Landslide Susceptibility Maps for the Kingston Metropolitan Area, Jamaica with Notes on Their Use

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1.0 Executive Summary

1.1 Purpose and Scope

Landslide susceptibility maps for the Kingston Metropolitan Area (KMA), scale 1:50,000, have been prepared by Unit for Disaster Studies, Department of Geography and Geology, University of the West Indies, Mona as a part of the Kingston Multi-Hazard Assessment administered by the Caribbean Disaster Mitigation Project (OAS/USAID).

The purpose of this report is to facilitate an understanding of the landslide phenomenon in KMA and preparation of the susceptibility maps. To this end geological information on areas susceptible to failure by landsliding, the methodology used in map preparation, and its advantages and limitations are presented.

A *Landslide Loss Reduction Manual* accompanies this report (Publication No. 6, Unit for Disaster Studies, UWI, Mona, 1999).

1.2 The Landslide problem in the Kingston Metropolitan Area

Landslide phenomenon: The geological processes and natural forces that have created the present-day landscape on the island of Jamaica are the same that makes it most vulnerable to natural hazards. The city of Kingston was founded on the coastal plain of Liguanea in 1692 following the devastation of Port Royal by a submarine landslide triggered by the earthquake of June 6, 1692. Landslide activity is one of the principal geomorphic processes through which hillslopes evolve. These features represent locations where the resisting strength of rock and soil masses that make up a slope are overcome by the force of gravity which is constantly acting on a slope to move slope materials downslope. Every location on a hillslope can be considered as a part of a continuous tug-of-war between the driving force of gravity and resisting forces due to materials that constitute a slope (DeGraff, 1987,1991). Both natural processes and human modifications of slopes can change this balance in the favour of gravity. The strength of the slope materials is reduced due to internal changes (weathering, seepage erosion, ground water changes etc.), while stresses on slope can be increased as a result of external factors (steepening of slopes through excavations, loading of slopes etc.). The landslide triggering mechanisms include rainfall associated with tropical storms and/or earthquakes.

Landslide impact in KMA: Landslides have occurred for thousand of years in KMA and rank high on the list of geohazards that affect this area. For the inhabitants of KMA, landslide hazard is a major constraint on land use. Unstable slopes pose a constant threat to their lives, property and the infrastructure, especially the road network. Landslides have affected both the natural slopes as well as those modified for human use and have caused significant damage to property and infrastructure.

Some of the residential areas of Kingston and St.Andrew are located on marginally stable slopes that were disturbed by pre-historic and historic landslides. For example, the Geological Map of Kingston area prepared by the Geological Survey of Jamaica (1994 b) shows that between Papine and Jacks Hill landslips cover an area of some 0.8 km^2 (80 hectares), or approximately 16.89 % of the total slope area of 4.75 km^2. Many of these ancient landslide scarps and their deposits are concealed by vegetation and have been extensively modified by both natural processes and human interventions. These areas may remain stable for a long period of time until natural processes (e.g. intense rainfall) and/or human interference (e.g. construction activity) disturb the slope stability conditions. An excellent example of this is provided by the widespread occurrence of debris and mudflows in the Jacks Hill area that were triggered by the rainfall associated with 1973 tropical storm Gilda, and more recently, the rainfall related to hurricane Mitch during 20th October to 3rd November 1998. A number of retaining walls were also destroyed in this area as a consequence of the failure of backfill.

The spectacular submarine landslide triggered by the MMI X, June 6, 1692, earthquake that destroyed the buccaneer town of Port Royal best illustrates the impact of landslides on the coastal environment of the capital city of Jamaica. This earthquake, as well as the M 6.5 Kingston earthquake of 1907, caused localized submarine slumping-related tsunamis and liquefaction in the coastal areas and also triggered widespread landslides in eastern Jamaica including the Port Royal Mountains. The M 5.4 earthquake of 13 January 1993 triggered some 40 landslides in KMA which caused damage to infrastructure (roads, water pipelines and submarine cables) and private property.

While not every landslide that has occurred in KMA since the time for which historic records are available can be classified as catastrophic, the cumulative damage from many small-scale rainfall induced landslides is more serious than a major slope failure.

It has been estimated that during the period 1910 to 1965, for which published data are available, some 7. 3% of the total expenditure of the Public Works Department, Govt. of Jamaica, accounted for damage-repair costs related to landslides and flooding and this trend continues (Naughton, 1984).

Landslide hazard: The goal of this study is landslide hazard assessment in the Kingston Metropolitan Area (KMA), which covers an area of 554 km^2 in the parishes of Kingston, St.Andrew, and southeastern St.Catherine. It has a population of some 700,000 and a population density of approximately 1528 persons/ km^2 .

The earliest historical record of widespread landslide activity in the area dates back to the earthquake of June 1692. However, the regional significance of landslide activity and its economic and societal impacts have not been fully appreciated. Detailed studies on landslides were initiated in 1980s (Ahmad, 1995).

Landslides in the Kingston Metropolitan Area (KMA) are of diverse origin and severity, reflecting wide variations in the nature of bedrock, their structure, soil types, and physiography.

A landslide inventory of KMA prepared in this study contains some 2,321 landslides. These landslides and their deposits cover 19.786 km^2 (or 3.57 %) of the entire study area. Excluding the Liguanea Plain, landslides cover some 4.77 % of the mountainous area. Landslides in this area occur in bedrock (deep landslides) and also in the surficial deposits that overlies deeply altered bedrock (shallow landslides).

Although most of the KMA population lives on the relatively low-relief gravel fan of Liguanea, a large number have settled along the coastline, on alluvial fans, and in the surrounding mountainous terrain. The sub-urban growth is increasingly taking place in the Port Royal Mountains, Red Hills, Long Mountain and Dallas Mountain. This terrain is subject to landsliding and landslide disasters are known since historic times. The affects of landslides are in some places sporadic, whereas in others rainfall-induced landslides are a recurrent phenomenon. Accelerated soil erosion in the watersheds preferentially occurs in areas that have been affected by landslides.

Definition of key hazard terms: *Natural Hazard* (H) means the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon. *Vulnerability* (V) means the degree of loss to a given element or set of elements at risk (see below) resulting from the occurrence of a natural phenomenon of given magnitude. *Specific risk* (Rs) means the expected degree of loss due to a particular phenomenon. It may be expressed by the product of H times V. The term *zonation* applies in a general sense to division of the land surface into areas and the ranking of these areas according to degrees of actual or potential hazard from landslides or other mass movements on slopes. It does not necessarily imply legal restriction or regulation by zoning ordinances or laws (From Varnes, 1984).

1.3 Landslide hazard assessment and preparation of landslide susceptibility maps

The concepts and methodology used in the assessment of landslide hazard in KMA and the preparation of hazard zonation maps are summarized below. These have been adapted from Varnes (1984) and DeGraff (1987, 1991).

The losses from landslides are termed vulnerability. This is one component in determining landslide risk. The other component is landslide hazard. Landslides are not currently amenable to risk assessment since there is no basis to determine the probability of landslides occurring within a given time period. Hazard assessments are possible and can be used in place of risk assessments. Hazard assessments are estimations of an area's susceptibility to landslides based on three inherent physical factors – distribution of past landslides, slope steepness, and type of bedrock and its structure. We have mapped these three factors for KMA during 1996 to 1998. The zonation of KMA according to these differing degrees of hazard has led to the production of landslide hazard maps. The degree of hazard is considered relative since it represents the expectation of future landslide occurrence based on the physical conditions of that particular area. Compilation of landslide hazard zonation maps is based on three principles (Varnes, 1984). First, the past and present are keys to the future; second, the main conditions that cause landsliding can be identified, and; third, degrees of hazard can be estimated.

We employ the landslide susceptibility matrix technique (DeGraff and Romesburg, 1980) to identify areas with high susceptibility for future slope failure. This technique (often termed the "DeGraff method") relies on an inventory map of past landslides, and man-made factors that may contribute to landsliding. Basically, the various factor maps are overlaid to create a mosaic of small areas that contain distinct combinations of slope angle, aspect, geology, vegetation, landuse, etc. The landslide inventory map is then overlaid on this mosaic map, and those distinct combinations of factors that are associated with each landslide are tabulated and ranked. This ranking in turn is used to classify the entire study area into landslide susceptibility zones. Unfailed areas that share many common factors with failed areas are placed in the highest susceptibility class. In this project we use the IDRISI GIS software (Eastman, 1997) to construct a raster (cell-based) map of the KMA based on a 15m by 15m cell size. The study area contains 2,461,462 such cells. The GIS software to produce the final landslide hazard maps digitized the landslide inventory and factor maps.

The landslide susceptibility in KMA has been presented on two derivative maps prepared on 1:50,000 metric topographic base maps, sheets 13 and 18, to portray deep-seated landslides in bedrock and shallow (active) landslides in the colluvium (that is, surficial materials on hill slopes). These maps are designated as:

i. Landslide Susceptibility Classes: Deep Landslides, and
ii. Landslide Susceptibility Classes: Shallow Landslides.

The purpose of these maps is to convey information on landslide susceptibility in KMA in non-technical form that may be understood by non-geologists. Only those geologic and geomorphic factors that have a direct bearing on the occurrence of landslides in the study area have been employed in the compilation of susceptibility maps.

Since it is difficult, even in best possible conditions, to specify a time frame for the occurrence of landslides in any area, the landslide hazard is generally represented by landslide susceptibility. A landslide susceptibility map, such as the one presented, only identifies areas potentially affected and does not imply a time frame when a landslide might occur. In this report, and as is the general practice, landslide susceptibility will be referred to as landslide hazard.

1.4 Uses of landslide susceptibility maps

Landslide hazard maps provide information that can be used to identify different levels of risks due to landslides, which in turn facilitates implementation of appropriate structural and non-structural loss reduction strategies for both existing and future development.

Five levels of relative susceptibility have been identified on the KMA Landslide Susceptibility Maps: (1) low; (2) moderate; (3) moderate-high; (4) high; and (5) very high. Predicting absolute hazard is impractical with current capabilities. These zones do not imply legal restriction or regulation by zoning ordinances or laws as laid down by the local government authorities.

Citizens, planners, engineers, and developers, however, can use these landslide hazard zonation maps as a tool to help reduce losses from existing and future landslides through prevention, mitigation, and / or avoidance.

The map is intended primarily for the assessment of landslide hazard for planning purposes on a regional scale. It indicates indirectly the extent and relative severity of landslide hazard and may be used in preliminary selection of areas for housing and infrastructure development. The enhanced readability of the map far outweighs the simplifications, errors and, omissions that could not be avoided.

The map should not be used to determine the stability of specific building sites.

The map can be used to identify areas where detailed geologic-geotechnical investigations are desirable prior to the development.

Citizens may use the map in a general way to determine relative hazard, because chances of landslides occurring in areas in a high susceptibility zone (4) are greater than in areas under low zone (1).

It should be understood that natural changes as well as human-induced changes can affect the susceptibility to landslides in any area, and that the absence of past or present landslides does not mean that slope failures will not occur in the future.

1.5 Limitations and advantages

"A derivative map is no more precise and complete than its source materials." Landslide susceptibility maps are derivative maps compiled from a variety of data sources. The pre-existing geologic-structural data have been modified to suit the needs of the present study. Landslide inventory includes both new and pre-existing data that have been verified in the field, and also data derived from aerial photo-interpretation. The precision and accuracy of the derivative map is, therefore, dependent on the original data, scale transformations, and the process of map compilation. As with any map, scale is an important consideration.

DeGraff method is purely driven by the landslide inventory, and will predict high landslide susceptibility for any areas that share common combinations of factors with failed areas. This purely empirical basis is both a strength and a weakness of the technique. Its strength is that it does not require abundant or detailed geotechnical data on slope materials or hillslope pore pressures, which are never available for most of a study area. It requires no assumptions on the mechanics and geometry of failure, which vary widely and are generally unknown. On the other hand, deficiencies in the landslide inventory will inevitably manifest themselves in the final hazard map.

2.0 Introduction

We have carried out regional landslide hazard mapping for the Kingston Metropolitan Area (Figure 1) as a part of Kingston Multi-Hazard Assessment Project of the Caribbean Disaster Mitigation Project (USAID/OAS) initiated in 1996.

The primary aim of this project is to recognize and map the landslide hazard in KMA in order to reduce loss of life, property damage, and social and economic disruption from slope movements. The goal of this study is to produce a landslide hazard map that identifies geographic areas where future landsliding is most likely to occur. Knowing such locations, planners and engineers can be forewarned as to the consequences of poor design for roads and other development in such critical areas.

For purposes of this report, the term ‘landslide’ is broadly defined as any gravity induced "downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials. The moving mass may proceed in any one of three principal types of movement: falling, sliding, or flowing, or by their combinations." (Varnes, 1978)

2.1 Location

The modern Kingston Metropolitan Area (KMA) has a population density of about 1528 persons / km^2 and hosts some 28% of islands total population. It is spread over a mosaic of coastal plains, reclaimed land, gravel fans, steep slopes and fault scarps totaling some 554 km^2 in the parishes of Kingston, St.Andrew, and St.Catherine (Figure 1). This terrain is subject to multiple seismic, atmospheric, landslide and flood hazards. Munich Re (1988) include Jamaica in the Earthquake Exposure Grading Zone 3 (a probable maximum MMI VIII once in 50 years for average soil conditions, firm sediments); the entire coastline is shown exposed to tsunamis and the frequency of Atlantic Hurricanes is 1.0 to 2.9 per year.

2.2 Landslide Hazard and impact

Landslides are a common occurrence in the Kingston Metropolitan Area and have caused death, injury, and a considerable damage to property and infrastructure, especially the road network. A landslide triggered by May 21, 1991 rainfall in the Lawrence Tavern area, Western St.Andrew, killed a senior citizen when his house was engulfed by landslide debris. In the same area, a 13 –year old girl sustained serious injury as debris swept through her house (Ahmad, 1991).

Landslides have affected rural schools. In October 1950, Woodford School was extensively damaged by landslides triggered by heavy rainfall and had to be relocated. Landslides induced by the earthquakes of 1907 and 1993 and heavy rains of 1933 and 1944 have repeatedly occurred on the slopes around Woodford Ridge where the school was located (Chubb, 1952).

On 14th November 1988, an engineered house in Jacks Hill, Upper St. Andrew, and a section of the Jacks Hill Road including a culvert were destroyed by a landslide following a brief spell of heavy rainfall and earthquake shaking (Plate 1). The road remained closed for more than six months. The house is located on old debris flow and mudflow deposits that were probably initially triggered by the June 1692 Earthquake. In the same area following the precipitation associated with hurricanes Flora, 4-7 October 1963, and Gilda, 16-18 October 1973, widespread debris flows and mudflows occurred on the southern slopes of the Liguanea Ridge causing extensive damage to houses and roads (Plate 2). Low-income housing is often severely affected by landslides (Plate 3; Ahmad, 1991). Debris flows and rock avalanches frequently block roads (Plates 4, 5, and 6; Manning *et al.*, 1992). Landslides have seriously affected the domestic water supply infrastructure in KMA and it appears that excessive siltation in the reservoirs is related to shallow landslides in the deforested watersheds and in some instances water pipelines have been damaged (Ahmad, 1996; Ahmad *et al*., 1993). Accelerated soil erosion in the watersheds occurs at sites that are affected by landslides. These examples are typical of the landslide activity in KMA and their impact on the Society.

The cumulative direct and indirect economic costs and social impacts as a result of the landslides in KMA can not be quantified due to a lack of event-by-event analysis of the impacts and also much of the damage remains undocumented. Since landslides and floods occur simultaneously, landslide damage is often incorrectly ascribed to the damage caused by floods. Costs are undoubtedly high

The destructive potential of landslides summarized above establishes that landslides should be considered as a serious and recurrent natural hazard in KMA.

2.3 Present Situation and Landslide Information

Although landslides are a major geomorphic process in KMA, being primarily controlled by the underlying geology and active tectonics, the landslide hazard is to a large extent a consequence of changing landuse (Ahmad, 1995). However, information on landslides is limited. Prior to this study a systematic evaluation of the landslide susceptibility at a regional scale that may be used in landuse planning was not available. Regional geological maps of the area, Geological Sheets 13 and 18, scale 1:50,000 (Geological Survey Division, 1994 a &1994 b) show a few major landslides and provide information on lithology and structure that may be used to indirectly assess landslide susceptibility. However, these special purpose maps are complex, include a variety of other geologic data, and are, therefore, of limited use to non-geologists. The Engineering Geology Section, Geological Survey Division of the Government of Jamaica (presently known as Mines and Geology Division) has, since its inception, investigated a number of specific landslide events and continue to provide information and advise to the relevant governmental agencies and others concerned. Landslide susceptibility maps have been prepared for only two small areas in St.Andrew by the graduate students at the Department of Geography and Geology, the University of the West Indies, Mona (Naughton, 1976; Maharaj, 1992 & 1993). Since 1990, a number of publications have dealt with landslides (Ahmad, 1989 &1991;McGregor and Barker, 1991;Manning, McCain and Ahmad, 1992; Eyre, 1992; Ahmad and others, 1993; Dalling and Iremonger, 1993; Ahmad, 1995).

We have incorporated landslide data contained in the above publications in the compilation of the landslide inventory for the present study.

3.0 Landslide Inventory (Map 1)

Field investigations and compilation of landslide inventory map followed the procedures outlined in *Landslides Investigations and Mitigation*, Special Report 247, National Academy Press, Washington, edited by A. K Turner and R.L. Schuster (1996, Part 2: investigations- articles by Turner and McGuffey, 1996; Soeters and van Westen, 1996; Keaton and DeGraff, 1996). The procedure comprised the following steps:

i. Stereoscopic interpretation of vertical aerial photographs (1961 Series, scale 1:50K and 1991-92 Series, scale 1:15K, Survey Department, Jamaica),
ii. Recognition of anomalous topographic features indicative of landslide landforms on aerial photographs and topographic maps (Jamaica Survey Department Sheets 13 and 18, scale 1:50K, Metric Edition),
iii. Compilation of landslide data from previous investigations including information provided by Mines and Geology Division (Section 2.3),
iv. Field verification of the above data , and
v. Compilation of the landslide inventory map and digitization of data (Map 1). Landslides were subdivided into the groups, each identified by a unique mapping symbol following the methodology of Weiczorek (1988). We use the term "scarp" to indicate the entire source area of a landslide, not just the headscarp, which is the more typical meaning. Thus, our label "Scarp" is synonymous with the entire landslide feature, its source area including the scar and the landslide deposit.

A Landslide inventory of the area (Map 1) includes:

1. Active landslide (small individual slide, 5 -10m wide)
2. Active landslide zone (zones of small slides, up to 30m wide)
3. Scarp-Definite
4. Scarp-Probable
5. Scarp-Questionable
6. Deposit-Definite
7. Deposit-Probable
8. Deposit-Questionable.

The landslide inventory of this area contains 2,321 landslides (Table 1). Landslides are subdivided into active (landslides, n=46; zones, n=341), scarps (definite, n=613; probable, n=958; questionable, n=340), and deposits (definite, n=18; probable, n=4; questionable, n=1). Landslides cover 19.786 square km, or 3.57% of the entire study area. Excluding the Liguanea Plain, landslides cover 4.77% of the mountainous areas.

Table 1. Statistics of Landslide Types

GROUP STATISTICS

Type	N	Total Slide Area (sq. km)
Active	46	0.181
Active Zone	341	0.712
Scarp-Definite	613	6.721
Scarp-Probable	958	5.536
Scarp-Questionable	340	4.891
Deposit-Definite	8	0.917
Deposit-Probable	4	0.582
Deposit-Questionable	1	0.425

INDIVIDUAL LANDSLIDE AREAS (sq. meters)

Type	Mean	Std. Dev.	Min	Max
Active	3,216	4,247	762	18,151
Active zones	2,088	na	na	na
Scarps-Definite	10,963	23,541	271	203,905
Scarps-Probable	11,698	13,205	417	89,954
Scarps-Questionable	9,715	16,042	116	173,749
Deposits-Definite	50,950	90,921	5785	381,609
Deposits-Probable	145,632	98,430	40,323	274,764
Deposits-Questionable	424,065	0	424,965	424,965

PROPORTION OF AREA COVERED BY LANDSLIDES

	All Slides	Scarps Def. & Prob.	Active Slides
Entire Area	3.57%	3.10%	0.16%
Mountains Only	4.77%	4.13%	0.22%

Active landslides

Active landslides are small (5- 10m wide) features portrayed as small circles on the landslide inventory map and in the IDRISI vector files. In the study area there are 46 active landslides mapped with an aggregate area of 0.181 km^2 (804 pixels). Many active landslides are close to roads. These landslides are dominantly shallow debris slides or debris avalanches, often derived from colluvium or residuum overlying bedrock on steep slopes. Generally, the age of active landslides is unknown but in heavily vegetated terrain they are probably <50 years old or they would not be identified today.

Active landslide zones

Active landslide zones contain more than one small active landslide as defined above, and are portrayed on the inventory map and IDRISI files as V shapes. There are 341 active slide zones in the study area, with an aggregate area of 0.712 km^2 (364 pixels). The V symbols on the 1:50,000- scale landslide inventory maps are larger than the actual slide zones themselves. For example, on a 1:50,000-scale map a 30m-wide landslide would be 0.6mm wide, which is too small for drafting. There are two distinct populations of active landslide zones. About 60% of the zones occur adjacent to roads, and the balance occurs on natural hillslopes far from roads.

Scarps-Definite

Landslides scarps whose identification is considered very confident are termed Scarps-Definite. Like the other scarp type, these were mapped (and digitized) as arcuate line bounding the margins of the scarp area, open in the downslope direction. Scarps-definite are much larger features than active landslides. Of the 613 Scarps-Definite mapped, their aggregate area= 6.721 km^2, mean area= 10,963 m^2. The largest Scarp-Definite (282,000 E; 151,500N) is 1km wide and 0.4lm long. Based on these dimensions, and the association of Scarps-Definite with thick landslide deposits in areas such as the Hope Gardens, we assumed that most Scarps-Definite represented the source areas of rather thick (>5-10m) landslides. However, some Scarps-Definite, especially those mapped as approximately located (dashed scarp line on original inventory maps), may be the source areas excavated by repeated shallower landslides over a long period of time.

Scarps-Probable

Scarps-probable represents topographic swales that resemble scarps-definite and are thus probably the source zones of deep or repeated shallow landslides. Like scarps-definite, scarps-probable occur widely in many types of natural and man-modified terrain. There are 958 scarps-probable in the study area, with an aggregate area of 5.536 km^2. Mean area of these scarps is 11,698 m^2, standard deviation 13,205 m^2, and range of 417 m^2 to 89,954 m^2.

Scarps-Questionable

Scarps-questionable are topographic swales that could be either the result of deep-seated landsliding or normal hillslope erosion processes (sheet wash overland flow, rillwash, etc.). There are 340 scarps-questionable in the study area, with an aggregate area of 4.891 m^2. Mean area of these scarps is 9.715 m^2, standard deviation 16,042 m^2, and range 116 m^2 to 173,749 m^2.

Deposits-Definite

Deposits-definite are unambiguous landslide deposits, often clearly linked to a scarp-definite zone, which can be easily delineated. The best examples of deposits-definite are the series of seven landslide deposits at the base of the Wagwater Fault range front, between Papine and the foot of Jacks Hill. These six deposits appear on Geological Sheet 18 (Provisional version, 1995) as "landslips", and constitute one of the few instances where features of the landslide inventory appear on a previously published geological map.

There are 18 deposits-definite in the study area, with an aggregate are of 0.917 km^2. Mean area is 50,950 m^2, standard deviation 90,921 m^2, and range 5785 m^2 to 381,609 m^2.

Deposits-Probable

Deposits-probable are diamictons that occur in topographic situations, and in association with landslide scarps, that make it likely they are landslide deposits. Examples include areas of limestone boulders north of Red Hills, near the contact with Cretaceous granodiorite. In the study area there are 4 deposits-probable with an aggregate area of 0.582 km^2. Mean area is 145,632 m^2, standard deviation is 98,430 m^2, and range is 40,323 m^2 to 274,754 m^2.

Deposits-Questionable

Only a single questionable deposit exists in the study area, on the north-facing fault-line scarp north of Red Hills. This elongate deposit is 1.5 km long and 0.4 km wide, and is composed of erratic limestone boulders. The boulders are presumably derived from the escarpment to the south, but no landslide morphology is preserved on the escarpment upslope of the landslide deposit comprising limestone blocks and boulders.

4.0 Methodology

We performed a landslide susceptibility study using the susceptibility matrix approach pioneered by DeGraff and Romesburg (1980). This technique (often termed the "DeGraff method") relies on an inventory of past landslides. First, we created factor maps for slope angle, slope aspect, downslope curvature, lithologic group, distance to faults, and distance to roads. The first three of these maps were based on a digital elevation model (DEM) created from 50-m contours on the published 1; 50,000-scale metric base maps. Lithologic groups were simplified from the Provisional editions of 1:50,000-scale geologic sheets of the Blue Mountains (sheet 13) and Kingston (sheet 18) (Geologic Survey Division, 194a and 1994b). Locations of faults and roads were derived from published maps.

The digital data were analyzed by the geographic information system (GIS) software IDRISI for Windows v. 2.0, running under Windows NT 4.0. IDRISI is a raster-based program. Therefore, all the digital vector data were rasterized onto a 15-m pixel raster base. Raster maps of the study area rectangle contain roughly 3.7 million pixels, of which about 2.5 million are within the boundaries of Kingston and St. Andrew parishes. We adapted the original matrix technique of DeGraff to IDRISI in the PC environment.

We performed separate DeGraff analyses for deep versus shallow landslides. Factor analysis for deep landslides shows they are sensitive (in order of decreasing importance) to lithologic group, distance to faults, slope angle, and slope aspect. By overlaying maps of those four factors we created a map of 249 composite categories of slope-aspect-lithology-fault distance. Those categories possess landslide densities between 0% and 71%. Landslide densities of 2%, 3.5%, 4.5%, and 6% bound our classes of low, moderate, moderate-high, high, and very high susceptibility for deep landsliding respectively. The highest susceptibility areas are in far eastern St. Andrew on Cretaceous volcanics, or on Eocene clastics or andesites within 60 m of faults. Granodiorite basement and limestones have low-moderate susceptibility.

Active landslides comprise only 16.7% of the number of total landslides and 4.5% of total landslide area. Most active landslides are small (200-300 square meters), shallow debris slides or debris avalanches that generally result from failure of colluvium. Controlling factors (in order of importance) appear to be lithology, slope angle, slope curvature, and aspect. Fault distance does not appear to affect shallow landslides. The overlay map contains 83 unique combinations of slope-aspect-lithology-curvature, which possess landslide densities between 0% and 0.25%. We subdivide this range into low, moderate, moderate-high, high, and very high susceptibilities. Highest susceptibilities are restricted to Eocene shales, sandstones, and andesites, particularly on north-facing slopes near ridge shoulders.

The final landslide susceptibility in KMA has been represented on two derivative maps, prepared on a 1:50,000 metric base maps, to portray deep-seated landslides in bedrock and shallow (active) landslides in the colluvium (i.e., surficial materials on slopes). These maps are designated as:

A. Landslide Susceptibility Classes: Deep Landslides, and
B. Landslide Susceptibility Classes: Shallow Landslides.

5.0 Factors Affecting Landslide Distribution in KMA

5.1 Road distance and all landslide types (Map 2)

The road network examined included all the major and minor roads outside of the Liguanea Plain area shown on Jamaica, 1:50,000 metric sheets 13 and 18. Due to the paper (non-stable) base maps from which we digitized the minor roads, there may be minor locational discrepancies between the road raster map and all other maps.

What Does Map 2 Show About Landslides?

Some landslide types appear to correlate strongly with distance to roads. In the granodiorite outcrop area surrounding Lawrence Tavern, all of the mapped active landslides (small circles) and active slide zones (small V's) occur very close to roads. These slides occur in two settings. Where the roads occupy ridge crests, active landslides are either downslope of the road grade, or on small roadcuts on the ridge crest itself. Where roads occupy the valley bottoms the landslides occur upslope of the road. In both cases it appears that human actions have caused the landslides, either by diverting concentrated roadside runoff onto slopes below the roads, or by cutting into steep sideslopes in the valley bottoms.

The landslide inventory contains 46 relatively small active landslides, and 341 zones of multiple small active landslides, with a combined area of 0.89km^2. On an areal basis 60% of these active landslides and zones (0.53 km^2) occur within 90m of roads, whereas the other 40% are spread rather uniformly across the terrain at distances of 90-2000m from roads. In terms of landslides density, within 90m of roads there are 2368 active slide pixels out of a total of 368,823 pixels in the study area yielding a landslide density of 0.642%. Beyond 90m from roads there are 1611 active slide pixels out of a total of 1,558,129 pixels (this pixel total excludes the Liguanea Plain, where slopes are too gentle for landsliding). Thus, density of active landslides within 90m of roads is 6.23 times higher than that beyond 90m from roads. The high concentration of KMA active landslides within 90m of roads is very similar to that described by Larsen and Parks (1997) for shallow landslides <50 years old in Puerto Rico. In Puerto Rico, Larsen and Parks (1997) found that landsliding densities within 85m of the road were 8 times higher than beyond that distance.

In the incised valley of the Wagwater River both small active landslides and larger scarps-definite and scarps-probable are mapped. Most of the active landslides are probably road-related, but some of the larger scarps may be natural failures on the steep valley walls.

Landslides are concentrated along the road from Stony Hill to Mount Airy and to Mount Telegraph on the St. Andrew-Portland divide. Similar landslides occur on the roads leading to Woodford, in the valley of the Hope River, and along the roads north and east of Gordon Town. It appears that most of these small active landslides and slide zones are human-induced.

5.2 Geomorphology: slope angle and slope aspect

KMA is divisible into three broad physiographic regions: 1) the low relief coastal plains, comprising the Liguanea Plain and the lower Rio Cobre Plain; 2) the rolling hills and limestone plateaus north-northwest of Kingston and west of the Wagwater Belt, and 3) the deeply dissected Port Royal Mountains comprising the rocks of Wagwater tectonic belt in St. Thomas parish, north, northeast, and east of Kingston (Map 1). All mapped landslides are also shown superimposed on the physiographic map.

A DEM was created from the topographic sheets 13 and 18 of the Jamaica 1:50,000 metric map series. The contour interval is 50m. These contours were hand-digitized from the contour lines on a paper map base. Due to the hand-digitizing process there were a few inevitable discrepancies between the shapes of some contour lines. All raster maps used in this analysis use this 15 m pixel size. We chose the 15 m pixel size for this project because, in the steepest parts of the Wagwater Belt, 50 m contour lines are as close as 15-20 m apart. Use of a larger pixel size (say 30 m) would result in having multiple contour lines within a pixel, which leads to averaging (and thus underestimating) the steepest slope angles. Because landsliding is especially sensitive to steep slope angles, we wanted to avoid underestimating steep slope angles. Throughout most of the Wagwater Belt there are 3-4 pixels between adjacent contour lines, so the elevations of those pixels are interpolated via the INTERCON module in IDRISI. In the KMA study area, striping was only a problem on the Liguanea Plain and in the low-relief areas on granodiorite, such as near Lawrence Tavern.

5.3 Physiography and landslides

On the low-relief slopes of the Liguanea Plain few landslides are mapped, with the exception of the toes of seven large landslides in the Jack’s Hill area. These landslides are derived from the steep range-front escarpment created by the Wagwater Fault. In the northwest part of the area, the limestone plateau near Red Hills (elevation ca. 500 m) has few landslides, except along the escarpment leading down across a major fault and onto the terrain underlain by Cretaceous granodiorite. This latter terrain lies between elevation of 200-300 m and has relatively few landslides, although small active slides are abundant along incised watercourses. Small slides are also abundant in the valley of the Wagwater River.

Most of the mapped landslides occur in the mountainous terrain of the Wagwater Belt north and east of the Liguanea Plain, the Port Royal Mountains. These mountains reach a maximum elevation of 1950 m along the boundary between St. Andrew and Portland parishes, rising as much as 1300 m in the 7 km between the highest (NE) part of the Liguanea Plain and the drainage divide. These mountains are deeply incised by rivers such as the Hope and Yallahs, and valley walls are high and steep. Landslides are abundant at all elevations in this terrain, from the range front (ca. 200-250 m) up to the divide. About the only topographic setting that contains few landslides are the rolling upland surfaces that exist along some of the higher ridge crests.

5.4 Slope angle and all landslide types (Map 3)

The ultimate data source for this slope map is the 50 m contour lines from the 1:50,000-scale topographic maps, as is true for the elevation map (DEM).

What Does the Map Show About Landslides?

Landslides become increasingly abundant as slope angle increases up to about 57^0 , beyond which slides are much less abundant. This letter phenomenon either means that slopes steeper than 57 ^{0} are composed of very resistant rock, or that there are too few slope pixels steeper than 57^0 to be statistically valid. Landslides are absent on the Liguanea Plain, except for the toes of the seven landslides between Jacks Hill and Papine. The toes of these landslides lie on slopes of 10-15 ^{0} at the head of the Liguanea Plain. On the Red Hills plateau landslides are absent except on the north flank escarpment, where they occur on slopes of 15-30 ^{0}. Several deposits of large limestone blocks and boulders lie atop Cretaceous volcanics on gently sloping interfluves and benches.

In the granodiorite terrain around Lawrence Tavern scarps and active landslides are shown on slopes of only 0-2 ^{0}, especially near roads. These small landslides actually occur on small but steep roadcuts that are too small to be represented on the original 50 m contour lines, thus those steep slopes are not represented in our DEM and resulting slope maps. This shortcoming could be rectified by hand-updating the pixels slope angle values with the IDRISI module UPDATE, but such an update would actually overestimate the area of the roadcuts, which are smaller than our 15 m pixel size. However the slopes could be more accurately represented in a raster GIS map that employed a smaller (e.g. 5 m) pixel size. For this regional study such a small pixel size would result in 9 times as many pixels as the 2.5 million in the existing 15 m pixel maps.

On the flanks of Long Mountain and Dallas Mountain landslides occur on steep slopes in the midslope position. These steep sideslopes may result from Quaternary folding and "tightening" of these anticlines, which may have steepened the dips and consequent slopes of each mountain.

In the mountainous terrain of the Wagwater Belt, i.e. Port Royal Mountains, landslides occur on a wide range of slope angles steeper than about 15 ^{0}. The only topographic setting relatively untouched by landsliding is the gentle terrain preserved atop some ridges. However, landslides often surround these gentle ridgetops. It appears that landslides will eventually regress headward and consume these gentle ridgetops, which must be remnants of old, low relief erosion surfaces that predate the Neogene uplift of the Wagwater Belt.

5.5 Slope aspect and Landslides

The relationship between slope aspect and landslides was evaluated by subdividing slope aspect into eight 45 ^{0} azimuth classes, with each centered about one of the eight cardinal compass directions (N, NE, E, etc.).

Landslides occur on slopes in all the eight aspect classes. On Long and Dallas Mountains landslides are generally restricted to northeast- and southwest-facing slopes, due to the shape of these linear northwest-trending fold mountains. In the Wagwater Belt, Port Royal Mountains, landslides occur on slopes of all aspects. In the northern part of the belt (north of Mount Airy) ridges have a distinct northwest-southeast trend, so most slopes there face northeast or southwest, as do the landslides on those slopes. In the central belt (Mount Airy to Hope River) most ridges trend northeast- southwest, so slopes and their landslides face west and south-southeast. South of the Hope River, ridges and slopes trend in many different directions and landslides thus occur on slopes of all aspects.

5.6 Geology: bedrock, faults, and landslides

A new simplified geologic map of KMA has been prepared based on the metric edition geologic sheets 13 (Blue Mountains) and 18 (Kingston) (Geological Survey Division, 1994a and 1994b). The geologic formations in Sheets 13 and 18 have been grouped into 11 lithologic groups. These lithologic groups contain formations of similar lithologic character and age (Table 2).

Table 2. Lithologic Groups in KMA, Map 4 (Map Abbreviation Description Units on Sheets 13 and 18)

QS	Quaternary sand	not labeled
FD	Fan deposits	Alluvium
AT	Alluvium and terraces	Alluvium and River Terrace
PCL	Clastics and limestones	Coastal Group
EL	Limestones, often marly	White Limestone Group
ELC	Limestone and clastics	Yellow Limestone Group
ESS	Shale and sandstone	Richmond Formation
ECV	Coarse volcaniclastics	Wagwater Formation
CV	Cretaceous volcanics	Volcanics and Volcaniclastics
EA	Andesite	Intrusive Newcastle Volcanic Formation
G	Granodiorite	Intrusive granodiorite

The KMA is centered on the coastal lowland of the Liguanea Plain and lower Rio Cobre, an area of 139 sq. km that faces the Caribbean Sea, upon which metropolitan Kingston is built. Flanking the plain on the north is a rolling upland terrain underlain by Eocene limestones and Cretaceous granodiorite (local basement) with inliers of Cretaceous volcanics. This upland is bounded on the east by the major physiographic and structural feature of the area, the northwest-striking Wagwater Fault and its associated mountain range front.

East of the Wagwater fault zone the mountains of the study area rise to elevations of 1950 m and are dissected by deep valleys. Complexly faulted slivers of Cretaceous granodiorite, upper Cretaceous volcanics, the Eocene Wagwater Formation (purple conglomerates and, sandstones) and Eocene shales and sandstones underlie this rugged terrain which makes up the Port Royal Mountains. It is generally agreed that in post-Cretaceous and Eocene time, the Wagwater fault was a normal fault downthrown to the northeast. This geometry allowed for the formation of intra-arc Wagwater trough in which thick accumulation of Eocene clastics and evaporites took place on the subsiding hanging wall accompanied by intrusion of andesitic volcanics, and the simultaneous stripping of earlier Cretaceous volcanics off the granodiorite basement on the foot wall. After a long period of tectonic quiescence and submergence, typified by limestone deposition (upper Eocene to middle Miocene), the Wagwater fault was reactivated as a thrust fault, up on the northeast side.

The present plate tectonic setting suggests that the Wagwater fault forms a transpressional bend in the throughgoing faults that define the southern most faults of the Caribbean plate boundary zone, transferring movement between large left-lateral faults at its south and north ends. This plate tectonic interpretation is supported by the existence of two post-Miocene anticlines (Long Mountain and Dallas Mountain) in the southeast corner of the Liguanea Plain. These anticlines trend parallel to the Wagwater fault, out in front of the Wagwater Belt.

What Does the Bedrock Map Show About Landslides?

Map 4 shows that landslides are concentrated in certain lithologic units, but this distribution also reflects the much different topography developed on those units. Landslide deposits extend out onto the fan deposits of the Liguanea Plain, although these originated from steep slopes above the plain, such as at Jacks Hill. Quaternary sand and alluvium/terraces have essentially no landslides. Some relatively small landslides occur on the flanks of Long and Dallas Mountains, involving lithologies PCL and EL. The only other place where group EL has slides is on steep fault-controlled escarpments. Group ELC has a moderate density of small landslides.

Deep-seated landslides are relatively uncommon on the large, low-relief outcrop area of Cretaceous granodiorite near Lawrence Tavern, but are very abundant on fault-bounded slivers in the Wagwater thrust zone, such as on the range front below Jacks Hill. This pattern shows that fault-shattered granodiorite on steep slopes is quite susceptible to failure.

Group ESS (mainly the Richmond Fm.) has a very high landslide density in the Port Royal Mountains, as do the other groups that underlie this steep terrain (ECV, EA, and CV).

5.7 Fault distance and landslides (Map 5)

The locations of faults were extracted from the geological maps Sheet 13 (the Blue Mountains, Provisional edition, 1994a) and Sheet 18 (Kingston, Provisional edition, 1994b). We reclassified the fault distance maps into 15 m-wide (1 pixel width) classes, where a fault distance of zero means the pixel (landslide) is atop a fault trace, and a fault distance of 1 means the pixel (landslide) is only 15 m or less from the fault trace.

What Does the Fault Distance Map Show About Landslides?

Landslides are apparently concentrated near faults in some parts of the map area. For example, the large landslide deposits north of Red Hills, and at Stony Hill, are associated with a major east-west-striking fault. In many cases faults have created steep topographic escarpments (south of Red Hills, Wagwater Range front at Jacks Hill, etc.). It appears that the abundant landsliding is caused directly by fault-related fracturing and alteration of the rock in the steep escarpment slopes.

Landslides are concentrated along the fault at the western bases of Long Mountain and Dallas Mountain. Within the Wagwater Belt faults comprise a dense rectilinear network bounding blocks of unfaulted terrain. Landslides are concentrated near the faults, but some also occur in the blocks between faults.

6.0 Landslide Susceptibility Maps (Maps 6 and 7)

6.1 Analysis of Deep Landslides (Map 6)

Many years of landslide research, plus theoretical considerations of landslide mechanics (Turner and Schuster, 1996) have shown that slope angle, strength of material, and pore water pressure are the dominant factors controlling landsliding of all types. Unfortunately, in a regional landslide study such as this, detailed information on the three factors above may not be available. The information that is available may bear some direct or indirect relation to those three factors. Thus, in regional landslide zonation we are often forced to use surrogate variable in place of the actual physical variables that directly control landslide mechanics.

6.1.1 Factors Controlling Deep Landslides

We analyze deep landslides separately from shallow landslides because the former represent failures of bedrock (often deeply weathered) whereas the latter typically involve failure of a residual or transported mantle (residuum colluvium). It thus follows that deep landslides will be affected by slope angle, the orientation of discontinuities in bedrock, overall bedrock strength, fracturing and alteration related to faulting, and groundwater flow in fractures. We have direct information on slope angle, but not on the other listed factors. Instead, we must infer overall bedrock strength indirectly from simplified lithologic groups, and infer fracturing related to faulting (including its effect on rock strength and ground water flow from distance to mapped faults.

For each analyzed factor we compute the landslide density for certain types of landslides in relation to given factors. For deep landslides, we analyze only scarps-definite and scarps-probable, those being the most confidently identified subgroups of the relatively large landslide group. *Landslide density is defined as the area of landslides in a given factor subcategory, divided by the total area of that subcategory*. Thus, if slopes of 15-20 ^{0} occupy 10 km^2 of our study area, and 1 km^2 of landslides occur on those slopes, the landslide density is 10%. A landslide density of 10% would indicate a severe landsliding problem, considering the fact that landslides may be visible on the landscape for decades to a few centuries. The overall landslide density of scarps-definite and -probable for the 554 km^2 study area (including the Liguanea Plain) is 3.10%, and 4.13% excluding the Plain.

6.1.1.1 Slope Angle

Our slope map indicates the slope angle of the ground surface but for deep, bedrock-hosted landslides the more important factor is orientation of weak discontinuities relative to the slope. Without detailed information on discontinuities we can use only the slope angle, and realize that we are implicitly assuming that the failure plane is subparallel to the ground surface, and thus steepens as slope angle steepens. This assumption is clearly untrue in many locations, so in this sense, the surrogate variable of slope angle does not clearly represent the critical parameter of interest. This part of the analysis could be improved by the addition of discontinuity data.

Slope angles in the study area range up to 63 degrees. Landslide densities for scarps-definite and -probable range from 0-13.8%, with the latter representing a small number of pixels on slopes of 57 ^{0}(Fig. 2). We subdivided slopes into six classes based on natural breaks in the frequency histogram. In general, landslide densities increase with increasing slope angle.

6.1.1.2 Slope Aspect

In the original landslide susceptibility study of DeGraff and Romesburg (1980) landslide densities were strongly controlled by slope aspect. Increased landsliding on slopes facing way from the sun has been noted in many temperate regions; for example, the original DeGraff study area was at 42 ^{0} N latitude. In temperate regions the shaded slopes have low ground temperatures, higher soil moisture, thicker residuum and colluvium mantles, thicker vegetation, and less sheet wash and erosion. The thicker colluvial mantles and greater moisture are thought to produce more shallow landslides. However, such controls may not be effective for deep landslides, or in general at latitudes as low as 18^0 N.

The graph of landslide density as a function of slope aspect (Fig. 3) does show higher densities for S, SE, and

SW- facing slopes. This is opposite to the pattern typically seen in temperate latitudes, and suggests that some control other than soil moisture is at work. An explanation for the high densities on SW- facing slopes is that fault scarps and faultline scarps of the dominant NW-SE-striking faults will face SW and NE. Prominent scarps-definite slides occur all along the SW- facing escarpment of the Wagwater Thrust near Jacks Hill.

The fault- controlled escarpment in Eocene limestones south of Red Hill faces south onto the Liguanea Plain, and also contains multiple landslides. Thus, aspect appears to be a useful factor for distinguishing landslide susceptibility, but mainly due to its indirect representation of fault-line scarps. Accordingly, we reclassified aspects into only two classes, those slopes facing S, SE, and SW, and all other aspects.

6.1.1.3 Lithologic Group

It is expected that lithology would be a major controlling factor for landsliding, and Fig. 4 shows that landslide densities vary widely among the 11 lithologic groups. Highest landslide densities are found on units EA (andesites, mainly the Newcastle Volcanic Formation), ESS (shales and sandstones, mainly the Richmond Formation), and ECV (coarse and fine volcaniclastics, mainly the Wagwater Formation). Coincidentally these three groups comprise almost all of the steep terrain of the Wagwater Belt. Based on landslide densities those three groups have a similar susceptibility to deep landsliding, and are thus placed in a single factor class. Group CV (Cretaceous volcanics) has densities intermediate between the highest class and the much lower densities associated with limestone units, so it is placed in a separate factor class. Class 3 includes G (granodiorite), FD (fan deposits, including the Liguanea Formation), and PCL (clastics and limestone mainly the August Town Series). The density of group FD is an artifact caused by the toes of some landslides protruding out onto the Liguanea Plain and other low-relief areas. Therefore, despite its density we reclassed group FD to factor 1, along with QS and AT. Granodiorite has the same overall landslide density as does group PCL, despite its much different age and composition. This grouping of such dissimilar lithologies based mainly on density can be a weakness in the DeGraff method, if the different lithologies respond differently to changes in the other factors (slope angle, aspect, distance to faults). Finally, the lowest densities are found in Eocene limestone groups EL and ELC, which coincidentally mainly occupy plateaus and other gently sloping terrain. Thus, there is some spatial covariance between lithologic group and slope angle, such that they are not strictly speaking independent variables.

6.1.1.4. Distance to Faults

Based on the vector layer of faults from Geological Sheets 13 and 18, we computed the distance of all pixels from the nearest fault, and then the landslide densities of scarps-definite and -probable as a function of fault distance (Fig. 5). A rather surprising pattern emerges that of steadily increasing density as faults are approached. We first anticipated that densities would reflect the severe fracturing and alteration in relatively narrow fault zones (on the order of one 15m-pixel-wide), outside of which rock was intact and sparsely but uniformly fractured. The steady increase in density toward faults suggests, if it is related to fracturing and weakening of the rock that fracture density progressively increases toward faults over distances of hundreds of meters. We subdivided landslide density into four classes. The first of which includes low- density areas on the Liguanea Plain and other regions farther than 41 pixels (615m) from a fault. The highest density class was defined as within 4 pixels (60m) of a fault. This designation arises from the histogram, and from field observations that mapped fault zones in the Wagwater Belt are often typified by altered zones up to 100m wide (50m on either side of the centre line). The remaining distances between 4 and 41 pixels were simply divided approximately in half to form the last two classes. Defining classes that span a large range of landslide densities is not a preferred technique, but (as described next) we are limited to defining 256 total permutations of slope, aspect, lithology, and fault distance classes, so no one factor can contain too many classes.

6.1.2 Landslide Susceptibility Matrix for Deep Landslides

The subdivision of factors into 6 slope classes, 3 aspect classes (including flat areas), 5 lithologic groups, and 4 fault distance classes creates 360 possible unique combinations of slope-aspect-lthology-fault distance. Of those 360 possible combinations only 249 occur in the study area. Of those 249 combinations, 50 contain no landslides, while the other 199 combinations having landslide densities of 0.001% to 71.4%. However, 15 of the 199 combinations have landslide densities > 10% (Fig. 6) and in 8 of those 15 combinations the density is based on <20 pixels. Thus, half of the highest landslide densities may not be statistically robust values. Many densities of 1- 8% in contrast are based on >1000 landslide pixels (Fig. 7).

A simple method for checking the distribution of landslide densities is to compare them with the product of the four factor class numbers. For each factor, the higher-class numbers contain higher landslide densities. Thus it follows that the lowest landslide densities should occur in pixels in class 1 for slope-aspect-lithology-fault distance, or a factor class product of 1x1x1x1=1. The highest densities should occur in the highest numbered class for each factor (6 for slope, 3 for aspect, 5 for lithology, 4 for fault distance), or the product 6x3x5x4=360.

Figures 8-11 show how the product of factor classes compares to landslide densities. For matrix classes containing >500 landslide pixels (Fig. 8) there is a well-defined linear relation between product and density. For matrix classes with 100-500 slide pixels, the linear relationship has increased variance (Fig. 9). For 20-100 pixels (11,925- 19,575 m^2). These areas approach the mean size of scarps-definite (10,963 m^2) and scarps-probable (11,698 m^2), meaning that slide density for this matrix class is probably being based on a single landslide. If that single landslide had not been mapped in the inventory, the density for those two matrix classes would fall from 16-19% (i.e. much higher than average) to zero. On the other hand, the anomalously high densities may in fact be true and reflect a uniquely high susceptibility for sliding in a particular combination of slop-aspect-lithology-fault distance. After all, this assumption of uniqueness underlies the entire DeGraff approach.

The two matrix classes with anomalous density-product relations both belong to lithology class 3, which includes two dissimilar lithologies, PCL (young limestones and clastics) and G (granodiorite basement), to slope category 5 (37 to 51^0), and aspect class 2 or 3 and fault distance classes 2 and 3. Thus, the low product of factor classes results mainly from the lithology group and far distance from faults. If either of these landslides occurred due to fractured rock along an unmapped fault, then the correct fault class would become 4, and the products increase fault class would become 4, and the products increase from 90 to 120-180. However, even with such an increase the points would still be outliers. There may be some additional extenuation circumstances, either on the ground or slight errors in the digital database, that account for these anomalous density-product relations. Without knowing the exact cause, we retain the landslide densities as calculated in the matrix.

For matrix classes with <20 slide pixels (4500 m^2) there are 7 anomalous points on Fig. 11. All of these points probably represent a single landslide in the inventory. These anomalous cases generally occur on steep slopes (classes 5 and 6, >37 ^{0}), and their low products are either caused by low lithology class number (half the points are in class 2, EL and ELC) or by considerable distance to faults (classes 1 and 2). It may be that, in massive limestones for example, other unmapped factors contribute to landsliding on steep slopes. Without having detailed information on rock strength, fracturing, groundwater flow at these anomalous sites, we retain the high densities calculated in the matrix, that being a conservative approach. However, even if the density in the matrix is unreasonably high, it will result in only a few pixels in the study area being assigned unreasonably high susceptibilities. For example, anomalous class 155 (Fig. 11) contains 5 slide pixels and has calculated density of ca. 0.3. That means there are only 17 total pixels in this matrix class, meaning that at most 12 pixels (out of 2.5 million in the study area) will be misclassified.

6.1.3 Landslide Susceptibility Zones

The definition of landslide susceptibility zones requires dividing the spectrum of landslide densities into a manageable number of discrete classes. DeGraff and Romesburg (1980) and Maharaj (1993, 1995) used cluster analysis to subdivide the spectrum into 4-5 groups, by maximizing the difference between those 4-5 groups. However, Maharaj (1993) had only 43 matrix classes to subdivide, whereas we have 249. A second difference is that cluster analysis will create groupings with maximized differences between them, but there is no guarantee that the lowest density groupings can be characterized as low susceptibility, or the highest as high susceptibility. Such judgments still require the personal intervention of the geologist. Therefore, we used a trial-and-error approach to defining susceptibility classes, based on the histogram of landslide densities (Fig. 12). We were guided by several decision rules. First, densities of <1-2% should fall in our low susceptibility category and densities >10% should definitely be in our high susceptibility category. Second, each susceptibility classes should contain roughly the same number of pixels, which produces a map with the maximum amount of spatial differentiation. Third, each susceptibility class should span a similar range of landslide densities. Rules 2 and 3 may not be compatible. Our final five classes (see Fig. 12) divide the density spectrum into roughly equal pieces, except for the highest class which must include densities as high as 71%. However, since there are very few pixels with densities of >10%, this highest susceptibility class does not occupy much area on the map.

The Landslide Susceptibility Class maps for deep landslides (MAP 6) shows the entire Liguanea Plain, most of the Red Hills, granodiorite outcrop, and Long and Dallas Mountains to have low susceptibility to landsliding. The moderate-susceptibility class includes gently sloping areas in the Wagwater Belt, mainly near wide valley floors, or on low-relief ridge crests and uplands. Some steeper slopes on the flanks of Long and Dallas Mountains, and along the fault line scarp north of Red Hills, are in this class. Moderate-high susceptibility is found on many valley slopes in the Wagwater Belt, on lithologic units EA, ESS, and ECV. Susceptibility becomes high within 4 pixels (60 m) of fault traces in this same terrain. If slopes are very steep, or aspects southerly, these fault-related areas may fall into the very high susceptibility class. Interestingly, the largest area with very high susceptibility is in far eastern St. Andrew east of the Yallahs River. These very high densities are found in Cretaceous volcanics (CV) on steep slopes traversed by closely spaced faults. Similar very high densities occur along the fault-line scarp north of Red Hills, and on the flanks of Long and Dallas Mountains. However, the densities for the latter areas are based on very few landslide pixels, and thus the susceptibility class may be too high.

6.2 Analysis of Shallow Landslides (Map 7)

Shallow landslides can be very destructive to life and property due to their high velocities and tendency to transform into debris flows. The active landslides mapped in the landslide inventory are primarily debris slide, debris avalanche, and debris flow failures of colluvium and residuum on steep slopes. Previous studies (e.g. Brabb *et al.*, 1989) have analyzed shallow and deep landslides separately, because the respective failure mechanisms, and thus the controlling factors, are significantly different. Thus, we created a separate landslide susceptibility matrix based on 341 shallow, active slide zones in the study area, but excluded those within 90 m of roads as being road-related. Excluding road related slides left us with a control set of 136 small active slide zones covering an aggregate area of 217,800 m^2. This is a much smaller number than used for deep landslides.

6.2.1 Factors Controlling Shallow Landslides

The factors controlling shallow landslides in colluvium are well described by Campbell (1975) in southern California (Fig. 13). The failure plane is typically located near the colluvium-bedrock contact, thus parallel to the ground surface. In this case, slope angle should be an excellent surrogate measurement for dip of the failure plane. Resistance to shearing is determined by the strength properties of the colluvium-residuum. Since we have only data on lithologic group, we must hope that bedrock lithology strongly controls the strength parameters of colluvium. The pore pressures in colluvium during rainstorms are affected by the infiltration capacity, which in turn is controlled by the grain size of the colluvium, which may be related to lithology. In recent years research in the USA has suggested that groundwater flowing in bedrock fractures causes some debris slides, at least for rapid snowmelt events (Mathewson *et al.*, 1990). Thus, distance to fault zones may also control the location of debris slides.

6.2.1.1 Slope Angle

Landslide densities for shallow landslides increase up to slope angles of ca. 28 ^{0}, then decrease (Fig. 14). Densities for slopes steeper 41^{0}are based on too few slide pixels to be statistically significant; this is also seen in the large variance in density between adjacent slope angles. However, the decrease in densities occurs at a sharp decrease (from ca. 40 to 20) in the number of landslide pixels. If we presume that the densities for slopes of 28-41^0 are correct, then it appears that the densities of shallow landslides do not progressively increase with increasing slope angle, as was observed for deep landslides. One interpretation of Fig. 14 is that colluvium-residuum becomes thinner or absent as slopes exceed 28^0. The commonly accepted angle of repose for granular unconsolidated material is ca. 35^0.Thus, one would not expect to find extensive colluvial deposits on slopes steeper than 35^0.

Based on this reasoning, we subdivide slope angles into three classes. The highest landslide densities occur in a class between about 20-35 ^{0}. Lower densities are found on slopes of 12-20^0 and 35-41^0. Lowest landslide densities are found on slopes of less than 12 ^{0} (due to the low dip of sliding planes) and on slope of greater than 41^0 (due to a scarcity of colluvium-residuum on bedrock).

6.2.1.2 Slope Aspect

For shallow landslides the densities are smallest for south-, southwest- and west-facing slopes, compared to other slopes (Fig. 15). This is nearly opposite to the pattern observed for deep landslides, but is similar to the pattern observed in temperate north latitudes. In more northerly latitudes, slopes that face the sun, particularly the afternoon sun, tend to have higher soil temperature, lower soil moisture, less vegetation, and thus more erosion and thinner colluvium. Thus, a reasonable interpretation of this pattern is that aspect affects the density of shallow colluvial slides by limiting the presence and thickness of colluvium on the drier slopes.

6.2.1.3 Lithologic Group

Landslide densities for shallow landslides are highest for lithologies EA (andesite) and ESS (shales and sandstones) (Fig. 16), which is similar to the pattern observed for deep landslides. However, deep slides were similarly abundant in group ECV, whereas shallow slides are relatively rare in group ECV. Groups EL and ELC (White and yellow Limestone Groups, respectively) have low landslide densities, with groups CV, ECV, and G having intermediate densities. There were no shallow slides mapped more than 90 m from roads in units QS, AT, FD, or PCL.

The large differences in density between EA-ESS, compared to ECV, begs some explanation, since all three groups occur on similarly steep slopes in the Wagwater Belt. We speculate that lithology is controlling the physical characteristics of colluvium that in turn control colluvium strength and permeability. Group ESS is the only lithologic group that contains abundant shales, thus colluvium derived from ESS would likely contain the highest percentage of clay. The weathering products of fine-grained andesites in a tropical climate would also be expected to contain clay. In contrast, the coarse clastics and conglomerates of ECV (including the Wagwater Fm.) would likely produce coarser-grained, more permeable colluvium. Colluvium derived from granodiorite would also be coarse-grained. Terra-rosa soils derived from limestones can be clay-rich, but are not likely thick on steep slopes. Thus, groups EA and ESS are inferred to produce clayey colluvium that cannot transmit infiltrated precipitation rapidly enough to dissipate high pore pressures. More freely draining colluviums derived from coarser-grained sedimentary and crystalline rocks are permeable enough to avoid this buildup of excess pore pressure.

6.2.1.4 Distance to faults

Landslide densities for shallow landslides do not regularly increase toward faults, as occurred for deep landslides. Instead, densities slowly increase toward faults, but the variance in density between adjacent distance classes is greater than the amplitude of the overall trend (Fig. 17). We interpret this pattern as indicating that no causal relationship exists between shallow landsliding and fault distance. An obvious reason for no relationship is that shallow failure planes do not penetrate bedrock, so the strength (and fracturing or faulting) of underlying bedrock is irrelevant to whether the colluvial mantle will slide. Due to non-correlation of density to fault distance, we do not include fault distance as a factor in the susceptibility matrix for shallow landslides.

6.2.1.5 Downslope Curvature

The shape of hillslope topography exerts a strong control over where colluvium will accumulate, and where sheet wash and overland flow will be concentrated. Numerous studies in the past two decades (see citations in Turner and Schuster, 1996, p. 535-536) have observed abundant colluvial slides in "hollows", i.e. heads of first-order drainages where contour lines are concave facing away from the ridge crest. Across-slope curvature of this type is difficult to calculate from a raster GIS. One method we attempted was to run the SURFACE module over an aspect map. This method will produce a first-derivative map of aspect, i.e. slope concavities and convexities in plan view, but cannot distinguish between concave and convex contour patterns.

Fortunately, the heads of first-order drainages are also typified by convex-upward curvature. This is because slope angles increase from the crest of a ridge, downslope across its shoulders and onto the long, relatively planar slopes leading down to the valley. Thus, in the downslope direction slopes are strongly convex (upward) on the shoulders of ridges, weakly convex on the upper valley walls, weakly concave on the lower valley walls, and strongly concave at the footslopes. We computed four qualitative classes of slope curvature by subtracting a smoothed DEM from an original DEM. For pixels that are higher than the mean trend defined by their neighbors (i.e., convex-upward), elevations on the smoothed image are lower than on the original DEM; for low points (concavities) the reverse is true. Unfortunately, the 15 m DEM created by INTERCON contains enough striping that a difference map between it and a once-smoothed DEM also has bad striping problems. Therefore we smoothed the DEM with a 5x5 pixels mean filter once, and then again, and subtracted the latter from the former. We then subjectively subdivided the range of elevation differences such that the largest 40% of he negative values were termed "strongly concave", the rest "weakly concave", the first 60% of the positive values were "weakly convex", and the largest 40% "strongly convex". Examination of the slope curvature map containing these 4 classes (with an additional class for flat pixels) confirms that this classification gives a reasonable representation of slope curvature types.

Fig. 18 shows that landslide densities on weakly convex and all concave slopes are very similar (.0004 to .0005), but densities on strongly convex slopes are 77% higher (.00083). Strongly convex slopes evidently constitute an attractive initiation point for debris slides, for reasons mentioned above. Therefore, we classified downslope curvature into three classes, flat slopes, strongly convex slops, and all other slopes.

6.2.2 Landslide Susceptibility Matrix for Shallow Landslides

The subdivision of factors into 3 slope classes, 3 aspect classes (including flat pixels), 4 lithologic groups, and 3 curvature classes creates 108 possible unique combinations of slope-aspect-lithology-curvature. Of those 108 possible combinations only 83 occur in the study area. Of the 83 combinations 36 contain no shallow landslides, with the remaining 47 combinations having landslide densities of .0003% to .025%. Landslide densities were computed using CROSSTAB on the four reclassed factor maps to create the matrix image, and then using EXTRACT and a binary map of active slide zones to count the number of slide pixels in each of the 83 matrix categories on the matrix image.

The landslide densities for the 47 matrix combinations are admittedly based on small numbers of landslide pixels. The maximum number of pixels within a class is 179, but the average is only 21. Only three matrix classes contain more than 50 slide pixels, whereas 28 classes contain fewer than 20 slide pixels. As with deep landslides, we compared the product of factor classes with landslide density (Fig. 19). There is considerable variance to the linear relationship, even for classes with more than 50 slide pixels. Part of this variance may be caused by the way that active slide zones were mapped on the 1:50,000-scale inventory maps, as V's roughly 2-3 mm long. Two mm at that scale is equivalent to 100 m on the ground, which is 2-3 times larger than a typical active slide zone. Thus, the actual landslides do not coincide with many of the pixels assigned to them in the GIS. This limitation could be overcome by more precise mapping of landslides, for example on a base map of 1:12,500 scale.

6.3 Landslide Susceptibility Zones for Shallow Landslides (Map 7)

The spectrum of landslide densities was divided into six subjective classes based on the frequency of various landslide densities (Fig. 20). The four highest susceptibility classes (very high, high, moderate=high, moderate) span roughly an equal range of landslide densities. Low susceptibility and non-susceptibility classes cover a much smaller range of densities, but contain many more pixels than the four high classes (e.g., the Liguanea Plain).

The Landslide Susceptibility Map (Map 7) shows the string effect of lithologic group. The three highest susceptibility classes (very high, high, and moderate-high) are almost exclusively restricted to lithologic groups EA and ESS (cf. Map 4). Recall that these two lithologies contained 68% of shallow landslides more than 90 m from roads, but cover only 21% of the study area. Their landslide densities are roughly 3.5 times higher than that of any other units. Within these lithologies, the highest susceptibilities are for pixels sloping 20-35 ^{0} on the shoulders of ridges where slopes are strongly convex-upward, on slopes that do not face south or west. IT MUST BE EMPHASIZED THAT THESE PIXELS REPRESENT SITES WHERE SHALLOW LANDSLIDES MAY INITIATE, AFTER WHICH THE DEBRIS WILL TRAVEL AN UNKNOWN DISTANCE DOWNSLOPE. The "runout distance" of debris slide material depends greatly on whether the debris liquefies after initial failure. Ellen and Fleming (1987) concluded that the mobility of debris slide material is controlled by the ratio of water content at the time of failure to the liquid limit. Materials most susceptible to debris liquefaction are low-density colluvium containing 8-25% clay, which collapses upon shearing (contractive behavior). Denser, clayey colluvium exhibits dilative behaviour upon shearing, thus failed slabs can absorb water, remain intact, and often come to rest not far downslope from the site of slide initiation. Therefore, additional hazards due to debris flows exist directly downslope of the high-susceptibility areas shown on Map 7. This has been observed during the debris flows triggered by October-November 1998 rainfall in KMA.

Several small areas of high susceptibility occur on Cretaceous volcanics (CV) both in eastern St. Andrew, and on the north-facing escarpment north of Red Hills. In all other lithologies the highest susceptibility attained, even on north facing convex slopes, is moderate-high. Most of the limestone areas (EL, ELC) have low susceptibility to shallow sliding, regardless of slope angle, aspect, or curvature. One explanation for this low susceptibility is that those lithologies yield little colluvium upon weathering, or that colluvium is permeable enough not to fail in debris slides.

7.0 Limitations of this Study

Like most regional landslide studies this study has limitations from several causes: 1) deficiencies in the variable data set, 2) non-correspondence between the available (surrogate) data and the actual physical mechanisms responsible for landsliding, and 3) deficiencies in the DeGraff method of predicting landslide susceptibility.

7.1 Limitations from data Deficiencies

The main limitation from data is the limited resolution of topography possible with the 50 m contour lines from the 1; 50,000-scale map series. With a closer contour interval slope angles and curvatures could be more accurately represented. This is particularly true of the steepest slope segments, whose angles are underestimated with too large a contour interval.

7.2 Limitations from Use of Surrogate variables

These limitations have been addressed specifically in earlier sections, as to the possible non-correspondence between the spatial data we have available at present, and the actual material properties and physical processes responsible for landsliding. Some additional information, such as attitudes of dominant discontinuities in various parts of the map area, could provide data more directly connected to the landslide process. Collecting data on other relevant parameters such as thickness and character of colluvium, or small-scale lithologic variability within bedrock formations (much less simplified lithologic groups), would be extremely time-consuming and expensive. Data on groundwater flow patterns in steep mountainous terrain may prove impossible to collect; hopefully landslides are insensitive to such processes.

7.3 Limitations of the DeGraff Method

The DeGraff method has many advantages for producing a landslide hazard zone map-- it is conceptually and computationally simple, and relies on the types of spatial data (topography, geology) that are commonly available.

However, the method has some inherent limitations that should be understood, in order to correctly interpret the maps of Landslide Susceptibility Classes. The first limitation is that landslide susceptibility classes describe only the susceptibility of the local landscape to landsliding under some undefined triggering mechanism. The temporal probabilities and spatial patterns of such triggering mechanisms constitute the opportunity for landsliding. The potential for landsliding is calculated by multiplying a map of opportunity times a map of susceptibility. From this concept arise two facts: 1) you cannot calculate a temporal probability or return period for landsliding from a susceptibility map, in the absence of an landslide opportunity map, and 2) the landslides that result from a given triggering (earthquake, hurricane, rainstorm) will probably occur in the highest susceptibility classes on the map, but only if the triggering event is similar to the typical triggering events that created all the landslides in the inventory. For example, if most triggering events in the past several hundred years have brought near-horizontal rain in from the southwest and induced most landslides on slope with a southwest aspect, an anomalous storm from the northeast may produce most of its landslides in areas labeled moderate susceptibility on these maps. Similar results could accompany earthquakes, where moderate-susceptibility areas fail near the epicenter, but only high-susceptibility areas fail far from the epicenter.

Second, the DeGraff technique relies solely on the landslide inventory, and the landslide densities computed therefrom, to define landslide susceptibility. There is basically no room for either theory or common sense when the landslide densities seem to defy logic. Any deficiencies in the inventory will be transmitted directly to the susceptibility map. Such deficiencies can come from the mistakes or omissions of landslide investigators, or from the polyglot nature of the landslides preserved in today's landscape. The landslides visible at any time are a complex mixture of large slides that range from very old to very young, intermediate-size slides that are young to very young, and small slides that are exclusively very young, often only visible for a few decades. The landslide inventory is thus heterogeneous, and some scheme (such as the one employed in this study) is necessary to separate definite landslides from features that just might be landslides.

Third, the DeGraff method is very sensitive to whether the "landslides' mapped include the source area, the deposit, or both. If the toes of long-runout landslides are not differentiated from source areas and are thus included in the inventory, the characteristics of the land beneath the toes become associated with landsliding. Imagine a series of inventoried landslide that slid off a steep escarpment, with its toe resting on a gently sloping surface underlain by fan deposits; this exact situation occurs at the base of Jacks Hill. Using the DeGraff method, low-angle fan deposits will be associated with all the slide pixels in the toe, a landslide density will be calculated for the class of low-angle fan deposits, and all low-angle fan deposits will be assigned that density, wherever they are in the study area. Pixels on the margins of Kingston Harbour, far from any escarpment, would have the same slide density as the pixels at the base of Jacks Hill.

To voice this problem, we performed this DeGraff analysis only for landslide source areas. However, the reader must understand that the areas downslope of pixels with high or very high susceptibility for initiating landslides may also have a high susceptibility for being the deposition site of debris. This is especially true of large landslides (such as at Jacks Hill) or long-runout failures such as debris slides-debris flows.

8.0 Uses of Landslide Susceptibility Maps

Preparation of landslide hazard zonation maps is a relatively young scientific pursuit.

In some cases, the methodologies employed in map preparation are still in an experimental stage and many of the published hazard maps have not been field-tested. It was possible, however, to field test the hazard maps produced in this study. Following the heavy rainfall associated with hurricane Mitch and rainfall associated with the stationary cold fronts during 15th October and 9th November 1998 triggered widespread landslides in KMA. Over 200 landslide were mapped in the area and a preliminary analysis of this data validates the accuracy of the KMA Landslide Susceptibility Maps.

Listed below are the main recommendations that will benefit a wide variety of users concerned with environmental management including disaster managers, planners and engineers.

Landslide susceptibility maps can be used to:

a. Recognize geographic areas where landsliding has already occurred and future landsliding is most likely, in other words , this map helps in understanding the constraints on land use and the scale of the landslide problems;
b. Adopt appropriate strategies for dealing with the problems that may arise because of landslides on marginally stable slopes;
c. Prepare for, modify, and/or mitigate the disastrous effects of landslides on communities and infrastructure by means of appropriate engineering practice and building codes;
d. Regulating new development in hazardous areas through planning controls; and
e. Public education.

Landslide risk can be computed using the susceptibility map together with information on existing or expected vulnerability. It is possible to estimate the risk associated with the critical facilities, especially the road network. Such information may be evaluated to arrive at a decision regarding an acceptable risk for a facility, or need for relocation, or applying appropriate mitigation measures. Planners may use different levels of landslide risk in KMA to control future development activities. The most practical and cost-effective loss reduction method is to avoid areas with a relatively high landslide hazard. If existing development falls under areas marked with a relatively high hazard and risk then preventive measures may be applied to counter the risk.

Landslide hazard maps can be used for a qualitative assessment of accelerated soil erosion in the watersheds. Areas of high to moderately high landslide hazard in KMA surrogate for zones of accelerated soil erosion or vice-versa. Such areas may be left as forestlands.

9.0 How to Use Hazard Maps?

Five levels of relative susceptibility have been identified on the KMA Landslide Susceptibility Maps: (1) low; (2) moderate; (3) moderate-high; (4) high; and (5) very high. Predicting absolute hazard is impractical with current capabilities. These zones do not imply legal restriction or regulation by zoning ordinances or laws as laid down by the local government authorities.

Citizens, planners, engineers, and developers, however, can use these landslide hazard zonation maps as a tool to help reduce losses from existing and future landslides through prevention, mitigation, and / or avoidance.

The map is intended primarily for the assessment of landslide hazard for planning purposes on a regional scale. It indicates indirectly the extent and relative severity of landslide hazard and may be used in preliminary selection of areas for housing and infrastructure development. The enhanced readability of the map far outweighs the simplifications, errors and, omissions that could not be avoided.

The map should not be used to determine the stability of specific building sites.

The map can be used to identify areas where detailed geologic-geotechnical investigations are desirable prior to the development.

Citizens may use the map in a general way to determine relative hazard, because chances of landslides occurring in areas in a high susceptibility zone (4) are greater than in areas under low zone (1).

It should be understood that natural changes as well as human-induced changes can affect the susceptibility to landslides in any area, and that the absence of past or present landslides does not mean that slope failures will not occur in the future.

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