest peaks in 2001, 2003, 2009, 2010, and 2012 (

Table 3).

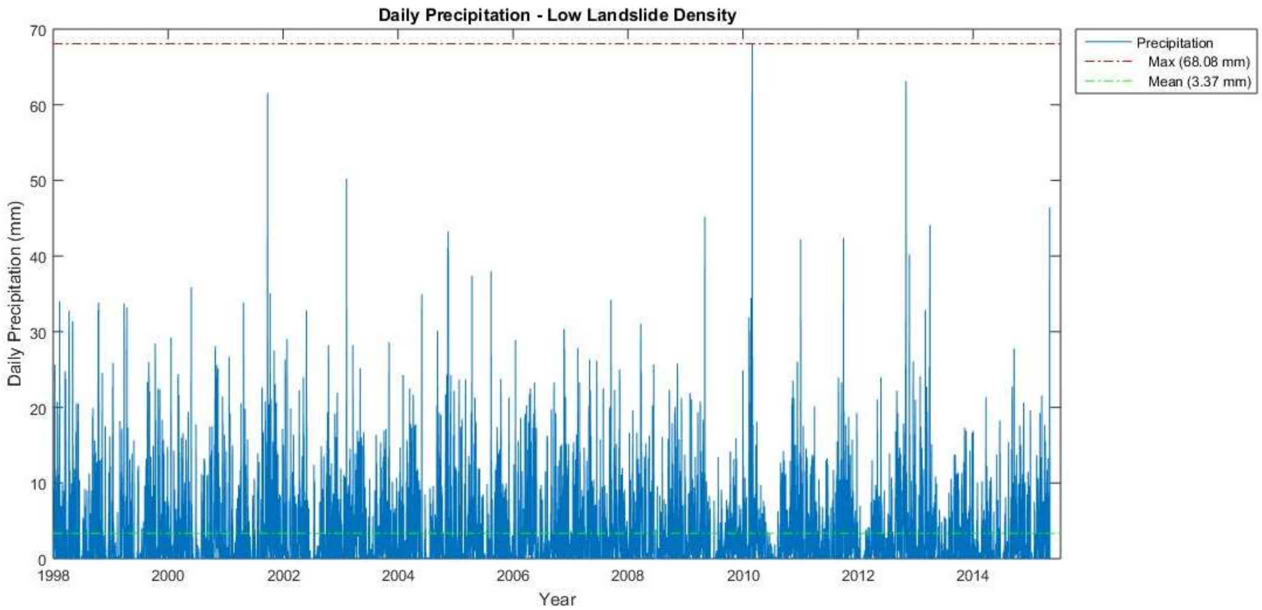


*Figure 10. Daily precipitation in Low Landslide Density study area- precipitation values in mm/day are shown for 16 years of available TRMM data. The maximum precipitation value was 68.08 mm/day (red dot-dashed line), and the mean was 3.37 mm/day (green dot-dashed line).*

In the high landslide density part of the study area, the precipitation ranged from zero up to a maximum of approximately 56 mm/day in 2001 (Figure 11). The seasonal pattern of rainy and dry seasons can again be seen. The time series for the high landslide density area has its five largest peaks in 1999, 2001, 2007, 2010, and 2013 (

Table 3).

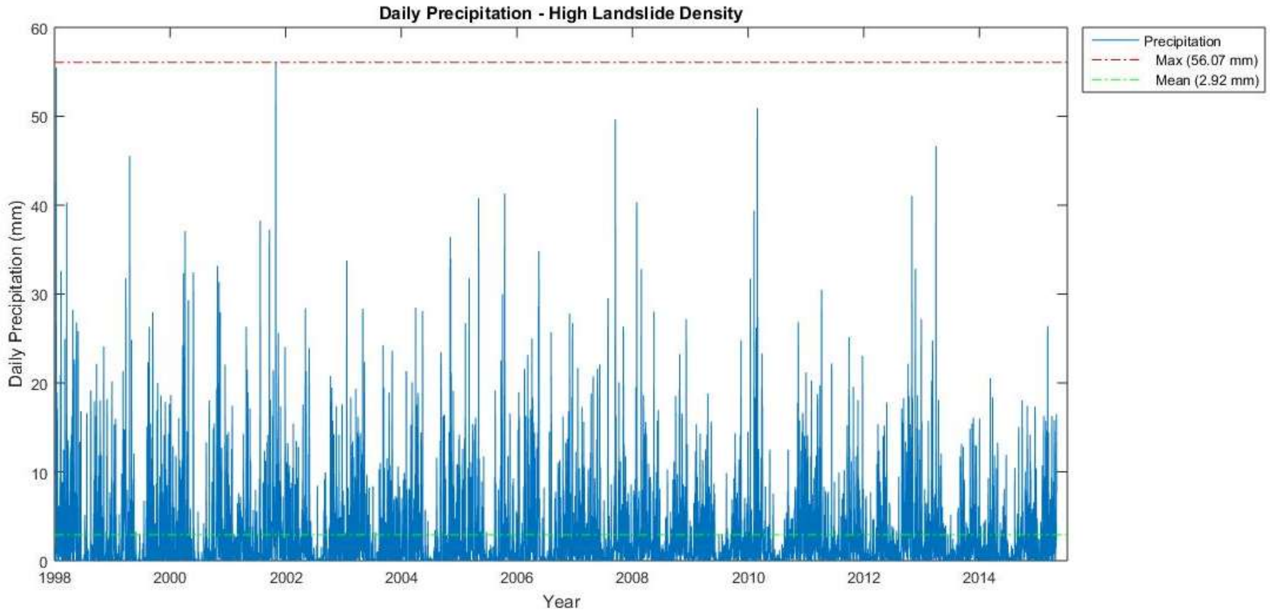


*Figure 11. Daily precipitation in the High Landslide Density study area - precipitation values in mm/day are shown for 16 years of available TRMM data. The maximum precipitation value was 56.07 mm/day (red dot-dashed line), and the mean was 2.93 mm/day (green dot-dashed line).*

*Table 3. Top five precipitation values for high and low landslide density areas*

| High Landslide Density | | |
|---|---|---|
| Date | Precipitation (mm/day) | Precipitation in Low Landslide Density Region on this day (mm/day) |
| 4/21/1999 | 45.53 | 17.34 |
| 10/30/2001 | 56.07 | 12.85 |
| 9/15/2007 | 49.65 | 34.25 |
| 2/28/2010 | 50.91 | 68.08 |
| 4/2/2013 | 46.62 | 44.13 |

| Low Landslide Density | | |
|---|---|---|
| Date | Precipitation (mm/day) | Precipitation in High Landslide Density Region on this day (mm/day) |
| 9/24/2001 | 61.54 | 13.04 |
| 2/8/2003 | 50.23 | 5.173 |
| 5/3/2009 | 45.21 | 7.58 |
| 2/28/2010 | 68.08 | 50.91 |
| 11/1/2012 | 63.12 | 41.05 |

The high landslide density region has precipitation peaks that don't match the peaks in the low landslide density region. The one peak they both have in common is 2/28/2010. To compare and see if there is a corresponding peak in landslide occurrence, I produced a plot of number of landslides per year (Figure 12). Landslides are classified by the year they were first observed in satellite imagery. This shows that the majority of landslides mapped occurred in 2014 or 2015, and a few in earlier years. There are large gaps in time where no landslides were mapped, and the peak precipitation dates in

Table 3 don't correlate to dates for landslides that were mapped. This is most likely because satellite imagery is not available for all years. Satellite data is not available for most of the years identified by TRMM as having a peak rainfall value.

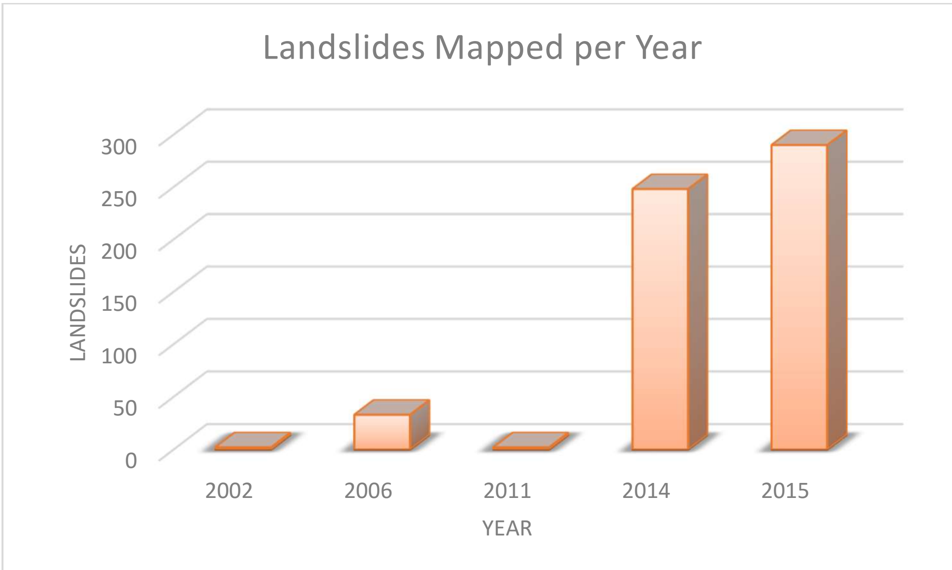


*Figure 12. Number of landslides mapped per year. Landslides are classified by the year they first appeared in satellite images. This means they occurred this year, or earlier. Years not shown either had no landslides, or no suitable satellite imagery available on Google Earth.*

The areas of mapped landslides range from 1 to 317,900 $m^2$. I split the areas of landslides into bins of 1000 $m^2$ size, and plotted the distribution on a log-log scale (Figure 13). Landslide areas generally ranged from 0 to 3500 $m^2$, with several extremely large (>100,000 $m^2$) slides. The data are approximately power-law distributed, which indicates that relatively rare but very large events may play an important role in setting the landslide erosion rate.

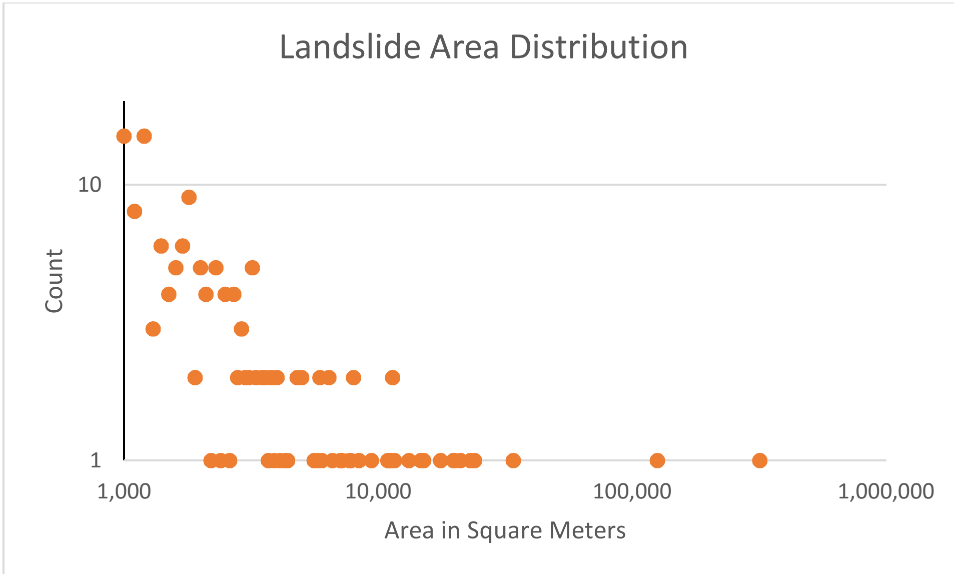


*Figure 13. Distribution of Landslide Area in square meters. 577 mapped landslides in the high density area are split into 1000 $m^2$ bins and plotted. The majority of landslides mapped are between 0 and 3500 $m^2$ in area and the largest landslide mapped is 317,900 $m^2$. The few extremely large landslides leads to a long tail distribution.*

In one more attempt to compare or contrast precipitation for the high density landslide area and the low landslide density area, I plotted precipitation versus recurrence interval for each region (Figure 14). The largest storm events for the high density and the low density regions occurred on different dates, and were a variety of sizes, but when the precipitation versus recurrence interval plots are shown on the same axis, it is clear that they are extremely similar. Despite the different dates for the storm events, the overall precipitation distribution is very similar for both the high density and low density regions.

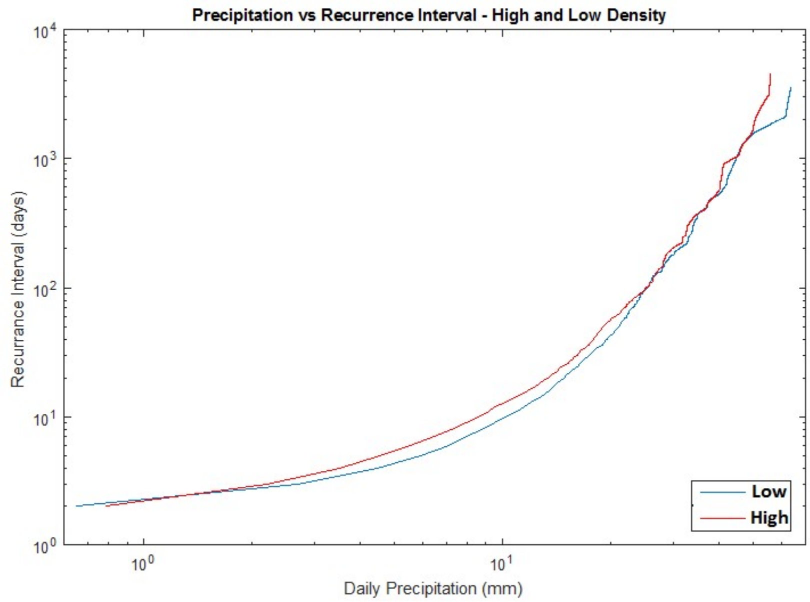


*Figure 14 Recurrence Interval vs. precipitation for low and high landslide density areas. Despite the fact that dates for storms were different, the overall precipitation pattern for the two regions is very similar.*

### *4.3 Focused Study Discussion*

The high landslide density region and the low landslide density region are not notably different in rainfall- overall, the time series for both regions look very similar. A relationship between precipitation and landslide density was not developed and the null hypothesis cannot be ruled out. This apparent lack of connection could result from several aspects of the available data and nature of the study area.

First, perhaps the grid size (0.25° by 0.25°) for the TRMM data is too large for this type of study, and relevant rainstorms are going "unseen" as they are smaller than the grid. This would assume that concentrated weather events that are more likely to trigger landslides are smaller than 0.25° by 0.25° (approximately 780 $km^2$ in the study area). This is also a problem that Turner et al. (2010) encountered in their study of landslide densities in Washington state. The TRMM data was not sufficiently accurate to capture rainfall amounts for the landslides they studied. This could be addressed by finding a different source of rainfall data with a smaller spatial grid, designing and deploying a rain gage system, or by interpreting precipitation through other related variables, like type of groundcover or measuring soil moisture, which can be estimated remotely via NASA's Soil Moisture Active Passive (SMAP) mission. SMAP was not used for this study because the google earth images available covered (2006 – mid 2015) and SMAP data is only consistently available after November, 2015. Soil Moisture can also be approximated from surface temperature and vegetation index, which can in turn be sourced from satellite data (Holzman et al. 2014).

While the spatial grid for TRMM was larger than desired, the temporal resolution (daily) was excellent, much better than the satellite imagery currently available. In contrast to this, high resolution topographic data from techniques such as airborne LIDAR would be excellent spatially, but not sufficient temporally due to cost and logistical constraints.

Satellite imagery could also be affecting the results because the temporal resolution is approximately yearly to decadal. In this study area, there were no satellite images for the years in which peak rainfall occurred, so landslides triggered by those storms might not be visible in the more recent imagery. Most of the study area is in agricultural land, and landslide scars are often re-planted or otherwise obscured within a few years of the landslide. It is likely that landslides are being promptly cleaned up and vegetation quickly grows back over or is replanted in landslide areas. Some landslides will not show up on satellite imagery unless they were very recent. But not all landslides in Rwanda seem to act this way- some landslides continue to be visible in many years of satellite imagery.

Landslides mapped as occurring in 2014 or 2015 could have occurred in earlier years. This could be addressed by purchasing satellite imagery for specific years after analyzing the precipitation data for a study area.

Alternatively, an unconsidered factor could be more significant, such as antecedent soil moisture. This could be a reason why a landslide would not tie directly to a storm event, but instead lag after, or not be triggered until a second storm event.

A change in data quality, be it satellite imagery or mapping technique, could also be relevant. Some years of satellite imagery are very dark images, and some years are better resolution than others. A landslide is more likely to be spotted on a lighter image with higher contrast than a darker, low contrast image. Especially combined with questionable image quality, mapping bias can lead to a lower quality landslide inventory than field mapping, even when conducted by experts (Van Den Eeckhaut 2005).

**5 Conclusions and Implications**

Landslide hazard in Rwanda is largely dependent on the slope of the topography and anthropogenic factors. Considering only these two factors, landslide hazard can be predicted with about an 80% accuracy. Water plays a large role in landsliding in Rwanda, with high intensity precipitation events of 40-50 mm/day occurring annually. The specific mechanism of how water is triggering landsides is difficult to determine from freely available satellite imagery and precipitation data.

In general, the effects of landslides are more significant in Rwanda than they would be in another location, all other factors being the same. It is estimated that 90% of urban housing is met through “informal settlements”, cheap unplanned housing in inappropriate locations with steep slopes and poor drainage (UNEP 2011).

While a complete picture of precipitation for the country of Rwanda is not available, this focused study shows a relationship between storm size and widespread land sliding. Available data suggests Rwanda experiences irregular and unpredictable rainfall patterns. One predicted effect of climate change is an increase in the kind of extreme rainfall events that cause flooding and landslides (UNEP 2011). This means conditions will continue or worsen, and landslide hazard mapping and landslide prediction are more crucial now than ever.

There are processes in place to improve some of Rwanda's land management practices, including buffers on farming and building, moving populations from the most dangerous locations, and green practices. However, they are not well enforced, and it is a slow process to get these to a level where they make a difference. Environmental governance is strong, though, and good policies have been established- destructive flooding and landslides, droughts and food insecurity have not gone unnoticed. Decentralization of government has also allowed regional communities to have a larger voice in environmental governance (UNEP 2011)

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## Appendix A:  Landslide Inventory for Focused Study

## Appendix B:  Matlab Script

2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 1 | 2015 | 539.125661 | -2.028604 | 29.567261 | |
| 2 | 2015 | 236.92899 | -2.028811 | 29.567405 | |
| 3 | 2015 | 7173.678658 | -2.029197 | 29.567697 | |
| 4 | 2015 | 598.927618 | -2.029278 | 29.566756 | |
| 5 | 2015 | 101.168661 | -2.027119 | 29.567356 | |
| 6 | 2015 | 156.2059 | -2.028641 | 29.566082 | |
| 7 | 2015 | 412.203142 | -2.027925 | 29.566068 | |
| 8 | 2015 | 155.664567 | -2.028482 | 29.565933 | |
| 9 | 2015 | 470.428732 | -2.027105 | 29.566132 | |
| 10 | 2015 | 1239.082116 | -2.024025 | 29.566251 | |
| 11 | 2015 | 752.180507 | -2.022613 | 29.566691 | |
| 12 | 2015 | 260.168472 | -2.023064 | 29.566895 | |
| 13 | 2015 | 82.050746 | -2.023118 | 29.566462 | |
| 14 | 2015 | 7749.290889 | -2.022528 | 29.565684 | |
| 15 | 2015 | 979.297688 | -2.021347 | 29.565737 | |
| 16 | 2015 | 3491.979157 | -2.021154 | 29.565272 | |
| 17 | 2015 | 127.354558 | -2.026888 | 29.564455 | |
| 18 | 2015 | 370.341859 | -2.026109 | 29.565204 | |
| 19 | 2015 | 98.547386 | -2.025811 | 29.565282 | |
| 20 | 2015 | 958.141349 | -2.025754 | 29.566156 | |
| 21 | 2015 | 366.064807 | -2.026247 | 29.566239 | |
| 21 | 2015 | 150.628973 | -2.025573 | 29.566594 | |
| 22 | 2015 | 145.933746 | -2.025715 | 29.566726 | |
| 23 | 2015 | 3121.359719 | -2.026215 | 29.56739 | |
| 24 | 2015 | 2404.261381 | -2.025447 | 29.567275 | |
| 25 | 2015 | 241.29347 | -2.025809 | 29.570409 | |
| 26 | 2014 | 402.296679 | -2.020398 | 29.569499 | and 2015 |
| 27 | 2014 | 4911.71597 | -2.020845 | 29.569962 | and 2015 |
| 28 | 2015 | 340.814179 | -2.021666 | 29.570663 | |
| 29 | 2015 | 23955.18473 | -2.015543 | 29.572446 | |
| 30 | 2015 | 3750.092038 | -2.030634 | 29.567938 | |
| 31 | 2015 | 215.710425 | -2.030657 | 29.566253 | |
| 32 | 2015 | 1905.490242 | -2.005745 | 29.573828 | |
| 33 | 2015 | 334.369729 | -1.995215 | 29.561609 | |
| 34 | 2015 | 503.641659 | -1.994989 | 29.561811 | |
| 35 | 2015 | 49.288274 | -1.995527 | 29.561254 | |
| 36 | 2015 | 138.56606 | -2.042492 | 29.563964 | |
| 37 | 2015 | 807.248678 | -2.02933 | 29.579075 | |
| 38 | 2015 | 150.756345 | -2.023017 | 29.578714 | |
| 39 | 2015 | 163.136565 | -2.023379 | 29.579396 | |
| 40 | 2015 | 588.108088 | -2.01676 | 29.594005 | |
| 41 | 2015 | 3703.565082 | -2.010219 | 29.586061 | |
| 42 | 2014 | 2994.984557 | -2.000861 | 29.597718 | |
| 43 | 2014 | 5920.57838 | -2.000724 | 29.599124 | |
| 44 | 2014 | 317859.5599 | -1.998161 | 29.601806 | |
| 45 | 2014 | 187.609066 | -1.995767 | 29.602294 | |
| 46 | 2014 | 374.711407 | -1.995548 | 29.602255 | |
| 47 | 2014 | 1060.949284 | -1.995023 | 29.602124 | |
| 48 | 2014 | 782.913619 | -1.994352 | 29.601427 | |
| 49 | 2014 | 2081.693589 | -1.994341 | 29.60095 | |
| 50 | 2014 | 1116.876015 | -1.993782 | 29.60081 | |
| 51 | 2014 | 54.049036 | -1.993518 | 29.600686 | |
| 52 | 2014 | 129.379695 | -1.994046 | 29.600526 | |
| 53 | 2014 | 19745.47216 | -1.994342 | 29.597824 | |
| 54 | 2014 | 11360.22353 | -1.991121 | 29.59687 | |
| 55 | 2014 | 3557.685817 | -1.993077 | 29.598021 | |
| 56 | 2014 | 1006.398639 | -1.992961 | 29.599214 | |
| 57 | 2014 | 137.737199 | -1.992778 | 29.599361 | |
| 58 | 2014 | 174.967966 | -1.992548 | 29.599365 | |
| 59 | 2014 | 1679.961678 | -1.992288 | 29.597825 | |

2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 60 | 2014 | 11153.2399 | -1.988014 | 29.601006 | |
| 61 | 2014 | 258.999625 | -1.989334 | 29.59919 | |
| 62 | 2014 | 206.334238 | -1.988924 | 29.598896 | |
| 63 | 2014 | 398.5662 | -1.986035 | 29.600249 | |
| 64 | 2014 | 837.156768 | -1.985263 | 29.599853 | |
| 65 | 2014 | 2712.352529 | -1.987575 | 29.604423 | |
| 66 | 2014 | 419.967901 | -1.99309 | 29.60958 | |
| 67 | 2014 | 7038.60939 | -1.985195 | 29.596043 | |
| 68 | 2014 | 4902.299026 | -1.986652 | 29.596242 | |
| 69 | 2011 | 6382.690435 | -1.986382 | 29.597854 | and 2014 |
| 70 | 2014 | 3160.17886 | -1.995753 | 29.606446 | |
| 71 | 2014 | 1079.084765 | -2.017914 | 29.603753 | |
| 72 | 2014 | 222.529013 | -2.016622 | 29.597572 | |
| 73 | 2015 | 882.139249 | -2.024047 | 29.571281 | |
| 74 | 2015 | 849.17498 | -2.012795 | 29.570846 | |
| 75 | 2015 | 364.002969 | -2.011933 | 29.570538 | |
| 76 | 2014 | 6327.868677 | -2.011736 | 29.585698 | looks older |
| 77 | 2014 | 242.409995 | -2.043804 | 29.600785 | |
| 78 | 2014 | 1203.888111 | -2.041811 | 29.597189 | |
| 79 | 2014 | 186.955279 | -2.02385 | 29.615983 | |
| 80 | 2014 | 90.22386 | -2.023442 | 29.631857 | |
| 81 | 2014 | 288.902814 | -2.014284 | 29.624983 | |
| 82 | 2014 | 219.91366 | -2.015525 | 29.615917 | |
| 83 | 2014 | 28.262073 | -2.010895 | 29.631583 | |
| 84 | 2014 | 275.071084 | -1.997739 | 29.628861 | |
| 85 | 2014 | 274.121166 | -2.002926 | 29.628007 | |
| 86 | 2014 | 11372.40679 | -1.978833 | 29.617738 | |
| 87 | 2014 | 1188.482634 | -1.986394 | 29.631285 | |
| 88 | 2014 | 208.710596 | -1.990926 | 29.623742 | |
| 89 | 2014 | 91.980959 | -1.987616 | 29.579747 | |
| 90 | 2014 | 146.078996 | -1.987051 | 29.580088 | |
| 91 | 2014 | 79.661488 | -1.986736 | 29.579655 | |
| 92 | 2014 | 115.741526 | -1.986621 | 29.579734 | |
| 93 | 2014 | 81.571111 | -1.98645 | 29.57978 | |
| 94 | 2014 | 142.05696 | -1.983741 | 29.590187 | |
| 95 | 2014 | 2646.215047 | -1.980184 | 29.595329 | |
| 96 | 2014 | 410.084362 | -1.975975 | 29.562988 | |
| 97 | 2015 | 955.593252 | -1.976266 | 29.572052 | |
| 98 | 2015 | 921.003641 | -1.97652 | 29.572191 | |
| 99 | 2015 | 339.437331 | -1.979397 | 29.570507 | |
| 100 | 2015 | 61.290744 | -1.987839 | 29.574214 | |
| 101 | 2015 | 481.844741 | -1.988456 | 29.562708 | |
| 102 | 2015 | 60.047511 | -1.948026 | 29.571985 | |
| 103 | 2015 | 671.503334 | -1.945951 | 29.563657 | |
| 104 | 2015 | 483.186676 | -1.986251 | 29.56182 | |
| 105 | 2015 | 289.396923 | -1.986721 | 29.561509 | |
| 106 | 2015 | 405.810595 | -1.957717 | 29.56801 | |
| 107 | 2015 | 230.726429 | -1.981198 | 29.559253 | |
| 108 | 2015 | 366.79361 | -1.98126 | 29.5594 | |
| 109 | 2014 | 686.402283 | -2.020783 | 29.551611 | |
| 110 | 2014 | 593.272197 | -2.020512 | 29.551856 | |
| 111 | 2014 | 83.764581 | -2.020492 | 29.552039 | |
| 112 | 2014 | 33903.72826 | -2.018671 | 29.550718 | |
| 113 | 2014 | 517.973992 | -2.019297 | 29.55173 | |
| 114 | 2014 | 182.935514 | -2.019177 | 29.551393 | |
| 115 | 2015 | 541.667011 | -2.020133 | 29.550615 | |
| 116 | 2014 | 417.878769 | -2.022123 | 29.54816 | |
| 117 | 2014 | 195.691399 | -2.022016 | 29.547613 | |
| 118 | 2014 | 163.44081 | -2.0279 | 29.55275 | |
| 119 | 2014 | 56.396134 | -2.028366 | 29.550329 | |

# 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
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| 120 | 2014 | 69.421082 | -2.02792 | 29.548657 | |
| 121 | 2015 | 55.959335 | -2.028083 | 29.545502 | |
| 122 | 2014 | 8330.70205 | -2.003462 | 29.551113 | |
| 123 | 2015 | 3001.350495 | -2.002717 | 29.549532 | |
| 124 | 2015 | 5761.418147 | -1.995628 | 29.543946 | |
| 125 | 2015 | 116.832083 | -1.993027 | 29.555298 | |
| 126 | 2015 | 161.624913 | -1.993237 | 29.554903 | |
| 127 | 2015 | 2008.649055 | -1.989672 | 29.556741 | |
| 128 | 2015 | 133.796854 | -1.985351 | 29.552441 | |
| 129 | 2015 | 279.366336 | -1.990169 | 29.556005 | |
| 130 | 2015 | 1170.315411 | -2.029867 | 29.55428 | |
| 131 | 2015 | 251.392124 | -2.044639 | 29.546596 | |
| 132 | 2015 | 165.157855 | -2.044705 | 29.546805 | |
| 133 | 2014 | 53.760219 | -1.971352 | 29.603501 | |
| 134 | 2014 | 935.375833 | -1.970043 | 29.602345 | |
| 135 | 2014 | 3418.383439 | -1.973088 | 29.592634 | |
| 136 | 2014 | 302.245021 | -1.969709 | 29.591746 | |
| 137 | 2014 | 1127.441854 | -1.969826 | 29.584354 | |
| 138 | 2014 | 500.374535 | -1.969039 | 29.584828 | |
| 139 | 2014 | 196.756307 | -1.97023 | 29.583747 | |
| 140 | 2014 | 254.831315 | -1.96897 | 29.58705 | |
| 141 | 2014 | 102.068382 | -1.961704 | 29.589933 | |
| 142 | 2014 | 94.328078 | -1.961785 | 29.589517 | |
| 143 | 2014 | 77.235774 | -1.960148 | 29.58752 | |
| 144 | 2015 | 58.994851 | -1.973214 | 29.573503 | |
| 145 | 2015 | 38.088711 | -1.973013 | 29.573021 | |
| 146 | 2015 | 311.305763 | -1.972987 | 29.572761 | |
| 146 | 2015 | 159.173148 | -1.973601 | 29.573527 | |
| 147 | 2015 | 75.858663 | -1.973473 | 29.572954 | |
| 148 | 2015 | 278.871881 | -1.973071 | 29.574211 | |
| 149 | 2015 | 39.717911 | -1.972997 | 29.574483 | |
| 150 | 2015 | 24.219851 | -1.973964 | 29.574352 | |
| 151 | 2015 | 367.073588 | -1.974176 | 29.560112 | |
| 152 | 2015 | 17556.65862 | -1.970569 | 29.571383 | |
| 153 | 2015 | 2421.225191 | -1.971306 | 29.571958 | |
| 154 | 2015 | 1116.691313 | -1.969731 | 29.572507 | |
| 155 | 2015 | 535.684134 | -1.961405 | 29.564043 | |
| 156 | 2015 | 1379.988312 | -1.960294 | 29.559823 | |
| 157 | | 3835.550238 | -1.966124 | 29.563321 | |
| 158 | 2015 | 164.353425 | -1.970446 | 29.577743 | |
| 159 | 2015 | 1103.687889 | -1.965997 | 29.56153 | |
| 160 | 2015 | 416.12872 | -1.965552 | 29.561771 | |
| 161 | 2014 | 106.31558 | -1.965132 | 29.562204 | |
| 162 | 2014 | 55.332253 | -1.965052 | 29.562269 | |
| 163 | 2015 | 140.477296 | -1.97261 | 29.561389 | |
| 164 | 2011 | 464.6711 | -1.968434 | 29.573069 | |
| 165 | 2015 | 3237.485948 | -1.968694 | 29.572547 | |
| 166 | 2014 | 104.614529 | -1.973731 | 29.576443 | |
| 167 | 2015 | 266.125595 | -1.969981 | 29.558052 | |
| 168 | 2014 | 1063.445038 | -1.95709 | 29.556319 | |
| 169 | 2015 | 380.510031 | -1.960515 | 29.553468 | |
| 170 | 2015 | 3913.923582 | -1.960605 | 29.549378 | |
| 171 | 2015 | 10853.81551 | -1.959665 | 29.547435 | |
| 172 | 2015 | 345.17444 | -1.966785 | 29.54486 | |
| 173 | 2014 | 318.261618 | -1.972543 | 29.544234 | |
| 174 | 2014 | 202.295597 | -1.96859 | 29.629105 | |
| 175 | 2014 | 517.040137 | -1.961937 | 29.614611 | |
| 176 | 2014 | 3693.617387 | -1.950651 | 29.629595 | |
| 177 | 2014 | 804.488433 | -1.951992 | 29.630107 | |
| 178 | 2014 | 2643.375677 | -1.94813 | 29.630305 | |

## 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 179 | 2014 | 1118.563813 | -1.947189 | 29.629646 | |
| 180 | 2014 | 424.218704 | -1.945318 | 29.628429 | |
| 181 | 2014 | 1842.7764 | -1.942029 | 29.629555 | |
| 182 | 2014 | 1022.794403 | -1.943939 | 29.623732 | |
| 183 | 2014 | 2657.469544 | -1.944103 | 29.623343 | |
| 184 | 2014 | 3181.018412 | -1.939789 | 29.619363 | |
| 185 | 2014 | 331.333423 | -1.952423 | 29.629762 | |
| 186 | 2014 | 34.578089 | -1.950882 | 29.630771 | |
| 187 | 2014 | 7901.20508 | -1.951228 | 29.631299 | |
| 188 | 2014 | 1461.951946 | -1.948603 | 29.629795 | |
| 189 | 2014 | 1924.640936 | -1.949052 | 29.629212 | |
| 190 | 2014 | 766.391059 | -1.949368 | 29.629897 | |
| 191 | 2014 | 466.288782 | -1.95009 | 29.629719 | |
| 192 | 2014 | 1538.396146 | -1.947552 | 29.631556 | |
| 193 | 2014 | 652.634989 | -1.951171 | 29.630044 | |
| 194 | 2014 | 21028.34379 | -1.934442 | 29.619138 | |
| 195 | 2014 | 125525.4435 | -1.931336 | 29.615723 | |
| 196 | 2014 | 15004.10663 | -1.936787 | 29.615972 | |
| 197 | 2014 | 2228.512631 | -1.937466 | 29.615378 | |
| 198 | 2014 | 425.642936 | -1.931918 | 29.626058 | |
| 199 | 2014 | 380.518819 | -1.930748 | 29.626451 | |
| 200 | 2014 | 14631.8474 | -1.9231 | 29.61764 | |
| 201 | 2014 | 6598.713412 | -1.927926 | 29.61345 | |
| 202 | 2014 | 3926.978541 | -1.927181 | 29.624886 | |
| 203 | 2014 | 3045.763948 | -1.930933 | 29.611428 | |
| 204 | 2014 | 23051.82421 | -1.928799 | 29.611941 | |
| 205 | 2014 | 19984.17262 | -1.928449 | 29.605938 | |
| 206 | 2014 | 511.326528 | -1.92608 | 29.605865 | |
| 207 | 2014 | 5839.381044 | -1.926893 | 29.605043 | |
| 208 | 2014 | 357.686759 | -1.9276 | 29.60337 | |
| 209 | 2014 | 397.970054 | -1.934871 | 29.601179 | |
| 210 | 2014 | 169.029695 | -1.934751 | 29.601885 | |
| 211 | 2014 | 2433.254153 | -1.929898 | 29.607507 | |
| 212 | 2014 | 125.508961 | -1.939213 | 29.602976 | |
| 213 | 2014 | 189.46336 | -1.946405 | 29.599424 | |
| 214 | 2014 | 333.904189 | -1.949338 | 29.61025 | |
| 215 | 2014 | 345.351893 | -1.948329 | 29.611715 | |
| 216 | 2014 | 1360.284355 | -1.952226 | 29.591595 | |
| 217 | 2014 | 182.532463 | -1.952554 | 29.592902 | |
| 218 | 2014 | 129.748988 | -1.952071 | 29.593078 | |
| 219 | 2014 | 68.376285 | -1.95348 | 29.594979 | |
| 220 | 2014 | 52.31525 | -1.954334 | 29.594641 | |
| 221 | 2014 | 408.767932 | -1.953513 | 29.58303 | |
| 222 | 2014 | 967.084138 | -1.944887 | 29.580053 | |
| 223 | 2014 | 249.818388 | -1.945 | 29.579721 | |
| 224 | 2014 | 287.728802 | -1.94416 | 29.579256 | |
| 225 | 2015 | 244.184012 | -1.948218 | 29.554231 | |
| 226 | 2015 | 148.241621 | -1.948423 | 29.55486 | |
| 227 | 2015 | 278.531882 | -1.948247 | 29.554592 | |
| 228 | 2015 | 254.427562 | -1.949253 | 29.55396 | |
| 229 | 2015 | 104.358936 | -1.950525 | 29.548874 | |
| 230 | 2015 | 248.714336 | -1.94959 | 29.548698 | |
| 231 | 2015 | 206.972095 | -1.941106 | 29.553324 | |
| 232 | 2015 | 117.504318 | -1.94004 | 29.549636 | |
| 233 | 2015 | 285.230034 | -1.954609 | 29.558323 | |
| 234 | 2014 | 165.762635 | -1.921788 | 29.595688 | |
| 235 | 2014 | 118.251375 | -1.92172 | 29.586809 | |
| 236 | 2014 | 1649.76438 | -1.922256 | 29.581737 | |
| 237 | 2014 | 230.322939 | -1.923687 | 29.588591 | |
| 238 | 2015 | 1785.415614 | -1.926219 | 29.556624 | |

# 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 239 | 2015 | 243.854758 | -1.934618 | 29.550806 | |
| 240 | 2015 | 2257.907811 | -1.926135 | 29.545565 | |
| 241 | 2014 | 499.160516 | -1.927891 | 29.544089 | |
| 242 | 2015 | 551.937905 | -1.952436 | 29.534598 | |
| 243 | 2015 | 258.406974 | -1.945501 | 29.532606 | |
| 244 | 2015 | 205.043275 | -1.94507 | 29.532587 | |
| 245 | 2015 | 182.13322 | -1.941302 | 29.527643 | |
| 246 | 2015 | 170.735336 | -1.941448 | 29.527199 | |
| 247 | 2015 | 524.150682 | -1.943583 | 29.531268 | |
| 248 | 2015 | 782.811801 | -1.943409 | 29.531906 | |
| 249 | 2015 | 473.523064 | -1.958725 | 29.536872 | |
| 250 | 2006 | 939.678098 | -1.967937 | 29.52956 | |
| 251 | 2015 | 342.923118 | -1.987427 | 29.526731 | |
| 252 | 2015 | 1596.24338 | -1.988968 | 29.524876 | |
| 253 | 2015 | 315.817866 | -1.989449 | 29.52448 | |
| 254 | 2015 | 2800.993294 | -1.990338 | 29.527267 | |
| 255 | 2014 | 1120.871876 | -2.000898 | 29.524492 | |
| 256 | 2014 | 312.803742 | -2.000767 | 29.52973 | |
| 257 | 2014 | 1305.665583 | -2.00358 | 29.531188 | |
| 258 | 2014 | 2144.177686 | -1.996912 | 29.516948 | |
| 259 | 2014 | 1109.364765 | -1.995266 | 29.516117 | |
| 260 | 2014 | 1317.46621 | -1.994995 | 29.515512 | |
| 261 | 2014 | 925.05476 | -1.995231 | 29.514696 | |
| 262 | 2014 | 156.320653 | -1.994945 | 29.514546 | |
| 263 | 2014 | 88.887598 | -1.994709 | 29.514107 | |
| 264 | 2014 | 133.705865 | -1.994554 | 29.513946 | |
| 265 | 2014 | 198.708423 | -1.995111 | 29.519441 | |
| 266 | 2014 | 444.213186 | -1.994776 | 29.519075 | |
| 267 | 2014 | 277.028711 | -1.977531 | 29.506472 | |
| 268 | 2014 | 371.544646 | -1.977497 | 29.507078 | |
| 269 | 2014 | 3248.663068 | -1.978027 | 29.507219 | |
| 270 | 2014 | 156.307791 | -1.978611 | 29.5077 | |
| 271 | 2014 | 108.757982 | -1.977598 | 29.507411 | |
| 272 | 2014 | 371.635227 | -1.977372 | 29.507421 | |
| 273 | 2014 | 226.740514 | -1.982353 | 29.518871 | |
| 274 | 2014 | 486.01856 | -1.982423 | 29.518186 | |
| 275 | 2015 | 158.592207 | -1.981476 | 29.518222 | |
| 276 | 2015 | 292.822712 | -1.981315 | 29.517969 | |
| 276 | 2014 | 298.855258 | -1.987775 | 29.515794 | |
| 277 | 2014 | 782.09506 | -1.987548 | 29.515358 | |
| 278 | 2006 | 1165.994316 | -1.993158 | 29.515035 | |
| 279 | 2015 | 840.733078 | -1.99255 | 29.514008 | |
| 280 | 2006 | 1614.474759 | -1.992125 | 29.513653 | |
| 281 | 2014 | 1492.704673 | -1.974994 | 29.514576 | |
| 282 | 2014 | 712.679054 | -1.975226 | 29.512767 | |
| 283 | 2014 | 446.738436 | -1.975388 | 29.512483 | |
| 284 | 2014 | 535.3022 | -1.975174 | 29.51193 | |
| 285 | 2006 | 1354.308259 | -1.974861 | 29.511847 | |
| 286 | 2014 | 1544.899104 | -1.974948 | 29.509642 | |
| 287 | 2014 | 610.245315 | -1.97407 | 29.508123 | |
| 288 | 2014 | 990.484549 | -1.973644 | 29.509062 | |
| 289 | 2014 | 368.068548 | -1.973511 | 29.509984 | |
| 290 | 2014 | 271.599729 | -1.973971 | 29.509973 | |
| 291 | 2006 | 208.668999 | -1.973198 | 29.50928 | |
| 292 | 2006 | 1625.122674 | -1.972498 | 29.507918 | |
| 293 | 2014 | 174.852604 | -1.956254 | 29.508804 | |
| 294 | 2014 | 38.194644 | -1.956033 | 29.50873 | |
| 295 | 2015 | 201.360646 | -1.956442 | 29.508848 | |
| 296 | 2014 | 1091.533215 | -1.955917 | 29.522273 | |
| 297 | 2014 | 359.47004 | -1.952527 | 29.523998 | |

# 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 298 | 2014 | 807.775875 | -1.951494 | 29.524747 | |
| 299 | 2015 | 284.340715 | -1.950265 | 29.529878 | |
| 300 | 2015 | 593.272852 | -1.950898 | 29.521911 | |
| 301 | 2015 | 688.134189 | -1.946967 | 29.51573 | |
| 302 | 2014 | 4702.033219 | -1.947106 | 29.518861 | |
| 303 | 2014 | 965.062276 | -1.947995 | 29.521357 | |
| 304 | 2015 | 481.803568 | -1.945251 | 29.519911 | |
| 305 | 2014 | 604.008676 | -1.941024 | 29.516105 | |
| 306 | 2014 | 423.369136 | -1.939286 | 29.513797 | |
| 307 | 2014 | 119.027206 | -1.940154 | 29.513697 | |
| 308 | 2015 | 169.704348 | -1.941981 | 29.513231 | |
| 309 | 2014 | 574.551038 | -1.946019 | 29.511029 | |
| 310 | 2015 | 90.34752 | -1.945423 | 29.508397 | |
| 311 | 2014 | 1138.659359 | -1.950003 | 29.504973 | |
| 312 | 2014 | 170.153083 | -1.941455 | 29.501659 | |
| 313 | 2014 | 95.03419 | -1.940461 | 29.499585 | |
| 314 | 2014 | 112.660962 | -1.940462 | 29.499779 | |
| 315 | 2015 | 282.843239 | -1.954947 | 29.519042 | |
| 316 | 2014 | 137.145975 | -1.954741 | 29.518534 | |
| 317 | 2014 | 55.808413 | -1.954884 | 29.518239 | |
| 318 | 2015 | 40.496312 | -1.953058 | 29.518955 | |
| 319 | 2015 | 114.876181 | -1.95273 | 29.507441 | |
| 320 | 2015 | 396.037439 | -1.944562 | 29.523158 | |
| 321 | 2015 | 1515.53947 | -1.948938 | 29.524178 | |
| 322 | 2015 | 115.186639 | -1.945647 | 29.521938 | |
| 323 | 2015 | 513.126371 | -1.950646 | 29.512695 | |
| 324 | 2014 | 54.809759 | -1.933638 | 29.506889 | |
| 325 | 2014 | 265.043407 | -1.921982 | 29.506905 | |
| 326 | 2015 | 87.926748 | -1.916229 | 29.517438 | |
| 327 | 2015 | 2898.859638 | -1.903754 | 29.51096 | |
| 328 | 2014 | 1285.73258 | -1.90955 | 29.53974 | |
| 329 | 2014 | 1108.283365 | -1.910358 | 29.53303 | |
| 330 | 2014 | 844.492147 | -1.909544 | 29.532766 | |
| 331 | 2014 | 108.906184 | -1.908058 | 29.557454 | |
| 332 | 2014 | 50.499126 | -1.908137 | 29.557502 | |
| 333 | 2015 | 421.77205 | -1.915725 | 29.55803 | |
| 334 | 2014 | 2438.971643 | -1.915908 | 29.543283 | |
| 335 | 2006 | 139.430865 | -1.918637 | 29.548691 | |
| 336 | 2015 | 5847.317924 | -1.907589 | 29.564386 | |
| 337 | 2014 | 1720.099349 | -1.908447 | 29.58803 | |
| 338 | 2014 | 2079.347611 | -1.910427 | 29.588064 | |
| 339 | 2014 | 2092.646166 | -1.904094 | 29.589933 | |
| 340 | 2006 | 292.754561 | -1.91211 | 29.598197 | |
| 341 | 2014 | 360.988139 | -1.912462 | 29.597937 | |
| 342 | 2014 | 254.347327 | -1.912699 | 29.597234 | |
| 343 | 2014 | 92.297222 | -1.912723 | 29.597603 | |
| 344 | 2014 | 845.103275 | -1.912696 | 29.598716 | |
| 345 | 2014 | 157.043368 | -1.912357 | 29.597173 | |
| 346 | 2014 | 726.93186 | -1.910533 | 29.605509 | |
| 347 | 2014 | 110.900706 | -1.910124 | 29.606053 | |
| 348 | 2014 | 567.826694 | -1.909363 | 29.610294 | |
| 349 | 2014 | 287.082633 | -1.907321 | 29.608687 | |
| 350 | 2014 | 171.4943 | -1.907184 | 29.608164 | |
| 351 | 2014 | 9358.722503 | -1.909257 | 29.612437 | |
| 352 | 2014 | 248.39119 | -1.916356 | 29.598951 | |
| 353 | 2014 | 711.939427 | -1.919073 | 29.628087 | |
| 354 | 2014 | 127.289109 | -1.918823 | 29.623906 | |
| 355 | 2014 | 215.484968 | -1.915641 | 29.623776 | |
| 356 | 2014 | 1736.152369 | -1.896607 | 29.629881 | |
| 357 | 2014 | 194.656492 | -1.898529 | 29.630264 | |

# 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
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| 358 | 2014 | 891.831565 | -1.892633 | 29.598267 | |
| 359 | 2014 | 427.670762 | -1.89275 | 29.598507 | |
| 360 | 2014 | 322.265483 | -1.893112 | 29.598922 | |
| 361 | 2014 | 877.70554 | -1.899538 | 29.601901 | |
| 362 | 2014 | 724.505063 | -1.892888 | 29.596084 | |
| 363 | 2014 | 349.621675 | -1.900553 | 29.60551 | |
| 364 | 2014 | 2701.285797 | -1.885494 | 29.585233 | |
| 365 | 2014 | 13157.98815 | -1.890537 | 29.583749 | |
| 366 | 2014 | 7629.94107 | -1.89398 | 29.581136 | |
| 367 | 2014 | 683.543256 | -1.90116 | 29.593078 | |
| 368 | 2014 | 116.230487 | -1.894832 | 29.568979 | |
| 369 | 2015 | 89.713512 | -1.894417 | 29.559893 | |
| 370 | 2014 | 114.344333 | -1.893437 | 29.529181 | |
| 371 | 2015 | 2317.848798 | -1.888208 | 29.527387 | |
| 372 | 2014 | 538.903801 | -1.887614 | 29.526041 | |
| 373 | 2015 | 174.845637 | -1.898993 | 29.533606 | |
| 374 | 2014 | 359.903716 | -1.900134 | 29.535062 | |
| 375 | 2015 | 122.40605 | -1.902586 | 29.507592 | |
| 376 | 2015 | 215.643385 | -1.902456 | 29.507244 | |
| 377 | 2015 | 165.635064 | -1.902152 | 29.507169 | |
| 378 | 2015 | 106.241964 | -1.897648 | 29.506474 | |
| 378 | 2015 | 1463.69568 | -1.890978 | 29.512346 | |
| 379 | 2015 | 41.502687 | -1.890949 | 29.512765 | |
| 380 | 2014 | 419.832423 | -1.889626 | 29.515106 | |
| 381 | 2015 | 565.341566 | -1.888801 | 29.518614 | |
| 382 | 2015 | 379.885579 | -1.895552 | 29.510133 | |
| 383 | 2015 | 530.752764 | -1.895781 | 29.510564 | |
| 384 | 2014 | 336.252382 | -1.879166 | 29.535074 | |
| 385 | 2015 | 367.039425 | -1.8728 | 29.542599 | |
| 386 | 2014 | 609.911775 | -1.867297 | 29.584917 | |
| 387 | 2014 | 50.008089 | -1.871566 | 29.586527 | |
| 388 | 2014 | 781.038305 | -1.875169 | 29.613213 | |
| 389 | 2014 | 280.614571 | -1.881065 | 29.607464 | |
| 390 | 2014 | 143.516204 | -1.877284 | 29.603322 | |
| 391 | 2014 | 42.558231 | -1.877137 | 29.602823 | |
| 392 | 2014 | 87.79735 | -1.868861 | 29.596485 | |
| 393 | 2014 | 55.389816 | -1.869143 | 29.596487 | |
| 394 | 2014 | 105.585181 | -1.869419 | 29.596715 | |
| 395 | 2014 | 143.849072 | -1.86909 | 29.596598 | |
| 396 | 2014 | 2566.356276 | -1.872642 | 29.615269 | |
| 397 | 2015 | 820.336371 | -1.990827 | 29.506219 | |
| 398 | 2015 | 1749.849445 | -1.990139 | 29.503133 | |
| 399 | 2015 | 333.237376 | -1.991414 | 29.502135 | |
| 400 | 2015 | 216.592556 | -1.984983 | 29.494863 | |
| 401 | 2015 | 594.820668 | -1.97723 | 29.506106 | |
| 402 | 2015 | 2951.542271 | -1.971109 | 29.506674 | |
| 403 | 2014 | 207.367435 | -1.957539 | 29.498376 | |
| 404 | 2014 | 238.831829 | -1.957791 | 29.498656 | |
| 405 | 2014 | 147.572247 | -1.966292 | 29.500551 | |
| 406 | 2014 | 200.794296 | -1.966459 | 29.501024 | |
| 407 | 2014 | 121.893212 | -1.966607 | 29.501248 | |
| 408 | 2014 | 193.591 | -1.968292 | 29.502726 | |
| 409 | 2014 | 77.136877 | -1.968058 | 29.502284 | |
| 410 | 2015 | 73.242702 | -1.936347 | 29.496153 | |
| 411 | 2015 | 96.254186 | -1.934071 | 29.49078 | |
| 412 | 2015 | 1990.538464 | -1.931289 | 29.490978 | |
| 413 | 2015 | 168.099047 | -1.930644 | 29.490462 | |
| 414 | 2015 | 245.239023 | -1.928386 | 29.495892 | |
| 415 | 2015 | 1148.071866 | -1.927984 | 29.495331 | |
| 416 | 2015 | 4736.044284 | -1.926951 | 29.494101 | |

2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 417 | 2015 | 1765.85269 | -1.919157 | 29.499617 | |
| 418 | 2015 | 467.804534 | -1.918275 | 29.497472 | |
| 419 | 2015 | 5586.12759 | -1.916138 | 29.497619 | |
| 420 | 2015 | 1621.480381 | -1.917278 | 29.498329 | |
| 421 | 2015 | 385.494949 | -1.914453 | 29.493098 | |
| 422 | 2015 | 2269.713708 | -1.911503 | 29.48837 | |
| 423 | 2015 | 306.117243 | -1.918402 | 29.493118 | |
| 424 | 2015 | 147.344242 | -1.894606 | 29.492597 | |
| 425 | 2015 | 802.553162 | -1.888142 | 29.490927 | |
| 426 | 2015 | 764.899185 | -1.88771 | 29.489272 | |
| 427 | 2015 | 746.353758 | -1.892983 | 29.501652 | |
| 428 | 2015 | 208.580582 | -1.891204 | 29.502129 | |
| 429 | 2015 | 135.189913 | -1.896735 | 29.503863 | |
| 430 | 2015 | 638.776761 | -1.88792 | 29.487177 | |
| 431 | 2015 | 182.342672 | -1.886324 | 29.487947 | |
| 432 | 2015 | 85.915889 | -1.886015 | 29.487939 | |
| 433 | 2015 | 754.364529 | -1.8852 | 29.480113 | |
| 434 | 2015 | 132.010453 | -1.889547 | 29.480352 | |
| 435 | 2015 | 89.42936 | -1.890457 | 29.474453 | |
| 436 | 2015 | 31.34196 | -1.891261 | 29.474237 | |
| 437 | 2015 | 117.340871 | -1.894747 | 29.473326 | |
| 438 | 2015 | 245.172109 | -1.885451 | 29.470034 | |
| 439 | 2015 | 281.703072 | -1.889273 | 29.459208 | |
| 440 | 2015 | 57.064446 | -1.889041 | 29.459467 | |
| 441 | 2015 | 46.725769 | -1.888888 | 29.459381 | |
| 442 | 2015 | 29.72723 | -1.888746 | 29.459321 | |
| 443 | 2015 | 116.337677 | -1.889944 | 29.461928 | |
| 444 | 2015 | 93.119053 | -1.889716 | 29.461618 | |
| 445 | 2015 | 68.870832 | -1.889762 | 29.461712 | |
| 446 | 2015 | 383.547143 | -1.889883 | 29.460006 | |
| 447 | 2006 | 965.01074 | -1.889335 | 29.460868 | |
| 448 | 2006 | 11512.58635 | -1.894147 | 29.465826 | |
| 449 | 2006 | 3526.092188 | -1.899689 | 29.463143 | |
| 450 | 2006 | 2806.058886 | -1.899779 | 29.461831 | |
| 451 | 2006 | 4290.374898 | -1.900733 | 29.466988 | |
| 452 | 2015 | 553.620911 | -1.880371 | 29.496272 | |
| 453 | 2015 | 1056.517822 | -1.870927 | 29.488209 | |
| 454 | 2015 | 328.103274 | -1.884328 | 29.484148 | |
| 455 | 2015 | 89.23789 | -1.881302 | 29.478415 | |
| 456 | 2006 | 2268.833917 | -1.878172 | 29.470267 | |
| 457 | 2015 | 10908.08468 | -1.879237 | 29.468219 | |
| 458 | | 969.339479 | -1.879132 | 29.466636 | |
| 459 | 2015 | 406.164568 | -1.878691 | 29.465836 | |
| 460 | 2006 | 1899.703328 | -1.86818 | 29.46568 | |
| 461 | 2015 | 1755.361673 | -1.874734 | 29.465087 | |
| 462 | 2015 | 182.66606 | -1.875645 | 29.46372 | |
| 463 | 2006 | 97.208271 | -1.880229 | 29.464541 | |
| 464 | 2006 | 52.838546 | -1.879878 | 29.464619 | |
| 455 | 2015 | 308.250798 | -1.879228 | 29.463662 | |
| 456 | 2015 | 400.306376 | -1.880013 | 29.463785 | |
| 457 | 2015 | 956.907763 | -1.880222 | 29.463397 | |
| 458 | 2015 | 247.586999 | -1.880663 | 29.462971 | |
| 459 | 2015 | 535.386541 | -1.880003 | 29.465258 | |
| 460 | 2015 | 223.342581 | -1.881535 | 29.465368 | |
| 461 | 2015 | 7965.463437 | -1.873574 | 29.462631 | |
| 462 | 2015 | 3190.901347 | -1.873323 | 29.461242 | |
| 463 | 2015 | 2281.212578 | -1.874818 | 29.461161 | |
| 464 | 2015 | 160.300772 | -1.874427 | 29.460666 | |
| 456 | 2006 | 1448.28768 | -1.870364 | 29.457179 | |
| 457 | 2006 | 346.186182 | -1.87015 | 29.45778 | |

## 2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 458 | 2006 | 1758.080331 | -1.870012 | 29.456311 | |
| 459 | 2006 | 62.176083 | -1.869817 | 29.455839 | |
| 460 | 2006 | 74.410048 | -1.869749 | 29.455694 | |
| 461 | 2015 | 224.623055 | -1.870017 | 29.453105 | |
| 462 | 2015 | 879.837308 | -1.86961 | 29.45307 | |
| 463 | 2015 | 216.870124 | -1.869523 | 29.453505 | |
| 464 | 2015 | 4097.469286 | -1.869705 | 29.453958 | |
| 465 | 2015 | 1784.050494 | -1.87169 | 29.453086 | |
| 466 | 2015 | 987.742973 | -1.872696 | 29.455124 | |
| 467 | 2015 | 1945.589627 | -1.873177 | 29.454426 | |
| 468 | 2015 | 109.051551 | -1.874545 | 29.454372 | |
| 469 | 2015 | 93.09637 | -1.87438 | 29.455275 | |
| 470 | 2015 | 171.6392 | -1.874334 | 29.454978 | |
| 471 | 2015 | 269.900105 | -1.874054 | 29.454315 | |
| 472 | 2015 | 95.226877 | -1.874372 | 29.455479 | |
| 473 | 2015 | 159.894253 | -1.874743 | 29.455151 | |
| 474 | 2015 | 43.597108 | -1.874576 | 29.45564 | |
| 475 | 2015 | 54.207238 | -1.874621 | 29.455708 | |
| 476 | 2015 | 518.325813 | -1.87466 | 29.45553 | |
| 477 | 2015 | 49.604476 | -1.875361 | 29.455682 | |
| 478 | 2015 | 29.130368 | -1.875394 | 29.45579 | |
| 479 | 2015 | 79.717982 | -1.875256 | 29.456002 | |
| 480 | 2015 | 65.430726 | -1.875173 | 29.456228 | |
| 481 | 2015 | 718.795155 | -1.874971 | 29.455995 | |
| 482 | 2015 | 1519.843864 | -1.873793 | 29.45623 | |
| 483 | 2015 | 847.622061 | -1.874001 | 29.456748 | |
| 484 | 2015 | 1796.694833 | -1.874037 | 29.457221 | |
| 485 | 2015 | 1998.247388 | -1.874391 | 29.457656 | |
| 486 | 2015 | 207.613144 | -1.873967 | 29.457994 | |
| 487 | 2015 | 79.567262 | -1.873698 | 29.457717 | |
| 488 | 2015 | 45.262565 | -1.874082 | 29.458164 | |
| 489 | 2015 | 890.635761 | -1.874092 | 29.458477 | |
| 490 | 2015 | 623.710667 | -1.876314 | 29.457189 | |
| 491 | 2015 | 273.950592 | -1.880205 | 29.462087 | |
| 492 | 2015 | 680.460866 | -1.879717 | 29.452375 | |
| 493 | 2015 | 222.836614 | -1.880036 | 29.4533 | |
| 494 | 2015 | 1130.951733 | -1.869662 | 29.455266 | |
| 495 | 2015 | 78.720729 | -1.869696 | 29.456656 | |
| 496 | 2015 | 78.191034 | -1.879407 | 29.460749 | |
| 497 | 2015 | 84.139548 | -1.879639 | 29.460532 | |
| 498 | 2015 | 165.447342 | -1.879894 | 29.460503 | |
| 499 | 2015 | 271.676827 | -1.877926 | 29.465552 | |
| 500 | 2015 | 532.314654 | -1.914668 | 29.46315 | |
| 501 | 2015 | 3183.845921 | -1.916546 | 29.459128 | |
| 502 | 2015 | 817.677557 | -1.915923 | 29.458599 | |
| 503 | 2015 | 162.735653 | -1.910865 | 29.45397 | |
| 504 | 2015 | 346.085043 | -1.905603 | 29.455978 | |
| 506 | 2006 | 358.435142 | -1.903035 | 29.452508 | |
| 505 | 2006 | 354.284385 | -1.903504 | 29.452609 | |
| 507 | 2006 | 173.126528 | -1.902789 | 29.45283 | |
| 508 | 2006 | 125.226984 | -1.902531 | 29.452275 | |
| 509 | 2006 | 597.750947 | -1.901522 | 29.452406 | |
| 510 | 2006 | 283.82975 | -1.906676 | 29.452531 | |
| 511 | 2006 | 289.563795 | -1.903975 | 29.45258 | |
| 512 | 2006 | 159.522504 | -1.904219 | 29.462995 | |
| 513 | 2015 | 1104.560348 | -1.907902 | 29.462102 | |
| 514 | 2015 | 107.815273 | -1.908466 | 29.462892 | |
| 515 | 2015 | 338.480755 | -1.914066 | 29.478361 | |
| 516 | 2015 | 600.87535 | -1.910991 | 29.478579 | |
| 517 | 2015 | 764.121933 | -1.912224 | 29.486626 | |

2016 Focused Study (Precipitation) Landslide Inventory

| Name | Landslide Date | Area | Latitude (in decimal degrees) | Longitude (in decimal degrees) | Notes |
|---|---|---|---|---|---|
| 518 | 2015 | 173.842684 | -1.912211 | 29.486403 | |
| 519 | 2015 | 250.235444 | -1.913183 | 29.48678 | |
| 520 | 2015 | 484.711238 | -1.917118 | 29.485623 | |
| 521 | 2015 | 625.884044 | -1.915029 | 29.471892 | |
| 522 | 2015 | 113.467443 | -1.936665 | 29.488163 | |
| 523 | 2015 | 129.942293 | -1.936543 | 29.487596 | |
| 524 | 2006 | 2694.747294 | -1.952183 | 29.469232 | |
| 525 | 2006 | 428.220184 | -1.952443 | 29.468887 | |
| 526 | 2006 | 130.443876 | -1.952531 | 29.468681 | |
| 527 | 2015 | 460.958203 | -1.951595 | 29.464215 | |
| 528 | 2015 | 262.22194 | -1.942228 | 29.459777 | |
| 529 | 2015 | 575.386025 | -1.942709 | 29.459973 | |
| 530 | 2015 | 1062.135271 | -1.947214 | 29.454122 | |
| 531 | 2015 | 206.200704 | -1.946211 | 29.452717 | |
| 532 | 2015 | 639.626328 | -1.943205 | 29.454605 | |
| 533 | 2015 | 827.618284 | -1.937926 | 29.475248 | |
| 534 | 2015 | 164.034604 | -1.948217 | 29.477354 | |
| 535 | 2015 | 191.700539 | -1.976255 | 29.469725 | |
| 536 | 2014 | 88.902612 | -1.982612 | 29.472645 | |
| 537 | 2015 | 100.508432 | -1.993319 | 29.476104 | |
| 538 | 2015 | 200.959428 | -1.995372 | 29.488837 | |
| 539 | 2015 | 320.154447 | -2.026337 | 29.488163 | |
| 540 | 2015 | 243.415042 | -2.016513 | 29.482576 | |
| 541 | 2015 | 74.218207 | -2.013842 | 29.477686 | |
| 542 | 2015 | 158.467072 | -2.013965 | 29.452469 | |
| 543 | 2015 | 271.865045 | -2.027519 | 29.457333 | |
| 544 | 2015 | 141.868884 | -2.010715 | 29.46165 | |
| 545 | 2015 | 96.687019 | -2.023274 | 29.468859 | |
| 546 | 2015 | 590.450659 | -2.024863 | 29.467457 | |
| 547 | 2015 | 222.12665 | -2.02965 | 29.45472 | |
| 548 | 2015 | 423.082423 | -2.043355 | 29.477824 | |
| 549 | 2015 | 463.065191 | -2.041049 | 29.481293 | |
| 550 | 2015 | 1623.426622 | -2.041988 | 29.459399 | |
| 551 | 2015 | 976.918585 | -2.043203 | 29.463938 | |
| 552 | 2002 | 4345.625143 | -2.043205 | 29.463013 | |
| 553 | 2002 | 1342.95527 | -2.043364 | 29.466003 | |
| 554 | 2015 | 113.940091 | -2.042751 | 29.454663 | |

```
clear all;
close all;

% This program is to read a TRMM 3B42 daily binary file
% By Angela Piller May 2016
%
% Info about TRMM binary files:
%The file size is about 2.25 MB (uncompressed). The data are stored in
%flat binary, as 4-byte floating numbers. Users who download these data
%will need to execute byte swapping if working on a little endian machine.
%These data have the first grid cell at (0.125,-49.875) (lon,lat), and
%data are stored in rows of 1440 longitudes. The first row is at -49.875
%latitude. In standard matrix notation, the grid is sized (400,1440)
%(rows, columns).
%---------------------------------------------------------------------------

%DATES (edit here if appropriate)

startyr= 1998;  %years available are 1998 - 2015. Last date available is 5/2/2015.
endyr= 2015;

%LOCATION (edit here if appropriate)
%Here is code to define the study area and then calculate minlon and min lat
%(round these values to the nearest .25 degree)
%Values for low landslide density area
%north = -1.5;
%south = -1.75;
%east = 29.75;
%west = 29.50;

%rounded values for high landslide density (main study) area
north = -1.75;
south = -2.25;
east = 29.75;
west = 29.25;

nlat = (north * -4) + 200;
slat = (south * -4) + 200;

if east >=0
    elon = (east * 4);
else
    elon = (east * 4 + 1440);
end

if west >=0
    wlon = (west * 4);
else
    wlon = (west * 4 + 1440);
end
```

```
%Define the start and unit (1 day) for time ('O' or the 3rd dimension of matrix).
%Time is measured in days. The first date for TRMM data was 1/1/1998 and
%the last was 5/2/2015.'minlat' and 'minlon' are 1 less than the minimums
%of the study area. This is used to locate the locations in the matrix
%that have my precipitation data in them (files contain data for the entire world).

firstday = 1;
timedim = 1;

minlat = (nlat - 1); %(study area is south of the equator)
minlon = (wlon - 1);

%Define the way calendar time works and use these rules to generate filenames
%'fname' and array name 'aname' (Not using aname for anything right now).

basename = 'C:\Users\apiller\Documents\School\Honors\Thesis Work\data\Data for↙
Rwanda\TRMM\3B42_daily.';

for i_fname = startyr:endyr %year 1998 - 2015
    if i_fname == 2015 % Last date available is 5/2/2015
        lastmonth = 5;
    else
        lastmonth = 12;
    end

for j_fname = 1:lastmonth %month
     if i_fname == 2000 && j_fname == 2 %leapyears
         lastday = 29;
     elseif i_fname == 2004 && j_fname == 2
         lastday = 29;
     elseif i_fname == 2008 && j_fname == 2
         lastday = 29;
     elseif i_fname == 2012 && j_fname == 2
         lastday = 29;
     elseif i_fname == 2015 && j_fname == 5 %Last date available is 5/2/2015
         lastday = 2;
     elseif j_fname == 2
         lastday = 28;
     elseif j_fname == 4
         lastday = 30;
     elseif j_fname == 6
         lastday = 30;
     elseif j_fname == 9
         lastday = 30;
     elseif j_fname == 11
         lastday = 30;
     else
        lastday = 31;
     end

     for k_fname = 1:lastday
```

```
            i_strfname = num2str(i_fname);
            j_strfname = num2str(j_fname);
            k_strfname = num2str(k_fname);

        if j_fname < 10
                j_strfname = strcat('0',j_strfname);
        end

        if k_fname < 10
                k_strfname = strcat('0',k_strfname);
        end

        fname = strcat(basename, i_strfname,'.',j_strfname,'.',k_strfname,'.7.bin');
        aname = strcat(i_strfname, j_strfname, k_strfname);
        aname = str2num(aname);
        timedim = timedim + 1; %for the 3rd dimension in the array

% Now read the information out of the TRMM files. Locate the file ID,
% change data from big endian to little endian, rotate contents of the
% array.
% Source: http://disc.sci.gsfc.nasa.gov/additional/faq/precipitation_faq.html#matlab
%('lat' and 'lon' aren't currently being used)

fid = fopen(fname,'r');
precipitation = fread(fid, [1440, 400], 'float','b');
fclose(fid);
precipitation = rot90(precipitation);

%for i_lat = 248:-1:216 %my addition- increase accuracy, though? to refect exact study
area
%for j_lon = 116:120 %my addition to reflect exact study area
for i_lat = (slat-1):-1:(nlat)
for j_lon = wlon:(elon-1)

    lat = 49.875 - 0.25*(i_lat - 1);
    if j_lon <= 720;
         lon = 0.125 + 0.25*(j_lon - 1);
    else
         lon = 0.125 + 0.25*(j_lon - 1) - 360.0;
    end

    daily_rain_total = precipitation(i_lat, j_lon);
    P((i_lat - minlat),(j_lon-minlon),timedim) = daily_rain_total;

end
end

close all


    end
```

```
end
end

%ONLY FOR MAIN STUDY AREA COMMENT OUT AND USE LOW DENSITY VERSION
%Average values for all four TRMM pixels together, put them in a new matrix.
%Weight them 54% North pixel, 19.5% North2 pixel, 19.5% South pixel, 7%
%South2 pixel.

for i = 1:timedim
    Q(1,i) = (((P(1,1,i))*.195) + ((P(2,1,i))*.07) + ((P(1,2,i))*.54) + ((P(2,2,i))*.
195));%[1,:]averaged precipitation value
end

%LOW DENSITY VERSION (next 3 lines)
%for i = 1:timedim
%    Q(1,i) = (P(1,1,i));
%end


%Determine the rank of each precipitation value "PR"
PR = sort(Q,'descend');

%Since interpolate won't work if there are multiple identical values, use
%"unique" to remove all but one zero. However, treat calculations as if the
%full number of records ('timedim') exist.
PR = unique(PR,'stable');

n=0;
PRdim = size(PR);

for j = 1:PRdim(1,2)
    PR(2,j) = n+1;%{2,:]Rank
    if PR(1,j) == 0;
        PR(2,j) = timedim;
    end
    n=n+1;
end

%Determine Exceedance Probability (Weibull method)
for k = 1:PRdim(1,2)
    PR(3,k) = 100 * ((PR(2,k)/(timedim+1))); %{3,:]Probability
    PR(4,k) = (1/((PR(3,k)/100))); %{4,:]Recurrance Interval
end

event = (1:(PRdim(1,2)));

Storm1 = interp1(PR(4,:),PR(1,:),event);
%Storm1 = interp1(PR(4,:),PR(1,:),event);
%%
plot(Storm1,event)
title('Precipitation vs Recurrance Interval - High Density')
```

```
xlabel('Daily Precipitation (mm)')
ylabel ('Recurrance Interval (days)')
%%
plot(Q)
%plot(squeeze(P(1,1,:)))
title('Daily Precipitation - High Density')
xlabel('Day')
ylabel('Daily Precipitation (mm)')
```