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18 LANDSLIDE HAZARD DATA FOR WATERSHED MANAGEMENT AND DEVELOPMENT PLANNING, ST. LUCIA, WEST INDIES

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ABSTRACT

Increasing annual losses resulting from landslides and associated hazards have prompted many island governments in the Eastern Caribbean to recognise the need to incorporate landslide hazard data as an integral component in watershed management programs and development planning. To be effectively used, however, such data must not only be based on sound scientific principles but must also communicate the technical information in a manner that is easily understood and interpreted by those potential users who are not landslide specialists. The paper describes the main features of a landslide hazard information package which was prepared for several watersheds in St. Lucia, West Indies, primarily for use in the management of the islands' watersheds. The data set consists of a suite of three annotated maps, at 1:25000 scale, and a companion guidance document. The map database contains an updated landslide inventory map, a debris flow hazard map and a map of primary areas of debris flow initiation and existing and potential debris flow runout regions. Each map contains a detailed legend and explanatory text on the appropriate use of the map and map limitations. The guidance document provides recommendations on land use feasibility in zones of varying debris flow stability. Incorporation of the hazard data into proposed watershed management programs should lead to major reductions in the potential economic and social losses associated with debris flows.

INTRODUCTION

Landslides and other types of mass movement represent a major natural hazard in many islands of the Eastern Caribbean, and historically they have been responsible for extensive property damage. To a large extent, the islands vulnerability is related to their geology and tectonic history. The islands form part of the Lesser Antilles island arc system, a chain of relatively young volcanoes of Tertiary age. Vertical incision of the volcanic cones accompanying tectonic uplift has carved steep-sided v-shaped valleys, resulting in a rugged dissected terrain. In addition, the volcanic rocks have been deeply weathered. Highly weathered rock and soil material exposed on steep slopes favors a high landslide incidence. A high annual rainfall provides the triggering mechanism for landslides.

Landslide losses are also related to human factors. In terms of property damage, the most important of these has been continuous deforestation of river watersheds to make way for agricultural crops. A scarcity of flat land and the islands' dependence on agriculture, in particular banana, as foreign exchange earners, have resulted in the expansion of cultivation, largely uncontrolled, on increasingly steep slopes and in higher locations in the watersheds. The loss of forest cover has heightened watershed vulnerability to erosion, in particular landsliding. Consequently, the vulnerability of urban and agricultural communities downstream of these sites to both soil erosion and flooding has increased.

Faced with high potential losses due to landslides and associated hazards, and the severe strain which these hazardous events have placed on the islands' limited resource base, there has been increasing recognition by island governments of the need to incorporate landslide hazard information as an integral component in watershed management programs and in development planning. Thus, there is significant incentive to develop landslide hazard data in formats suited to inform decision-making for land use and development planning. The paper describes the main features of a comprehensive landslide hazard information package which was developed for this purpose for selected watersheds in St. Lucia, West Indies.

SITE DESCRIPTION

St. Lucia forms part of the Windward Islands in the Eastern Caribbean (Fig. 1). The island lies between latitude 13° 43 N and 14° 07 N and longitude 60 ° 55 W and 61° 05 W. It has a land area of 616 square kilometres. The island is geologically young and is of volcanic origin. The volcanic rocks range from dacites in the south to andesites in the central region to basalts in the north. Tuffs, agglomerates, conglomerates and coral reefs are exposed along the coast.

The island has a characteristic youthful topography. Active downcutting of the volcanic deposits have resulted in a highly dissected, rugged topography. A high drainage density and steep, elongated slopes are typical. The relief is dominated by a central ridge which extends along the north-south axis of the island. The highest mountains occur in the southwest central region, where slopes are extremely steep; the maximum elevation, at Mt. Gimie, is 960 metres. To the north, erosion of the older volcanics has resulted in a less rugged topography; the highest peak is 675 metres. A narrow coastal plain occurs to the south east (Newman, 1965).

The island experiences a humid tropical climate. Mean annual temperature is 27°C, with a maximum of 31°C. The rain regime consists of a drier season from January to May and a wet season from June to December During the wet season, the island is invariably affected by tropical storms and hurricanes. Rainfall is orographic, so that mean annual precipitation ranges from less than 1780 mm in the lower elevations in the north and southwest, to more than 3800 mm in the interior (Organisation of American States, 1984). In these latter areas, rainfall is perennial. The vegetation of the mountainous interior consists of tropical rain forest. At lower elevations, secondary forest predominates. Scrub vegetation occurs in drier areas on the west and east coasts. An appreciable proportion of the forest cover in middle watershed regions has been replaced by small scale farming.

LANDSLIDE HISTORY

Landslide incidence on the island has historically been relatively high and widespread. Failure of valley sides are a common annual occurrence. The majority of slope failures are debris flows, shallow soil failures initiated on hillslopes during periods of heavy rainfall; their characteristic spoon-shaped scars (initiation sites) and tracks (runout areas) are often conspicuous on the landscape. Debris slides, earthflows, and rock slides are less common.

In addition to the annual occurrence of landslides, the island has experienced several major landslide events. The most well-known of these occurred in November 1938, when, within a one-hour interval, two landslides developed in the Ravine Ecrivisses and nearby Ravine Poisson areas. Sixty-two lives were lost and 32 injuries were sustained. This incident is reported to be one of the worst landslide disasters in the Eastern Caribbean (DeGraff *et al.*, 1989).

Within recent time, landslide incidence and landslide hazard impact has risen to a large extent. This is attributed to i) the increase in frequency and severity of low pressure systems which affect the Lesser Antilles region and ii) the encroachment of forested areas by agricultural crops, in particular banana. The severe negative impact of the latter trend was manifested most recently during Tropical Storm Debby (September 1994), when numerous landslides, mainly debris flows, were triggered on hillslopes. Widespread debris flow activity led to the removal of large tracks of forest, the loss of vast acreage of agricultural crops and extensive soil erosion, particularly in the upper watersheds of the major rivers. The significant volume of soil moved downslope by debris flows contributed to increased erosion and flooding in the urban and agricultural communities in the lower regions of watersheds. Severe infrastructural damage resulted, including the loss of 58% of the islands banana crop. It was the severity of landslide impact by this single event which initiated the study presented in this paper.

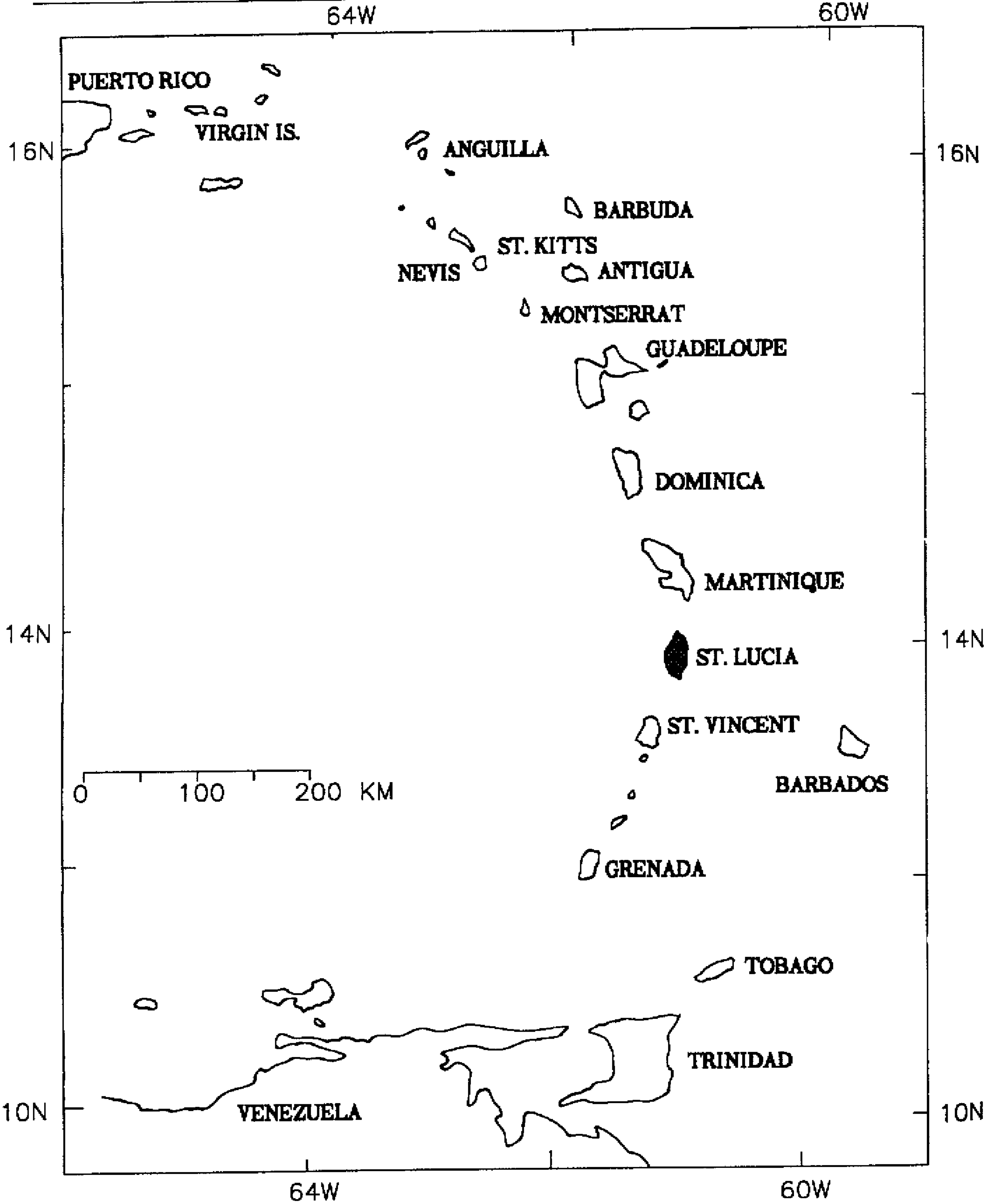

Fig. 1 - Location map.

LANDSLIDE HAZARD INFORMATION STUDY

The primary purposes of the investigation were to prepare landslide hazard information products with the necessary and sufficient information to enable potential users who are not landslide specialists, in particular planners, decision makers and engineers, to include landslide hazard data as land use and development criteria. To be effectively utilised by target users, such landslide hazard information products must not only be based on sound scientific principles but in addition, must be able to communicate the technical information in a manner which will encourage its wide usage. This means that the data must be presented in formats which are easily understood and interpreted. In addition, the relevant hazard data must be developed at a level of detail appropriate for the intended application.

In the case of St. Lucia, the considerations of soundness of the technical data and its ease of understanding by potential users took on greater importance, in light of the unavailability of required source data, and past experience of non-use of landslide hazard data previously generated for the island. For example, at the time of this investigation, the basic data on physical factors controlling debris flow occurrence, such as slope gradient, was not available. Indeed, this information, along with other relevant topographic parameters, could not be rapidly generated from digital topography, since a digital elevation model of the island was not available at the time of the investigation. Further, the existing landslide hazard map of the island (DeGraff, 1985) had not been significantly utilised by the planning department or by other agencies. The reasons for non-use are numerous and varied, and include the lack of recognition on the part of the relevant agencies of the significance of the data. It was felt, however, that a major reason may be related to a lack of understanding of the manner in which the hazard data should be used.

As a consequence, a landslide hazard information package was developed to provide a comprehensive view of landslide hazard on the island at the regional level, using formats which promote greater understanding. The hazard information package was prepared for eleven of the islands watersheds (representing 47% of the island; Fig. 2), the catchments of which had been identified by the Ministries of Planning and Agriculture as requiring priority protection. The data set generated consists of the following documents:

i) An annotated landslide inventory map
ii) An annotated debris flow hazard map
iii) An annotated map of primary debris flow initiation sites in the upper watershed of rivers and existing and potential debris flow runout areas.
iv) A companion guidance document to accompany the maps.

In order to enhance understanding and to facilitate interpretation, each annotated map provides detailed explanations of map elements, such as hazard categories, and includes explanatory text on the appropriate use of the map data, with examples of use, and of map limitations.

The study was concentrated on the upper regions of the identified watersheds. In addition, due to the prevalence of debris flows over the islands' landslide history, the study focused on debris flow hazard. The mapping exercise on which the investigation was based was conducted at the regional level, map scale 1:25000.

Landslide Inventory

The landslide inventory (Fig. 3) records the location, types and areal extent of past and existing landslides of all types. Based on available data, the inventory includes:

i) Landslides which were generated prior to 1985, as recorded on the inventory map of DeGraff (1985);
ii) Landslides which were initiated between 1986 and 1991, as indicated on 1:10000 scale black and white 1991 air photo coverage of the island. Since this coverage was limited to coastal areas, the inventory does not include landslides which may have initiated in the island's interior during this period;
iii) Landslides which were initiated during Tropical Storm Debby in September 1994. This data was obtained via field mapping and a review of existing reports. Field mapping was done at the reconnaissance level, using a 1:25000 scale topographic base. Since the mapping exercise focused on the upper regions of the priority watersheds, it does not constitute a complete record of landslides generated in these watersheds during the storm. In addition, because portions of the upper watersheds of some rivers were difficult to access and/or were made impassable due to landslide damage along forest roads, landslide occurrence in these areas could not be mapped in the field.

The inventoried landslides are classified into shallow and deep seated failures. Shallow-seated failures are further classified into debris flows, debris slides,

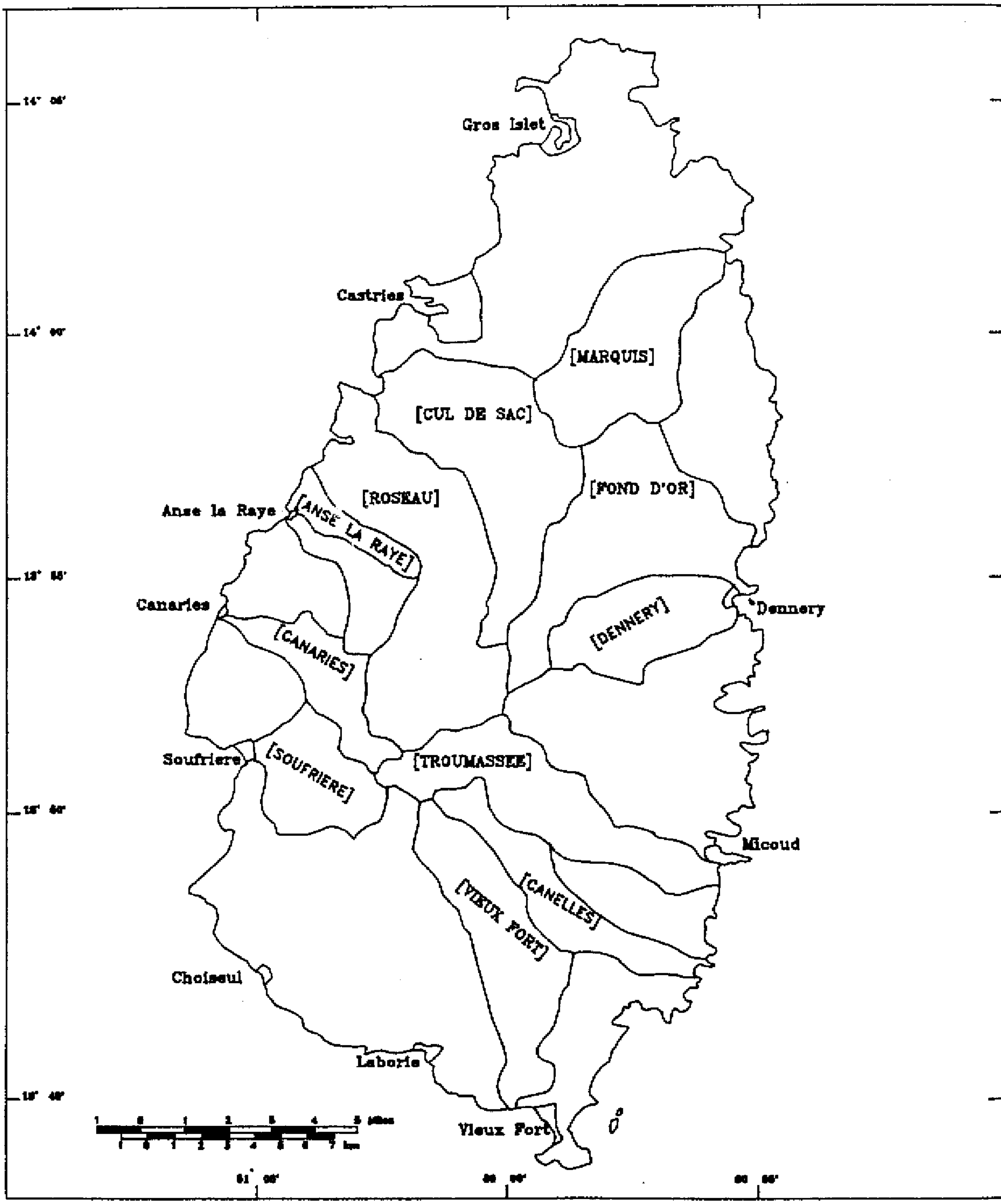

Fig. 2 - Priority watersheds.

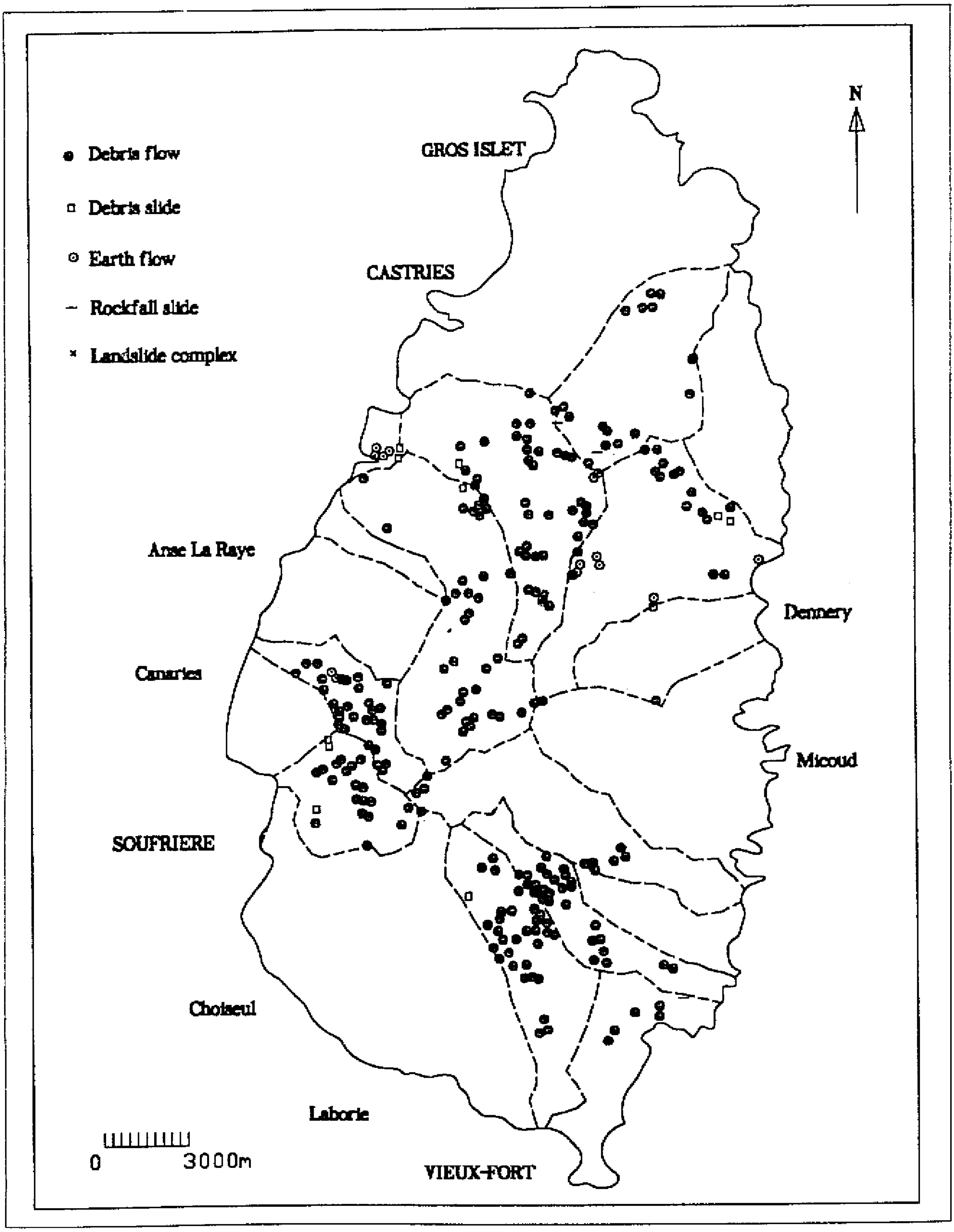

Fig. 3 - Landslide inventory map.

rockfalls and rockslides and landslide complexes. Deep-seated failures are classified into rockslide, earth flow and landslide complexes. Where data was available and the size of the landslide permitted, both the locations of the landslide scar and its associated deposit are indicated on the map. In all other instances, landslides are indicated as point locations.

In addition to indicating the specific locations of landslides, the inventory map shows the distribution of past landslides in the watersheds. This information can be used to identify broad areas which are prone to landslides and to determine the density of landslides in a given watershed. Landslide density in individual watersheds can be used to distinguish general areas which are potentially landslide-prone from those that are potentially stable.

Debris Flow Hazard Map

The debris flow hazard map (Fig. 4) zones the study area into four hazard categories, viz low, moderate, high and extreme. The map shows the relative degree of hazard associated with debris flows in the study area, and thus, can be used to identify areas of the terrain where debris flows are either likely or unlikely. The map is suitable for use as a regional planning tool, to identify regions where debris flows may pose a threat to regional development. Thus, the hazard map can be used as a basis to prevent development in identified hazardous areas, to control the density of development in different hazard zones, or to permit development in hazardous regions, after detailed engineering investigation. The map is not suitable for evaluating debris flow stability at the site or project levels. For these purposes, a detailed engineering geological investigation is required.

The map legend provides detailed explanations of the meaning which should be associated with each hazard zone, including the likelihood of debris flows within the zone and typical slope locations in the watershed where debris flows are likely to occur in each zone (Fig. 5). Guidelines on use of the map are also provided, along with examples of use, as described above. In addition, the limitations of the map data are indicated in the explanatory text. Some of these limitations include the following:

i) the hazard map identifies the hazard associated with debris flows only; it does not indicate the hazard associated with other landslide types;

ii) the map identifies hazard associated with debris flow initiation sites only and does not indicate the hazard associated with their runout areas;

iii) the hazard degree indicated does not consider variation in debris flow size;

iv) the hazard evaluation methodology assumes that the hazard zone determined at the centre of individual grids, each 200 metres by 200 metres, is representative of the entire grid;

v) since the typical width of the debris flows are significantly less than 200 metres, the map generalises the hazard. Thus within one hazard zone, the degree of hazard may vary, and pockets of a given zone may have a higher or lower hazard;

vi) the hazard zonation method does not include the effects of human activities, such as deforestation and poor agricultural practices, on the severity of the hazard. Where these occur, the debris flow hazard is expected to increase.

Debris flow hazard was evaluated using factor correlation techniques. This technique is based on knowledge of:

i) the critical physical factors controlling debris flow occurrence and the relative contribution of these factors to debris flow hazard, and

ii) subsequent correlation of the distribution of factor values (as indicated on factor maps) with the distribution of debris flows (as indicated on the inventory map).

Based on previous work (Reneau and Dietrich, 1987; Ellen and Wieczorek, 1988; Rogers, 1993), observation of debris flow behaviour on the island, and available physical data, four factors, viz slope gradient, slope curvature, rainfall (as indicated by mean annual precipitation) and soil type, were assumed to be the critical factors influencing debris flow hazard.

Each of the four factors were divided into factor classes. Each factor was subjectively assigned a relative weight (from 1 = unimportant to 4 = extremely important) according to their relative importance in influencing debris flow hazard. Similarly, subjective ratings were assigned to associated factor classes The factor weights and factor class ratings are presented in Fig. 6. The factor classes associated with the four factors were then grouped into factor combinations. Each factor combination represents an area of the terrain with unique characteristics of slope gradient, slope curvature, soil type and mean annual precipitation, and thus is assumed to respond uniquely to debris flows. A hazard ratio is then calculated for each hazard unit as the weighted product of the individual factors and factor classes, divided by the maximum number of hazard units. A hazard category (low, moderate, high, extreme) is then assigned to the hazard unit based on the value of the hazard ratio. The complete procedure is outlined in Rogers (1995).

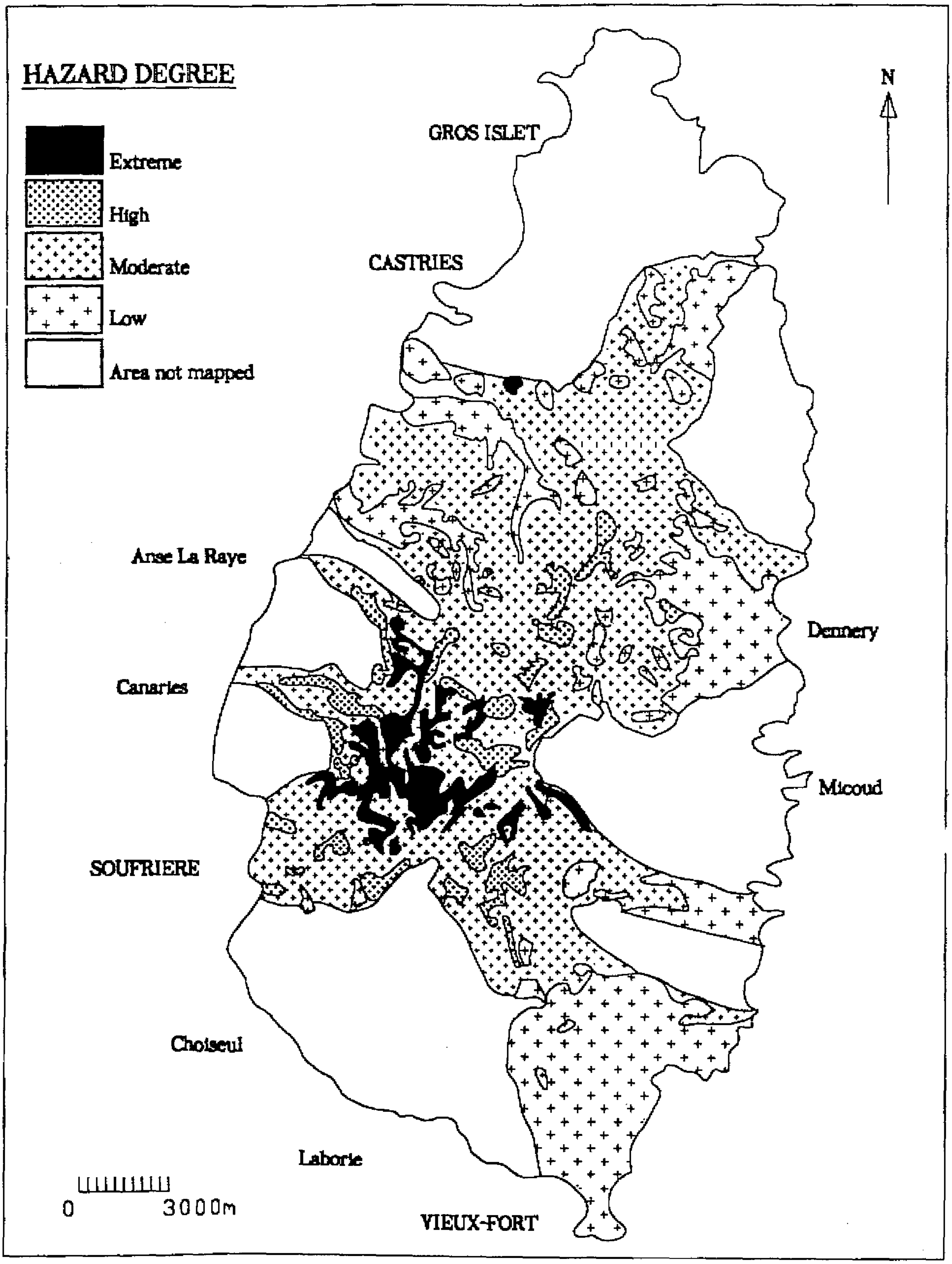

Fig. 4 - Debris flow hazard map.

	HAZARD ZONE	EXPLANATION	APPROPRIATE USE
L	Low	In some areas, viz. along flood plains of major rivers, no evidence of past debris flow activity exists and debris flows are highly unlikely. In the remainder of this zone debris flows are unlikely, i.e. few debris flows are likely to occur, and these may occur only on the steepest and most concave slopes in the zone	Refer to Guidance Document
M	Moderate	Debris flows are likely to occur; with moderate density and typically at heads of drainages and on concave slopes, 20° - 30°	Refer to Guidance Document
H	High	Debris flows are highly likely to occur; typically at the heads of first and second order drainages in upper watersheds, along steeply sloping (30°), concave sections of hillslopes, and along the steepest planar slopes in the zone. The runout areas of flows may coalesce due to a high debris flow density	Refer to Guidance Document
E	Extreme	Debris flows are very highly likely; numerous flows may develop in first and second order drainages in upper watersheds, in concave sections of hillslopes and on steep planar slopes. In some parts of the zone, nearly all hillslopes may be affected Flows commonly coalesce die to a high debris flow density	Refer to Guidance Document

Fig. 5 - Debris flow hazard categories, as presented on the hazard map.

FACTOR WEIGHTS

Slope Gradient	4
Slope Curvature	4
Rainfall (Mean Annual Precipitation)	3
Soil Type	2

FACTOR CLASS RATINGS

Slope Gradient (°)

Class	Rating
< 10	1
10 - 20	1.5
20 - 30	2
30 - 40	3
> 40	4

Soil Type

Class	Rating
Soils on excessively steep slopes	1
Skeletal soils	1.5
Smectoids	2.5
Latosols/Polysols	3
Colluvial soils	4

Slope Curvature

Class	Rating
Ridge/Nose	1.5
Concave/Straight Slope	3.5

Mean Annual Precipitation (ins)

Class	Rating
< 80	1.5
80 - 120	3.5
> 120	4

* Alluvial soils, beach sand and salinas were automatically assigned a low hazard rating

1 = unimportant
2 = important
3 = very important
4 = extremely important

Fig. 6 - Factor weight and factor class ratings.

Factor maps showing the distribution of the factor classes were then prepared for each factor. Generic maps of slope gradient and slope curvature, at 1:25000 scale, were developed manually from existing soil data (Stark et al., 1966) and land capability data (Jalloh, 1993), using procedures outlined in Rogers (1995). In addition, to facilitate manual analysis, the existing soil map was regrouped into six soil classes and the rainfall map of the island (Organisation of American States, 1991) was reclassified into three rainfall classes.

In the absence of a computerised database of physical factors for the island, all factor and hazard maps were prepared manually on a topographic base using a raster grid of 200 meters by 200 meters. Although this raster is significantly larger than the average size of debris flows which occur on the island, this represented the minimum grid size in which manual analysis could be performed in the specified time.

Primary Areas of Debris Flow Initiation and Existing and Probable Runout Areas

This map (Fig. 7) shows, for primary areas of debris flow initiation i) the specific locations of past and existing debris flow initiation sites and their tracks (runout areas) mobilized of existing debris flows, and ii) the specific probable locations where debris flows are likely to be initiated and subsequently mobilised in the future.

Primary areas of debris flow initiation were assumed to be those regions having a high or extreme debris flow hazard, as indicated on the debris flow hazard map (Fig. 4). Runout areas were determined from both existing and probable initiation sites. The locations of existing initiation sites were obtained from the landslide inventory map (Fig. 3). Probable initiation sites were assumed to be those topographic locations, as indicated on the 1:25000 topographic map, which occur at the concave heads of channeled drainages, along concave sections of hillslopes.

It was assumed that debris flows will runout along paths defined by the steepest slope, and that the mobilised debris will be deposited where the flow encounters a decrease in slope gradient or where it enters a major stream channel. These criteria were used to map the runout areas of those existing initiation sites not previously mapped in the landslide inventory, and the runout areas of probable initiation sites. Both the width of a debris flow and its distance of travel are dependent on the volume of material removed from the initiation site, obstructions in the path of the flow (e.g. vegetation) and slope gradient. Since the first two of these parameters were unknown, runout areas were represented in terms of their travel paths (line) rather than as "zones".

The data represented on this map is complementary and additional to the landslide inventory and the debris flow hazard map. Unlike the landslide inventory, it shows the distribution of debris flow scars and tracks in those regions of the watersheds associated with the greatest hazard. The collective information on existing and probable debris flows presented on the map gives an indication of the areal extent and severity of the likely hazard. It also indicates the likely intensity of debris flow activity which may result from a single debris flow -producing storm event. Such data may be used by planners in the following manner:

i) to identify communities and activities at risk, i.e., which either lie in the path of an existing or probable debris flow, or are likely to be affected by associated erosion and flooding downstream;
ii) to identify the specific slope locations which should be avoided for development and which may be developed only with the application of specified mitigative measures (for example, slope stabilisation in the case of existing sites and tracks and protective measures in the case of probable sites and associated tracks);
iii) to prioritise which areas would benefit from detailed site-specific mapping and investigations.

Additionally, this map, in conjunction with the debris flow hazard map and rainfall intensity data, may be used by planners and emergency response personnel during an approaching storm to identify those watersheds most likely to be affected by debris flow activity resulting from the storm, and to issue warnings to vulnerable communities of the likely impending danger.

In the maps explanatory text, the user is notified of several limitations of the map. The most important of these is the fact that, due to generalisations of the topography associated with the mapping scale, the map does not identify all existing or probable debris flow initiation sites and runout areas. It indicates however, that in general, topographic depressions at the heads of drainages may be assumed to be the most likely locations from which a debris flow may be generated.

Guidance Document

The guidance document serves as a companion to the three landslide hazard maps. It provides additional hazard information on:

i) recommendations as to the feasibility of utilising land of differing stability (as identified in the hazard map) for different land uses, viz

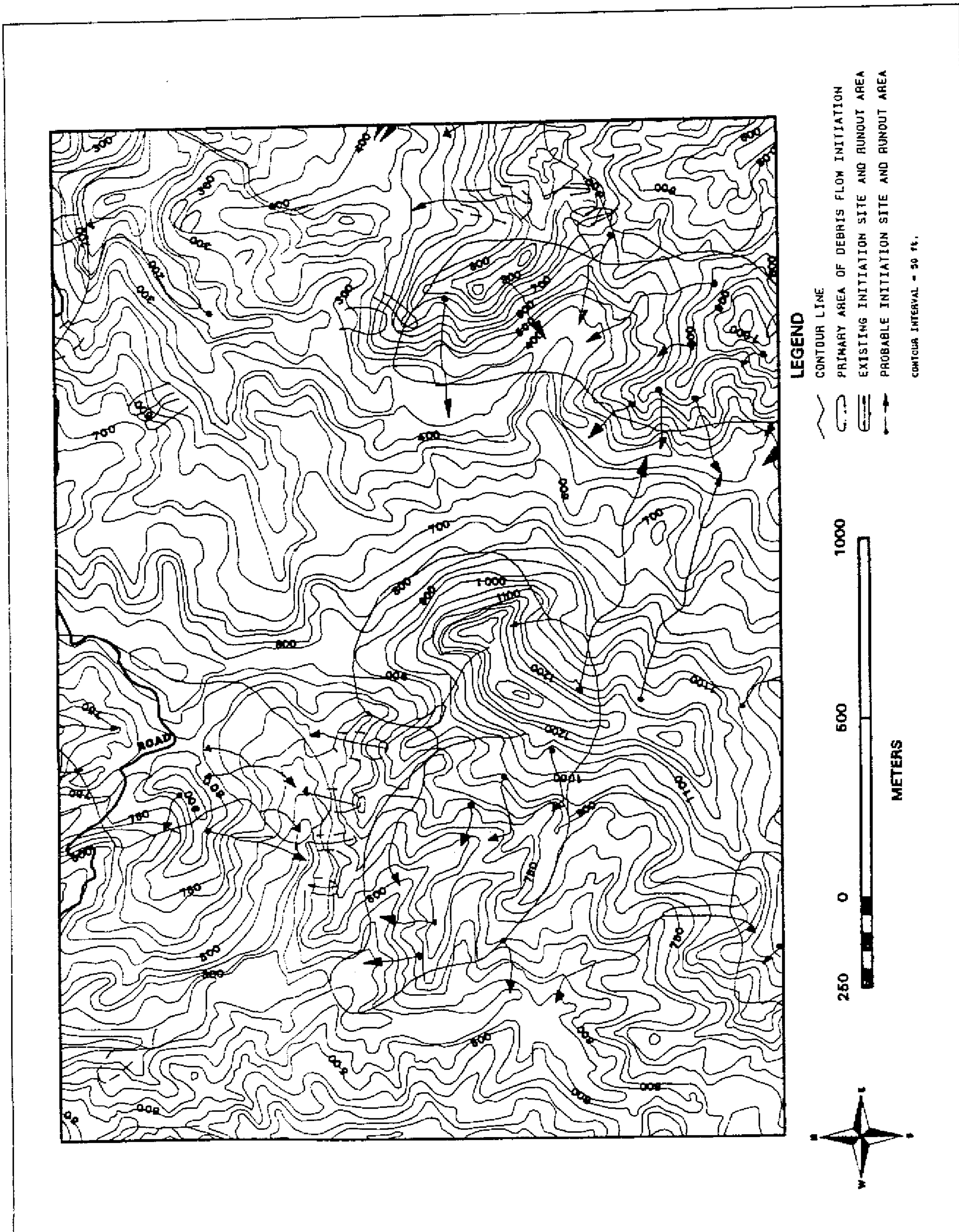

Fig. 7 - Map of primary areas of debris flow initiation and existing and probable runout areas.

agricultural development, infrastructual development and major and minor roads

ii) guidelines of the procedural action to be taken to reduce the vulnerability of planned activities to debris flow activity.

The recommendations and guidelines have been developed with consideration given to the hilly terrain which characterises most of the island, the high competition for limited land and the benefits of utilising both passive (avoidance) and active (stabilisation measures) approaches to debris flow hazard mitigation.

Recommendations and guidelines are included for a total of 16 possible landslide hazard locations. The hazard locations were derived from the combination of the four hazard zones (low, moderate, high and extreme (Fig. 4) and the four possible hazard settings which may occur in any given hazard zone viz, an existing or probable debris flow initiation site, an existing or probable debris flow runout area, an existing or probable landslide site other than a debris flow, and any other part of the hazard zone other than the three locations indicated above. Each of the 16 locations were assigned a unique two-letter hazard code. A flow chart is provided to assist the user in the determination of the relevant hazard code for a given site of interest. Once the code is identified, the user can refer to a guidance chart (Fig. 8) for recommendations and guidelines on land use feasibility for the proposed site.

SUMMARY AND CONCLUSIONS

Landslide hazard data must not only be based on sound scientific principles, but must also be presented in formats which facilitate understanding and interpretation of the hazard data by those potential users who are not landslide specialists. The landslide hazard information products described here provide the basic landslide hazard information, in particular that associated with debris flows, which can be used by non-landslide specialist users to better manage watersheds and in development planning. The data are presented in map format, accompanied by annotated legends and detailed explanatory texts on the appropriate use of the map and of map limitations, and are complemented by a guidance document which provides recommendations on land use feasibility in differing zones of debris flow stability. This mode of presentation is specifically designed to provide planners, decision-makers and engineers with a comprehensive and easily-understood view of debris flow hazard at the regional level.

The enhancement in user understanding which this mode of presentation provides, should enable planning departments to incorporate landslide hazard data as essential criteria for land use and development planning with greater confidence. Further, it should encourage wider usage of the data, including as a tool in hazard education. Incorporation of this data into proposed watershed management programs should lead to major reductions in the potential economic and social losses associated with debris flows. Wider application of the method of presentation of landslide hazard data described here, in other islands of the Caribbean, is likely to lead to a greater willingness, on the part of all potential users, to utilise such data in a manner which would lead to long term reductions in landslide losses and ensure environmental protection.

It should be noted that since this investigation was completed, St. Lucia and several other islands in the Eastern Caribbean have acquired geographic information systems (GIS). Many have since converted existing physical factor data, including topography, from analog to digital format. This move will significantly improve the islands' capability to generate and update accurate landslide hazard data for landslide hazard mitigation and response. GIS technology is currently being used to generate debris flow hazard data for the watersheds not covered in this investigation and to prepare vulnerability and risk maps for the island.

ACKNOWLEDGMENTS

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HAZARD CODE	AGRICULTURAL ACTIVITY / FORESTRY	INFRASTRUCTURAL DEVELOPMENT	MAJOR AND MINOR ROADS / BRIDGES	OTHER RECOMMENDATIONS
Mo	Require detailed investigation by engineering geologist or soils engineer to determine site stability (MCWT); Recommended if determined to be either i) stable or ii) unstable but stability can be improved with appropriate stabilisation measures ; in such cases (1) site activity away from concave sections of slope; Avoid otherwise	Require detailed investigation by engineering geologist or soils engineer to determine site stability (MCWT), Recommended for development if determined to be either i) stable or ii) unstable but stability can be improved with appropriate stabilisation measures ; in such cases (1) site activity away from concave sections of slope; Avoid otherwise	Require detailed site investigation by engineering geologist or soils engineer to assess stability of slopes; may require specially designed cuts and fills (MCWT)	
Hdi	Not recommended	Not recommended	Not recommended	If existing debris flow and soil is exposed in scar (rather than bedrock), stabilise soil with bioengineering or vegetative materials to stabilise soil/encourage soil recovery (MALFF)

MCWT - Contact the Ministry of Communication, Works and Transport for assistance
MALFF - Contact the Ministry of Agriculture, Lands, Fisheries and Forestry for assistance

Fig. 8 - Extract of guidance chart indicating feasibility of land uses inzones of varying debris flow stability.

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