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Landslide Susceptibility of Portland, Jamaica: Assessment and Zonation

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ABSTRACT. The Government of Jamaica commissioned landslide susceptibility assessment of the parish of Portland represents a response to the continuous landslide problem experienced there. Portland is known for the frequent occurrence of landslides, induced by rainfall or seismic activity. Losses amounting to millions of dollars and numerous disaster-related deaths are attributed to landslide activity. Medium-scale (1:50,000) landslide susceptibility analysis through a combination of direct (field) and indirect (statistical) methods is used to generate a landslide susceptibility model for the parish. Using an inventory of known landslides, the bivariate statistical method, specifically simple map combination, is applied to compute weightings for the predisposing factors of landslides originating from topography and geology. The methodology used attempts to maintain full objectiveness in the model. Field experience is introduced where statistical methods fall short of realistically predicting the natural environment. Experience is also used to test the practicality of the map, bridging the void from the ideal theoretical model to the realistic ground truth. The susceptibility model ideally predicts existing landslides with approximately 80% accuracy; a value that is highly acceptable. The model may be employed as a tool for rural and physical planning, engineering works, building and infrastructure developments, and importantly natural hazard mitigation.

Key words: landslide; susceptibility; Portland, Jamaica; bivariate statistics.

1. INTRODUCTION

Increasing loss of property and lives from landslide disasters has led the Government of Jamaica, through the Mines and Geology Division (the local Geological Survey) to undertake landslide susceptibility analysis of different regions of the island. The eastern parishes of Jamaica are historically known for the frequent occurrences of damaging landslides. Examples include the popular Judgment Cliff landslide of St. Thomas of 1692 (Zans, 1959), the Millbank landslide of Portland of 1937 (Harris, 2002) and the Preston landslide of St. Mary of 1986 (Bryce et al., 1987). These have induced large losses and caused numerous deaths and have highlighted the urgent need for zonation of the land surface according to the probability of occurrence, that is, the propensity or the susceptibility for land slippage. Under the landslide susceptibility assessment programme started by the Government in 1998, a pilot study was done on the Rio Grande Valley (Mines and Geology Division, 2000) and St. Thomas and St. Mary parishes were subsequently zoned (Mines and Geology Division, 2004a, b). The study of Portland followed (Bhalai, 2007; Mines and Geology Division, 2007).

Landslides in Jamaica are generally triggered by earthquakes or during heavy rainfall events. Sometimes both processes work in tandem. The Judgment Cliff landslide is one such case which occurred either during or shortly after the Great Port Royal Earthquake of 1692, when there was also a period of torrential rains where the Yallahs River was in spate. Jamaica is tectonically active and the eastern end shows dominance in seismic activity. In terms of earthquake frequency western Portland is classified as having the potential to experience 8 to 15 damaging earthquakes of MMI VI or greater per century as computed by Pereira (1979). Central Portland has a frequency of 6 to 7 events per century whereas east Portland may experience 4 to 5 events per century. Other regions in Jamaica have an average expected frequency of 3 to 5 events per century. The January 13, 1993 earthquake of MMI VII had epicentre at the Blue Mountain Ridge between St. Andrew and Portland. Forty landslides were triggered in these parishes, many of which were in Portland. Roads were blocked and water pipes and electricity poles damaged (Ahmad, 1996). In one case, at Greenhill, on the Newcastle to Buff Bay road, 100 m of roadway was destroyed (Harris, 1996).

Figure 1. Rainfall-induced landslide (November 2005) at London along the Seamans Valley to Moore Town Road, Rio Grande Valley, in weathered volcanic rock and shale. Classified as a rock slump–debris/earth flow. Damage included blocked road, four houses obliterated along with personal effects of occupants, light pole toppled and water main severed. (A) View up-slope of landslide (left-hand side facing the landslide). The scarp is the source area for the material. Perched groundwater emerging from the landslide body results in the spring. (B) View along road looking towards Moore Town (right-hand side facing the landslide). The spring in (A) has eroded a channel in the road. Unstable debris continued blocking the road as the material settled. The partly stable boulder in the foreground threatened road users. The inset shows the size of the boulder compared to the size of a man. (C) Remains of houses destroyed by the landslide (toe-area of landslide). Three of the obliterated houses were at this location; only two are visible. Note the toppled electrical pole. [S. Bhalai, Dec. 2005 and R. Green, Nov. 30, 2006].

Eastern Jamaica receives on average 500 cm of rainfall annually with Portland receiving more rainfall than any other parish. During the period of rainfall from January 3 to 4, 1998, Portland received between 200 mm and 300 mm of rainfall. Many landslides were triggered causing severe damage and destruction to agriculture, buildings, roads and infrastructure. Thirty-five houses were damaged and 25 were destroyed. Damaged roadways total 1.27 km and 0.8 km was destroyed. Of the total damage estimate of JA$384.2 million (1998 dollars), 60% or JA$231.1 million was accountable to landslide events (Harris, 2002). Landslides continue to cause large economic losses through damage of property and infrastructure; unfortunately sometimes lives are lost (**Figures 1-5**).

Figure 2. Rainfall-induced landslide at 4 Red Hassle Road between Port Antonio and Breastworks. Rainfall period Nov. 19 – 25, 2006. A: View from main road at base of landslide; note that the house has been mangled with the landslide debris. B: Side view of destroyed house. The body of a woman that died was dug from the doorway of this partially intact bedroom (marked by arrow). [R. Green, Nov. 30, 2006].

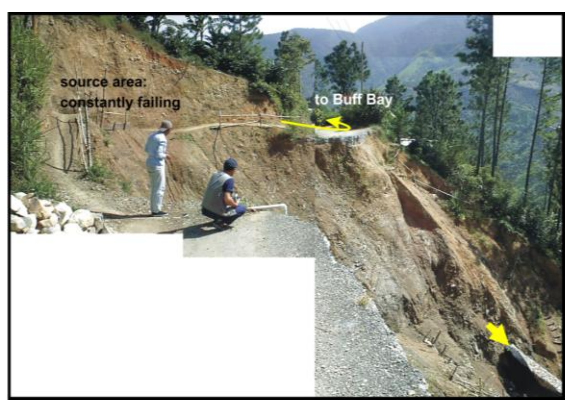

Figure 3. Composite showing break-away at Section, Newcastle to Buff Bay main road. The source area of the landslide is continually retreating, constantly destroying the footpath cut on the left. At the extreme bottom-right-hand corner of the plate is the remediation gabion works under construction (thick arrow). Informal communication with resident in 2006 revealed that this installation will cost $3 million. [S Bhalai, Aug. 2006]

Figure 4. Elaborate gabion works installed at Spring Hill, Buff Bay River valley. Landslide (background) had obliterated the road. The source area still having portions of the slipped mass is clearly visible. This structure is a combination of step-gabion baskets and mattress gabion baskets (partially seen at base of photograph). Note the large drainage pipe at the centre of the photo. Poor drainage is a major trigger of slope failures throughout Portland. Remediation measures such as this are quite costly [R. Green, Feb. 2007]

It is therefore necessary to be able to predict the landslide susceptibility, that is, the probability of the occurrence of potentially damaging landslides across the parish in order to reduce disaster-related costs and proactively save lives. Many techniques are currently available for predicting landslide susceptibility employing direct (landslide inventory approach) and indirect (heuristic, statistical and deterministic approaches) methods (Hansen, 1984; Soeters and van Westen, 1996). For Portland a combination of both methods was employed. The direct method involves surveyors indentifying and documenting past and present landslides, and making interpretations of the potential for failure. Indirect methods follow where landslide distribution obtained by the surveyor is analyzed statistically using factors that can cause landslides, such as, elevation, slope gradient, slope aspect, lithology and geological faults, to determine weightings or the respective role of each factor.

Bivariate statistical analysis, introduced by Brabb et al. (1972), is the approach of choice. The landslide distribution map is simply combined with individual maps of elevation, slope gradient, slope aspect, lithology and geological faults. This comparison shows numerically the correlation of landslides with the causative factors. This is further used to compute the weight or level of susceptibility (Susceptibility index) for each factor. This index is applied to the maps of each causative factor as a weighting value, and these spatial coverages are simply combined to generate the final model.

Figure 5. Fig. 5. Landslide at Friday, south of Ginger House, Rio Grande valley. Landslide (centre) has reduced the road to narrow single lane. The landslide is very active, continually retreating over the last 10 years. It continues to fail as the unstable colluvial material slips from the steep slope above in the zone of unstable material delineated by secondary shrubbery. Colluvium consists of debris of volcanic rock and limestone originating from across the river (behind photographer). Note that the colluvium overlies the shale which shows distinct bedding in the river bank (lower left-hand corner). Beds dip towards the river encouraging planar failure in the colluvium. This particular landslide has made several news reports as the locality is hazardous to road users. The latest was 2009 when a vehicle toppled over and became lodged just below the roadway. [S. Bhalai, June 2009]

This final model is classified into zones of increasing landslide susceptibility. Guidelines defining each susceptibility zones are created to support the model and increase its usefulness to planners, engineers, developers and citizens who may have an interest in understanding the landslide propensity of the parish.

2. PHYSIOGRAPHY AND GEOLOGY

The parish of Portland covers 814.5 km^2, or approximately 7% of the area of Jamaica, and includes the northern flank of the Blue Mountains. The parish is dominantly mountainous with low hills on the northern edge and the steeper, higher slopes of the Blue Mountains on the southern extent (**Figure 6**). Blue Mountain Peak, the highest peak in the range, culminates at 2256 metres above sea level. There are also the John Crow Mountains, a low cuesta in the east. Surficial drainage is dominant in Portland; the parish hosts five watersheds having large rivers, such as, the Rio Grande, Buff Bay, Swift, and Spanish Rivers. These are rarely dry, because their headwaters are constantly fed by rainfall in the mountains.

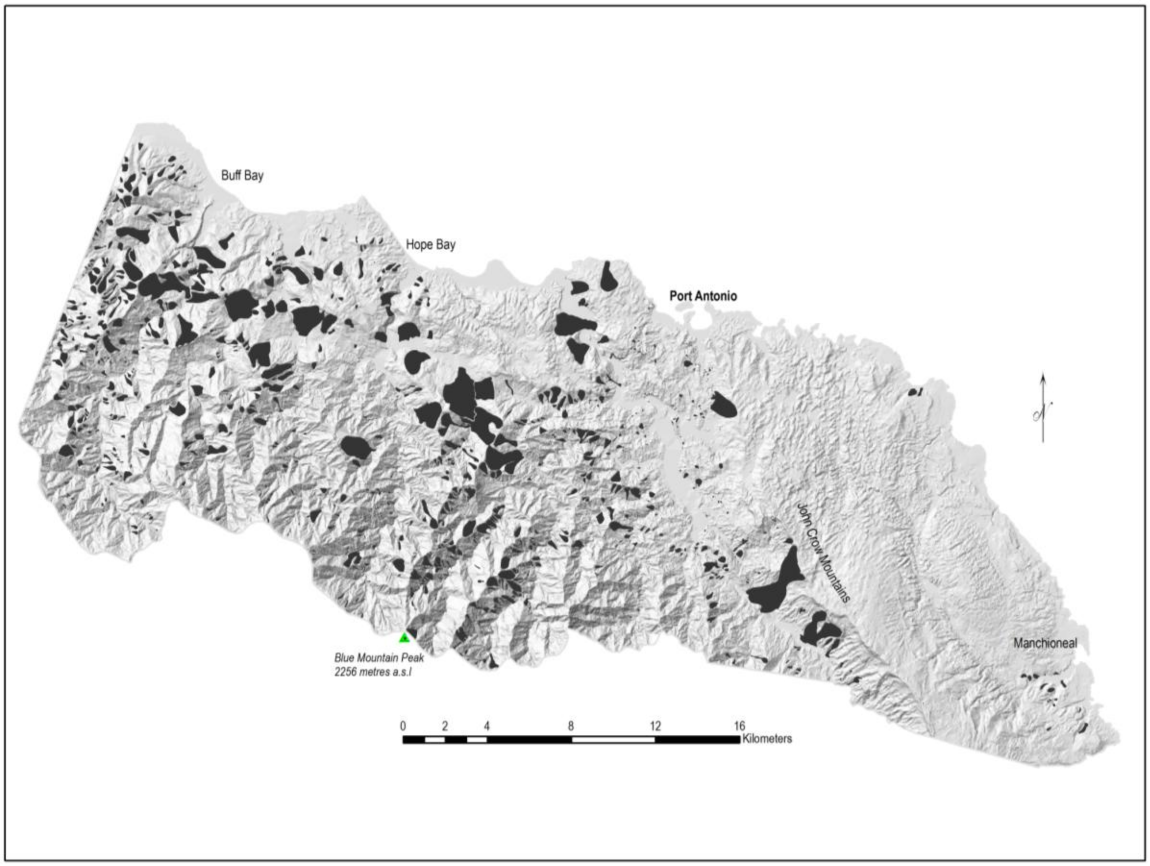

Figure 6. Digital Terrain Model of Portland with landslide inventory.

Sedimentary and igneous rock types dominate though metamorphic lithotypes are present (**Table 1**; Mines and Geology Division, 1997a-d). These are of Cretaceous to Neogene age (**Figure 7**). The Cretaceous rocks occur in the Blue Mountains inlier and include quartzo-feldspathic and basic schists, tuffs, lava flows and granodiorite intrusions. Cretaceous lithologies comprise the upper sections of the Blue Mountains extending from Silver Hill Peak in the west to the left bank of the Rio Grande in the east. These extend northwards as far as Port Antonio.

Paleocene to Miocene sedimentary rocks encircle the Blue Mountain inlier. Paleocene-Eocene rocks dominate, and range from conglomerates, sandstones and shales, to impure to pure limestones. The John Crow Mountains comprise shale capped by deep-water micrites. There are also minor Miocene volcanic rocks (tuffs and lava flows) in the north central section of the parish. Elevated rocks of the Coastal Group fringe the coastline. Fluvial deposits extend from the coastal areas inland along some of the river valleys. Large masses of colluvium consisting of rock and debris drape the landscape in many areas such as Shrewsbury, Tranquility, Milbank and Cornwall Barracks.

The dominant structural feature of Portland is the northern extension of the Blue Mountain Inlier superimposed with an intricate fault pattern reflective of polyphase deformation due to overprinting of tectonic events. The mountainous terrain consists of densely fractured rocks that have been exposed to long periods of deep weathering, and are highly susceptible to landslides.

3. METHODOLOGY

Many approaches have been employed in Jamaica for landslide susceptibility assessments (Miller et al., 2007; Northmore et al., 2000; Unit for Disaster Studies, 1999). These generally involve combining direct and indirect methods. The methods are similar, with field surveys conducted initally and statistical approaches used in the analytical stage. The differences arise in the specific statistical techniques chosen. Miller et al. (2007) and Northmore et al. (2000) use bivariate statistical analyses in their studies. Miller et al. (2007) used Bayesian conditional probablility in zoning the parish of St. Thomas and Northmore et al. (2000)

Table 1. Lithostratigraphic record of Portland. Groups of similar geotechnical behaviour used in the landslide susceptibility analysis are also listed. Data extracted from Mines and Geology Division (1997a-d).

AGE	GEOLOGIC GROUP	GEOLOGIC UNIT	SYMBOL	LITHOLOGICAL DESCRIPTION	GEOTECHNICAL GROUPING
Recent		Colluvium	-	Loosely or poorly consolidated rock, debris and soil material.	COLLUVIUM
Recent to Miocene		Alluvium	Qa	Unconsolidated or partly consolidated river sediments	ALLUVIUM
	COASTAL GROUP	Elevated reef	Ql	Elevated reef	COASTAL GROUP
		Low Layton Lava	MP1	Basalt pillow lavas and breccia	TERTIARY VOLCANICS
		Buff Bay and Manchioneal Formations	MP	Fossiliferous reefal limestone, sandstone and marls	COASTAL GROUP
Miocene to Mid-Eocene	WHITE LIMESTONE	Montpelier Formation	Mm	Chertiferous planktonic chalk and micrite	WHITE LIMESTONE
		Gibraltar-Bonny Gate Formation	Egb	Evenly bedded chertiferous chalky micrites	WHITE LIMESTONE
	YELLOW LIMESTONE	Fonthill Formation	Ef	Well bedded impure micritic limestone	YELLOW LIMESTONE
Lower Eocene	WAGWATER GROUP	Newcastle Volcanics	En	Lavas, volcanic breccias and tuff	TERTIARY VOLCANICS
		Halberstadt Volcanics	Ev	Basaltic lava including pillow lavas	TERTIARY VOLCANICS
		Richmond Formation	Er	Well-bedded sandstone and siltstone	SHALE
		Chepstowe Limestone	El	impure limestone and interbedded shale	YELLOW LIMESTONE
		Wagwater Formation	Ew	Red and purple conglomerates and sandstones	CONGLOMERATE
Maastrichtian	PLANTAIN GARDEN GROUP	Bowden Pen Conglomerate	Kbp	Polymictic conglomerate and tuff	CRETACEOUS SEDIMENTARY
		Bonny View Formation (or Spring Bank Andesite)	Ksb	Plagioclase feldspar porphyry	CRETACEOUS VOLCANICS
		Cross Pass Shale	Kcp	Brown weathered shale, siltstone, sandstone and conglomerate	CRETACEOUS SEDIMENTARY
		Spanish River Formation	Ksr	Purple andesitic tuffs, lava and polymictic conglomerate with limestone	CRETACEOUS VOLCANICS
Lower Maastrichtian to Upper Campanian	ALLIGATOR CHURCH GROUP	Rio Grande Formation	Kr	Weathered green volcanic rocks and grey recrystallized limestone	CRETACEOUS VOLCANICS
		Ginger House Formation	Kgh	Tuffaceous conglomerate	CRETACEOUS VOLCANICS
		St. Helen's Gap Formation	Ksg	Dark green trachytes to olivine basalts; deeply weathered in some areas	CRETACEOUS VOLCANICS
		Bellevue Formation	Kbe	Mudstone, siltstone, porphyry, tuffs and limestone	CRETACEOUS SEDIMENTARY
	CORN HUSK GROUP	Back Rio Grande Limestone	Kbr	Rubbly limestone and conglomerate with volcanic sediments	CRETACEOUS SEDIMENTARY
		Catalina Formation	Kc	Tuffaceous andesite and conglomerate	CRETACEOUS VOLCANICS
	METAMORPHIC	Westphalia Schist	Kw	Felsic and basic schists	METAMORPHICS
	INTRUSIVE	Granodiorite	KG	Hornblende granodiorite	IGNEOUS INTRUSION
		Minor porphyritic intrusions	g		IGNEOUS INTRUSION

applied simple map combination in their study of part of the Rio Minho valley in the parish of Clarendon. Multivariate statistical techniques have been employed by Unit for Disaster Studies (1999) for modelling the Kingston district.

This assessment of Portland represents medium-scale (1:50,000) analysis of landslide susceptibility utilizing a bivariate statistical approach, specifically simple map combination. It is based on the fundamental principle that “the past and present are keys to the future” (Carrara et al., 1995). This simply means that the conditions that generated landslides in the past and even those occurring today are likely to generate slope failures in the

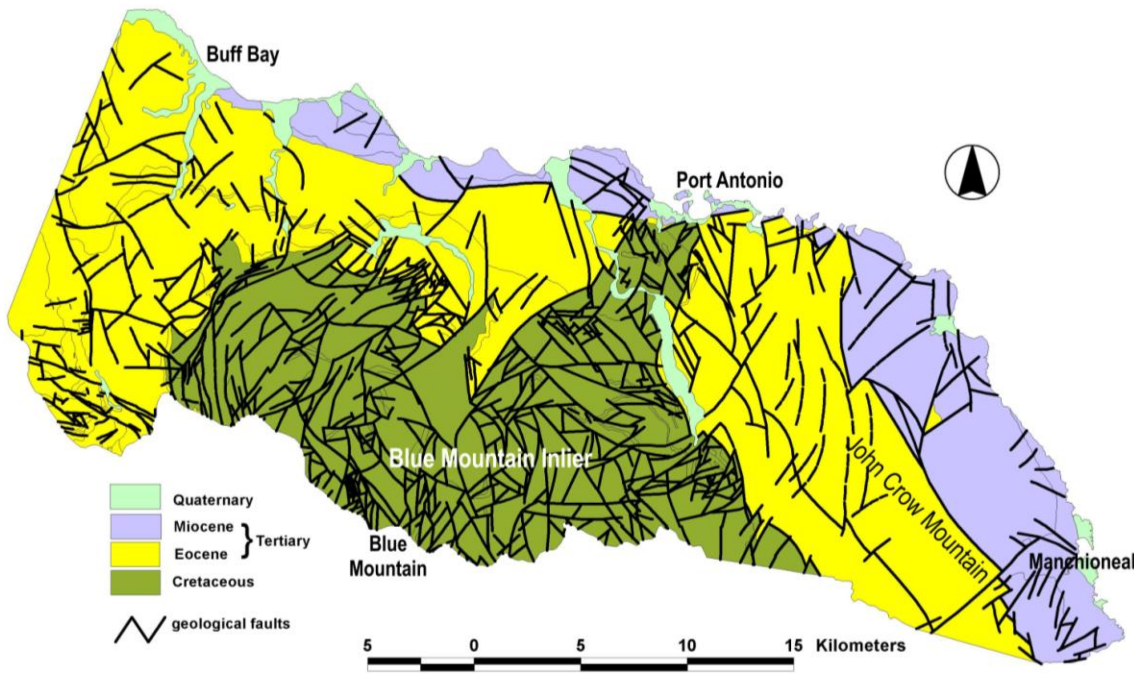

Figure 7. Age distribution of rock types in Portland. The Blue Mountain Inlier is a tectonic window of Cretaceous rocks surrounded by younger lithology. It is enclosed in the south (not shown).

future. These conditions are topographical or geomorphical, and geological in nature. Topographical causative factors are elevation, slope gradient and slope aspect. Geological factors are rock type (and their respective geotechnical behaviour) and structural features, which in the case of Portland, is the network of faults.

The assessment process, consistent with the usual practices, involves combining direct (field) and indirect (statistical) methods (Soeters and van Westen, 1996; Hansen, 1984) simplified into the following steps:

i). Remote sensing interpretation and review of records of landslide occurrences;

ii). Data collection (topographic and geological causative factors);

iii). Field surveys and confirmation checks;

iv). Statistical analysis and generation of susceptibility model (including testing);

v). Compilation of supporting guidelines for using the susceptibility model.

Documented evidence of landslide events in the form of damage assessments and reconnaissance field reports were extremely useful in determining the magnitude of the landslide problem. The local Parish Council and the Mines and Geology Division are the main bodies that generate these reports. Data collected for the susceptibility assessment may be classified as topographical or geomorphical, and geological. Geomorphical data comprise an inventory of all the landslide occurrences that can be mapped, and local terrain conditions such as elevation, slope gradient and slope aspect.

A preliminary inventory of landslides was generated primarily from remote sensing imagery interpretation, specifically aerial photographs. Monochromatic (e.g., **Figure 8**) and panchromatic photographs of varying scales (1:12,000 – 1:25,000) spanning a wide temporal range (1953 - 1992) were used. Landslides post-dating the photographs were added to the inventory based on the descriptions provided in the documented damage assessments. Landslide boundaries were plotted on 1:12,500 topographic maps. The source area, loosely defined as the upper half of the landslide (Parise and Jibson, 2000), or that part of the scarp and zone of depletion where the material originated, was defined on the maps and carefully confirmed in the field.

Field surveys and checks aided the addition of new landslides and confirmation and adjustment of the landslides in the preliminary inventory. This corrected and updated preliminary inventory represents the final inventory (Figure 6) used for analysis to generate the susceptibility model. Additionally, a part of this inventory (25%) was reserved for use in testing the new susceptibility model.

While the landslide inventory is important, for the analytical stage specific input parameters of the

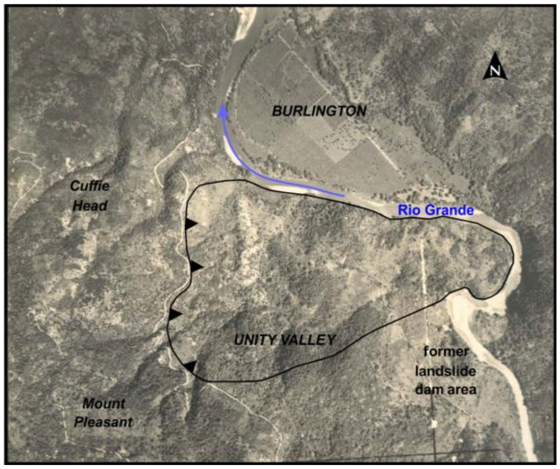

Figure 8. Monochromatic aerial photograph of the Unity Valley Landslide in the Rio Grande Valley, south-east of Port Antonio. Note the broad flat area in the bottom right hand corner of the image where a landslide dam developed. The landslide is approximately 2 km long (east-west). Long arrow shows flow direction. [1953–54 Aerial Photography by Hunting Aerosurveys Ltd.]

predisposing factors are also necessary, that is, topographical and geological features. Elevation and slope characteristics were derived from 1:12,500 topographic survey maps published in the 1960s. Geological information was extracted from the 1:50,000 geological maps published in the 1990s (Mines and Geology Division, 1997a-d). Using various computer algorithms, spatial coverages of elevation, slope gradient and slope aspect were generated from the topographic maps. In the case of slope coverage the topographic maps were limited in the areas disturbed by older landslides. For landslide areas older than the maps, it is the landslide morphology that defines contour alignment. However, it is necessary to investigate which slope gradients were originally causative. In the areas of older landslides the topographic maps show the final disturbed slope, not the original pre-failure gradient. To overcome this limitation the computer algorithm for generating the slope gradient map was modified in order to carefully regenerate the natural slope before failure. Analysis was conducted using this regenerated topography.

Coverages of rock types, grouped according to similar geotechnical behaviour, and distances from geological faults were also generated. Geotechnical behaviour was determined based on the classification of O'hara and Bryce (1983) confirmed by observations of the surveyor. Geological faults were obtained from the published geological maps. Distance from faults was easily calculated using computer algorithms.

The coverages of the causative factors were each subdivided into various classes or ranges to understand the correlation with landslide activity and further detail the analysis. Elevation was split into ranges of 100 m (**Figure 9**). Slope gradient was grouped into 10° ranges (**Figure 10**) and slope aspect according to the eight major cardinal directions (**Figure 11**). Lithology was grouped into thirteen geotechnical classes (**Figure 12**; **Table 1**). Distances of 50 m-ranges were outlined from major geological faults. The highest resolution permitted by the datasets was utilized, ensuring no compromise to the true natural characteristics of the features. This was dependent on the scale of data collection.

From the landslide inventory the landslide source areas were extracted for use in the analytical step. The source areas were then unevenly split where 75% was used for analysis and the remaining 25% was reserved for testing the final model. Bivariate statistical methods were used in the first stage of the susceptibility analysis to identify correlations between the predisposing factors and the landslide sources, and to generate a numerical value (numerator of equation 1) indicative of the influence of landslides on the different classes of the predisposing factors. This bivariate statistical approach was introduced by Brabb et al. (1972) where landslide distribution was combined with a slope map and a lithology map to derive the landslide susceptibility for part of California. In the past the technique of overlaying maps was cumbersome but today Geographic Information System software conveniently and efficiently facilitates this step.

The numerical values derived for each causative factor were used in equation 1 to compute the respective weighting value or Susceptibility index.

$$\text{Susceptibility} = \left(\frac{A_1 / A_2}{A_3 / A_4} \right) \times 10 \quad \text{..........} [1]$$

Where:

A1 = area of landslide sources within class of predisposing factor
A2 = area of class of predisposing factor
A3 = total area of landslide sources in parish
A4 = area of parish

The calculated Susceptibility indices were further applied to the respective coverage of each causative factor as weightings. The weighted maps were all summed to generate the final susceptibility model.

The susceptibility model generated from the summation of maps of all the predisposing factors comprised a wide range of values. These were grouped into five zones of susceptibility, where low

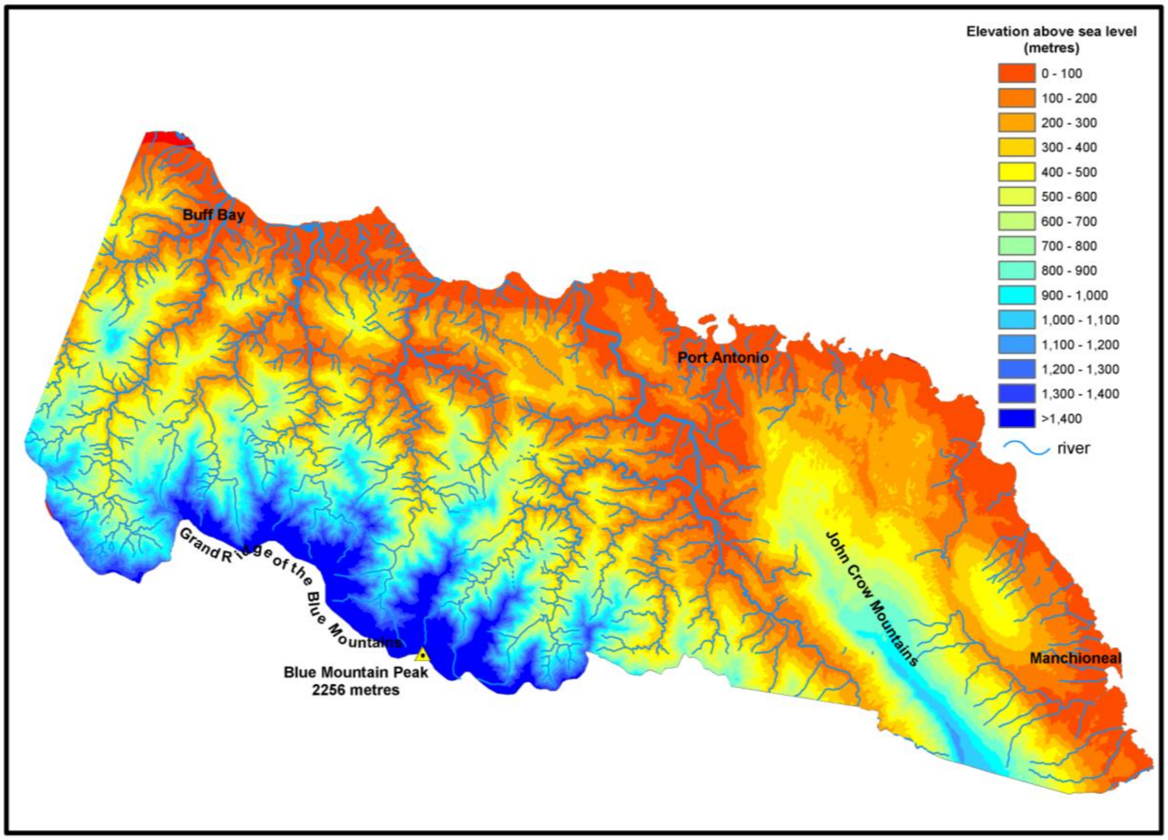

Figure 9. Elevation classes of Portland. The drainage network is included to show depth in the coverage.

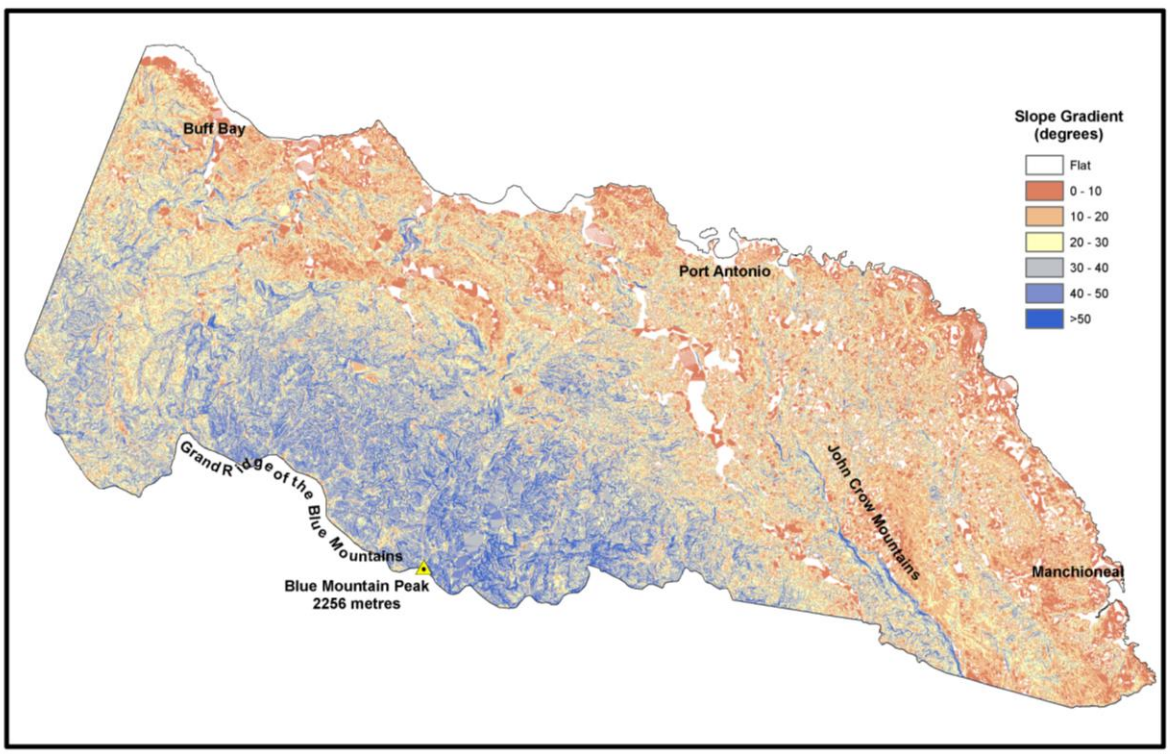

Figure 10. Slope gradient distribution in Portland. Note that steep areas are on the Blue Mountains upper slopes.

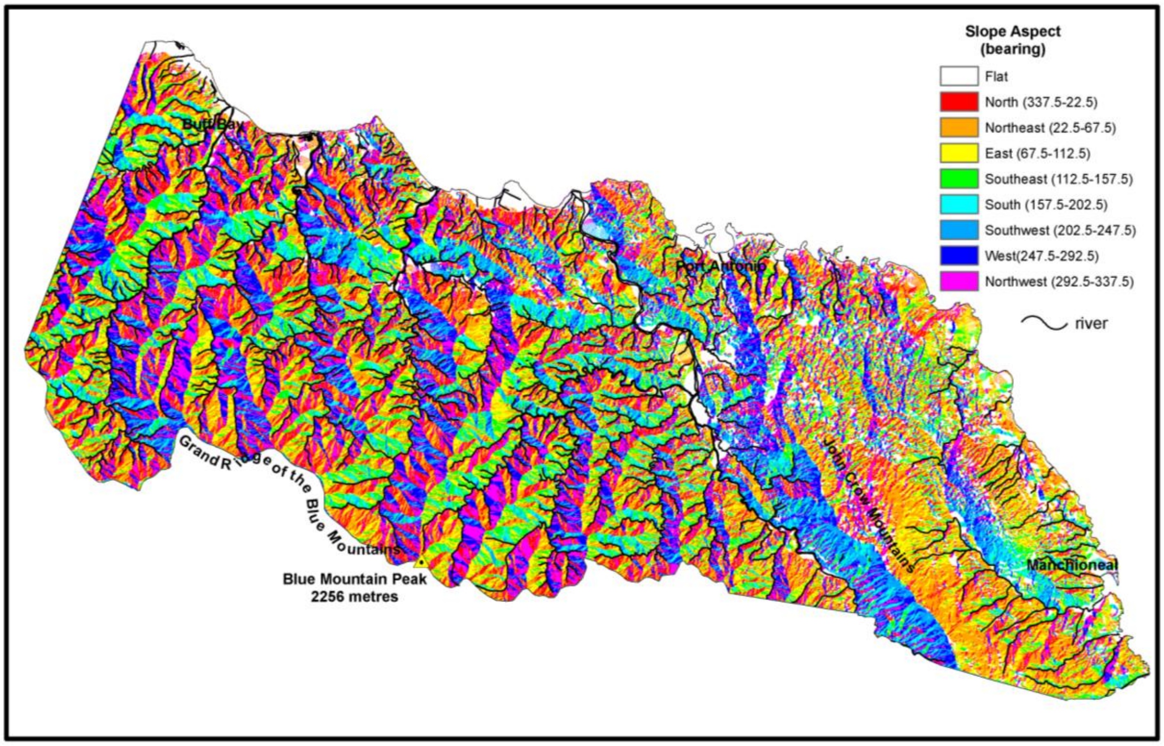

Figure 11. Slope aspect of Portland. The drainage network is included to show topographically low areas. Note the dominant pattern of the west and southwest facing scarp slope and the northeast facing dip slope of the John Crow Mountains.

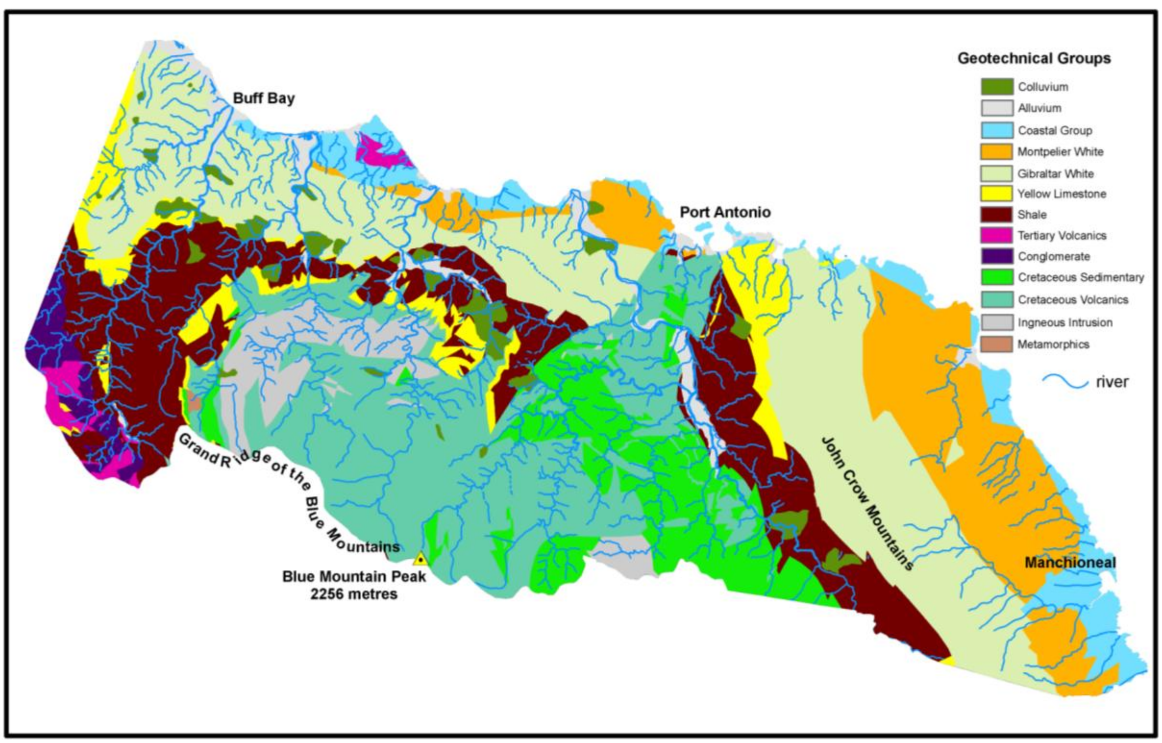

Figure 12. Distribution of the Geotechnical Groups used in the susceptibility analysis.

Table 2. Landslide susceptibility of elevation classes

ELEVATION CLASSES (m above sea level)	AREA OF CLASS (km²)	SCARP AREA IN CLASS (km²)	SUSCEPTIBILITY
0- 100	136.4554	1.0236	2.6
100 -200	123.6003	2.3686	6.6
200 -300	119.1669	3.5889	10.4
300 - 400	92.2470	3.5363	13.3
400 -500	69.2677	2.7572	13.8
500 -600	51.2632	2.7784	18.8
600 -700	43.5436	1.9553	15.5
700 -800	37.8315	1.5051	13.8
800 -900	32.3153	1.2444	13.3
900 - 1000	24.9282	0.7943	11.0
1000 - 1100	20.4351	0.5646	9.6
1100 - 1200	14.7251	0.3899	9.2
1200 - 1300	12.1366	0.2729	7.8
1300 - 1400	10.0427	0.1708	5.9
>1400	25.7290	0.5940	8.0

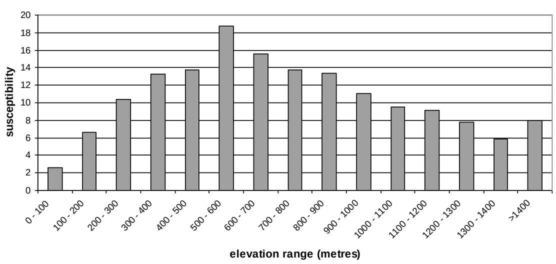

Figure 13. Elevation ranges and susceptibility. Note that the interval hosting the Blue Mountain Ridge (the area of highest elevation) shows relatively low susceptibility.

values represents lower susceptibility zones and high values represents the zones of higher landslide susceptibility.

The model generated was tested using two methods which also aided in its refinement. The first includes the use of a reserved inventory of landslide sources and the second involves a comparison with areas of known susceptibility based on field experience. For analytical purposes the final inventory of landslide sources was split into two uneven populations where 75% of the landslide sources were used for the analysis, whereas the remainder was reserved. The reserved inventory was randomly selected but carefully chosen so that this population accounted for an area of approximately 25% of the total area of the landslide sources.

The susceptibility model is designed to be used by non-technical professionals hence an understanding of the defined zones is necessary. Guidelines explaining the characteristics of each zone were created. These guidelines considered the prevailing geological and geomorphical situations in the parish in order to present a simplified understanding of the landslide probability.

4. RESULTS

4.1. *Landslide Inventory.* The mapped landslides that comprised the final inventory numbered 1041 and covered an area of 66.24 km^2 or 8.13% of the area of the parish. The sources of these landslides covered 29.73 km^2 or 3.65% of the parish area. Twenty-five percent (25%) or 260 of the total source areas, covering 6.19 km^2 were reserved for testing. Landslides may be grouped according to area, into two general classes; large and small. Small landslides were classified as those that have area less than 100,000 m^2. There are 916 small landslides, 50% of which exceeded 10,000 m^2. Large landslides are fewer, numbering 124; 80% are less than 500,000 m^2. Eleven of these larger occurrences are extremely large and the largest is 3.2 km^2, occurring in the Rio Grande Valley. The second largest at Shrewsbury, along the valley of the Back River, is 2.6 km^2.

4.2. *Geomorphic Causative Factors.* A strong correlation was revealed in the individual classes of the topographical predisposing factors. Elevation tested at 100 m intervals showed the highest correlation with the area of landslide sources. High values of susceptibility (>10) were computed over the range between 200 m up to 1000 m above sea level (**Table 2**; **Figure 13**). Within this range there is 58% of the parish area and 77% of the landslide sources analyzed. In contrast, for the lower (<200 m) and upper (>1000 m) ranges of elevation decreasing susceptibility values were derived.

Slope gradients divided into ranges of 10° showed the highest susceptibility on gradients steeper than 10° (**Table 3**; **Figure 14**). As gradients increased, susceptibility consistently increased with the highest recorded for the steeper slopes (up to 50°). Slopes less than 50° occupied a very small area and susceptibility was derived from field surveys. In consideration of slope aspect, slopes facing easterly directions all showed the highest levels of landslide susceptibility weights (**Table 4**; **Figure 15**). Additionally, north-westerly facing slopes also had high susceptibility values comparable to the east-facing slopes. South-facing slopes account for the smallest spatial coverage within the parish. The north-east facing slopes, accounting for 17% of the parish area, hosted nearly 20% of landslide source area. This is also

Table 3. Landslide susceptibility of slope gradient classes

CLASSES	AREA OF CLASS (km^2)	SCARP AREA IN CLASS (km^2)	SUSCEPTIBILITY
FLAT	5.10	0 (undefined)	0
0 - 10	303.58	2.75	3.13
10 - 20	295.59	9.18	10.75
20 - 30	159.19	8.26	17.95
30 - 40	49.13	3.45	24.30
40 - 50	1.94	0.15	26.75

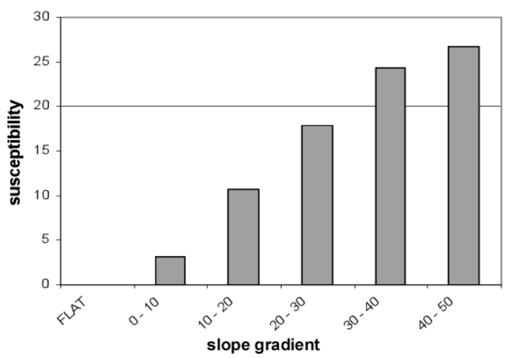

Figure 14. Slope gradient and susceptibility. Although not shown, the susceptibility of slopes of gradient >50° is low.

Table 4. Landslide susceptibility of slope aspect classes

CLASSES	AREA OF CLASS (km^2)	AREA OF SCARP IN CLASS (km^2)	SUSCEPTIBILITY
FLAT	69.820	0	0.00
N	113.185	2.279	6.97
NE	140.739	4.559	11.21
E	109.019	4.393	13.94
SE	75.120	2.814	12.96
S	59.158	1.712	10.01
SW	66.502	2.120	11.03
W	81.576	1.730	7.34
NW	99.414	3.937	13.70

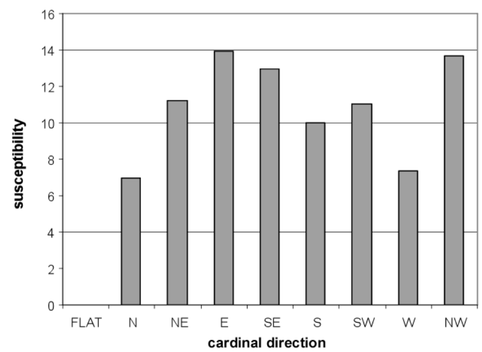

Figure 15. Slope aspect and susceptibility.

comparable to the east-facing slopes which accounted for 13% of the parish area but which hosted 20% of landslide sources. The north-easterly facing slopes correspondingly had slightly lower susceptibility values.

4.3. ***Geological Causative Factors.*** Of the thirteen geotechnical groups, six had high landslide susceptibility weights, two of which were exceedingly high (**Table 5**; **Figure 16**). The Shale, Gibraltar White and the Cretaceous Volcanics groups accounted for 16%, 23% and 20% of the source areas respectively. These had approximately equal weights of susceptibility. Colluvium and Yellow Limestone, accounting for only 2% and 5% of sources respectively, had exceedingly high susceptibilities. Alluvial areas showed extremely low landslide susceptibility. No correlation was observed with the distance from geological faults (**Table 6**; **Figure 17**). Susceptibility remained unchanged even as distance increased further away from specific faults.

4.4. ***Susceptibility Model.*** The susceptibility weights calculated for each class of the predisposing factors for landslides (**Table 7**) were used as weightings to the respective class for the generation of the susceptibility model. A form of heuristic approach is somewhat introduced where some weighting were adjusted to ensure realistic representation of the parameters. This considers field experience and general knowledge of the respective geotechnical behaviour of the predisposing factors. Summation of the final weighted coverages produced the susceptibility model (**Figure 18**).

Five zones of increasing landslide susceptibility were identified in the final model. These are zones of Negligible to Low, Moderate, Moderately High, High and Very High landslide susceptibility. Using (i) the reserved source area inventory, and (ii) areas of known landslide susceptibility, the model was tested to determine the reliability of making predictions and provide for refinement. Using the first testing technique approximately 80% of the reserved source areas were confidently predicted in

Table 5. Landslide susceptibility of the geotechnical groups

CLASSES	AREA OF CLASS (km²)	SCARP IN CLASS (km²)	SUSCEPTIBILITY
YELLOW LIMESTONE	39.5566	3.0224	26.44
SHALE	127.7602	4.4274	11.99
TERTIARY VOLCANICS	8.1901	0.2084	8.80
COASTAL GROUP	39.0423	0.1288	1.14
GIBRALTAR WHITE	187.2914	6.2035	11.46
MONTPELIER WHITE	94.2267	0.5668	2.08
CONGLOMERATE	12.3843	0.1857	5.19
IGNEOUS INTRUSION	32.8550	0.4587	4.83
ALLUVIUM	25.0663	0.0648	0.89
CRETACEOUS VOLCANICS	161.0578	5.4518	11.71
CRETACEOUS SEDIMENTARY	68.9166	0.9608	4.82
METAMORPHICS	0.5042	0.0160	10.98
COLLUVIUM	18.2420	1.8492	35.08

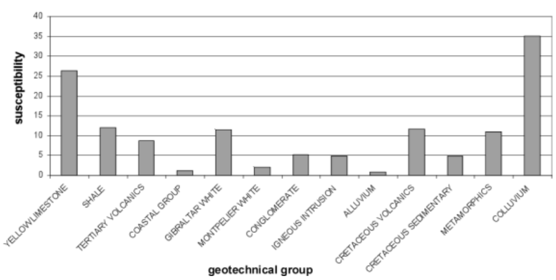

Figure 16. Susceptibility of the geotechnical groups of the rock types in Portland. Colluvium has the highest weight indicating the proportion of source areas developed in this material.

Table 6. Calculation of the landslide susceptibility of the distance from major faults classes. Susceptibility values are generally between 9 and 12 suggestive of no correlation at this distance range.

CLASSES	AREA OF CLASS (km²)	SCARP IN CLASS (km²)	SUSCEPTIBILITY
50	111.6070	3.2739	10.15
100	101.3532	2.9324	10.01
150	88.6597	2.6460	10.33
200	76.0916	2.1780	9.90
250	64.4274	1.8606	9.99
300	53.8286	1.5575	10.01
350	45.1130	1.3554	10.40
400	37.8970	1.2442	11.36
450	32.2589	1.1371	12.20
500	27.3190	1.0088	12.78
550	23.0559	0.7687	11.54
>550	153.5429	3.5347	7.97

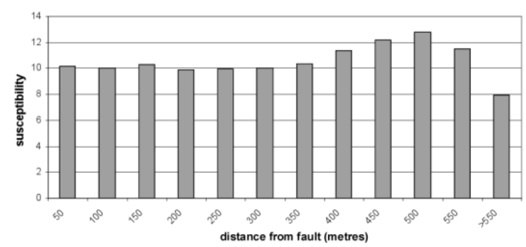

Figure 17. Susceptibility of the classes of distance from major faults. Note that with increase in distance, there is no correlation. The increase in susceptibility at and after 400 m is irrelevant, considering that the parish contains a dense fault pattern and at this distance, the zone of influence of another fault becomes active.

the three highest zones of susceptibility. With the second technique selected districts of known landslide susceptibility (areas having either high or low susceptibilities) were used and these include the Rio Grande Valley, Claverty Cottage, Buff Bay Valley, Passely Gardens, Manchioneal and Shrewsbury. The model favourably predicted the respective level of landslide susceptibility as interpreted from field observations (**Table 8**). **Table 9** shows the distribution of the refined susceptibility zones.

5. DISCUSSION

Both geomorphical and geological predisposing factors all show correlation with landslide events. An exception to this is the distance from geological faults, where no correlation was seen. The geomorphical factors all show positive correlations with landslide occurrence. High levels of landslide susceptibility between elevations of 200 m to 1000 m are possibly related to the climatic conditions prevailing at this topographic level. It is highly likely that humid conditions dominate, encouraging rapid physical and chemical breakdown of the local rock types. The rock types at these ranges may also be responsible. The Shale and Yellow Limestone geotechnical groups are dominant at these elevations and these rock types have also been found to have high landslide susceptibility, as observed in the Moore Town area in the Rio Grande Valley.

Lower levels of landslide susceptibility occur at the low and high extremes of the elevation in the parish. The extent of flat areas and alluvial plains account for the low susceptibility at elevations less than 100 m. At the higher extreme of elevation, as the rocks are decomposed, the residue is eroded during periods of rainfall, removing the weathering

Table 7. Weighting values of landslide susceptibility applied to the classes of the causative factors

PARAMETER	GROUPING	SUSCEPTIBILITY VALUE
GEOLOGY (geotechnical groups of lithology)	Yellow Limestone	26
	Shale	12
	Tertiary Volcanics	9
	Coastal Group	2*
	Gribraltar White	7*
	Montpelier White	2
	Conglomerate	5
	Igneous Intrusion	5
	Alluvium	1
	Cretaceous Volcanics	12
	Cretaceous Sedimentary	5
	Metamorphics	11
	Colluvium	28*
ELEVATION (metres)	0 – 100	3
	>100 – 200	7
	>200 – 300	10
	>300 – 400	13
	>400 – 500	13
	>500 – 600	19
	>600 – 700	15
	>700 – 800	14
	>800 – 900	13
	>900 – 1000	11
	>1000 – 1100	10
	>1100 – 1200	9
	>1200 – 1300	8
	>1300 – 1400	6
	>1400	8
SLOPE GRADIENT (degrees)	Flat	0
	0 – 10	3
	>10 – 20	11
	>20 – 30	18
	>30 – 40	24
	>40 – 50	27
	>50	3
ASPECT (bearing)	Flat	0
	N	7
	NE	11
	E	14
	SE	13
	S	10
	SW	11
	W	7
	NW	14

* denotes those values adjusted based on field experience

blanket overburden. However, the susceptibility at the highest elevation class range was high and may represent movement of dislocated fractured rocks on the steep upper slopes of the Blue Mountains.

The increase in landslide susceptibility with slope gradient is consistent with observations in other eastern parishes such as St. Mary and St. Thomas. As slopes steepened over 50º, susceptibility decreased. Weathered material accumulates on slopes, but tends to fail when the shear strength is reached as the downward pull of gravitational forces overcomes the cohesiveness of the material. The addition of moisture by rainfall (inducing an increase in mass and volume), or shaking during an earthquake, triggers movement of weathering blanket or fractured rock on slopes. On the steeper slopes exceeding 50º, it was observed that the weathering blanket is easily eroded and generally does not accumulate significantly. Landslides on these slopes are generally comprised of fractured rock material that fails when pore water pressure increases during wet conditions.

High landslide susceptibility computed for east-facing slopes possibly represent a higher degree of tropical weathering on these faces. Easterly slopes (northeast, east and southeast) are exposed to longer durations of insolation and accelerated decomposition of component material compared to slopes facing other directions. The orientation of the bedrock on these slopes with high susceptibility (including those facing northwest) may also explain these findings. The Palaeogene rock types generally dip away from the Blue Mountain inlier towards the northeast and northwest azimuths.

Five geotechnical groups displayed the highest landslide susceptibility; Yellow Limestone, Shale, Gibraltar White, Cretaceous Volcanics and Colluvium. The Yellow Limestone, Shale and Cretaceous Volcanics all decompose to clay-rich residues. Clays generally behave unpredictably when wet and show high propensity to failure. The Gibraltar White group also decomposes to clay-rich sediments which under moist conditions, and will fail especially when located on poorly drained slopes. Generally the rocks of the Yellow Limestone, Shale, Gibraltar White and Cretaceous Volcanics when fractured, fail easily. Colluvial deposits have residual strength and occasionally are partly consolidated. These fail easily especially when the angle of repose was not attained when the slipped material was deposited. These deposits commonly contain labile minerals (amphiboles, pyroxenes, micas and feldspars) that

Table 8. Prediction capability of the landslide susceptibility model of Portland. This is tested against areas of known landslide susceptibility, based on field experience

AREAS	LANDSLIDE SUSCEPTIBILITY (based on field experience)	MODEL PREDICTION
Moore Town to Holland Mountain	Moderately High to Very High	Moderately High to High
Maidstone to Rock Hall	Moderately High	Moderately High to High
Passley Gardens	Negligible/Low to Moderate	Negligible/Low to Moderate
Breastworks	Moderately High	Moderate to Moderately High
London (near Moore Town)	High	High
Friday (near Ginger House)	High to Very High	High to Very High

Table 9. Spatial distribution of landslide susceptibility zones.

SUSCEPTIBILITY ZONE	AREA (km^2)	AREA (%)	DISTRIBUTION
Negligible to Low	122.2	15	Alluvial plains, northern coastline
Moderate	228.1	28	Northern half of parish, area east of Rio Grande valley
Moderately High	211.7	26	Western river valleys, west side of Rio Grande valley, extreme upper slopes of Blue Mountain
High	228.1	28	Upper slopes of Blue Mountain, east side of Rio Grande valley
Very High	24.4	3	Patchy distribution, areas centre of parish, east side of Rio Grande valley
TOTAL	**814.5**	**100**	

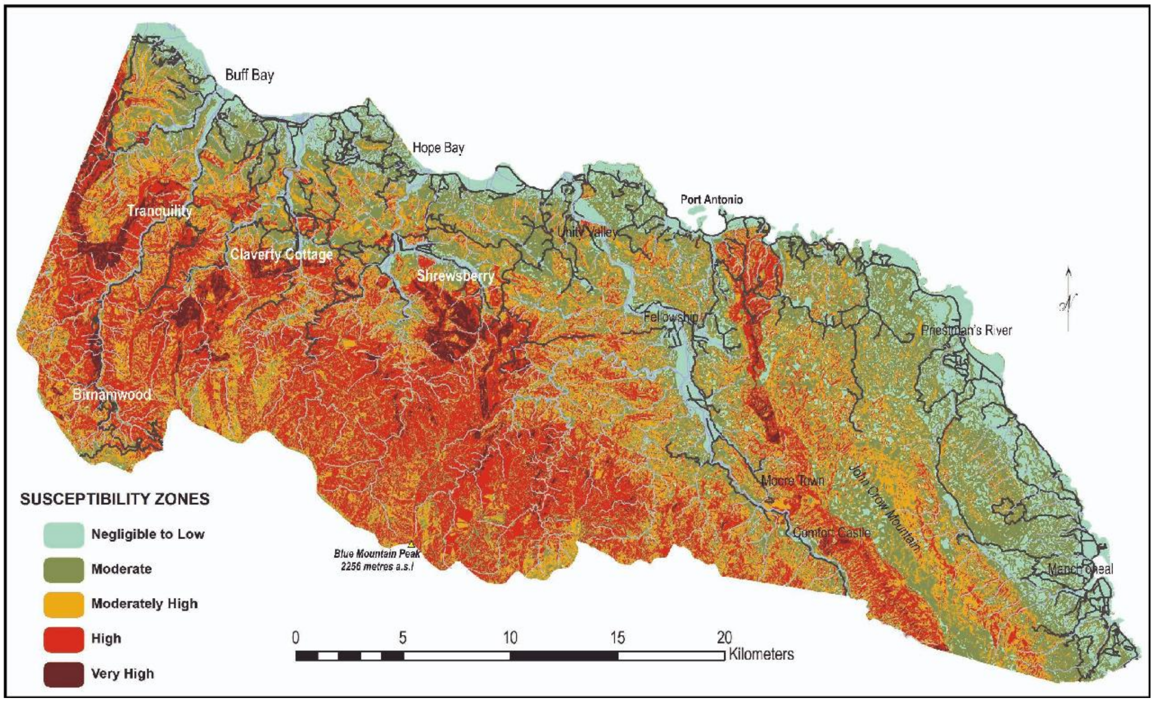

Figure 18. Landslide Susceptibility of Portland. Five zones of increasing susceptibility are chosen. These show the increase in influence of the predisposing factors of landslides

continue to decompose long after the mass has failed. As these minerals decompose, the mass and volume of the Colluvium correspondingly change making the material unstable. There was no correlation between the distance from geological faults and landslide distribution. The distance between adjacent faults was not appreciable because of the dense network and nearly all the source areas were located in close vicinity to a fault.

The susceptibility model generated has the ability to predict nearly 80% of known landslides which were not initially incorporated into the inventory for analysis. This is highly acceptable considering that the zone of moderate landslide susceptibility predicted nearly all of the remaining source areas. The model generated is intended for use by civil engineers, planners, developers, disaster managers, other professionals and citizens. Guidelines affixed to the model assist the user in understanding and appreciating the level of landslide susceptibility of each zone. These guidelines indicate the spatial distribution of the zones and present an expert's opinion as to the general size of landslides that may occur. Geotechnical problems that may arise and recommendations including possible mitigation measures are included. This is particularly important for contingency planning and gives an understanding of the economic requirements and outlays necessary for the mitigation measures that may be needed if development proceeds in a particular zone.

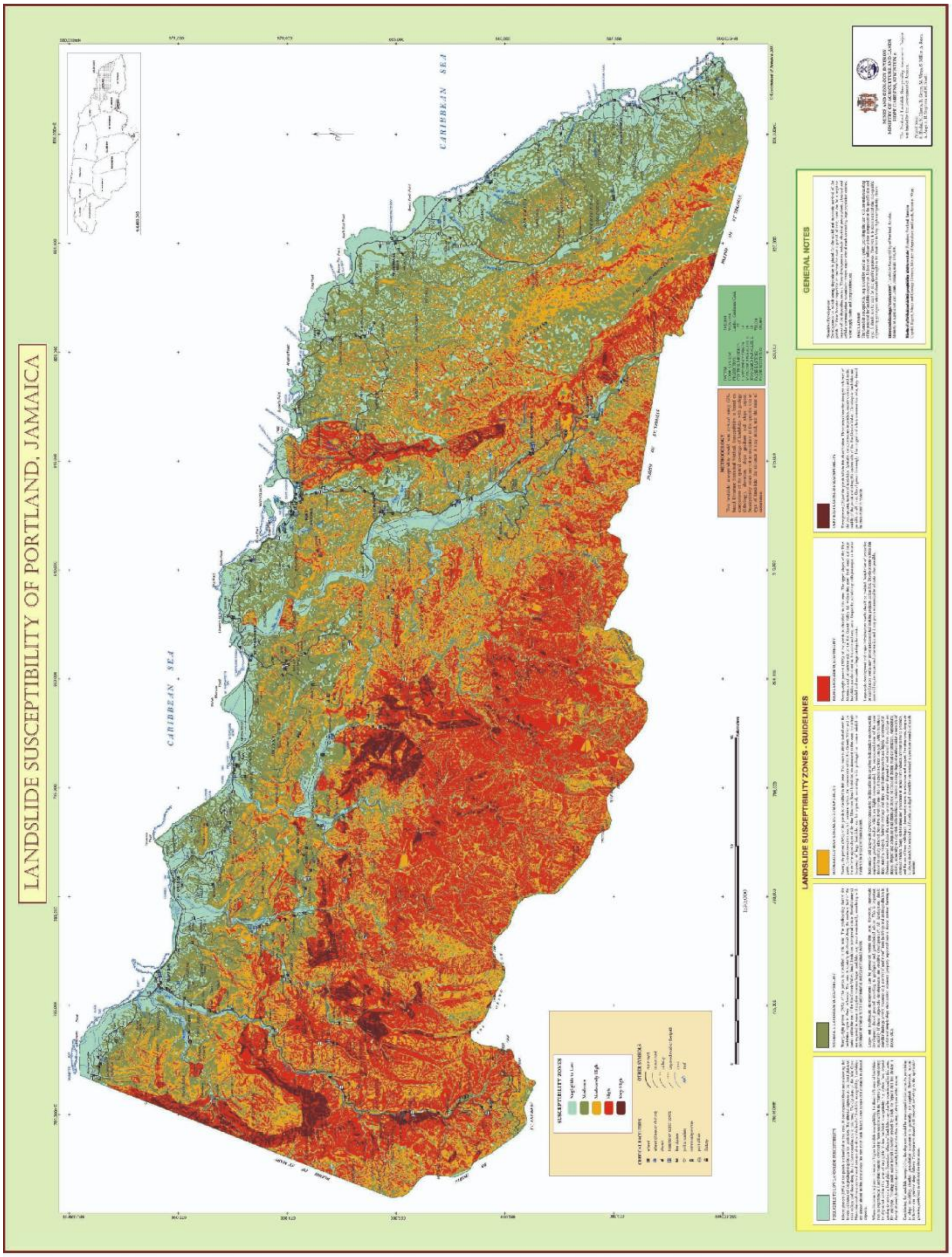

Figure 19. Landslide Susceptibility of Portland, Jamaica - map published by the Government of Jamaica (Mines and Geology Division, 2007). This document is available to planners, developers, engineers, professionals, citizens or anyone seeking an understanding of the probability for occurrence on potentially damaging landslides

6. CONCLUSION

The parish of Portland is known for the prevailing landslide problems. This is particularly due to the higher annual rainfall and seismic activity than other places in Jamaica. Bivariate statistical method, specifically simple map combination, is employed to generate a model that predicts landslide susceptibility using the predisposing factors of landslides, namely elevation, slope gradient and aspect, lithology and geological structure compared with an inventory of known landslide occurrences. The coverages of these causative factors are weighted based on the comparisons and combined to generate the final model. This model, tested and refined with an inventory of known landslides (not used in the primary analytical stage), predicted 80% of the landslide sources in the zones of higher landslide susceptibility. This model (assembled with the guidelines; **Figure 19**) represents an effort of the Government of Jamaica to respond to the need to safeguard citizens from disaster-related losses. This landslide susceptibility assessment procedure used in creating this model for Portland is continually refined as the geotechnical properties of the local terrain is increasingly understood. The refinements are applied in the creation of new models and are extended to boost the prediction capacity of earlier models. The 2009 edition of the landslide susceptibility map for St. Thomas (Mines and Geology Division, 2009) represents the latest model which is a refinement of that model (Mines and Geology Division, 2004b) created five years ago.

REFERENCES

Ahmad, R. 1996. The Jamaica earthquake of January 13, 1993; Geology and geotechnical aspects. *Journal of the Geological Society of Jamaica*, **30**, 15-31.

Bhalai, S. 2007. *Landslide Susceptibility and Zonation, Portland, Jamaica.* Unpublished Report, Mines and Geology Division, Ministry of Agriculture and Lands, Jamaica, 50pp.

Brabb, E. E., Pompeyan, E. H. and Bonilla, M. G. 1972. Landslide Susceptibility in San Mateo County, California. *Miscellaneous Field Studies Map MF360*, U.S.G.S., Reston, Virginia, 1:62,500.

Bryce, R., Harris, N. and Rammelaere, M. 1987. Preston Lands – A Geological Phenomenon. *Geological Survey Division Biennial Report April 1985 – March 1987*, 20-30.

Carrara, A., Cardinal, M., Guzzetti, F. and Reichenbach, P. 1995. GIS-Technology in Mapping Landslide Hazard. *In:* **Carrara, A. and Guzzetti, F. (Eds.)**, *Geographical Information Systems in Assessing Natural Hazards,* Kluwer Academic Publishers, Dordrecht, Netherlands, 135-176.

Hansen, A. 1984. Landslide Hazard Analysis. *In:* **Brunsden, D. and Prior, D. B. (Eds.)**, *Slope Instability*, Wiley, New York, 523-602.

Harris, N. 2002. Rain-Induced Slope Failures and Damage Assessment in Portland, Jamaica, Related to the Flood Event of 3-4 January 1998. *In:* **Jackson, T. A. (Ed.)**, *Caribbean Geology: Into the Third Millennium*, *Transactions of the Fifteenth Caribbean Geological Conference*, UWI Press, Kingston, Jamaica, 235-255.

Harris, N. 1996. Preliminary Observations on Groud Response and Performance on Non-engineered Buildings: The January 13, 1993 Earthquake. *Journal of the Geological Society of Jamaica*, **30**, 32-40.

Miller, S., Harris, N., Williams, L. and Bhalai, S. 2007. Landslide Susceptibility Assessment for St. Thomas, Jamaica using geographical information system and remote sensing methods. *Geological Society of London Special Publications*, **283**, 77-91.

Mines and Geology Division. 2009. *Landslide Susceptibility Map of St. Thomas, Jamaica*. (3rd edition) Mines and Geology Division (Ministry of Energy and Mining), Jamaica, 1:50,000.

Mines and Geology Division. 2007. *Landslide Susceptibility of Portland, Jamaica*. Mines and Geology Division (Ministry of Agriculture and Lands), Jamaica, 1:50,000.

Mines and Geology Division. 2004a. *Landslide Susceptibility Map of St. Mary, Jamaica.* UNDP and Mines and Geology Division (Ministry of Land and Environment), Jamaica, 1:50,000.

Mines and Geology Division. 2004b. *Landslide Susceptibility Map of St. Thomas, Jamaica.* (2nd edition) Mines and Geology Division (Ministry of Land and Environment), Jamaica, 1:50,000.

Mines and Geology Division. 2000. *Landslide Susceptibility Map of the Rio Grande Valley, Portland, Jamaica.* DIPECHO and Mines and Geology Division (Ministry of Mining and Energy), Jamaica, 1:50,000.

Mines and Geology Division. 1997a. *Port Maria Provisional Geological Sheet 9.* Mines and Geology Division (Ministry of Mining and Energy), 1:50,000.

Mines and Geology Division. 1997b. *Blue Mountains Provisional Geological Sheet 13.* Mines and Geology Division (Ministry of Mining and Energy), 1:50,000.

Mines and Geology Division. 1997c. *Port Antonio Provisional Geological Sheet 14.* Mines and Geology Division (Ministry of Mining and Energy), 1:50,000.

Mines and Geology Division. 1997d. *Morant Bay Provisional Geological Sheet 19.* Mines and Geology Division (Ministry of Mining and Energy), 1:50,000.

Northmore, K. J., Ahmad, R., O'Connor, E. A., Greenbaum, D., McDonald, A. J. W., Jordan, C. J., Marchant, A. P. and Marsh, S. H. 2000. Landslide Hazard Mapping: Jamaica case study. *Natural Environment Research Council, British Geological Survey Technical Report* **WC/00/10**, *Overseas Geology Series*. 41pp.

O'hara, M. and Bryce, R. 1983. A Geotechnical Classification of Jamaican Rocks. *Geological Survey Division, Ministry of Mining and Energy, Bulletin* no. **10**, 44 pp.

Parise, M. and Jibson, R. W. 2000. A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake. *Engineering Geology*, **58**, 251-270.

Pereira, J.A. 1979. Frequency of Damaging Earthquakes in Jamaica. *Seismic Research Unit Special Publication* No. **1AP-1979**, Seismic Research Unit, University of the West Indies, Kingston, Jamaica 29 pp.

Soeter, R. and van Westen, C. J. 1996. Slope Instability Recognition, Analysis and Zonation. *In*: **Turner, A. K. And Schuster, R. L. (Eds.)**, *Landslides: Investigation and Mitigation. Special Report* **247**, Transport Research Board, National Research Council, National Academic Press, Washington D. C. 129-177.

Unit for Disaster Studies, 1999. Landslide Susceptibility Maps for the Kingston Metropolitan Area, Jamaica, with notes on their use. *USAID-OAS Caribbean Disaster Mitigation Project and Unit for Disaster Studies (UDS), UDS Publication* No. **5**. 1:50,000.

Zans, V. A. 1959. Judgement Cliff Landslide in the Yallahs Valley. *Geonotes* **2**, 43-48.