Landslide susceptibility and risk in Saint Lucia

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ABSTRACT
Landslides are relatively common on the eastern Caribbean island of Saint Lucia, being most frequently associated with heavy rainfall. Landslides have caused numerous fatalities, and have often damaged buildings, roads or other infrastructure, resulting in a significant economic and social cost. This paper summarizes work to examine landslide occurrence in relation to several sets of geospatial data and uses the weights of evidence method, a bivariate statistical approach, to develop a landslide susceptibility model for the entire island. The results suggest that a significant proportion of the island has elevated susceptibility to landslides, but that the susceptibility is not particularly focused in any specific part of the island. The susceptibility model was extended to develop an exposure model for landslides affecting existing human habitation, as part of preliminary analysis of landslide risk to human habitation. The analysis could have benefited from improvements to the landslide inventory and from consideration of additional bedrock and surficial geology data. The work is intended to be used on the regional scale in setting broad priorities for further study, and is not intended for use at specific sites.

RÉSUMÉ
Les glissements de terrain sont relativement communs sur l'île des Caraïbes de l'Est de Sainte-Lucie, est le plus souvent associée à des fortes précipitations. Les glissements de terrain ont causé de nombreuses victimes et ont des bâtiments, de routes ou d'autres infrastructures souvent endommagés, entraînant un coût économique et social important. Ce document résume les travaux d'examiner glissement de terrain dans le cadre de plusieurs ensembles de données géospatiales et utilise les poids de la méthode de preuve, une approche statistique à deux variables, à développer un modèle de susceptibilité de glissements de terrain pour l' ensemble de l'île . Les résultats suggèrent qu'une proportion importante de l'île a élevé la susceptibilité aux glissements de terrain, mais que la sensibilité n'est pas particulièrement concentré dans une partie spécifique de l'île. Le modèle de sensibilité a été étendu à développer un modèle d'exposition pour les glissements de terrain qui affectent l'habitat humain existant, dans le cadre de l'analyse préliminaire des risques de glissement de terrain à l'habitation humaine. L'analyse aurait pu bénéficier d' améliorations à l'inventaire des glissements de terrain et de l'examen du socle supplémentaires et des données de géologie de surface . Le travail est destiné à être utilisé à l'échelle régionale dans la mise grandes priorités pour une étude plus approfondie, et n'est pas destiné à être utilisé sur des sites spécifiques.

1 INTRODUCTION

Saint Lucia is one of the northernmost Windward Islands in the eastern Caribbean, part of a chain of islands comprising two volcanic arcs (Figure 1). This paper presents the results of work examining landslide occurrence in Saint Lucia with the objective of developing a regional scale landslide susceptibility map and a risk map showing qualitative landslide risk to existing human habitation across the island. The work uses the weights of evidence method, a bivariate statistical approach that compares landslide absence/presence with several other layers of geospatial data in a geographic information system (GIS) to obtain a predictive model for relative spatial frequency of future landslides. Other researchers have produced landslide susceptibility or hazard maps for parts of the island. The present work relies on a relatively large landslide inventory and on recently acquired topographic data. The analyses show that landslide hazard is relatively widespread across most of the island, rather than being confined to a relatively low proportion of the surface area. The landslide susceptibility model has been combined with inferred population density to develop a regional scale qualitative risk map for landslides affecting human habitation.

Figure 1. Site Location

1.1 Geographic, Physiographic and Geologic Setting

The following summary is synthesized from descriptions by Martin-Kaye (1969), Earle (1923), Tomblin (1965) and Roobol et al. (1983), and supported by field observations by the author where noted. The island is approximately

45 m long from north to south, and 22 km wide, with total area of just over 600 km^2. The population of approximately 174,000 is distributed among a number of towns and villages, primarily along the coast, and with the largest concentration in the Capital of Castries. The island has a central mountain range with lateral ridges extending out to the ocean (Figure 2). The overall topography is hummocky, with more gentle terrain to the north and south, and elevation ranging up to about 950 m above sea level. Several wide, fertile and almost flat valleys are present, containing most of the major drainages. Canyon-like gorges are present near the west coast between Anse-la-Raye and Soufrière.

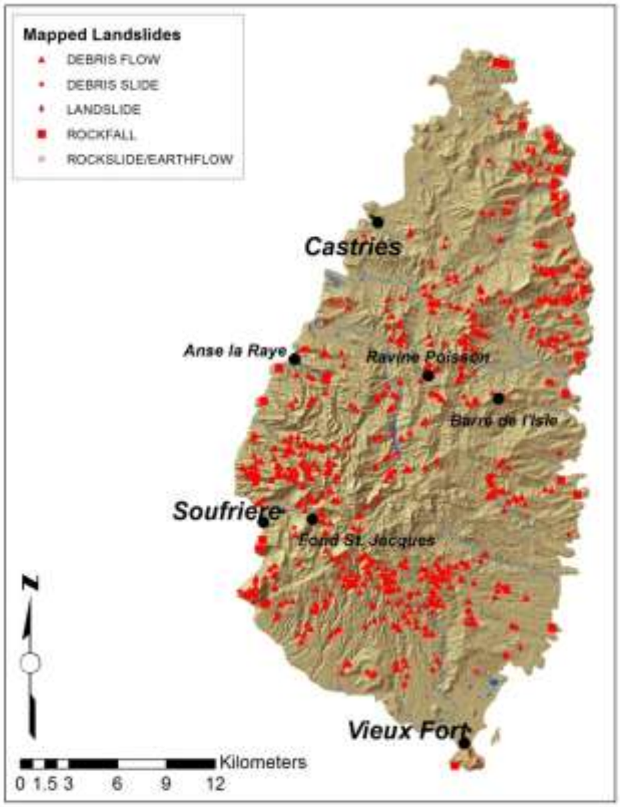

Figure 1. Hillshade image of island with documented landslides shown.

Bedrock is almost entirely volcanic in origin, with minor exceptions including coralline limestone near Soufrière, and some fossiliferous limestone north of Castries. Most bedrock dates to about 30-40,000 years before present, and overlying older volcanic bedrock, comprised of andesite, dacite and some older basalt. Rocks tend to become progressively younger south of Castries toward the most recent volcanic centre, of Pleistocene age, in the Qualibou depression near Soufrière. This depression has been interpreted as either the root zone of a gravity slide, or more likely a collapsed caldera, and contains fifteen volcanic cones and seven craters. The inferred caldera is pre-dated by basalt lava flows, and was followed by growth of andesitic strato volcanoes.

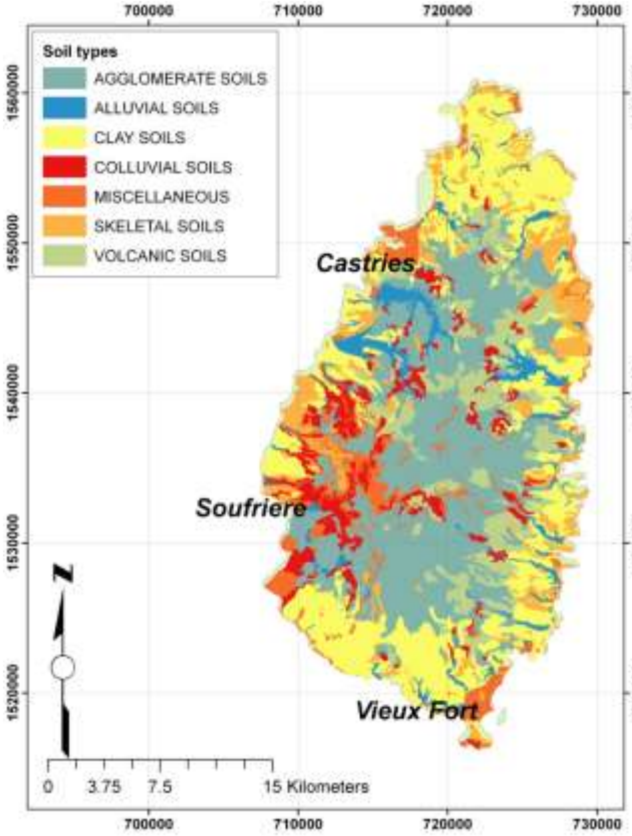

Figure 2. Distribution of soil types.

Younger rocks consist of ashes, grits, volcanic agglomerates and breccias. Bedrock outcrops are rare in the central mountains, where red clay with residual boulders of andesite or basalt is encountered to great depth. Bedrock exposures observed by the author tend to consist of massive volcanic rock, with joint sets or evident faults being very rare. Surficial soils are predominantly clayey tropical soils derived from highly weathered volcanic rock, with alluvial soils present in river valleys. Distribution of primary soil types in illustrated in Figure 3. It may be noted that soil types are based on agricultural mapping, and no surficial geological map is available for Saint Lucia.

1.2 Landslides in Saint Lucia

DeGraff et al. (1989) report that the most common landslide types are debris flows and debris slides. Earth flows, rock slides and rock falls are common but less frequent, and slumps and complex landslides are present but less common. Most landslides involve translational movement or flow, and most have shallow failure planes, often 2 m depth or less. Prior and Ho (1972) investigated the mineralogy of soil materials involved in landslides by x-ray diffraction and atomic absorption analyses. They found that complex landslides occur in purely montmorillonite clays, which are found on coastal sites where sodium ions are relatively more abundant. Rotational slides and slump-earthflows were associated with mixtures of kaolinite, montmorillonite, illite and chlorite clay mineral soils, and translational slides were associated with pure kaolinite soils.

Anderson (1983) reported relationships between slope stability/instability and slope length, plan curvature, slope angle, soil strength and soil permeability. Anderson found that stability was not strongly related to slope length, but correlated with both slope angle and curvature. Convex slopes were much more stable than concave, suggesting that concentration of drainage, and the associated pore pressure effects, is more important than the additional confining pressures present in concave slopes. Anderson also found that the effect of curvature diminishes with decreasing permeability. Anderson and Kneale (1985) extended the work of Anderson (1983), and presented stability envelopes for three different permeability classes, 10^{-3}, 10^{-4} and 10^{-6} cm/s, given slope angle, curvature, and soil strength. Anderson and Kneale (1985) conducted mineralogical analyses of the soils involved in 23 landslides and found no relationship between mineralogy and instability, contradicting the findings of Prior and Ho (1972). However, it may be noted that the more recent work considered inland shallow landslides, and therefore excluded coastal sites with higher montmorillonite content.

Numerous damaging landslides have occurred in recorded history, with notable very severe events including the following: 1938 at Ravine Poisson and Ravine Ecrivisses; 1960 at Fond St. Jacques; 1980 at Barre de l'Isle after the passage of Hurricane Allen; 1994 island-wide following the passage of Tropical Storm Debby; 1999 at Black Mallet/Maynard Hill; and, 2010 island-wide following the passage of Hurricane Tomas. These major landslide events each resulted in significant infrastructure damage, injury and/or fatalities, and each was associated with heavy rainfall, which was often, but not always, associated with tropical storms or hurricanes. The 1938, 1960 and 1999 events were associated with significant rainfall that did not occur during tropical storms or hurricanes. Less severe landslide events occur commonly between major rainfall events, and can also be triggered by significant seismic shaking. DeGraff et al. (1989), however, reported that no significant earthquake-induced landslides have been documented, and triggering by heavy rain has been the norm.

Figure 4 (data from NOAA 2012) shows the tracks of recorded tropical storms and hurricanes, including Allen (1980), Debbie (1994) and Tomas (2010). This figure gives an indication of the frequency of potentially damaging storm events. Hurricane Tomas caused significant landslide damage in many areas. Notably, ten residents were killed during Tomas by a debris flow at Fond St. Jacques (ECLAC, 2011). Figure 5 is an aerial view of the debris flow that engulfed several homes at Fond St. Jacques. Landslides during Tomas had a significant effect on transportation infrastructure, with numerous landslides blocking or undermining roads, leading to complete closure of the main road network for many days. Figure 6 is an example of a large slide adjacent to the main road through Barre de l'Isle. Figure 7 shows a landslide at Fond St. Cocoa that affected homes and a minor road. Total impact to Saint Lucia associated with Hurricane Tomas has been estimated as US$336M (ECLAC, 2011).

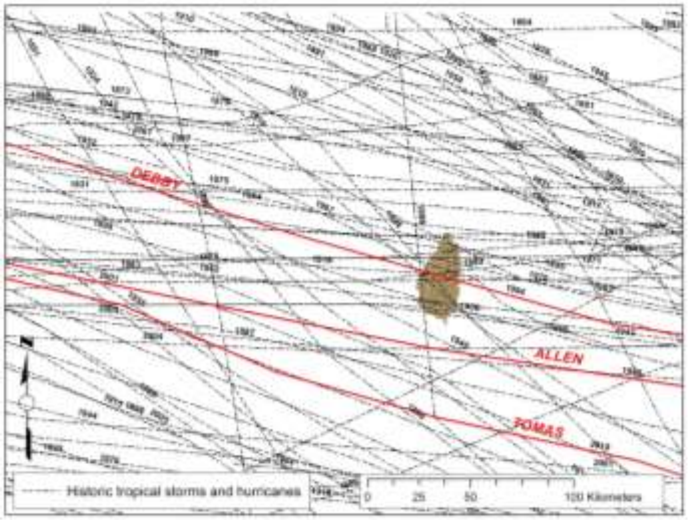

Figure 3. Historical storm tracks in the vicinity of Saint Lucia since 1848 (NOAA 2012).

Figure 4. Debris flow at Fond St. Jacques during Hurricane Tomas (photo courtesy DFL Consult, Castries, Saint Lucia).

Figure 5. Landslide adjacent to main high way at Barre de l'Isle (photo courtesy DFL Consult, Castries, Saint Lucia).

Figure 6. Landslide at Fond Cocoa (photo courtesy DFL Consult, Castries, Saint Lucia).

1.3 Prior Landslide Susceptibility and Hazard Mapping

Landslide susceptibility, hazard and risk mapping methods have evolved considerably with the development of effective GIS analytical techniques. In this paper, landslide susceptibility means the expected spatial distribution of future landslides, with no consideration of temporal distribution. Hazard incudes the additional consideration of temporal probability of future landslide occurrence. Risk relates to expected loss associated with the hazard, and thus also includes consideration of the spatial and temporal presence, and vulnerability, of potentially affected elements at risk.

Several previous attempts have been made to develop predictive maps for landslide susceptibility or landslide hazard, in an effort to identify parts of the island with relatively lower and high landslide incidence, as a means of isolating hazard and risk, and to help focus the allocation of resources for landslide risk mitigation. DeGraff (1985) developed a landslide susceptibility map for most of the island, based on subjective evaluation of three input parameters: bedrock, with 24 rock types grouped into 11 similar classes; slope angle, with three classes (< 20 %, 20-60 %, and > 60 %); and, a hydrologic factor, taking mean rainfall into account. The latter factor was found to provide limited correlation with the available landslide data, and was thus set aside from the model, leaving only bedrock and slope angle for inclusion. The resulting model divided the island into four classes, with the vast majority of the island categorized as “moderate hazard.” The “low hazard” areas were confined to floodplains, which constitute a very small proportion of the island, and small areas of “high hazard” and “extreme hazard” were identified at the Barre de l’Isle ridge in the centre of the island and rugged terrain around Soufrière.

Rogers (1997) prepared a similar susceptibility map, but only for debris flows in eleven selected high priority watersheds, comprising approximately half of the total surface area of Saint Lucia. That work relied on the landslide inventory developed by DeGraff (1985), plus additional coastal landslides interpreted from 1991 black and white air photos at 1:10000 scale, and additional landslides initiated during 1994 Tropical Storm Debby, as interpreted from reconnaissance level field mapping and available reports. The work generated a debris flow hazard map covering roughly 2/3 of the island, based on subjective, expert-based combination of factors expected to correlate with debris flow occurrence. The model considered: slope gradient, given a relative weight = 4; slope curvature, weight = 4; rainfall, as interpreted from elevation, weight = 3; and, soil type, weight = 2.

The DeGraff and Rogers predictive models are both included in the Saint Lucia Landslide Response Plan (Government of Saint Lucia, 2008). These two maps show limited spatial correspondence between each other, although both show lower hazard in the floodplains of major drainages, and relatively higher hazard in the central Barre de l’Isle ridge and in the southwest part of the island around Soufrière. Both maps are incomplete, with the Rogers map missing information for about seven watersheds, or roughly 1/3 of the island, and the DeGraff map missing the central part of the island, where bedrock data were not available.

More recent susceptibility mapping work has been done by the Caribbean Development Bank and Caribbean Disaster Emergency Response Agency (2006). However, this more recent work involved only a small pilot study area near Castries. This work combined four factors: elevation, with seven intervals of 50 m; slope angle, with seven intervals of 10 degrees; slope aspect, with three intervals (“leeward” or 225-315 degrees, “neutral,” and “windward” or 45-135 degrees); geology, considering four bedrock types encountered around Castries (out of 32 island-wide); and, soils, considering 10 local soil types (out of 58 present island-wide). This work used a bivariate statistical comparison of landslide incidence with each factor to determine individual susceptibility factors, as described later in the paper. Aspect was found to be unimportant in the model, so susceptibility was calculated as a combination of elevation, slope angle, geology and soil factors, with slope angle weighted twice the other factors.

Each of the three maps discussed above represent interesting and useful contributions to the study of landslide susceptibility in Saint Lucia; however, none of the three existing maps covers the whole island. Recent high quality topographic data and a more complete landslide inventory are now available, and these support a more detailed statistical analysis of spatial relationships between landslides and terrain features.

2 MODELLING APPROACH

The purpose of the work was to generate a landslide susceptibility map that subdivides the island into areas with greater or lesser potential for future landslides to occur, and to extend this to model hazard, with consideration of temporal probability, and qualitative risk to human habitation, considering the potential for loss associated with future landslides. The susceptibility mapping work used an adapted approach to the weights of evidence method (Bonham-Carter et al. 1989), which was first developed for mineral exploration, but has since been adapted successfully for use in landslide susceptibility modeling (see for example van Westen et al. 2003, Dahal et al. 2008, and Quinn et al. 2010). The specific method used in the susceptibility analysis was previously described in detail by Quinn et al. (2010). The susceptibility map was extended to a hazard map by estimating rough temporal probability for different susceptibility categories. A qualitative risk map was developed by overlapping landslide hazard with population density, inferred from available topographic data.

2.1 Geospatial Data

Recent topographic data available from the Government of Saint Lucia were interpreted from aerial photography flown in 2009, and included 2.5 m elevation contours. The elevation data were converted to a digital elevation model (DEM) in raster format. The DEM was subsequently manipulated to produce several interpreted raster data sets, including: elevation; slope aspect; slope curvature (overall curvature); plan curvature; profile curvature; and, slope angle.

Soils mapping data in shapefile format were also available from the Government of Saint Lucia. This layer, derived from agricultural or forestry soils mapping, included a number of attributes of possible importance to landslide incidence, including soil type (61 distinct type names, in seven broad classes, which are shown in Figure 3), erosion potential (six distinct classes), and average gradient (seven distinct classes) for each distinct soil polygon. Individual rasters were generated for soil type (seven classes), erosion class (six) and gradient (seven) for consideration in the analysis. Bedrock mapping information is also available for the island, however this information was not available in GIS format, and so this theme was excluded from the analysis.

Landslide location and type data were extracted from Government of Saint Lucia (2008). This included 692 landslides, of which 669 were used in the DEM-based analysis, and 663 were used with the soils data. Some landslides were excluded from the analysis due to lack of overlap with the available geospatial themes.

2.2 Preparatory Work and Image Processing

Available data for analysis were available in three forms: point data for locations of existing landslides; vector data (polygons) for available soils mapping; and, raster data for the DEM and associated interpretations.

The vector data required little manipulation. The landslide point data were checked for consistency, and a small number excluded from the analysis due to spatial inconsistencies (i.e. several landslides did not overlap the other available spatial data). The soils data were converted to rasters for the comparative analysis once it was decided which attributes would be considered in the analysis (i.e. major soil type, erosion class, and average gradient, as discussed previously).

The DEM and its derivatives (i.e. aspect, curvature, slope angle) required further image processing to support efficient analysis. There are several different ways possible to process the data to obtain the inferred weights. In the author's experience, none of the approaches is necessarily "better," but each introduces different biases into the analysis, along with different uncertainties or errors in the result. A common approach is to divide the input map into equal intervals, or equal areas. For example, elevation could be discretized either on the basis of equal 50 m intervals, or alternatively on the basis of unequal elevation intervals that divide the map into, say, 20 equal area slices. In each of these cases, the number of landslides associated with the resulting elevation slices will be variable, and weights will be calculated from landslide populations of different size. This leads to weights with different relative uncertainty, as one slice's weight could be calculated on the basis of 5 out of 669 landslides, whereas another slice's weight could be calculated on the basis of 325 of 669 landslides. Intuitively, the former weight would carry much greater uncertainty than the latter, which could be important to the final model, depending on the relative proportion of map area associated with each weight.

A third approach, which was adopted here, was to divide each raster map into ten slices, with each slice corresponding to approximately equal numbers of landslide points (i.e. ~ 67 of 669). This is accomplished by extracting raster values for each landslide point location, then obtaining decile values for the specific raster in the landslide population, then reclassifying the raster into ten slices corresponding to those decile values. This approach was taken to prepare the DEM (i.e. elevation) and DEM-interpretations (i.e. aspect, curvature, plan curvature, profile curvature, slope angle) for analysis. Figure 8 shows the elevation raster reclassified into ten slices with roughly equal numbers of landslides. It can be seen that these slices have unequal areas, leading to the expectation that certain elevation intervals will have relatively higher or lower association with landslide activity.

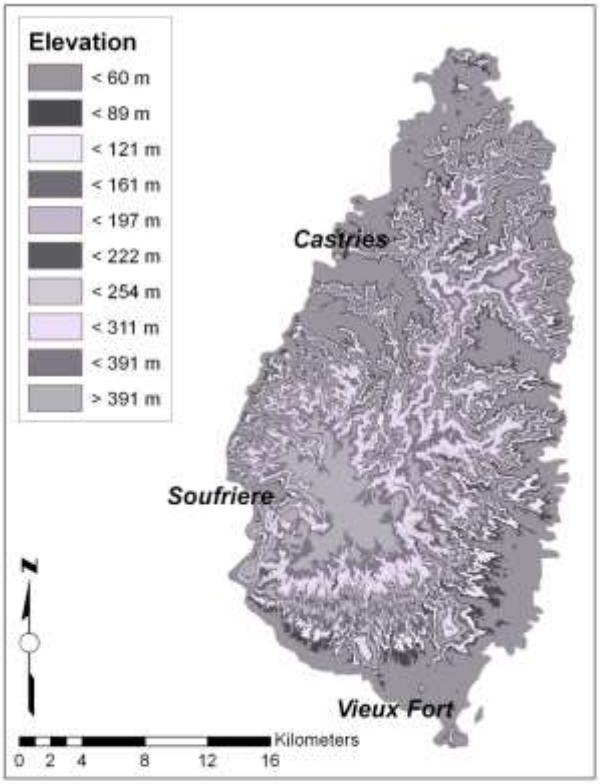

Figure 1. Reclassified elevation raster with ten slices with roughly equal numbers of landslides

Table 1. Slice limits for reclassified continuous rasters interpreted from the digital elevation model.

Slice Number	**% Rank**	**Attribute limits for indicated raster slice (% of map area)**					
		Elevation (m)	**Aspect (degrees)**	**Curvature**	**Plan Curvature**	**Profile Curvature**	**Slope (degrees)**
1	10	60 (30.3)	34 (10.1)	-2.46 (7.3)	-1.54 (5.6)	-1.23 (8.1)	12.9 (34.3)
2	20	89 (9.6)	75 (12.2)	-1.36 (7.6)	-0.75 (7.2)	-0.65 (7.9)	16.6 (11.6)
3	30	121 (9.7)	127 (13.8)	-0.74 (8.9)	-0.38 (8.7)	-0.33 (9.2)	19.9 (11.3)
4	40	161 (10.6)	155 (7.9)	-0.28 (12.5)	-0.16 (10.8)	-0.15 (8.9)	21.8 (6.5)
5	50	197 (8.7)	181 (7.7)	-0.01 (13.7)	0.01 (19.1)	-0.02 (10.0)	24.1 (7.1)
6	60	222 (5.2)	204 (7.0)	0.34 (16.9)	0.16 (13.7)	0.09 (13.2)	27.4 (8.6)
7	70	254 (5.7)	232 (8.6)	0.73 (9.4)	0.35 (9.9)	0.31 (13.5)	30.6 (6.2)
8	80	311 (7.5)	274 (11.4)	1.35 (8.5)	0.66 (8.9)	0.63 (11.1)	34.4 (5.4)
9	90	391 (6.7)	327 (13.0)	2.56 (8.2)	1.43 (9.1)	1.20 (9.1)	40.3 (5.1)
10	100	637 (6.2)	360 (8.4)	10.09 (7.0)	7.60 (7.0)	6.38 (9.0)	64.4 (3.9)

Table 2. Soil type attribute data.

Unit	Soil Type	% Area	# LS	% LS
1	Agglomerate	32.9	268	40.4
2	Volcanic	10.9	63	9.5
3	Clay	26.1	132	19.9
4	Skeletal	10.1	76	11.5
5	Colluvial	7.0	46	6.9
6	Alluvial	5.1	1	0.2
7	Miscellaneous	7.9	77	11.6
Unit	Erosion class	Relative Area (%)	# of LS	% of LS
1	No apparent	22.2	111	16.7
2	Slight	60.2	445	67.1
3	Moderate	14.1	97	14.6
4	Severe	2.6	8	1.2
5	Very severe	0.8	2	0.3
6	Extr. severe	0.1	0	0
Unit	slopes	Relative Area (%)	# of LS	% of LS
1	Unclassified	7.9	77	11.6
2	0-2 deg.	7.7	6	0.9
3	2-5 deg.	2.3	2	0.3
4	5-10 deg.	10.0	34	5.1
5	10-20 deg.	26.5	137	20.7
6	20-30 deg.	36.4	308	46.5
7	> 30 deg.	9.2	99	14.9

Table 3. Calculated weight factors for topographic data.

Sl.	**Calculated Weight**					
	Elev.	**Asp.**	**Curv.[1]**	**Plan Curv.**	**Prof. Curv.[1]**	**Slope**
1	-1.096	-0.025	0.325	0.576	0.224	-1.236
2	0.0014	-0.171	0.269	0.341	0.191	-0.150
3	0.059	-0.312	0.115	0.120	0.150	-0.123
4	-0.063	0.249	-0.254	-0.062	0.073	0.435
5	0.156	0.250	-0.293	-0.726	-0.005	0.357
6	0.616	0.353	-0.528	-0.219	-0.264	0.136
7	0.553	0.146	0.045	0.059	-0.305	0.445
8	0.310	-0.144	0.176	0.021	-0.108	0.653
9	0.404	-0.251	0.201	0.089	0.100	0.664
10	0.493	0.169	0.365	0.375	0.105	0.940
Range:	*1.712*	*0.665*	*0.893*	*1.302*	*0.529*	*2.176*

Note. 1. These attributes were not included in the final susceptibility model.

Table 4. Soil type attribute weight factors.

Major Soil Type		Soil Erosion Class		Soil Gradient Class	
Unit	Weight	Unit	Weight	Unit	Weight
1	0.205	1	-0.319	1	0.260
2	-0.135	2	0.109	2	-1.783
3	-0.272	3	0.032	3	-1.367
4	0.127	4	-0.406	4	-0.838
5	-0.013	5	-0.772[1]	5	-0.273
6	-3.516	6	-0.772[1]	6	0.299
7	0.390			7	0.446
Range:	*3.906*		*0.881*		*2.229*

Note. 1. Very extremely severe erosion classes were grouped.

Table 5. Susceptibility modelling results and proposed engineering categorization.

Slice #	Upper Value of Susc.	% of map area	Relative LS Density	Proposed Susc. Category
1	-0.816	38.2	0.26[1]	Low Relative landslide frequency ~ 0.26 island-wide average
2	-0.338	9.6	1.04	Low-moderate Relative landslide frequency ~ 1.05[2]
3	0.113	11.6	0.86	
4	0.375	8.6	1.16	
5	0.622	8.3	1.20	
6	0.795	5.8	1.73	Moderate-high Relative landslide frequency ~ 1.73
7	1.015	6.2	1.61	
8	1.257	5.3	1.87	
9	1.483	3.4	2.97	High Relative landslide frequency ~ 3.08
10	2.301	3.1	3.22	

Notes. 1. Obtained by dividing 10 % (proportion of landslides in slice 1) by 38.2 % (proportion of total map area).
2. Obtained by dividing 40 % by 38.1 % (proportion of map area covered by slices 2 to 5).

The discretization of the spatial themes used in the analysis is detailed in Table 1 for the raster data and Table 2 for the vector data. In Table 1, the spatial percentages can be used to infer relative weight, since each slice has an equal number (10 %, or 67) of landslides. Therefore a slice with, say, 5 % of the total map area has a higher than average landslide density, and will yield a positive weight. The weights obtained from the soil class data are less intuitive from the data in Table 2, since the slices have neither equal areas nor equal numbers of landslides.

2.3 Weights of Evidence Analysis

The individual weights are calculated as the natural logarithm of a ratio of spatial conditional probabilities, as follows:

$$W_i = \ln\left[\frac{P\{F_i | L\}}{P\{F_i | \overline{L}\}}\right] \qquad [1]$$

where F_i represents the presence of a specific, i-th, factor, and L and $\overline{L}$ represent presence and absence of landslides, respectively. The spatial probabilities in Equation 1 can be obtained by totalling the number of landslide observations where a specific factor (e.g. aspect SSW) is also present or absent. This weight is obtained by computing the following:

$$W_i = \ln\left\{\frac{[N_i / P_i]}{[N / P]}\right\} \qquad [2]$$

Where:

Ni = number of landslides within the i-th sub-factor of a given spatial theme (e.g. ground elevation < 60 m when obtaining weights for elevation ranges);

Pi = number of map pixels corresponding to the i-th sub-factor of the given spatial theme;

N = total number of landslide observations (N = 669 for DEM-based themes, or 663 for soil type); and

P = total number of pixels in the thematic map (P varies for different thematic raster maps).

The overall susceptibility is obtained by adding the weight value of each individual thematic weight map on a pixel by pixel basis as follows:

$$W_i = \ln\left\{\frac{[N_i / P_i]}{[N / P]}\right\} \qquad [3]$$

Traditional approaches involving the Weights of Evidence method typically consider both positive and negative weights, which are associated with presence, and absence, respectively, of landslides given the presence of a spatial factor. In the author's experience on a wide variety of susceptibility investigations, use of the negative weights adds little or no additional predictive power, and these have been neglected in the current study. The calculated susceptibility value in Equation [3] correlates with the expected number of landslides per unit area.

2.4 Limitations

There are three main limitations to be noted by the reader. First, while the landslide inventory is relatively large (692 identified landslide locations, which appear to cover the entire island), there are some issues with data integrity. The landslide point data are drawn from Government of Saint Lucia (2008), which does not provide a detailed description of the methodology used in compiling those points, some of which are clearly taken from DeGraff (1985), but many of which are not. It is therefore not known if there is any systematic bias due to, for example, some form of spatial censoring (i.e. identification of landslides only in selected parts of the island, as described in the air photo interpretation and terrain mapping of Rogers, 1997). The landslide points have also been extracted manually from a digital copy of the landslide inventory map. Examination of selected point locations in relation to available information suggests that identified landslide locations are perhaps within 100-200 m of their true locations. This difference is not particularly important when comparing locations with certain data that do not change rapidly over that span, but likely have an impact on comparison with data derived from available topography.

The second key limitation is that the work addresses landslide initiation only, and does not consider landslide runout. Since landslides in Saint Lucia tend to occur during heavy rain, they are likely to be accompanied by swollen rivers, which can carry landslide debris considerable distances as debris flows/floods or concentrated flows. The Ravine Poisson landslide of 1938, with 99 fatalities, was a series of three such flow events within a span of 24 hours, and occurred in gently sloping floodplains at the convergence of Ravines Poisson and Ecrivisse. This location has been identified as low hazard by both DeGraff (1985) and Rogers (1997) and will be identified as low hazard for landslide initiation by any method, due to the gentle slopes in the area. The potential for channelized flow of landslide debris therefore requires separate consideration, and is not addressed in this paper.

The third and final limitation relates to scale of analysis. This work was done at the regional scale, based on data available for the whole island. The map is not intended to be interpreted for site specific hazard or risk assessment at a local property or facility, and is rather intended only to guide the establishment of priorities for more detailed study.

3 LANDSLIDE SUSCEPTIBILITY

The results of the weights of evidence analysis are summarized in Tables 3 and 4. These Tables provide individual weight factors for all sub-factors within each of the geospatial themes considered in the analysis, along with the range of weights within each theme. This range provides an initial indication of the probable importance of the given theme within the resulting susceptibility model, since relatively high positive or negative weights indicate stronger positive or negative correlations between a sub-factor and landslide incidence. However, the relative importance of a given theme is also influenced by the spatial proportions of the sub-factors with high or low weights. For example, the strongest weights might be associated with a very small area, with the rest of the map having weights close to zero; in this case, the resulting weight map would have little power to discriminate susceptibility except in the small area with strong weight, hence it would have relatively little overall value in the combined susceptibility map, except in a small area.

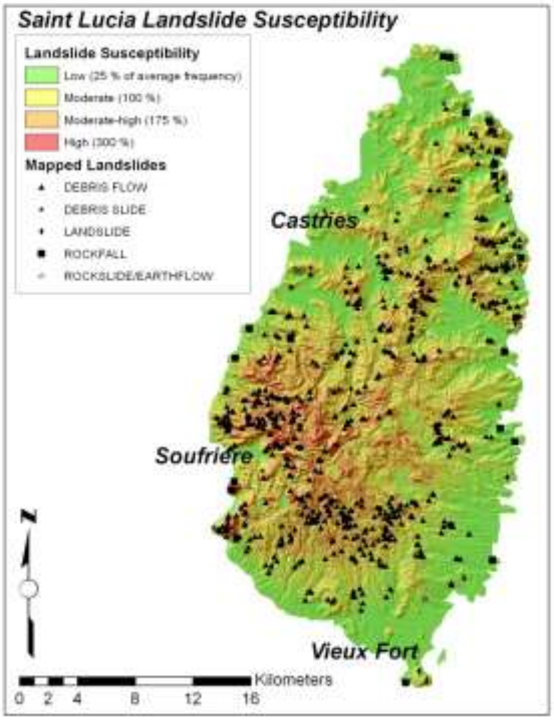

Figure 9. Landslide susceptibility map for Saint Lucia.

The susceptibility model with best overall performance resulted from a combination of the weight maps for elevation, aspect, plan curvature and slope angle. Inclusion of the soil class weights either yielded no change to the model effectiveness, or decreased model performance, hence these were excluded from the final model. The combination of these four DEM-interpreted thematic weight maps yielded a new continuous raster with values ranging from a low of -3.387 to a high of 2.485. This raster was reclassified into ten new slices, each corresponding to an equal number of landslides. The results of this analysis and reclassification are tabulated in Table 5. The equal-landslide slices were further re-grouped on the basis of similar landslide density to produce a final map with four broad engineering categories: low, low-moderate, moderate-high, and high. The resulting map is illustrated in Figure 9. A simplified version of this map is included as Figure 10. This latter map shows areas of the island that are expected to have roughly two and three times as many landslides, on average, as compared with the island-wide average landslide density. Therefore this map emphasizes areas of expected higher landslide density, where landslide hazard is elevated.

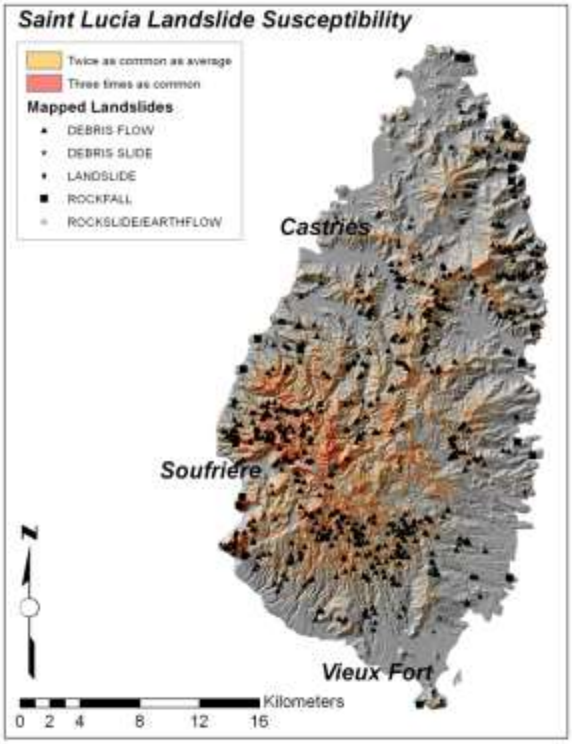

Figure 10. Simplified landslide susceptibility map for Saint Lucia.

4 QUALITATIVE LANDSLIDE RISK TO HUMAN HABITATION

The landslide susceptibility map provides an indication of the likely spatial distribution of future landslides. Landslide hazard can be inferred from this map in a relative sense: areas with higher susceptibility have higher hazard, due to the higher spatial probability of future landslide activity. An understanding of hazard cannot be deduced directly from the map directly without some indication of temporal distribution, which is currently unavailable; however, the temporal distribution of future landslides is expected to be associated with prolonged heavy rainfall, which is generally felt island wide, so spatial differences in hazard are expected to be strongly linked to the spatial distribution of susceptibility. Therefore hazard and relative risk can be inferred directly from susceptibility, provided one has information about the spatial and temporal distribution of elements at risk.

Available topographic data provided by the Government of Saint Lucia includes vector data showing the footprint of all buildings on the island. These data were used to estimate the distribution of population density, as illustrated in Figure 11, with values ranging up to approximately 6400 persons per square kilometre. This map can be combined with the susceptibility map to delineate areas with higher relative landslide risk, as an aid to prioritizing future efforts in island-wide landslide risk mitigation. Figure 12 shows the distribution of qualitative risk to human habitation, obtained by multiplying the relative landslide frequency from the susceptibility map in Figure 9 (e.g. 0.25 for “low” and 3.0 for “high”) with population density in Figure 11.

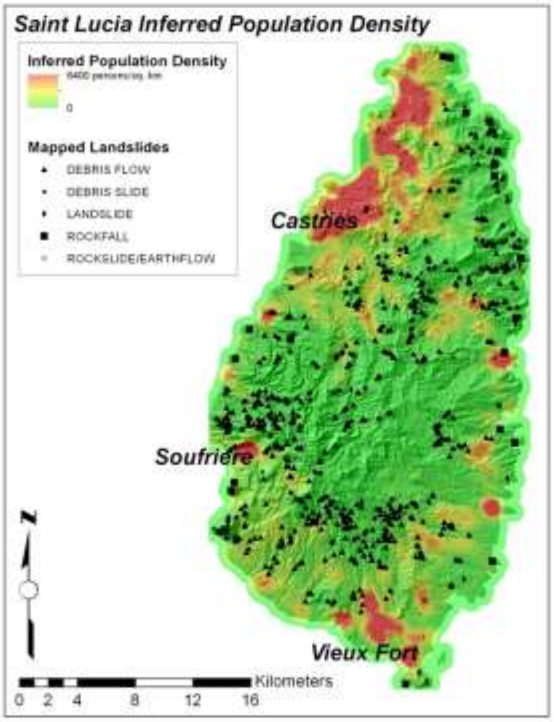

Figure 11. Inferred population density in Saint Lucia.

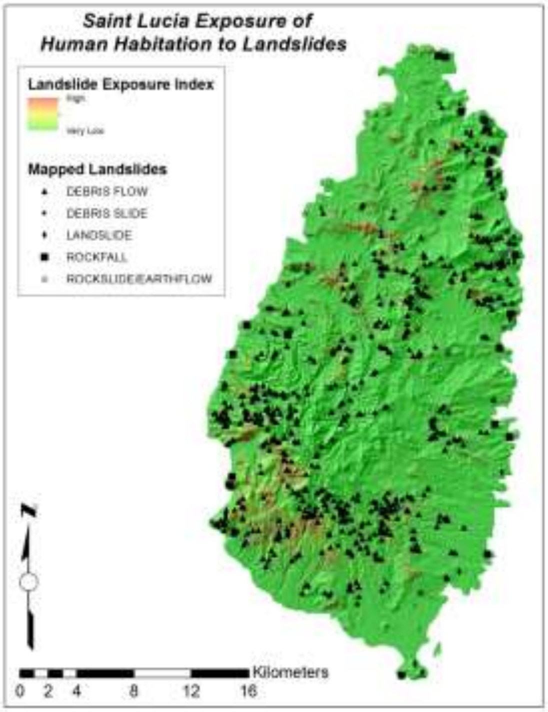

Figure 12. Landslide exposure map for human habitation in Saint Lucia.

5 DISCUSSION

The findings of the this work confirm and expand on the work of prior researchers, with some new insights, and the primary additional benefits of covering the whole island and being supported by recent topographic data and a relatively substantial landslide inventory data.

The analysis reveals a trend for increasing landslide incidence with increasing elevation, due to orographic effects. Landslide incidence is elevated for slope aspect ranging from about 130 to 270 degrees, and otherwise lower than average, suggesting a relationship with prevailing winds.

Prior work by Anderson (1983) and Anderson and Kneale (1985) suggested relationships between landslide incidence and topographic plan curvature. The present analysis confirmed this prior finding, although both concave and convex slopes tend to be more susceptible to landslides than flat slopes, which differs from their finding for landslides in the Barre de l'Isle area, where concave slopes were more susceptible except with low permeability soils, where curvature had little significance.

Slope angle is the strongest predictor of landslide incidence, with landslides generally more frequent for slopes greater than 20 degrees.

Relationships between the major soil types and landslide incidence were not very strong, except in the case of alluvial soils, where landslides tend to be absent, due to their gentle grades and to lower rainfall associated with their typically lower elevation. Since both of these factors are addressed through DEM-interpreted themes, consideration of the soils data added no benefit to the overall model. It was expected from work by DeGraff (1985), DeGraff et al. (1989) and Caribbean Development Bank (2006) that soil type should influence landslide incidence; however, it is believed that the general soil classification scheme, applicable for agricultural or forestry applications, does not adequately reveal the textural or mineralogical differences that would be associated with landslide incidence. Availability of a surficial geology map, with soils classification based on geomorphology and/or genesis, is expected to lead to stronger relationships with landslide incidence, and should thus improve the model. The soil erosion class map yielded generally weak weights, and was thus of little importance in the analysis. The slope gradient map from the soils data yielded stronger weights, but added no value to the map since this attribute was already addressed by the DEM-interpreted slope map, which had finer discretization of the slopes of interest (i.e. the higher slope angles). Bedrock data were not available in GIS format and were therefore not considered; digitization and incorporation of the bedrock map should also improve the model.

The combination of the landslide susceptibility and inferred population density maps to produce a qualitative risk map has some potential utility in planning and prioritization of future landslide risk mitigation efforts. Elevated landslide risk is concentrated in a relatively small proportion of the island, with concentrations of risk in the highlands around Castries, in many parts of the Qualibou depression around Soufrière (including a high risk area indicated at Fond St. Jacques, the site of 10 fatalities during Hurricane Tomas), and in several other steeply sloping areas with human settlement.

It may be noted that the qualitative assessment of risk to human habitation considers existing development patterns, and is not suitable for guiding decisions on future development. The landslide susceptibility map would be a more suitable starting point for examining hazard and risk affecting new development; however, it is intended for use on an island-wide scale, and lacks adequate resolution to guide decisions for individual local sites. Site specific study is necessary to check any interpretations of landslide hazard made from the susceptibility map.

6 CONCLUSIONS

This paper presents a landslide susceptibility model for the island nation of Saint Lucia, developed using the weights of evidence approach. Nine different geospatial factors were compared spatially with an inventory of 692 landslide points. Of these nine factors, six were drawn from an available DEM, and three were drawn from available soil mapping. The final model was based on ground elevation, slope aspect, plan curvature and slope angle. The soils data and two other DEM-based interpretations were set aside from the analysis as the selected four themes were demonstrated to give the strongest predictive model.

The landslide susceptibility model has been combined with inferred population density to obtain a qualitative representation of landslide risk to human habitation. Landslide risk is presently concentrated in selected highlands around Castries and Soufrière, and in several other steeply sloping areas with human settlement.

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