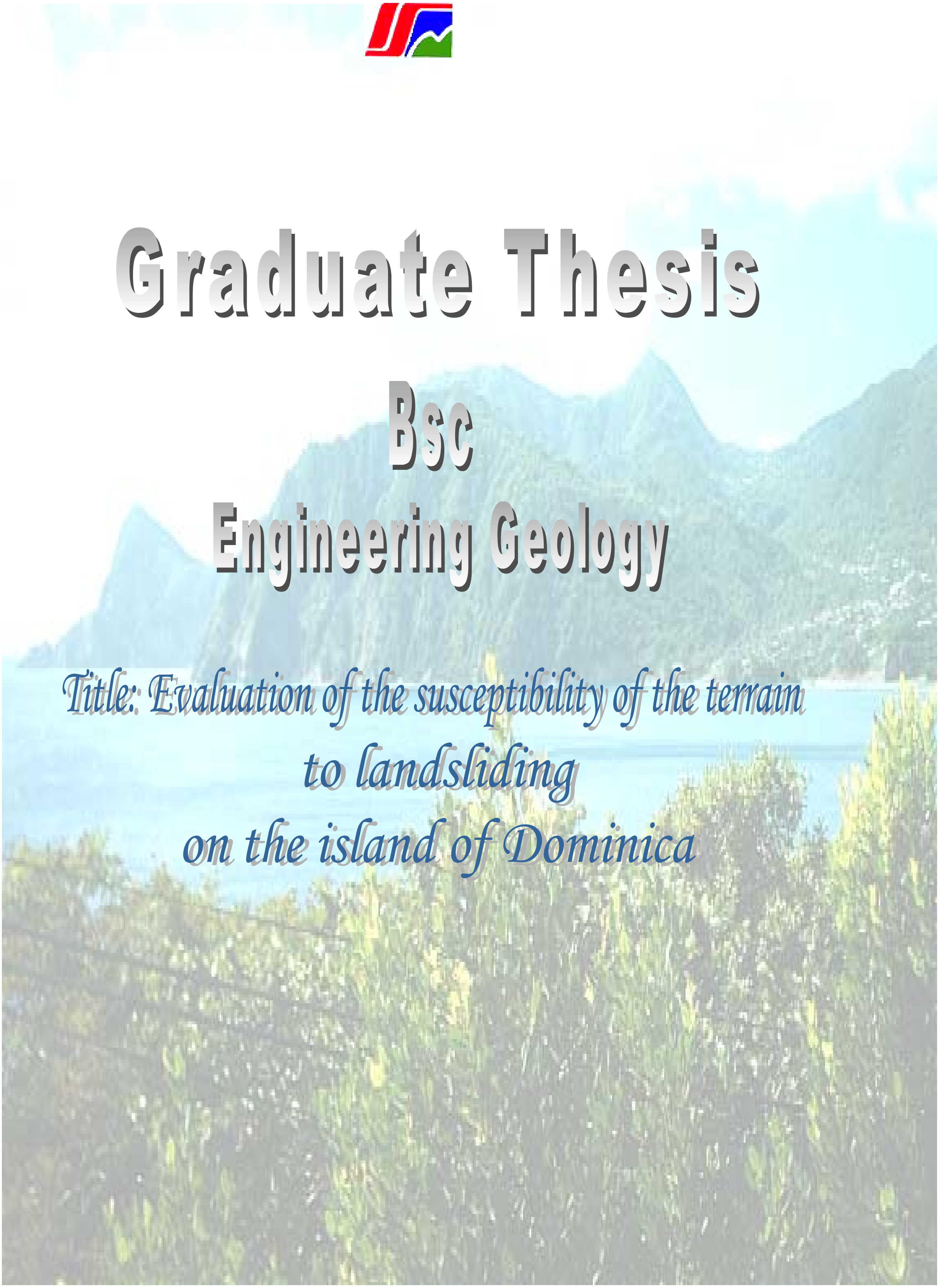

Graduate Thesis

Bsc

Engineering Geology

Title: Evaluation of the susceptibility of the terrain
to landsliding
on the island of Dominica

Dedication

To my parents, Miss Lucille St.Luce and Mr.Ted Baron for their unconditional love, support, understanding and advice through out my entire life.

Acknowledgements

I would like to thank the following persons, some of which who have not only helped with the period of preparation of my thesis but during my six years here in Cuba.

- My parents Miss. Lucille St.Luce and Mr. Ted Baron for loving and believing in me even more than I believed in myself and for sacrificing so much into making me a professional.
- To my immediate family who without them I could not have reached thus far, their love, care and helped me make it through the years; Daddy Selah, Montex Baron, Isejah Vision Thomas, Tedina Baron Basil and Mama.
- Jared Moss for his love, support, companionship, concern and advice which was all so important.
- Aunts Lucia, Ignatia, Maudlyn, Carvel; Nicky, Denrick, Joel, Sylvester Jno. Baptiste for their support in one way or another during my six years in Cuba.
- To my tutor Dr. Rafael Guardado Iacaba for his ideas, guidance and correction during this study.
- Yuri Almaguer for his unconditional help, support and dedication which was of paramount importance in completing this study; thanks a million.
- Mr. Brian Bynoe for useful information which he gave me which I used in this study.
- My friends who have made my stay here in Cuba more fun and interesting; Yanquiel, Jais-ann, Anika, Felix, Porvy, Jeff, Evert, Alonzo, Yanara & family, Katy, the collective of the Caribbean students here in Moa, students of fifth year Engineering Geology, Jesus and Mayito.
- To Commandant in Chief Fidel Castro Ruz and the Cuban Revolution for giving me this opportunity to become a geologist.
- The department of geology (staff) for assisting me in my five years here in Moa.
- Saving the best for last, as it always good to have a powerful ending, I would like to thank the almighty God for being with me every step of the way, loving and guiding me to make it thus far. Without blessing none of this would have been possible.

Thought

“Success is not determined by how far you have reached, but by the obstacles you have overcome to get where you are”

Lucille St.Luce

Summary

This study entitled "Evaluation of the susceptibility of the terrain to landsliding on the island of Dominica" has as its main objective the evaluation of the susceptibility of the terrain for the occurrence of landsliding on the island of Dominica. It has been carried out as a thesis presented upon completion of a five year Bsc course en Engineering Geology.

Many parts of the island of Dominica has proven to be very susceptible to landsliding, proof of which is the existence of a total of approximately 810 recorded past and present landslides of different magnitudes and categories.

The present causes of such massive landsliding on the island include, precipitation (heavy rainfall), rock type (geological make up of the island), past landsliding, topography, geomorphology and agricultural practices.

This study has used the information pertaining to this hazard (landsliding) to formulate thematic landslide hazard or susceptibility maps based on landuse and geology applying GIS (Geographic Information System). Although a susceptibility map already exists for the island the maps done in this study is in no way related or based upon it. This project includes a study of the geological engineering characteristics of the terrain and an evaluation of the factors which influence landsliding (rocks types,, precipitation and hydrology).

The author has interpreted and analyzed some of the existing information and maps which was used as base material. Moreover, recommendations for mitigation and prevention with reference to the level of susceptibility of the terrain. Furthermore this study will serve to increase the general knowledge pertaining to landslides on the island of Dominica.

Resumen

Este presente trabajo titulado “Evaluación de la susceptibilidad del terreno frente a los deslizamientos en la isla de Dominica” tiene como su objetivo principal la evaluación del terreno para la ocurrencia de deslizamientos en la isla de Dominica. Muchas áreas en la isla de Dominica han demostrado susceptibilidad a los deslizamientos, prueba de cual es la existencia de aproximadamente 810 deslizamientos documentados desde el pasado hasta el presente, de diferente magnitudes y categorías

Las causas de estos deslizamientos en el presente son, la precipitación intensa, el tipo de roca (constitución geológica), deslizamientos del pasado, topografía, geomorfología y la agricultura.

Este estudio ha utilizado la información pertinente al riesgo (deslizamiento) para formular mapas temáticos de la geología y uso de suelo de susceptibilidad para la isla de Dominica aplicando GIS (Sistema de Información Geográfica). Aunque ya existe un mapa de susceptibilidad para la isla de Dominica el mapa generado en este estudio no esta basado o relacionado a el en ningún manera. El estudio incluye un análisis de algunos de los factores que influye la ocurrencia de los deslizamientos (tipo de roca, precipitación e hidrogeología).

La autora ha interpretado y analizó información y mapas preexistentes, estos se emplearon como materiales de base para el estudio. También, se propuso recomendaciones para la mitigación y la prevención de la ocurrencia de deslizamientos según los niveles de riesgo. Además este estudio va a servir para aumentar el conocimiento a cerca de los deslizamientos en la isla de Dominica.

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Introduction

Dominica is susceptible to a wide range of natural hazards, tropical storms, hurricanes, earthquakes, volcanoes, floods and storm surges to a lesser degree. Some of these hazards are further interrelated, meaning that one can lead to the occurrence of the other. A typical example is that the occurrence of storms /hurricanes which bring heavy rainfall levels can lead to mass movements.

Nature alters the surface of the land through a variety of processes. Some processes such as volcanic activity increases the land surface by adding layers of rock material. Landslides are one of the erosional processes creating the opposite effect (it removes layers of materials instead of adding to it). Thus it is very important to study the susceptibility of particular areas, as to the occurrence of such a phenomenon as landsliding.

The susceptibility of an area to sliding depends on various determining factors. Such factors include rock type, structure, relief, topography, climate, tectonics, and history of mass movement in that area. Another factor which affects and increases the susceptibility of mass movement in an area is poor land use practices which can lead to the degradation of the land; thus making it more susceptible to movements given the correct elements and balance which are necessary to provoke such movements.

The analysis of the susceptibility of an area to landsliding is very important for the following purposes with reference to this study: To improve and upgrade landuse in low risk areas; improve mitigation efforts and to improve engineering practices in the construction of roads and houses in order to reduce risk. As will be seen in this study, these factors are very important because in areas which are more susceptible, hazards tend to restrict and even control landuse practices.

In this study, we make use of various maps already published and also those created in order to reach our conclusions and have applied of GIS (Geographical information system) technology in the preparation, analysis and interpretation of maps.

Object

The object of this study is landslides on the island of Dominica.

Problem

This study arises as a lack of ample knowledge in light of the conditions and causes of the phenomenon of mass movements in slopes and hillsides; and a lack of regionalization (development) of the susceptibility to such phenomenon on the island of Dominica.

Hypothesis

If the location of mass movements (past and present), their causes, conditions within which they develop and their influence in the system is known; then it is possible to determine the levels of susceptibility of an area to landsliding and propose a plan for correction and mitigation.

General Objective

- Study of the evaluation of the susceptibility of the terrain for the occurrence of landsliding on the island of Dominica as a means of improving the sustainable development and better territorial planning.

Specific objectives:

- Evaluation of the factors which influence landsliding (geology, landuse, hydrology).
- To establish a cartographic system, relating mass movements.
- To make recommendations and suggest measures in accordance with the level of susceptibility of the terrain.

Analysis of past projects related to this study

In the history of Dominica, very few attempts have been made to map and asses landslide hazards. This however does not reduce the importance of such on the island. Dominica as can be seen even by traveling through the country side is an island very susceptible to landsliding and even more now than before. There for there is a growing need for landslide risk assessment as the number and frequency of landsliding increases.

In 1987 a landslide hazard assessment was prepared by the OAS at the request of the government of Dominica. The study was carried out by Jerome V. DeGraff of the United States Forestry department.

The study found that the volcanic origin of the country, resulting in steep slopes and unstable bedrock, and the abundant rainfall together create conditions which readily generate landslides. A full 2 percent of the land area of the country is disturbed by existing landslides, of which the most abundant type is debris flows. The landslide analysis team first delineated all past landslides on black -and –white 1:20,000 aerial photographs and prepared a landslide map at a scale 1:50,000. Next a map of surface geology was compiled from the existing information and overlaid on the landslide map to determine which bedrock units were associated with existing landslides. Six of the eight block units were found to be so associated. Next a map of slope classes was compiled, again from existing information. Four classes were defined that corresponded to present land uses. Hydrologic factors were examined but no correlation between rainfall distributions or vegetation zones with landslides could be established. Finally, the bedrock and slope units were combined, the composite units were compared with the landslide map, and the proportion of each bedrock-slope unit subject to landslide disturbance was determined.

The landslide hazard map was used to locate areas suitable for development. Surprisingly it also showed an active landslide area could dam a tributary of the Trois Pitons River, threatening the lives of the downstream population. The map was constructed in six weeks at a total cost of US $13,000.

Other studies with reference to landslide occurrence and related phenomenon has been made but the assessment of landslide susceptibility has some what been neglected even with the rising number of slides occurring all over the island.

Methodology of Research

For the completion of this study, the author developed a series of investigation leading to obtain the aforementioned objectives. The study was divided into the following steps:

- Research of information and analysis of the past projects done, which relates to the topic of study.
- Field exploration and investigation of the different mechanisms of mass movements in slope and hillsides were carried out.
- Landslide risk analysis. Determination of the different causes and conditions which generate the different mechanisms of landslides and its evaluation.
- Selection of cartography of risks based on a geographical information system.
- Office work and research

This study has been divided in three main parts; the first part is based on the general information of the region of study. In this chapter a special emphasis is placed on the factors such as relief, rainfall, geological setting, tectonics, volcanism and hydrology; which are all important for the study and analysis of landslides. This chapter also presents an analysis of the different natural resources.

Chapter two presents the methodology applied in the study, as well as the different types of mechanism and types of mass movements, taking in consideration the factors which cause and create the conditions which generate landsliding; which permit an analysis of the factors which serves as triggers to landsliding. This chapter also includes the methodology and methods used for risk cartography particularly landslides. The methodology includes the use of ArcView 3.2 GIS which was the main program applied in this study; it permits the overlaying of maps, merging of maps and interpretation of information in a clear and complete way; moreover it allows the analysis and management of landslide risk.

Chapter three presents a detailed description of the causes, conditions and mechanisms of landsliding, in the area of study and gives a classification of the types of landslides which is found on the island of Dominica. It also presents a risk analysis based on GIS. The author has based this study in giving a determined weight and value to the different factors which provoke mass movement in slopes and hill slides. A category of 3 values have been chosen. Methods of mitigation were also formulated.

The conclusions and recommendations: the author have given the best interpretation possible to the different factors, types of landslides, their mechanism, their dynamics and cartography, in a way by which it permits through a cartographic system of GIS, to find solutions to the problems of such a magnitude.

A glossary of terms and definitions and terms which permits a better understanding of the terms used in this study, has also been included.

Finally, the appendix where the maps, tables, charts and photographs necessary to explain the risk analysis done in this study.

Scientific Record: This study serves as a first for a student of engineering geology from the island of Dominica to prepare a landslide hazard map for the island.

Scientific Results:

- Landslide hazard map for the island of Dominica.
- Geological analysis of the relation between landslides and other factors such as hydrology and geology in the island of Dominica.

Fields of application: The results of this study can be applied in physical planning, agriculture and disaster preparedness for mitigation.

Limitations encountered in this study

The limitations encountered in this study are as follows:

1. Lack of equipment for measuring.
2. Absence of certain key information and maps, which could have helped in reaching even better conclusions.
3. Lack of time and financial resources which could have improved the quality of the study.

CHAPTER 1

Physical-geographic characteristics

This chapter presents the general physical-geographical characteristics of the island of Dominica such as it climate, vegetation etc.; as well as its geological characteristics, geological history, tectonics and volcanism, natural and georesources among others. Lastly is a general overview of the economic situation of the island of Dominica.

- **Location of study area**
- **Climate**
- **Physical geographic characteristics**
- **Geological characteristics**
- **General Information**

Figure 1a Caribbean map showing the location of the island of Dominica.

1.1-Location of study area

Dominica is situated in the Caribbean, Lesser Antilles at $15°N$ and $61°W$. It has an area of approximately 751km^2. The island is of volcanic origin, with rugged terrain and is also the most mountainous of the Lesser Antilles. It is located between the islands of Martinique to the south and Guadeloupe to the north. Its highest point is Morne Diablotins with an elevation of 1447m, Morne Trois Pitons with an elevation of 4422m, while Morne Trois Pitons has an elevation of 1424m. Besides these two, there are two other mountains with 1200m. The topography is the most unique of the Caribbean, marked by many deep valleys, galleys, rivers, waterfalls and lakes. Evidence of the island's volcanic nature is wide spread with geysers, hot springs and volcanoes. Hills of more then $30°$ make up 60% of the island. Dominica for it lush green vegetation and thanks for it volcanic nature, and rugged terrain is known has the nature island of the Caribbean. It is home to the Morne Trois Pitons national park a world heritage site.

1.2-Climate

The island experiences high temperatures, usually between 24-29 °C. The island is also affected by hurricanes and tropical storms from the months of June to December, which is during the six month long hurricane season. It is an island very susceptible to these storms because of its location in the path of the trade winds.

Atmospheric humidity is very high, while relative humidity varies from place to place. The temperatures decreases at approximately 1 for every 100m increase in altitude, which serves as an explanation for the lower temperature experienced towards the canter of the island. The high year round temperatures are due to its location in the tropics close to the equator. In these latitudes the sun is high overhead all year, so there is little variation from day to day between the times of sunrise and sunset.

The sun's heat is moderated by the cool temperatures of the Atlantic Ocean and by the trade winds, which blow from the northeast throughout the year. These winds blow more strongly from January to April, bringing cooler temperatures and showers from far out in the Atlantic.

1. Physical-geographic Characteristics

Figure 1b Photograph of Dominica landscape

1.3 Hydrographic Network

Dominica has a very interesting and unique hydrographic network; it is very dense and the rivers run mainly from the central dome elevations in the rain forest towards the low lying coast. Based on the 1:25000 topographic map the drainage system is predominantly dendritic. The drainage system is supported by high annual rainfall levels on the island which averages approximately 1800mm. Within this network, the largest rivers are the Indian River in the north, Layou River in the West, Melville Hall River in the North-east, Geneva River in the South, Roseau (Queens) River (youngest) in the south-west and the Castle Bruce River in the east. Among these the Layou River has a longitude of 27 km. Generally the rivers and their tributaries flow in two directions, from the center to the east and from the center to the west. There are 10 main rivers flowing to the west and 6 to the east.

From an analysis of the stream order, within the network it was observed that there are a high number of first and second order streams, a notable amount of the third order while those of the fourth order is very rare or even absent in many parts of the island.

Figure 1c Photograph of a River in Dominica

Though the density of the drainage system remains primarily constant for the entire island, it is slightly higher towards the southern central part. Evidence of this is the presence of three natural lakes within that area. The Fresh Water Lake and Boeri Lake which are both fresh water lakes and Boiling Lake which comprises of highly mineralized water boiling constantly at high temperatures; all located at elevations exceeding 2500m. The two fresh water lakes are located in inactive volcanic calderas.

The network also includes several waterfalls and small rapids which are dispersed in many different locations due to the topographical and lithological setting of the island which include deep gullies, valleys and ravines.

It can be noted that all the rivers flow uniformly from the mountains and volcanic dome areas which are located in the center of the island which is an indicator that the main source rocks are located primarily in that area; which in this case would be impermeable, acidic effusive volcanic rocks. This area also corresponds to the location of a series of active pelean volcanic domes (andesitic/dacitic). These geological factors aforementioned encourage higher levels of surface runoff and lower levels of infiltration of rain water towards the center of the island.

1.4-Vegetation

Figure 1d photograph of Dominica vegetation

The vegetation includes montane rain forest, elfin alpine meadow, Litoral wood land, mature rain forest, montane thicket, scrub woodland, secondary rain forest and swamp and wetlands.
The entire interior of the island is dominated by montane rainforest and submontane rain forest; while the rest of the vegetation is diversified on the coastal areas, the dominant vegetation being semi-deciduous forest.

- **Elfin Woodland** grows at the highest elevation, above 3,000 ft., and is almost constantly covered by mist, subject to wind, high rainfall and cool temperatures. The vegetation consists of mosses, ferns, shrubs, some palms, *Lobelia Cirisifolia* and stunted Kaklin trees *Clusia Venosa* covered by lichens.
- **Montane Thicket** is transitional between elfin woodland and montane forests, dominated by spindly trees about 12-15m high with small canopies. The most common tree found on steep slopes is *Podocarpus Coriaceus*, the island's only native conifer. In more level areas, the main tree is *Amanoa Caribaea*.
- **Montane Rainforest** grows above 2,000 ft. and is often in cloud cover or mist. Most trees here are also to be found in mature rain forest, though much reduced in stature. Many trees have arial roots and are home to mosses, lichens, orchids and a variety of bromeliads. Common among the ground vegetation is fern brake and razorgrass (a sedge). Non-vascular epiphytes cover most montane rain forest trees and plants.
- **Mature Rainforest** grows below 1,500 ft. This zone contains the most luxuriant growth, with trees averaging 100 ft. in height. The massive tree trunks are often littered with bromeliads and various species of anthurium. Some, like the *Chataignier*, are heavily buttressed, whilst the *Gommier* is straight-boled. Also dominant are *Dacryodes Excelsa*, *Sloanea spp*., and *Licania Ternatensis*. Due to the thick canopy, there is little ground vegetation other than patches of *Selaginella* fern.
- **Secondary Rainforest** grows in areas once cultivated but are now abandoned, or in areas which have suffered landslides or other natural disasters. Most common here are tree ferns, of which there are 4 varieties, and *Bois Canon.* Other widely found species include *Cyathea spp*., *Miconia guianensis, Simarouba amara* and *Chimarrhis cymosa.* A less dense and often broken canopy permits shrubs and small plants to grow freely.
- **Seasonal Formations** occur at lower elevations and contain trees which blossom spectacularly in the dryer season. Also found here are ariods, orchids, *Z'ailes Mouches,* ferns and a variety of vines which rapidly proliferate.
  (See landuse map Appendix 14)

1.5- Natural and Georesources

Dominica is an island very rich in natural untouched resources and georesources. Its natural resources includes, water, timber, hydrothermal energy (not yet being exploited), land. Of all these resources, the most important and useful is its water; because it is found in large quantities both superficial and underground and is uncontaminated. Most of Dominica's natural resources are found up to this day in an almost untouched state. The hydrothermal energy though not yet being used has a capacity twice of that of the island of St. Lucia. The presence of the hydrothermal energy is due to the volcanic origin and present activity on the island. Dominica has many fumaroles and sulfurous hotspots (areas of mineral water boiling at very high temperatures at the surface).

- Economic geology/Georesources:
- Geothermal power (potential high, twice that of St Lucia) untapped
- Aggregate, including lightweight (pumice) some exported
- Minor accumulations of minerals (low grade sources)
- Minor diatomaceous earth, impure clays, low grade thin layer alumina and limestone
- "Sponge" which holds and guides water to our very productive rivers

Hot springs found in Dominica (Morne Espaniol area)

- Hot water (now covered), Toucari
- Submarine hot spring, Prince Rupert Bay, (known locally as Longhouse Vent off government jetty)
- Submarine hot spring area, Prince Rupert Bay
- Gloshow spring
- Hot spring, near mouth of Picard River
- Balvin hot spring
- Area of hot ground that forms conspicuous steam cloud after rainfall
- Submarine hot spring, Prince Rupert Bay (known locally as Black Coral Vent off Coconut Beach hotel)
- Manies sulfur spring
- Submarine hot spring, off Morne Espaniol

2. Geological Characteristics

2-1 Geomorphology

In order to analyze the geomorphology of Dominica, several key factors must come into play: geology, climate, relief, hydrology e.t.c Dominica has in general terms two physiographic regions, the rugged, high-relief interior where the highest volcanic domes can be found, and the relatively low-relief coastal periphery where the general population has settled. The interior of Dominica is dominated by mountain peaks, steep ridges, and deep narrow valleys, waterfalls and fast flowing streams with high gradients occur in the valley bottoms. Relief is very high, with a 2000 foot drop over 1 mile horizontal distance in some areas. The volcanic geology of the island is the significant factor in the sculpturing of such unique landscape. A chain of volcanic domes in the interior of the island have given rise to numerous major mountain peaks. Morne Diablotins is the tallest of these 1447 ft. The coastal periphery of Dominica presents a landscape which is much more subdued than the interior. However the influences of the central volcanic domes deposits continue to be manifested in the coast, except in areas where there are a few sedimentary fluvial deposits. The coast is quite “flat” compared to the interior thus permitting settlement. Originally, the topography of the coast could have been even more rugged, but mass-movement and fluvial processes may have reduced the relief by removing material from the highest elevations depositing them in the lower areas. Climate is an important factor in the formation of topography. As is the case of Dominica and the rest of the Lesser Antilles, the small variation in temperature between sea level and the higher elevations is not of great geomorphological importance, but the great difference in rainfall is very significant. An analysis of rainfall indicates that annual rainfall varies directly with elevation. Since water is the principle erosive agent on the Island, the high elevations are eroding at a greater rate than the lowlands. Over time, this disparity in erosion will serve to reduce the relief between the interior and the coastal periphery. Also important is the analysis of the effects of weathering and soils on the landscape. The geomorphology of any area serves as an important factor in any geological analysis.

2.2 Geology

Dominica is built on a broad submarine ridge of (probably) Early Tertiary age (that is about 60 million years ago) or perhaps even older deposits. It is one of the Volcanic Caribees, the more western line of a double island-arc, the other line of which is mainly built of limestone. Dominica is almost entirely composed of volcanic rocks.

Geological history

The earliest rocks visible on Dominica are found along the east coast (Pagua-Rosalie and some remnants further north and south.) These are lavas and breccias of late Miocene and dykes of Pliocene age (up to 7 million years old). The lavas may appear as red, deeply weathered materials and they are often partly covered by much younger ash deposits.

In early Pliocene time (perhaps 2-3 million years ago), coarse sedimentary rocks comprised of volcanic materials and some limestones were laid down (and are exposed in west coast cliffs). They form the basal part of Morne Diablotins. Foundland and the Cochrane area, which form the basal part of Morne Trois Pitons are older, possibly late Miocene.

In middle Pliocene time (about 2 million years ago) basaltic-andesitic shield volcanoes were built in the south of the island and west of the earlier lavas. Some of the deposits are pillow lavas deposited under the sea, and examples can be seen near here, (Springfield), by the public road at Antrim.

But the most important mountain building period was in the Pleistocene, when a line of dacitic-andesitic composite volcanoes was superimposed over the less lofty earlier shield volcanoes: Morne au Diable (Pelean), Morne Diablotins, Morne Watt, Morne Anglais, Morne Plat-Pays, are all about 400,000-500,000 years old.

Still later, only 30,000 years ago, a very large eruption, the Roseau ignimbrite eruption took place from near where Trois Pitons stands. Ash and pumice flows filled several valleys and the deposits extended several hundred km from Dominica. The whole deposit is equal in volume to about 60 cubic kilometers of solid rock.

After this, large dome complexes, of which Morne Trois Pitons is the most spectacular example, were formed , usually in the crater of a large volcano, the latest being that of Morne Patates, the most recent dated deposits of which are about 450 years old (Holocene). (See geologic map Appendix 22)

2.3 Lithology and Stratigraphy

The principal rock types found on the island are of volcanic origin with very few sedimentary deposits which are found mainly as fluvial deposits. The rocks are dated from the Miocene (7.0-5.3 M.a.) to the Pleistocene (younger, less than 1.8 M.a.). The principal rock types are basaltic lavas, andesitic tuffs (some welded), ash deposits, and a few dacite (dacitic materials which include diamond shaped quartz crystals confined to the north east e.g. Calibishie). There are also dacitic/ andesitic lavas (Micotrin, Trois Pitons) and some microdiorite (David Lang, 19). The sedimentary deposits include river gravel and alluvium found mainly on the western coast; conglomerate and raised limestones found near the mouth of the largest rivers on the western coast.

According to the geological map of Dominica, scale 1:100,000; within the general chronology of the deposition of the different rock types there are 5 major unconformities. There is an unconformity between the Miocene and Pliocene, between two deposits of assorted volcanic rocks but within the older deposit there are mafic flow rocks. The age of this unconformity according to the geologic time scale is 5-4 m.a. The second unconformity is overlain by 10 meters of saprolite-laterite (2.0 M.a.) and is found between the Pelean deposits of the Pliocene and the block and ash flow deposits of the Pleistocene. The third unconformity is dated at 1.6-1.2 M.a. between the Pelean dome deposits (andesite and dacite) and ignimbrites of the younger Pleistocene.

The other two unconformities are within the sedimentary deposits, thus being between the Pliocene and the Pleistocene conglomerate and raised limestone deposit and the other between the conglomerate and raised limestones and the river gravel deposits.

The lithological types found on the island vary very little because of its size and geologic make-up. (See geologic map Appendix 22)

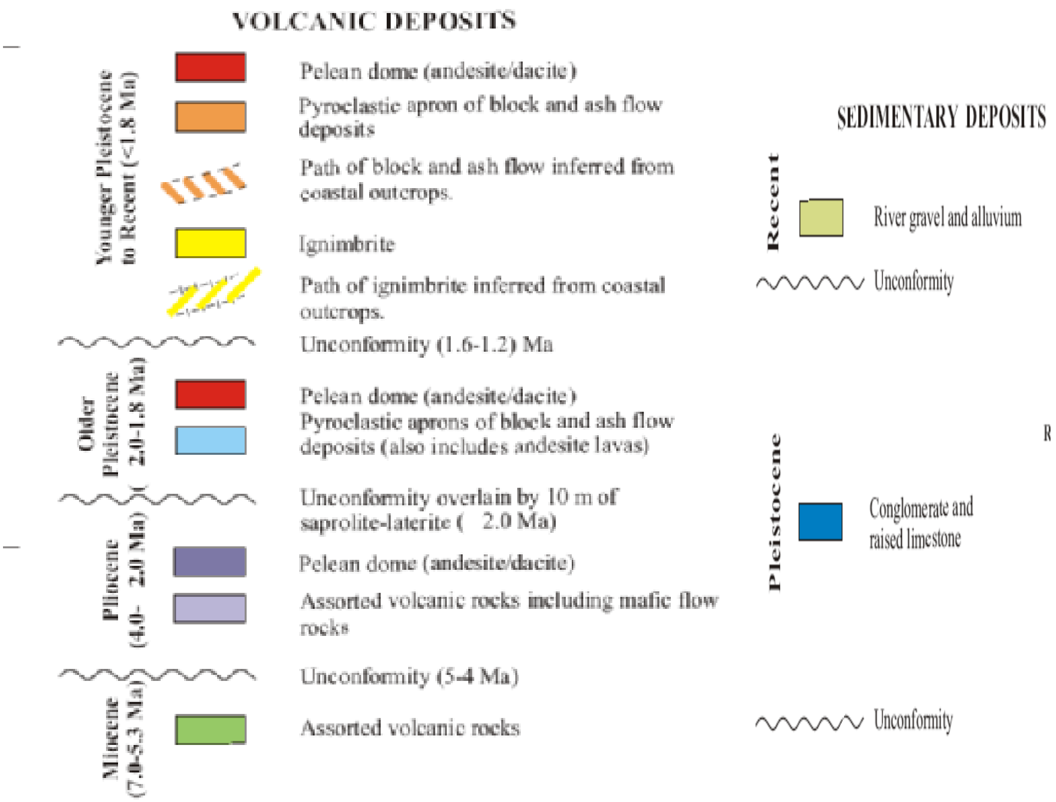

Figure 1e Geological column of Dominica

2.4 Tectonics

Dominica is located within the Lesser Antilles island arc which is about 850 km long and has a radius curvature of about 450 km. It stretches from the South American continental margin (eastern Venezuela) to the Anegada passage, which marks the present boundary with the Greater Antilles (Puerto Rico, Virgin Islands platform).

Seismic refraction has shown that the crust of the arc can be broadly divided into three layers (Officer and others, 1959; Dorel and others, 1979; Boynton and others, 1979). The uppermost layer is very heterogeneous: It has a wide range of seismic velocity and comprises mainly of volcanics and sediment. The middle layer has an average seismic velocity of 6.2 km/ S^{-1} but varies greatly in thickness and velocity. The lower layer has a seismic velocity of 6.9 km/ S^{-1} which suggest a basic composition.

The Lesser Antilles arc is on the eastern margin of the Caribbean plate, at the site where the Caribbean plate is underthrust by the subducted Atlantic oceanic crust. The rate of convergence is low compared to other subduction zones; it is generally assumed to be about 2 cm/yr (Jordan, 1975; Minister and Jordan, 1978; Tovish and Schubert, 1978).

Faulting and folding is not a very common geological phenomenon on The Island. Though some faulting and inferred graben faulting to be more specific is present, folding is almost completely absent.

The two recorded faults according to the Geological map of Dominica scale 1: 100000, one is an inferred graben fault which is located below Morne Couronne in the viscinity of the Harris Soulton Estate. The associated rock type is block and ashflow (volcanic deposits). The other 'possible' fault is a mega fault which extends from Crayfish River in a southwesterly direction to the Layou River area.

The scarcity of faults and folds on the island can be justified due to the island being located in a volcanic island arc which is still in its early stages of development.

2.5 Volcanism

Figure 1f active volcanic area in Dominica

Dominica is made up of exclusively volcanic rocks (Wills, 1974); at least 10 volcanic centers have been active during the Pleistocene. The oldest formations are exposed along the east coast of the island; they are massive lava flows and breccias intruded by numerous dikes. During middle Pliocene time, basaltic-andesitic shield volcanoes were built on the southern half of the island and on the western flank of the earlier formation; some of their lower units are pillowed. The basal part of Morne Diablotin overlies early Pliocene limestone (P.Andreiff, 1984, personal commun.), where as the basal part of the Foundland and Cochrane areas (basal part of Morne Trois Pitons) appear to be older than was previously stated (Briden and others)numerous morphologically well-preserved Pleistocene composite andesitic volcanoes are superimposed over the Pliocene volcanoes. From north to south, they include Morne aux Diables (a small pelean type edifice), Morne Diablotins (a large strato-volcano), and smaller volcanoes such as Watt Mountain, Morne Anglais ans Morne Plat Pays (ca. 0.5-0.4 m.y. old). A usually voluminous (for the Lesser Antilles) ignimbritic eruption-the Roseau ignimbrite-occurred about 30 ka (Sigurdsson, 1972). Up to 60 km^3 of tethra (equivalent dense rock value) were erupted (Carey and Sigurdson, 1980).The Roseau ignimbrite eruption is the largest recorded pyroclastic debris flow, which originated at Dominica and traveled 700 km south through thee Grenada basin. On land, partly welded and columned ash and pumice flows filled several valleys and Morne Trois Pitons. After this eruption, volcanic activity became much more effusive in character and domes and large dome complexes were erupted e.g., Micotrin and Morne Trois Pitons; (Roobol and others, 1983). According to field relations, preservation of its morphological shapes, and petrology of its lavas, Grand Soufriere Hills is thought to be contemporaneous with this event. A similar conclusion is drawn for Morne Patates which is emplaced into a caldera like depression at the southern end of the island, which maybe a gravity slide structure (Roobol and others, 1983). Very small volcanoes developed near Roseau: Du Mas Estate (a phreato magmatic crater opened) and the phreatic centers of the valley of desolation and the boiling lake (the last eruption which occurred in A.d. 1880). This last eruption produced surface manifestations of ash. However, visible signs of continuing volcanic activity is apparent with soufrieres hot springs and lakes. Several volcanic alerts associated with periods of increased seismic activity have also occurred. The most recent activities are a series of earthquakes which occurred in 1998, in November 2004 and the most recent 14 February 2005.

Earthquakes in Dominica derive from two separable forces. The eastern Caribbean is a zone of subduction in which the Atlantic plate pushes under the Caribbean plate causing tectonic earthquakes. The second the source of the earthquakes originates from the seismic events relating to Dominica's origin as a volcanic island, a consequence of plate-tectonic forces (Rowley, 1992).

Volcanoes in the Lesser Antilles have long been known to suffer volcano-seismic crises that consist of swarms of subvolcanic earthquakes that are not followed by eruptions (e.g., Shepherd and Aspinal, 1982; Shepherd and others, 1971; Robson and others, 1962).

<u>Present activity</u>

- Soufrieres (Soufriere, Roseau Valley, Morne aux Diables, Valley of Desolation)
- Hot springs (Check Hall, Layou,Titou, etc) G
- Geysirs (Wotten Waven)
- Boiling Lake
- Seismic activity (mainly in the south, especially La Plaine area

2.6 Natural Hazards

Dominica is susceptible to a wide range of natural hazards. The most common, most probable and historically most significant are tropical storms and hurricanes. The islands susceptibility and vulnerability to volcanic activity in the future is now a major cause for concern. There is a related risk of earthquake. Landslides are a common feature of life and landscape. Other potential hazards include drought, storm surges, floods, bush fires and tsunamis.

- Tropic al storms and hurricanes: Dominica's location as the most northerly of the Windward Islands places it well within the Atlantic hurricane belt. Officially, the hurricane season extends from June to November. Since 1978 the more physically damaging or economically and socially significant have been: 1979 David a category 4 hurricane which directly impacted the country and was particularly devastating and in that same year; Frederick. In 1980 Allen, 1984 Klaus, 1989 Hugo, 1994 Debbie, 1995 Viz Iris, Luis, Marilyn and 1999 Lenny.
- Earthquakes: Earthquake in Dominica derives from two separable but related forces. The eastern Caribbean is a zone of subduction in which the Atlantic plate pushes under the Caribbean plate, causing tectonic earthquakes. The second source of earthquakes originate from the seismic events relating to Dominica's origin as a volcanic island, a consequence of plate-tectonic forces (Rowley,1992). Earth quakes have not caused serious disruption in recent times. There is little public information available on potential hazards and risks.
- Volcanic activity: Only one volcanic event in Dominica's recorded history has produced surface manifestations, an ash event in 1880 in the Valley of Desolation. However, visible signs of continuing volcanic activity are apparent, with Soufrieres hot springs and lakes. Several volcanic alerts with periods of increased seismic activity have also occurred. There were a series of shallow earthquake swarms that were widely felt in October 1998 to March 1999.

Most recently in November 2004 there were also earthquake activity and in February 2005. The potential risk of and vulnerability to volcanic activity remains at a relatively high level with the focus of risk on the south of the island, where 20% of the population live. There has been no loss of life recorded due to volcanic activity.

- Landslides and mudslides: Many forces and features combine to make Dominica extremely vulnerable to landslides and mudslides. The most abundant being debris flows. At least 2% of the total land area has been disturbed by landslides (De Graff 1987, Degraff and others, 1989).
- Other hazards: Droughts, storm surges, floods, bush fires and tsunamis have been recorded as lesser hazards in that the overall combination of their manifestations, effects and frequencies have been comparatively smaller than those of hurricanes, earthquakes and landslides.

Other hazards and the environment: Landslips have environmental effects, such as damage to forests and riverine and estuarine siltation. The other potential source of massive environmental damage is volcanic eruption-ash deposits, Pyroclastic flows and lahars can, as the effects of the persistent Soufriere Hills eruption since 1995 on the nearby island of Montserrat demonstrate, have catastrophic impacts and preclude access to environmental assets for extended periods (Clay and others, 1999)

Human intervention could also become a potential source of longer term damage to environmental assets-excavation of deltaic silts for building material, pollution from human habitation and industrial activity could affect coastal marine resources, but these are longer term than disaster related issues.

3-General Information

3-1 Economy

The economy is dependent on agriculture and thus is highly vulnerable to climatic conditions, notably tropical storms. Agriculture, primarily bananas, accounts for 26% of GDP and employs 40% of the labor force. Development of the tourist industry remains difficult because of the rugged coastline, lack of beaches, and the lack of an international airport. Hurricane Luis devastated the country's banana crop in September 1995; tropical storms had wiped out one-quarter of the crop in 1994 as well.

Gross Domestic Product (GDP) - composition by sector:

- Agriculture: 26%
- Industry: NA%
- Services : NA% (1995)
- Labor force:
- Total : 25,000
- By occupation: agriculture 40%, industry and commerce 32%, services 28% (1984)

Industries: soap, coconut oil, tourism, copra, furniture, cement blocks, shoes

Agriculture - products: bananas, citrus, mangoes, root crops, coconuts; forestry and fisheries potential not exploited

Exports:

- Total value : $40 million (f.o.b., 1996)
- Commodities: bananas 70%, soap, bay oil, vegetables, grapefruit, oranges

Partners: UK 55%, Caricom (Caribbean community) countries, Italy, US

Imports:

- Total value: $122 million (f.o.b., 1996)
- Commodities : manufactured goods, machinery and equipment, food, chemicals

In this present moment Dominica’s economy is undergoing restructuring as an attempt to resolve the unfavorable economic conditions found on the island.

CHAPTER 2

Methodology applied in the investigation

- **Natural hazard and risk analysis**
- **Mechanism and dynamics of mass movements**
- **Methodology and materials used in the investigation**
- **Description of ArcView 3.2 GIS**

Introduction

The areas susceptible to landsliding can be analyzed or studied based on the physical factors associated with landslide activity: history of past landslides, rock type, slope and hydrology. It is impossible to predict when and where landslides will occur, no matter how much information is available on any given area or region. However it is possible to identify areas susceptible to landsliding.

This chapter will explain the construction of a landslide hazard map applying different methods, such as, the use of inventories; by consideration of site conditions including geology, hydrology, topography, and geomorphology and by statistical correlation of landslide frequency with geologic and geomorphic factors.

Here the effectiveness of geographic information systems will be demonstrated, specifically personal-computer-based systems, as a tool for natural hazard management. Geographic information systems (GIS), is a systematic means of geographically referencing a number of "layers" of information to facilitate the overlaying, quantification, and synthesis of data in order to orient decisions. This project is GIS based due to the fact that the preparation, analysis and interpretation of the maps were all done using ArcView 3.2 a GIS program.

Further more as it will be explained in detail, the methodology used in this project for field work, analysis of the maps and preparation of the maps. As well as the description of some key terms which have been used or which will be used later on in this project.

Chapter two will be divided into three main parts, part one will be dedicated to description of landslide hazard and risk analysis, part two will serve as a clarification of the key phenomenon of mass movements and landsliding as it pertains to this study and part three will be dedicated to a detailed description of the methodology used in this project as well as a brief description of the GIS program used (ArcView 3.2).

2-1 Landslide hazard and risk analysis

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 a few key factors. These are each capable of being mapped and allow land areas to be evaluated on their relative susceptibility to landslides.

Three principles guide landslide hazard assessment. First, landslides in the future will most likely occur under geomorphic, geologic, and topographic conditions that have produced past and present landslides. Second, the underlying conditions and processes which cause landslides are understood. Third, the relative importance of conditions and processes contributing to landslide occurrence can be determined and each assigned some measure reflecting its contribution (Varnes, 1985). The number of conditions present in an area can then be factored together to represent the degree of potential hazard present.

Landslide hazard has been determined with a high degree of reliability for only a few locations. These have required careful, detailed study of the Interaction of pertinent permanent and variable conditions in the target area. This can be a very expensive and time-consuming process that is unjustified for the purpose of broad-scale development planning. Landslide hazard zonation is one technique that can be used in the early stage of a planning study.

Most assessment procedures for landslide hazard zonation employ a few key or significant physical factors to estimate relative landslide hazard. The method described here requires a minimum of three factors mentioned earlier: distribution of past landslides, type of bedrock, and slope steepness, and a fourth, hydrologic factor may be added to reflect the important role which groundwater often plays in landslide occurrences (Varnes, 1985, and USGS, 1982).

Each factor is represented in a quantitative or semi-quantitative manner to facilitate the identification of different degrees of landslide hazard in an area.

Since all of these are permanent features, it is usually possible to map each factor. Specific combinations of these factors can be associated with differing degrees of landslide hazard. By extending these combinations over an entire area, a landslide hazard map is produced

2-2 Mechanism and dynamics of mass movement

Mass-Wasting is defined as the down slope movement of rock and regolith near the Earth's surface mainly due to the force of gravity. Mass-wasting is an important part of the erosional process, as it moves material from higher elevations to lower elevations where transporting agents like streams and glaciers can then pick up the material and move it to even lower elevations. Mass-wasting processes are occurring continuously on all slopes; some mass-wasting processes act very slowly, others occur very suddenly, often with disastrous results. Any perceptible down slope movement of rock or regolith is often referred to in general terms as a landslide. However, as we will see, landslides can be classified in a much more detailed way that reflects the mechanisms responsible for the movement and the velocity at which the movement occurs.

Types of Mass-Wasting Processes

The down-slope movement of material, whether it be bedrock, regolith, or a mixture of these, is commonly referred to as a landslide. All of these processes generally grade into one another, so classification of such processes is somewhat difficult. We will use a classification that divides mass-wasting processes into two broad categories.

1. **Slope Failures** - a sudden failure of the slope resulting in transport of debris down hill by sliding, rolling, falling, or slumping.
2. **Sediment Flows** - debris flows down hill mixed with water or air.

2-2a Mechanism of mass Movements

Causes of mass movements

Mass movements are caused by various conditions:

- Volcanic activity many times causes huge mudflows when the icy cover of a volcano melts and mixes with the soil to form mud as the magma in the volcano stirs preceding an eruption.
- Mudslides can also develop when water rapidly accumulates in the ground, such as during heavy rainfall or rapid snow melt, changing the earth into a flowing river of mud or "slurry.".
- Earthquake shocks cause sections of mountains and hills to break off and slide down.
- Human modification of the land or weathering and erosion help loosen large chunks of earth and start them sliding downhill.
- Vibrations from machinery, traffic, weight loading from accumulation of snow; stockpiling of rock or ore; from waste piles and from buildings and other structures.
- However, the trigger mechanism for mass movement is the gravitational pull of the earth on soil, rocks, and mud.

2-2b Landslides

Types of landslides

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing.

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement.

Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of

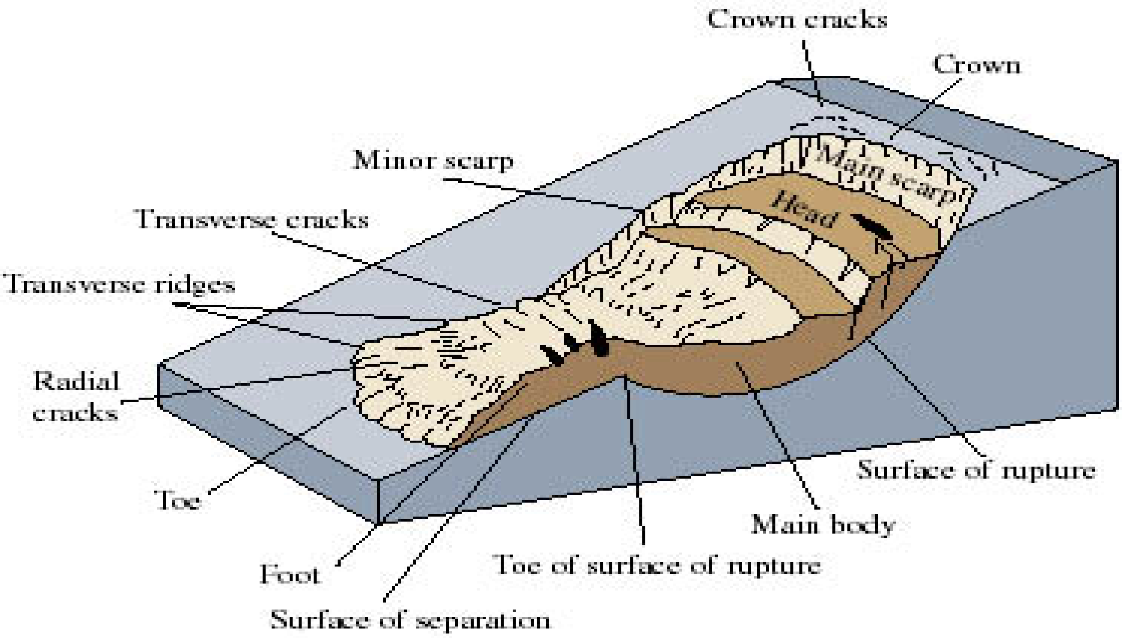

Figure 2.2a Diagram depicting features of a landslide (see glossary for terms)

Slides: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides. Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (fig.2.1b). Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (fig.2.1c). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (fig.2.1d).

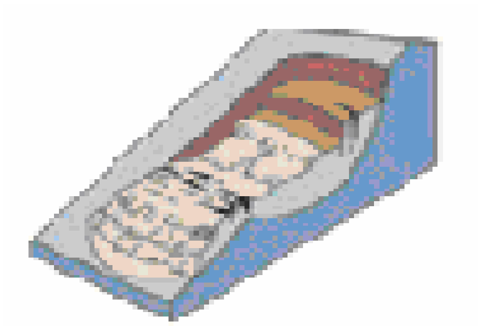

Figure 2.2 b Rotational slide

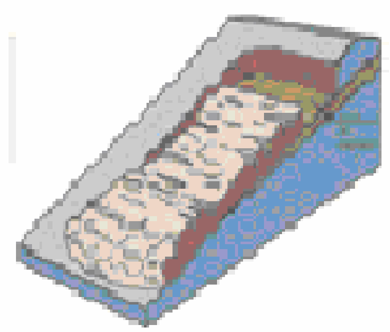

Figure 2.2 c Translational slide

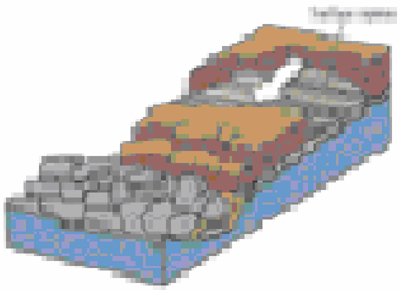

Figure 2.2 d Block slide

Falls: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (fig.2.1d). Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

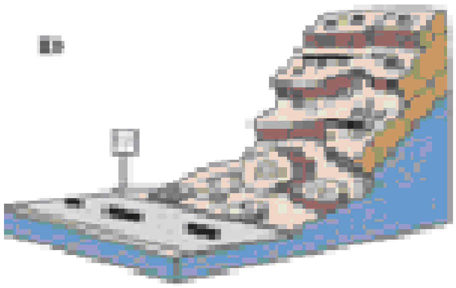

Figure 2.2e Rock Fall

Topples: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (fig. 3E).

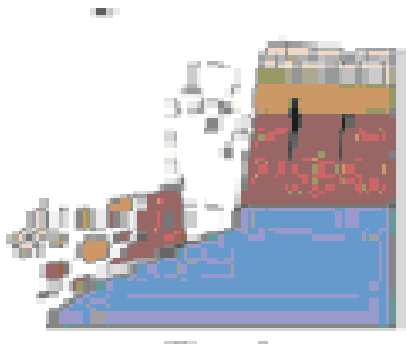

Figure 2.2 f Topples

Flows: There are five basic categories of flows that differ from one another in fundamental ways.

a. **Debris flow**: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (fig. 2.2g). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

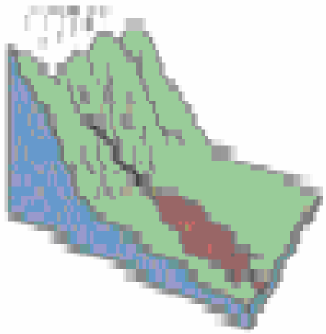

Figure 2.2 g Debris flow

b**. Debris avalanche**: This is a variety of very rapid to extremely rapid debris flow (fig. 2.2h).

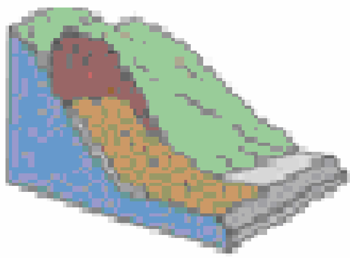

Figure 2.2h Debris Avalanche

c. **Earthflow**: Earthflows have a characteristic "hourglass" shape (fig.2.2i). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

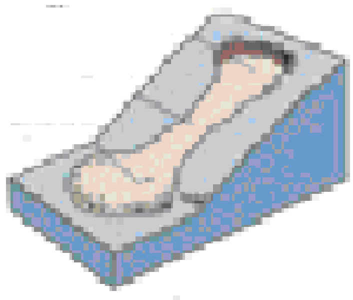

Figure 2.2 i Earth Flow

d. **Mudflow**: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides."

e. **Creep**: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (fig. 2.2 j).

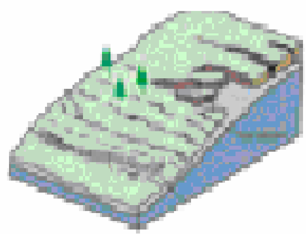

Figure 2.2 j Creep

Lateral spreads: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (fig. 3J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

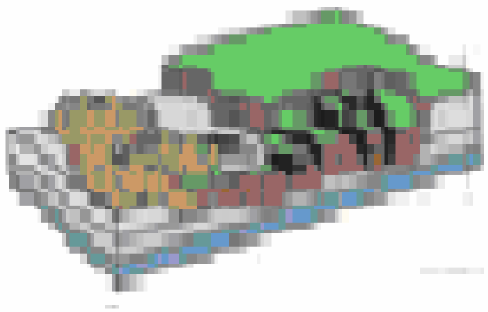

Figure 2.2 k Lateral Spread

2-2c Landslide causes

1. Geological causes

a. Weak or sensitive materials

b. Weathered materials

c. Sheared, jointed, or fissured materials

d. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)

e. Contrast in permeability and/or stiffness of materials

2. Morphological causes

a. Tectonic or volcanic uplift

b. Glacial rebound

c. Fluvial, wave, or glacial erosion of slope toe or lateral margins

d. Subterranean erosion (solution, piping)

e. Deposition loading slope or its crest

f. Vegetation removal (by fire, drought)
g. Thawing
h. Freeze-and-thaw weathering
i. Shrink-and-swell weathering

3. Human causes
a. Excavation of slope or its toe
b. Loading of slope or its crest
c. Drawdown (of reservoirs)
d. Deforestation
e. Irrigation
f. Mining
g. Artificial vibration
h. Water leakage from utilities

2.3 Methodology Followed: The following is a detailed explanation of the methodology applied in every stage of this research.

2-3.1 a Collection of available information

Preliminary research and revision of bibliography

This is the very first stage which was carried out as a pre-investigation. Here an initial review was made of the type and content of available information. It was done so as to verify the availability of geologic, topographic, hydrologic, and landuse maps which in this study will be the key maps. These maps are essential for executing a landslide hazard zonation. Also during this stage of the study, available information was collected and reviewed concerning assessments of natural hazards, including landslides and disasters, which are known to have affected the study area. As will be seen later in this chapter this phase of the study has proven to be the most important one, due to the fact that it served as a preview of what the end product of the study would be like through the assessment of the available key information.

Key factors which were clarified at this stage:

- It was clarified whether geologic, topographic, hydrologic, and vegetation maps were available and at what scale.
- Whether the study area has a history of landslides or disasters caused by landslide events.
- Whether landslide hazard assessment information is available.
- The existence of sufficient information to prepare a landslide inventory map, an isopleth map of existing landslides, and/or a landslide hazard map using factor analysis available.
- The determination of the method which will be used to carry out the assessment and the time frame.
- Determine at what scale the map should be prepared

In this stage a revision of all the available information on the topic was made. Past articles which were written on landsliding in Dominica and maps were revised so as to collect any necessary information. The information presented in chapter one was found mainly during this revision. Moreover available maps were collected in which ever format available.

2-3.1b Field work

The field work carried out in this study was not very extensive. It was done during a one week period where several landslide sites were visited. The areas visited are well known landslide areas which have been active for years (see chapter three case studies**).** The slides were documented as three case studies which will be seen in chapter three.

Materials used in this phase of the study are the following:

1. Camera
2. Note book / pencil
3. Topographic map of Dominica 1:25,000

2-3.1c Office work and research

This stage included the collection and organization of all the data obtained with reference to this study, such as the preliminary information, information obtained from field work and also from other stages of the study. In this stage all the information necessary for the formulation of the final report is processed.

2-3.2 Methodology used in the analysis, interpretation of the maps and the preparation of the susceptibility map.

Materials used in the preparation and analysis phase

1. Maps (Geology, Topography, landuse, Hydrology, landslide inventory, precipitation)
2. Software/ Computer based programs: ARC View 3.2, Microsoft Word and Excel.

Phase I: Project formulation

Here all the key factors were collected were analyzed and a plan for the project was formulated. Important decisions were also made with relation to the use of other maps which were available; such maps include contour (100 and 250). Finally the programs which were used in this study were selected; the key program used was ArcView 3.2 GIS (see page 48 for a detailed explanation of this program).

Project Plan: The plan was formulated in order to fulfill the objectives aforementioned in chapter 1. The final products of this entire investigation will be landslide susceptibility maps of the island of Dominica based on landuse and geology. At this stage it is already known the type, quantity and quality of the available information (In this case the maps which were available were in the program ArcView 3.2). The plan include individual interpretation of each map, then the combined interpretation which is basically overlaying maps and analyzing the common factors which could help in the hazard zonation. With the proper interpretation of these maps, results should include numerous tables and charts which will help in the interpretation of the final map. Also, new maps will be generated which will lead to the formulation of the susceptibility maps. Such maps include: Buffers (showing area of influence) to be generated from the hydrology map using the program ArcView 3.2 GIS.

In order to carry out the plan the following prerequisites were met:

1. Have the following maps georeferenced and digitized in ArcView 3.2: Geology, hydrology, landuse, coast, landslide inventory, contour (100 and 250). (The maps must all be in the same scale in order to be used in the program)
2. Have ample knowledge of the program ArcView 3.2 since it will be used in every stage of map preparation and interpretation of all the maps.

Phase II: Implementation of plan

Preparation of maps: In this stage the maps were prepared to be used in the program ArcView 3.2. As a prerequisite for use in ArcView the maps had to be georeferenced and digitized. All the maps available met the mentioned prerequisite with exception for the geology map. The geology map available was already georeferenced in the program ArcView 3.2 but was not digitized. Thus at this stage the digitizing of this map was carried out in order to continue to the detailed individual and combined analysis. In this stage the methodology used for the analysis of the maps and generation of others will be explained.

Phase II. First the maps were analyzed individually and then combined

Phase II.a Description of the methodology used for the individual analysis:

1. Analysis of Landuse map
2. Analysis of Geology map
3. Analysis of Landslide inventory map

1. Individual Analysis of the landuse map

The individual analysis of the landuse map consisted of the identification of the types of land use; then for each type its area (km^2) was determined. Later the percentage which each type of landuse occupies in the entire country was calculated. This analysis will help in the calculation of V (value of the conditional probability of the classes) (see page 45). The product of this analysis is a table consisting of three columns, landuse, area and percentage of total area (see appendix 7).

2. Individual analysis of geologic map

The individual analysis of the geologic map consisted in the identification of the different lithologic types and for each type its area (km^2) was calculated. Later the percentage which each lithology occupies in the entire country was calculated. From this analysis a table was created in Microsoft word containing three columns: lithologic type, area and percentage (see appendix 3).

3. Individual analysis of landslide inventory map

The landslide inventory map analysis was less complicated than the others. It consisted of classifying the types of landslides from the total. Then a calculation the percentage of each type with relation to the total amount of slides was carried out. Using Microsoft Excel 2003 a pie chart was made depicting the types of landslides and their respective percentages (see appendix 10 and 11).

Phase IIb Description of the methodology used for the combined analysis of maps:

1. Description of the methodology used for the combined analysis of landuse and landslide inventory maps.
2. Description of the methodology used for the combined analysis of geology and landslide inventory maps.

1. Combined analysis of landuse and landslide inventory maps

The combined analysis of the landuse and landslide inventory map consisted in overlaying the inventory map over the landuse and analyzing them together. The total number of landslides found in each type of landuse was counted and documented. The percentage of landslides for each landuse with relation to the total number of slides for the entire island was calculated. Then within each individual landuse the landslides found were further divided into their specific types (debris slide, debris flow and rock fall) and the percentage of each type was calculated with relation to the total number of landslides for each individual landuse. A table was created using this information which will be used later in the interpretation phase (see appendix 5). A pie chart was also made in Microsoft Excel depicting the percentage of landslides for each landuse type (see appendix 6).

2. Combined analysis of geology landslide inventory maps

The combined analysis of the geology and landslide inventory map consisted in overlaying the inventory map over the geology map and analyzing them together. The total number of landslides found in Lithology was counted and documented. The percentage of landslides for each lithologic type with relation to the total number of slides for the entire island was calculated. Then within each lithologic type the landslides found were further divided into their specific types (debris slide, debris flow and rock fall) and the percentage of each type was calculated with relation to the total number of slide in each individual lithology. The information from this analysis was documented in two forms, as a table and as a pie chart (see appendix 1); both will be used in the interpretation phase and in making the landslide susceptibility map.

Phase II.c Generation of other maps and calculations carried out: Here the methodology used to generate or prepare new maps will be explained in detail.

1. Buffer
2. Landslide susceptibility maps

1. Preparation of Buffer: The following is the methodology used to prepare the Buffer of the area of influence around the rivers in the hydrology map.

The hydrology map of Dominica was selected as the map to be used to create the buffers. Buffers can be used to show that is places that are less significantly impacted by a given phenomenon because they are within a certain distance of an object. These sorts of buffers are known as zones of protection. The buffers were created in the program ArcView 3.2 GIS using the theme options.

1) Start up ArcView and open a new view.
2) Add the hydrology theme.
3) The lines were selected, and the lines were converted to shapefiles. In order to do this, Theme->Convert to Shapefile.
4) At this point the theme hydrology was ready to create the buffer.
5) The buffer was created by going to Theme->Create Buffers. The buffers were created using two rings each 100m apart. The buffers were selected to appear as a new theme in the same view.

Description of the methodology used for the combined interpretation of the buffer and Landslide inventory map

In the buffer, each ring was analyzed separately; the number of landslides located within 100 meters (Ring 1) and 200 (Ring 2) meters respectively was determined and those found further were also determined. The results were tabulated and presented in chart form (See appendix 12, 13 and 17)

2. Calculations

Calculation of V for the landuse map
V= value of the conditional probability of the classes

Total Number of landslides = 810
Total Area = 751.198723411 km2b

$$V = \left(\frac{\#\text{ landslides in landuse type}}{\text{Area of individual landuse}} \times \frac{\text{Total number of landslides}}{\text{Total area}} \right) \times 100$$

Example:

$$V_{(Agriculture)} = \left(\frac{149}{237.1987234} \times 1.0783 \right) \times 100 = 67.578$$

$$K\ (\text{constant}) = \frac{\text{Total number of landslides}}{\text{Total area}} = \frac{810}{751.198723411} = 1.0783$$

Methodology followed for the calculation of V (probability) in the landuse:

The data used in the calculation of V (probability) was derived from two maps, the landuse map and the landslide inventory. In the program ArcView 3.2 the maps were analyzed together and the number of landslides for each landuse type was determined. The area for each landuse types was determined and also the total number of landslides was derived from the table. Having all the necessary data at hand, the probability for each landuse type was calculated using the formula; as shown in the example which shows the calculation of V for agriculture. The results of the calculation was documented and presented in the form of a table (see appendix 8).

Calculation of the V for the Geology map

V= value of the conditional probability of the classes

$$V = \left(\frac{\text{\# landslides in lithologic type}}{\text{Area of I individual lithology}} \times \frac{\text{Total number of landslides}}{\text{Total area}} \right) \times 100$$

Example:

$$V_{Ignimbrite} = \left(\frac{15}{25.988} \times 1.0783 \right) \times 100 = 62.23$$

Methodology followed for the calculation of V (probability) for the geology:

The data used in the calculation of V was derived from two maps, the geology map and the landslide inventory. In the program ArcView 3.2 the maps were analyzed together and the number of landslides for each lithologic type was determined. The area for each rock type was determined and also the total number of landslides was derived from the table. Having all the necessary data at hand, the probability of occurrence of landslide for each rock type was calculated using the formula; as shown in the example which shows the calculation of V for ignimbrite. The results of the calculation was documented and presented in the form of a table (see appendix 4)

2-3.3 Methodology used for the preparation of the susceptibility maps for landuse and geology.

The following describes the generation of two maps in ArcView 3.2 using the data generated from the calculation of V (probability) for the landuse and geology maps:

Land use/ Susceptibility map: Using the data derived from the calculation of V(probability) for the landuse map a new map was processed in Arc View 3.2. In the option 'Table' in ArcView 3.2, there is an existing database for the landuse map depicting area, perimeter, class, type e.t.c. These are

known as fields, the map being shown at any moment depend on the field which is chosen for display. Thus, a new field was added named value and the values of V for each landuse type was entered next to the corresponding polygon. The field was saved in the table and became part of the database of the landuse map. This field was chosen to be displayed on the map. The resulting new map contained a color coded legend depicting the values for V for each different land use. Another field was added named susceptibility which was used to generate a susceptibility map, with three levels of susceptibility; low, high and medium. The levels of susceptibility were given values with reference to the values obtained from the calculations. The values for susceptibility range from 0-315.6, thus, the range of probability were given the following values: 0-50 Low, 51-149 Medium and 150+ High. The result was a landslide susceptibility map for landuse in the island of Dominica. (See appendix 16)

Geology / Susceptibility Map: Using the data derived from the calculation of V(probability) for the landuse map a new map was processed in Arc View 3.2. In the option 'Table' in ArcView 3.2, there is an existing database for the landuse map depicting area, perimeter, class, type e.t.c. These are known as fields, the map being shown at any moment depend on the field which is chosen for display. Thus, a new field was added named value and the values of V for each rock type was entered next to the corresponding polygon. The field was saved in the table and became part of the database of the landuse map. This field was chosen to be displayed on the map. The resulting new map contained a color coded legend depicting the values for V for each different rock type. The levels of susceptibility were given values with reference to the values obtained from the calculations. The values for probability range from 0-313.86, thus, the range of probability were given the following values: 0-50 Low, 51-149 Medium and 150+ High. The result was a landslide susceptibility map for lithology/geology in the island of Dominica.(see appendix 15)

2-3.4 Methodology applied for the interpretation and analysis of the results phase

After obtaining the landslides susceptibility thematic maps for landuse and geology maps were analyzed in terms of levels of low, medium and high susceptibility. The landuse map was analyzed by calculating the area for each susceptibility level and then calculating the percentages with reference to the total land area. Each landuse was analyzed according to there level of susceptibility an attempt was made to justify there roles in promoting landsliding activities in there respective areas. They were analyzed taking into consideration other factors such as precipitation, associated rock types and slope quality (according to observations from the contour maps).

After the interpretation, the conclusions were reached according to the results obtained. Then the recommendations were made. In this last stage the project was revised and corrections were made where necessary.

This concludes the detailed description of how this study was undertaken to suit its aims and objectives this methodology is not a replica of any methodology of other studies, it was designed specifically.

2-3.5 Description of ArcView 3.2

ArcView 3.2 is a desktop geographic information system which allows the creation of intelligent, dynamic maps using data from virtually any source and across most popular computing platforms. It provides the tools to let you work with maps, database tables, charts, and graphics all at once. You can also use multimedia links to add pictures, sound, and video to your maps. It has a set of wizards, dialog boxes, and tools that provide easy-to-use access to advanced functionality. Create buffers or map graticules, add callout labels, and perform spatial operations such as clip and merge with the help of wizards.

- **Easily use data in varying projections and datums** - The ArcView 3.2 Projection Utility is a stand-alone wizard-based tool that lets users project shapefiles from geographic coordinates to projected coordinates or from one projection to another. It also performs datum transformations on shapefiles. The ArcView 3.2 Projection Utility is available on Microsoft Windows platforms only
- **Powerful query and analysis** - ArcView 3.2 gives you hundreds of new ways to query and analyze your data. You can query your data according to location, content, proximity, and intersection. For example, you can add data to maps to find the geographic factors that drive trends and distributions or locations at which particular characteristics coincide. You can aggregate data geographically by summarizing it based on areas such as census tracts, states, or sales territories. You will literally start to see things in a new light. Furthermore, the output from one analysis can be used as the input to the next analysis, enabling you to create advanced geoprocessing applications
- **Professional-quality maps and data displays**- ArcView 3.2 provides automatic data-driven classifications, color ramps of data ranges, graduated symbols, chart symbols, standard deviations, normalization, and business graphics. This program comes with a huge selection of TrueType fonts and symbols. It can also be used with many types of output devices such as printers, plotters, and film output devices
- **Sophisticated reports** - ArcView 3.2 allows you to easily generate professional reports, including embedded maps and charts, which help you more successfully communicate the

results of your GIS analysis. The report writer extension integrates the industry-leading Crystal Reports report generation and editing.

It allows the creation of your own basemap layers with. You can modify existing maps to meet your exact needs; or if no maps currently exist, you can create your own quickly and easily. You can edit on-screen with the mouse or, for more accuracy, use a digitizing tablet (support for digitizing only available for Windows platforms).

CHAPTER 3

Interpretation of results

- **Analysis of the conditions which generate slope instability on the island of Dominica.**
- **Analysis of landslides (Case studies).**
- **Interpretation**
- **Proposal for measures of control and mitigation in function of the level of susceptibility of the areas**

Introduction

In this chapter we will make an analysis of the factors and conditions which promote the occurrence of landslides in Dominica. Three case studies are presented as examples of the type of landsliding which takes place on the island. Moreover the maps and results will be presented, analyzed and interpreted in this chapter. From this interpretation and analysis of the maps obtained we will then present our conclusions and make valuable recommendations depending on our results.

3.1 Analysis of the conditions which generate slope instability in Dominica

Conditions influencing landsliding in Dominica

Landslides in Dominica are strongly influenced by its geologic past. Dominica shares a similar geologic heritage with its neighbors; Guadeloupe to the north and Martinique to the south. Dominica is the northernmost island in the Windward Islands the geology of the island is predominantly volcanic bedrock emplaced by repeated eruptions from multiple vents. This has created an island of about 47 kilometers long and 25.7 kilometers wide. The area of Dominica is approximately 751 km^2. The bedrock is andesitic; a mixture of the minerals plagioclase and biotite with some hornblende, quartz, and pyroxene. In general, the central highlands host former vents plugged by andesite lava domes (Roobol and others, 1983). Young lava domes including Morne Diablotins, Trois Pitons, Micotrin, and Patates are aligned on a north-south trend through the central part of the island. Radio carbon dating show that deposits from Morne Patates are as recent as 450 + 90 years B.P. (before present) (Wadge, 1985). An apron of block and ash-flow deposits surrounds the plugged vents. Ignimbrites representing valley infills are found at points of periphery of this apron. Ignimbrite rock is deposited by hot ash fall and nuee ardantes. The resulting fine-grained, hard rock can be seen from nearly vertical cliffs in places like lower Layou and Roseau river valleys. Deposits of volcanic rocks by repeated eruptions from centrally located vents results in contacts between successive rock units dipping or being inclined away from the central highlands.

The only significant different bedrock found on Dominica are two sedimentary bedrock units (Anonymous, 1959, Lang 1967). The consolidated sedimentary bedrock is limestone consisting of coral, shells, and limey muds. The other sedimentary bedrock is unconsolidated alluvium. The limestone unit is exposed in road cuts and the ground surface along the west coast between Colihaut and Roseau. In places, younger volcanic rocks overlies the limestones indicating a period of lessened volcanism sufficiently long for reef development. The exposed limits of this unit are poorly defined and deserve improve mapping (case, 1981). Completing the geologic description of Dominica are deposits of alluvium found scattered around the coastal areas. These deposits represent eroded sediment from highlands transported by large streams and rivers.

As a consequence of its volcanic origin, Dominica has a landscape dominated by steep slopes. The repeated volcanic eruptions formed an extensive volcanic pile with the highest elevations near the vent areas. The highest point on the island is Morne Diablotins with an elevation of 1420 meters Lang (1967) notes that from Diablotins south to Morne Plat Pays only one point is lower than 1500 feet in the central chain of peaks. With as many points on this chain rising above 854 meters only four mile from the sea, slopes are commonly moderate to steep. These slopes cause the force of gravity to act more effectively on the ground surface. All of this force is acting to hold the material on the slope. On an inclined slope the force of gravity act both perpendicular and parallel to the ground surface. Most of the force is acting perpendicular to the ground surface on a gently inclined slope. The amount of force acting parallel to the ground surface increases as slope become steeper. This means more of the force of gravity is acting on the slope in the direction that will move material than is acting to hold it in place.

The strength of rock and soil resisting the force of gravity depends on the volcanic origin of the bedrock and climatic conditions controlling the weathering processes. The layering of volcanic rock units can promote landsliding.

Discontinuities in a rock mass always reduce its overall strength. The contact between each layer in an interbedded sequence provides a potential sliding surface compared to a similar thickness of massive rock. The effect of this type of discontinuity on landsliding increases when the layers are inclined or dipping at angles gentler than the ground surface. Layers of rocks may decrease bedrock strength where weak rocks underlie stronger rocks. Progressive, small scale failure on the weak unit can lead to a larger failure when the stronger unit is undermined. Vertical fractures are another important type of discontinuity. Massive rock units such as ignimbrites and lava flows are composed of strong rock. However, fractures: 1) decrease strength of the rock mass, 2)promote weathering by admitting water, and 3) provide potential surfaces upon which movement may occur.

Climatic conditions, especially warm temperatures and abundant rainfall, enhance the weathering process. Weathering of volcanic rocks changes their mineral composition and physical character. The andesitic bedrock found in Dominica weathers to form clay and other secondary minerals. Lang (1967) found amorphous clay and clay minerals, gibbsite, kaolinite, and montmorillite, present in soils in Dominica. Volcanic rock forming a slope begins to weather immediately after being emplaced. The zone of weathered material on the surface extends deeper into the rock as the time passes. The strength of the weathered material or soil is typically less then the unweathered rock. Hartford and Mehigan (1984) determined internal the internal angle of friction of residual soil on Dominica to be 31^o. This means friction between soil particles in a saturated or undrained soil mass will resist gravity at angles of 30^o or less. In some instances, the weathered rock may retain the appearance of its unweathered state while suffering significant loss in strength.

The influence of water on landsliding is secondary only to gravity in its importance (Varnes, 1985). In Dominica water plays a role beyond facilitating the chemical weathering process. This can be seen in the coincidence of landslides with intense storms and prolonged rainfall. Precipitation causes the spaces present in soil to become filled with water. This produces a saturated soil mass. In some instances, ground water from fractures in the underlying rock may contribute to this saturation. Precipitation might not be sufficient to induce a landslide at some locations without this added ground water flow. The water - filled spaces or voids in the soil increase the weight of the soil mass. This enhances the driving force of gravity. Also, water reduces the soil strength by developing pore-pressure that tends to push individual soil particles away from each other. This reduces the friction between particles which accounts for much of the internal strength of a soil mass. Rock is often notably less permeable than the overlying soil. As a consequence, positive pore-pressure develops in the soil just above the contact between the soil and rock reducing soil strength along a potential sliding surface. The development of saturated soil masses during precipitation events and high pore-water pressures is made possible by the highly permeable nature of soil on Dominica (Lang, 1967, Walsh, 1980). Prolonged rainfall during the rainy season is capable of producing landslides as the Good Hope landslide demonstrates. There is no evidence of landsliding being triggered by earthquakes or volcanic activity.

Debris flows, debris slides, rock slides, rock falls, slumps and complex slides are among the types of landslides found on throughout island (Faugeres, 1966, Prior and HO, 1972, Walsh, 1982, DeGraff, 1985, 1987, 1988). Moat slides involve either flow or transitional movement.

Debris slides and debris flows are common on mountainous slopes in the Windward Islands. Walsh (1985) noted the many debris slides and flows triggered by hurricanes David and Federic involved failure at depths of 2 meters or less. Similarly shallow depth to the failure plain for these landslide types is documented for Ignimbrite defined joints or similar discontinuities. Slumps and complex landslides are the least common types found on the island. Most slumps or rotational failures observed are associated with man-disturbed slopes. Rotational failures seen in Dominica are limited to small failures. The steep slopes prevalent in the island are one of the principal conditions favoring landslide development. Examination of drainage patterns indicate an early phase of landscape development. The resulting slopes are often at angles close to the angle of repose for materials underlying them. Only small changes in instability conditions are required to bring such slopes close to failure.

The nature of materials underlying slopes on the island plays a major role in landslide development. Their volcanic origin creates stratigraphic and lithologic conditions favoring landslides. Layers of alternating ash, lava and breccia lead to locations on slopes where weaker bedrock weathers faster and undermines more competent bedrock overlying it.

Human activities are another triggering mechanism for landslides in the island. Roads cut into steep slopes remove support from the soil or rock mass above. The road prism may interfere with natural subsurface drainage in the slope leading to the higher pore-water pressures than would occur under normal conditions. The terrain in Dominica makes it almost impossible to build roads without cutting along steep slopes.

Agricultural practices are another human activity contributing to slides in Dominica. Some farmers slash and burn the rainforest on very steep slopes to clear areas for planting their crops. The shallow rooted crops which are used to replace the trees are unable to reinforce the soil stability. It is suspected that these differences make the slopes more susceptible to landsliding.

3.2Analysis of landslides (Case studies)

3.2-1Good Hope Landslide

The village of Good Hope is located on the eastern coast of Dominica; it is comprised of very steep slopes and valleys. The main rock type found there are assorted volcanic rocks (andesite, dacite e.t.c.). The village receives high rainfall levels throughout the year and the agricultural practice in that area is very high. The vegetation includes submontane rainforest and rain forest. It has a main river the Good Hope River and a few ravines.

The landslide at Good Hope happened after several days of intense rainfall. According to residents, a small landslide occurred in the cutslope of the Castle Bruce – Petit Soufriere road above the village on November 11, 1986. The main landslide developed in the slope above the road. The previous day's failure area was encompassed with this new landslide obliterating evidence of its existence.

The landslide moved on a plane coinciding with the boundary between the overlying weathered soil and the unweathered to partly weathered bedrock. Bedrock exposed on the failure plane consisted of fractured andesitic lava flows. No distinct weathered zoned or seepages were noted. The failed plane is inclined at a 70 to 80% slope. The soil involved in this failure appears to be a residual material weathered from the underlying andesitic bedrock. Changes in color, particle size distribution or other indicators of colluvial accumulation are not found in the cross section of material exposed in the margins of the slide area. The soil is plastic but non sticky. It is bright red in color and consists of clay to sand size particles with an abundance of gravel size clasts. The clasts appear to be harder than the fine grained material, but are found to be easily crushed by the hand. The soil characteristics in the area where the landslide originated are indistinguishable in the field from the characteristics of the material in the deposit.

The landslide is classified as a debris slide (Varnes, 1978). This means soil with many coarse fragments moved as a unit or series of units roughly parallel to the slope on a discrete surface. The description of the slide material given above fits the criteria for calling the displaced soil, debris. The landslide moved as a mass which then disrupted into many units. Evidence of flowing rather than sliding motion, such as levee deposits along the slide path and related flow features, are absent. Therefore, it seems reasonable to conclude that movement was transitional in nature i.e. along a planar surface. The failed area which generated the slide is roughly parabolic in plane view. The base is roughly is roughly 300 feet wide and parallels the main road. It extends upslope for a small distance of 61 meters. The slide plane is at an average depth of 4.5 meters. The volume of displaced material is estimated to be 20,000 cubic yards.

The debris slide was triggered by rainfall which produced saturation of the soil above the soil-bedrock boundary. This apparently occurred as deep percolation into the hillslope was exceeded by the rate of water infiltration. Soil strength was r educed to less than necessary to reduce the pull of gravity by the pore-water pressures inducing during the saturated state. Ground water contributed from flow through the cracks in the underlying bedrock may have aided to creating saturated conditions.

In contrast to the triggering event, the cause of this debris slide involved several factors. The steep slope was originally stable when formed with solid rock exposed at the surface. As weathering altered the rock to soil to an increasing depth, the strength of the material on the slope decreased and the chance of landsliding increased. This is a natural long-term change leading to landslide occurrence. As natural circumstances increased the potential for slope failure, man-caused changes added to this potential. The main road created a cutslope which reduced the lateral support to the hillslope above. Soil strength was further reduced by replacing trees with bananas and other shallow rooted crops. The combination of natural and man-made factors created a tenuous balance between the strength of the material on the slope and the pull of gravity. This balance remained tipped in favor of a stable slope until the triggering circumstances of the rainfall described above took place.

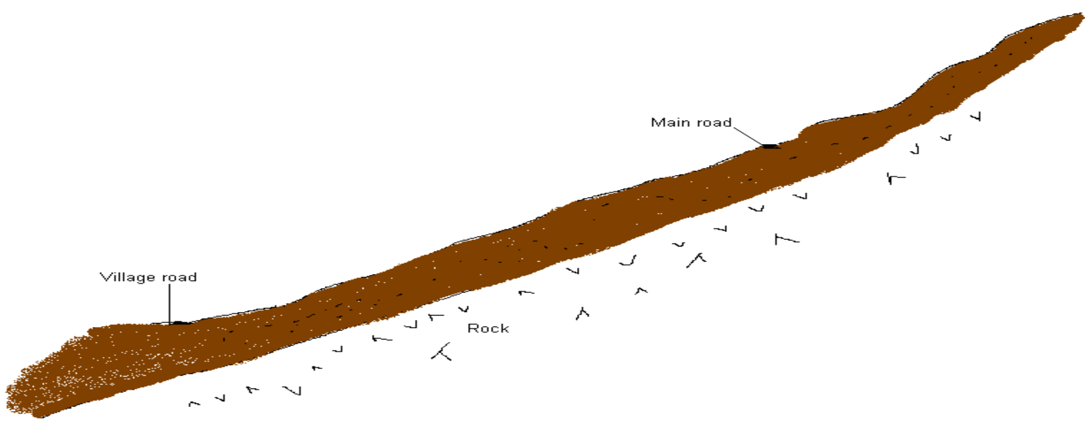

Figure 3a Pre-failure Cross section through the middle of the hillslope site of the Good Hope landslide.

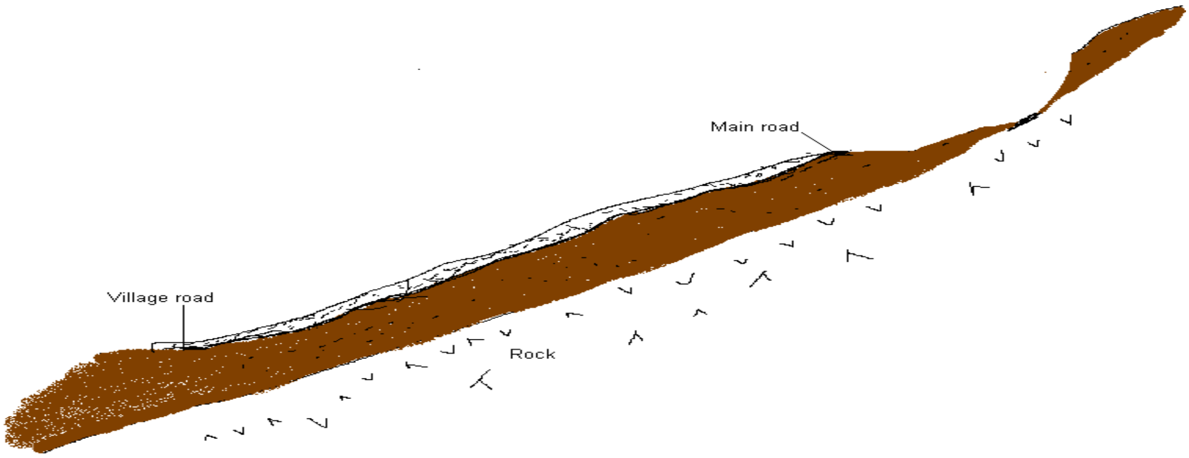

Figure 3b Post failure Cross section through the middle of the hillslope site of the Good Hope landslide.

3.2-2 D'Leau Gommier Landslide

Landslide in the D'Leau Gommier area impacts the main highway between Marigot and Pont Casse. This road is the principal route between Roseau and Marigot.

The problems at D'leau Gommier consist of many small failures instead of a single landslide. The bedrock exposed in the cutslope is deeply weathered. The bedrock is assumed to be an ash deposit. The material appears to be highly permeable. Even during the dry time of the year ground water flows freely through numerous seeps. Loose material saturated by this water has a consistency resembling wet concrete. Ground water did not seem confined to a particular horizon or fracture set in the bedrock. The presence of ground water at this dry time and the obviously intense weathering of the rock indicate the ground water percolation is a common condition at this location.

3.2-3 Bellevue Slopes Landslide

The main highway connecting Roseau, on the west coast, to the Grand Bay area at the southern end of the island is impacted by the Bellevue Landslide. The affected road section is a switchback just west of the village of Bellevue Chopin. Instability in this site became evident during road construction in 1984. Two landslides were triggered at the time earth moving was in progress on the road. Three other landslides has occurred since in the same area.

The landslide is complex and is best described as a debris-flow (Varnes, 1978). Dimensions of the failed area are roughly 43 meters wide and 52 meters long. The average depth to the failure plane is assumed to be 3 meters. It is assumed that the four failures at the site have generated a volume of nearly 6,000 cubic yards.

Landsliding at this site involves both soil and weathered bedrock. There are two bedrock units present. The upper unit is a volcanic breccia; it is grey in color with a gradation ranging from cobble to silt/clay size particles. The volcanic breccia is underlain by a brown ash deposit. Stratification is prominent; and both bedrock units are inclined out of slope at an angle subparallel to the hillslope. Soil overlying these bedrock units appears to be a mixture of colluvium and weathered volcanic breccia. It is discernible from the breccia by its brown color.

Hartford and Mehigan (1985) described a gradation for Dominica soil sampled in a road investigation which resembles the volcanic breccia. It is possible their study was completed as part of the preconstruction investigation for this road. Tests on their soil samples indicate the internal angle of friction is 31^0 for a saturated (undrained) condition. In other words, slope angles in the material greater than 30^0 are likely to become unstable when fully saturated. The upper part of the landslide where the volcanic breccia is exposed is presently inclined at a 60% slope equivalent to the angle of repose for this material.

No obvious seeps were found in the area where the landslide occurred. However, seepage points are visible in a few places in the ash deposit. Even during the drier part of the year ash is moist even with the surface being exposed to the sun. About 800 meters downslope, a pipe into this bedrock unit supplies water to a standpipe. This suggests that the ash deposit is a local aquifer.

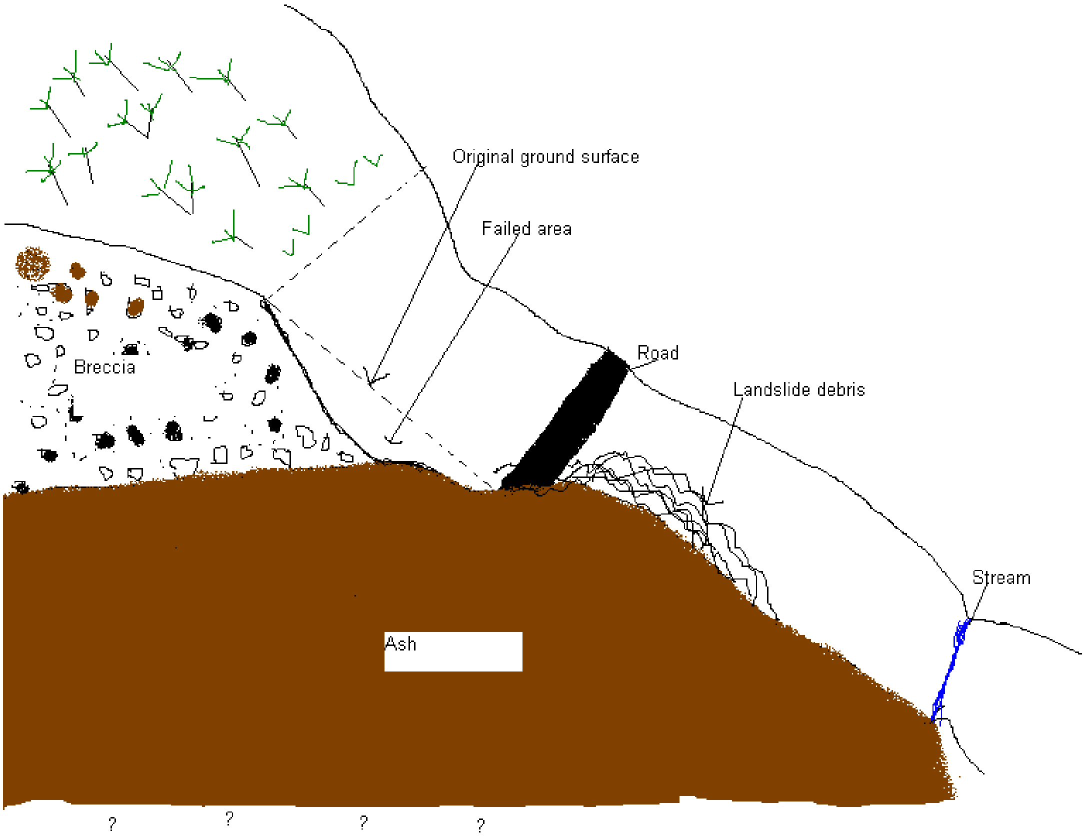

Figure 3c A cross-section showing the general subsurface conditions at the Bellevue slopes landslide. This is not drawn to scale.

3.3-Interpretation, Analysis and Results

In this section the results of all the materials which has been analyzed and interpreted will be discussed this includes the principal maps used such has landuse, soils, geology, hydrology, buffers and landslide inventory map. Each map will be analyzed and the new susceptibility maps created will be analyzed and interpreted.

3.3-1 Interpretation of maps and results

Combined analysis of the Landslide Inventory and Geology maps: From the combined analysis of these two maps it was determined that the lithologic type with the highest total of landslides is the assorted volcanic rocks (Pliocene) with 39% of the total landslides. Followed by the Pelean domes

(Pleistocene) with 21%, Pyroclastic deposits of block and ash flow (Pleistocene -1.8ma) 16%, Pyroclastic deposits (Pleistocene 2-1.8ma) 14%, Ignimbrite and assorted volcanic (Miocene)5% each respectively, Pelean domes (Pliocene) 0%, conglomerate & Limestone 0%, River & Gravel Alluvium 0%. The three types of landslides in Dominica are debris slides, debris flow and rock fall. The lithology with the highest number of debris flow (204) and debris slides (101) is the assorted volcanic rocks of the Miocene where as the highest number of rockfalls are found within the pyroclastic deposits of block and ash flow (1.8ma) with a total number of three rock falls. As can be noticed the total number of landslides are concentrated within four main lithologic types: assorted volcanic Pliocene, Pelean Domes (Pleistocene) and the two pyroclastic deposits. Within these four lithologic types 90% of the landslides are distributed leaving a mere 10% to the other lithologies. (See appendix 1 and 2).

Combined analysis of Landslide inventory and Landuse maps: There are a total of twelve landuse classes on the island of Dominica, the bulk of the landslide activity according to the combined interpretation of the landuse and landslide inventory map is concentrated within five of these areas, which is partly justified by the fact that these five landuses combined in area constitute of 90% of the total area of the island (see appendix 5 and 6). In order of their total percentage, landslides per landuse are as follows: mature rainforest 24%, without information 19%, agriculture 18%, semi evergreen 18%, secondary rainforest 12%, scrub woodland 5%, montane rainforest 3%, elfin alpine meadow 1%, litoral woodland 0%, swamp & wetland 0%, montane thicket 0%, urban 0%. The highest distribution of debris slides, flows and rockfalls are as follows: approximately 30% of the total of debris flows is found in the mature rain forest, 23% of the debris slides are found in agricultural areas and 62% of the rockfalls are found in scrub woodland areas.

The presence of a high percentage of landslides in the mature rain forest is not a surprising factor due to the fact that the rain forest receives at least 200 cm of rain annually, while some rainforests can receive as much as 400 cm and tree roots are often shallow, forming a thick mat on the surface of the soil. The tropical rainforests are found in areas above 610 meters which are steep areas. In the case of the agricultural areas, diverse agricultural practices have rendered the top layer of the soil in a highly weathered mass thus making it vulnerable to sliding and in some areas even exposing the bedrock below to weathering as well. With the protective “layer” removed, zones of fracture in the soil and bedrock become areas for the development of potential landslides. According to the characteristics of the semi evergreen forest it is characterized by high annual rainfall but are not found at elevations as high as the other forested areas. Secondary forest is rainforest that has been disturbed in someway, naturally or unnaturally. Secondary forest can be created in a number of ways, from degraded forest recovering from selective logging, to areas cleared by slash and burn agriculture that have been reclaimed by forest thus making it an area with a high potential to landsliding given its natural characteristics.

Analysis of landuse map: The total area of the island is approximately 751.2 km^2. The land use map constitutes of 12 different landuse types, the following is each type and the percentage which they occupy within the total area: agriculture 31.66%, litoral woodland 0.62%, urban 0.91%, montane rainforest 1.3%, semi evergreen rainforest 9.11%, swamp & wetlands 0.04%, mature rainforest 27.7%, secondary rainforest 10.76%, scrub woodland 6.55%, elfin woodland 0.41%, montane thicket 0.22% and areas without information 10.72%. Agriculture constitutes the highest landuse area because the economy of Dominica is almost predominantly agricultural and it has been practiced on the island from since the early settlers. The areas which have not been occupied by agriculture is due to the steepness of the terrain, such areas are found towards the center of the island. As can be seen on the landuse map the agricultural areas are restricted to the coastal areas of the island and closer to the road network. The bulk of the mature rain forest is found in the center of the island where the precipitation levels are the highest all year round. The secondary rain forest and semi evergreen forests are found nearer to the coasts but are not predominant on the eastern coast of the island. (See appendix 7 and8).

Analysis of Geology map: The rock types found on the island of Dominica according to the geology map are, Pelean domes of the Pliocene and Pleistocene, ignimbrite, Pyroclastic apron of block and ash flow deposits of the older and younger Pleistocene, assorted volcanic rocks of the Pliocene, assorted volcanic rocks of the Miocene; also, Path of block and ash flow inferred from crustal outcrops (younger Pleistocene) and path of ignimbrite inferred from crustal outcrops. There are also the sedimentary deposits, conglomerates and limestones, river and gravel alluvium. (See appendix 3 and 22)

Analysis of the landslide inventory map: According to the landslide inventory map of the island of Dominica there are a total of 810 documented landslides, classified into debris flows 484; debris slides 318 and 8 rockfalls. The debris flows occupy a total area of 3.6620 km^2, the debris slides 1.9840 km^2 and the rock falls 0.0610 km^2. The landslides occupy a total area of 5.7020 km^2 which is 0.79% of the total land area. The land slides are distributed unevenly throughout the island but are not concentrated in the coastal areas. (See appendix 10 and 11).

Analysis of buffer: The buffers were analyzed using the two rings which are 100 meters apart. First the number of landslides which are found within 100 meter range were counted and documented.

Then the buffers found within the 200 meter range from the rivers were also counted and documented. From the analysis of the buffers, it was determined that's 29% of the total landslides in Dominica are found within 100m of the rivers, of that 62.98% are debris flows and 0.85% are rock falls. It was also determined that 57% of the total landslides ere found in within 100-200 meters from rivers; of that 58.5 % are debris flows, 41.3% are debris slides and 0.2% are rock falls/slides. At distances more than 200 meters from the rivers, a mere 14% of the slides were documented, in that area, 57.8% are debris flows ,38.1 % are debris slides and 4,4 % are rock falls/slides. From this analysis it was determined that approximately 86% of the total landslides are located within 200 meter distances from water sources. In this study it cannot be factually proven that the hydrology influence to a very high degree landsliding activity; however, after a close analysis of the map where the values stated above were the results, it can be said that the hydrology has an influence, since 86% of the landslides are located within a 200 meter range from river channels whether they are big or small. This could also mean that maybe in many areas the landslides are located in area of aquifers which could speed up soil saturation given heavy rainfall and favorable slope conditions, promote landslides. (See appendix 12, 13, 17 and 21)

Interpretation of geology-susceptibility map

The geology –susceptibility map which was generated depicts three levels of susceptibility to landsliding; high, medium and low. Medium level of susceptibility occupies 88.83% of the total area of the island; high occupies 10.18% and low a mere 0.99%. According to this map the island of Dominica 99.01% has a moderate-high level of susceptibility to landsliding (see appendix 14, 15 and 22). The rock types with a high susceptibility to landsliding are Pelean domes, path of block and ash flow inferred from crustal outcrops, assorted volcanic rocks (Miocene). Those with medium susceptibility are Pyroclastic block and ash flow (older Pleistocene), Ignimbrite, Assorted volcanics (Miocene), Pyroclastic apron of block and ash flow (younger Pleistocene) and path of ignimbrite inferred from crustal outcrops. Low susceptibility types are Conglomerates and limestone, river sand and gravel; and Pelean domes (Pliocene).

In the assorted volcanic rocks with mafic flow there is the highest number of landslides, however it does not have the highest density of landslides on the island. The fact that these rocks have different compositional characteristics is something which serves as a justification that the area occupied by this rock type present the higher number of slides. It does not present the highest susceptibility however because it also has a very high area; as a matter of fact the highest area found on the island. When a number of types of volcanic rocks are found associated with each other, the exogenic processes which provoke their alteration act in a different way over each and every one of the rocks due to the difference in the chemical and mineralogical compositions. These exogenic processes act in a differing manner upon each of the rocks. This heterogeneity in the level of weathering of these rocks provokes their high level of instability.

Taking into account that this association is characterized by tuffs of varying compositions, andesite, dacite and mafic flow rocks (basaltic mantle); it is supposed that the level of alteration of the rocks of basic composition over those of medium or acidic composition is higher. The zones of contact between alternating layers of rocks, creates structural weaknesses through which the displacement is produced of the material with the highest alteration with respect to the others.

In this case the principal factor which produces the landsliding of the rock mass constitutes the areas of basaltic flows. These rocks change easily when attacked by the agents of weathering, making them incoherent. These together with the high level of alteration due to high precipitation which make them saturated are the main reasons for the presence of a high number of landslides on the island. Moreover, there are no coherent materials such as ash, volcanic breccias, volcanic agglomerates, which in there collective, form a series of rocks totally vulnerable to landsliding.

With all this, the factor of the slope of the island which in these sectors are relatively high and gravity plays a primordial role in the movement of slopes being, debris flows, debris slides and rockfalls or slides.

In the case of the volcanic domes, theses are characterized by a high number of landslides, but less than the first case. However these structures have the highest density of landslides; due to the fact that in difference to the last case and all the other cases the rocks have a total absence of cohesion and are quite loose. More over, they are found in the highest slopes on the entire island. The lack of cohesion between the grains, the action of gravity and the exogenic agents, make these domes the place of the highest number of landslides by unit of area and the highest density of susceptibility to landsliding.

The zones of a medium level of landsliding, according to the geologic landslide susceptibility map the areas occupied by the Pyroclastic deposits of block and ash flow of the older and younger Pleistocene, assorted volcanic rocks of the Pliocene and Miocene and ignimbrite. In these cases, the presence of pyroclastic deposits and flows from crustal out crops favors less landsliding activity than those discussed before. These rocks, although being more angular in nature are more cohesive with respect to each other. The slope of the terrain in these areas are not as steep as the areas of Pelean domes, but still continue being steep. The older rocks would generally have less landsliding activity due to the fact that they are more consolidated and compacted and this have a higher strength and less zones of weaknesses than the younger one.

The absence or near absence of slope movements in the zones occupied by conglomerates & limestones, river and gravel alluvium is justified by the fact that these rocks have a high level of consolidation. The conglomerates and limestone are cohesive sedimentary rocks which although may reach high levels of saturation are resistant to landsliding activity due to the fact that they are more compacted. The river sand and gravel are fond in areas with much lower slopes being associated exclusively to depositional zones of river channels. Also the level of precipitation in these areas are quite low and these rock types are confined to the lower coastal areas thus are not directly affected by the movement of masses which topographically occupy a higher hypsometric level on the island.

As can be seen the types of rocks found in Dominica are a major determining factor in the initiation, occurrence and promotion of mass movements along with several other key factors. The type of landuse of an area is also a determining factor in the occurrence of landslides on the island of Dominica. The following section is has been dedicated to explain the different types of land uses and their levels of susceptibility to landsliding on the island of Dominica.

Interpretation of Landuse-susceptibility map

The resulting land use – susceptibility map which was generated from processed data has three levels of susceptibility; high, medium and low. Medium level of susceptibility occupies 77.27% of the total area of the island; high occupies 21.547% and low a mere 1.16%. From analysis of this map it was determined that 98.84% of the island is has a moderate to high susceptibility to landsliding (see appendix 14, 16 and 18). Of the twelve land use classifications there are five with a medium level of susceptibility to landsliding; they are agriculture, litoral wood land, mature rain forest, scrub woodland and secondary rain forest. Of the others elfin alpine meadow, montane rainforest, semi evergreen forest and the area without landuse information have a high susceptibility. The low susceptibility landuse types are urban, montane thicket, swamp and wetlands.

The level of susceptibility of any region with mass movements depends on several factors. Including the number of landslides and the area. For example, a region with a large area and a high number of landslides will have a lower susceptibility to landsliding in comparism with a small region with fewer landslides.

The landuse with the highest level of susceptibility is the region with Elfin alpine meadow. It has an area of approximately 3.0793 km2 which is only 0.41% of the total land area, 9 landslides (1%) of the total number of landslides. Despite this however it has a high susceptibility of 307; meaning that for every unit of measurement of this area there are approximately 3.07 landslides. From a close analysis of the Elfin alpine meadow area the following was derived: It is found in two main areas, but all the landsliding activity is concentrated in one which is located in the region of the Pelean domes which also has a high susceptibility to landsliding as explained in the previous section. It has very steep slopes and high rainfall levels all year round which is one of the highest for the island and is found at an elevation of approximately 914m. The important question at hand here however is the following: what besides the influence of rainfall, rock type and the geomorphic features of the land, does the types of trees which grows in this area have any influence over landsliding activity? Well in order to explain this, first the types of trees indigenous to that particular area and their characteristics must be discussed. The vegetation consists of mosses, ferns, shrubs and some palms. These are all trees which are unable to provide sufficient stability to the soil and rock mass found in that region given the geologic, climatic and geomorphic conditions found in that area. Thus the vegetation cover here though might not be the principal factor which promotes landsliding but aids in its occurrence and development.

The Semi evergreen rain forest has a total of 145 landslides which is 18% of the total number found on the island. It occupies an area of 68.45 km2 which is 9.11% of the island's area. Its susceptibility to landsliding is high according to our classification; its corresponding value is 228.41. It is found on steeps slopes and the rain fall levels vary from relatively low to high. The associated rock types are assorted volcanic rocks (mafic flow rocks Pliocene), Pelean domes, Path of block and ash flow inferred from crustal outcrops. The bulk of its area is associated with Pelean domes which have a high susceptibility to landsliding. However not all of its total area has a high level of landslide activity. The conditions described above constitutes of primary factors which promote landsliding in this associated landuse type.

Agriculture constitutes of the highest landuse area because the economy of Dominica was once predominant on it. In this moment though it might not be the most important economic activity or rampant as before, it continues to be widely practiced. The areas on the island which have not been used for agriculture is mainly because of the steep slopes (although it is being practiced in quite a number of steep areas) inaccessibility and low soil fertility. Most agricultural practices have been almost confined to the areas closest to roads for accessibility.

The agricultural areas have a total of 149 landslides which constitutes of 18% of the total number of landslides found on the island. Its areas is approximately 237.749 km^2 which corresponds to 31.66% of the total land area. According to the susceptibility scale established in our study it corresponds to a medium value (67). The rain fall levels in the agricultural areas vary from 1500mm in most areas to 2000mm in a few areas. The slope quality varies but is generally moderate to high. The rock types in its region are assorted volcanic rocks (Miocene), Pelean domes, assorted volcanic rocks (including mafic flow rocks) Pliocene, ignimbrite and path of block and ash flow inferred from crustal outcrops , pyroclastic apron of block and ash flow of the older Pleistocene. Even though the agricultural areas are found to be associated with all the rock types mentioned, the bulk of the activity is found where it is associated with assorted volcanic, Pelean domes and assorted volcanic (mafic flow rocks) all of which corresponds with high to medium values of susceptibility.

Agricultural practices on the island of Dominica together with the high precipitation steep slopes and geologic conditions are one of the suspected principal causes of landsliding. The farmers practice slash and burn where the original trees are removed and in some many instances are deep rooted trees which help uphold the soil strength and are replaced by shallow rooted crops like bananas, potatoes, various fruits vegetables which are unable to compensate for the original trees and thus reducing the strength of the soil. Also, in such practices the upper layer of the soil is plowed and reworked making the upper layer less cohesive and with sufficient rainfall it because saturated and the top layer can be moved, especially when found in areas with the right slope conditions. More over, when this upper layer has been remove though processes of mass movements, further movements are provoked, if the underlying bedrock is exposed to the exogenic processes such as weathering, both chemical and physical. Depending on the type of rock found, the slope, soil properties and specific types of agricultural practice, the level of landslide activity in agricultural regions in Dominica may vary. However, as seen earlier its susceptibility to landsliding is moderate.

Mature rain forests constitute of 208.084 km^2 which is 27.7% of the total landuse, it has 194 landslides which corresponds to 24% of the total number. According to our set susceptibility scale it has a moderate susceptibility to landsliding. The associated rock types are Pelean domes, assorted volcanic rocks (Miocene), ignimbrite flows and the pyroclastic block and ash flow deposits of the Pleistocene which vary from moderate to high susceptibility levels according to our susceptibility scale. Precipitation levels in its areas vary from 1000-3000mm +. It grows below 457m Together with the rocks which favor landsliding in these areas, the precipitation; the quality of slopes in this area plays an important role in landsliding. The slopes are quite steep in the mature rain forest area. How ever to be more specific, the characteristics of the mature rain forest promote the development of landslides given the right conditions as is in the case of Dominica. The trees in the mature rain forests are tall some growing above 30 meters, but their roots are quite shallow, and cannot provide a high level of stability for the soil.

Secondary rain forests in Dominica constitute of 80.86 km^2 which is 10.76% of the total land area and has a total of 95 landslides. Precipitation levels vary from 1000mm to over 3000mm. The slopes are in some places quite low lying and in others steep. The associated rock types are ignimbrite, assorted volcanic rocks (Miocene) and pyroclastic aprons of block and ash flow deposits. The secondary rain forest grows in areas once cultivated but are now abandoned, or in areas which have suffered landslides or natural disasters. The nature of the characteristics of the secondary rain forests makes it an area vulnerable to landsliding .Such areas usually have lost some or all of the upper top soil layers exposing bedrock to the agents of weathering facilitating the zones of weakness within them. Also, in these areas the soils are easily saturated and with a little excessive rain fall, landslides can be triggered. According to our susceptibility level scale the secondary rain forest has a medium susceptibility to weathering, its value is 126.686.

The other land uses with moderate susceptibility levels are litoral woodland (92.913) and scrub woodland (81.037); they are all associated with volcanic rocks, high precipitation levels and steep slopes favoring landsliding activities. The area without information has a high susceptibility (203.41), but was not analyzed or interpreted like the others due to the fact that its data is unknown, so a factual justification cannot be made in terms of its contribution to landsliding in the area which it occupies.

Montane thicket, urban; and swamp and wetlands correspond to the areas with low susceptibility to landsliding. The urban areas are free of any landsliding activity because they have been built on the flattest areas, the swamp areas are unable to generate landslides because they are also flat areas, the litoral woodland occupy a very small land area and is restricted mainly the low-lying coastal areas. Montane thicket occupies the smallest land area and is found in two areas practically free of landsliding activities and in Dominica is found in areas with elevations higher than 750m.

As we discussed above all the landuse contribute directly to the occurrence of landsliding which take place in their area, whether it is high, moderate or low. (See appendix 19, 20 and 21)

3.4- Proposal for measures of control and mitigation in function of the level of susceptibility of the areas

3.4-1 Mitigation

Based on the susceptibility thematic maps of landuse and geology formulated in this study over 70% of the Dominican terrain has a moderate to high susceptibility to landsliding. This is poses a serious problem to the island in almost every term; the infrastructure, roads, environment (vegetation, soils), economy and most importantly it is a tremendous threat to human lives. Since the occurrence of landslides at a specific time cannot be calculated, the danger caused by landslide is almost always catastrophic to any one or more of the variables mentioned before. Thus the only means of reducing the effects of landslide hazard is the identification of the level of risk at which an area is to landsliding, and with that information to develop a plan of mitigation. How ever, it must be noted that mitigation cannot in any way prevent the occurrence of landsliding or any hazard but it helps reduce the number of persons who are it risk if it occurs.

In areas with landslide hazards, mitigation measures should be selected if they are not already part of the plan in construction codes. It is possible to reduce the possible impact of natural landslide activity and limit landslides which occur as a result of human activity. There are two basic approaches: first, to avoid landslide-susceptible areas, and second, to design measures to compensate for the inducement of landslides (see the box below). For example, make location decisions so as to avoid building in certain areas, such as placing dwellings and critical infrastructure outside areas with a high likelihood of natural landslide activity. In some instances, the potential effects of a landslide can be mitigated. Landslide hazards resulting from development can be reduced by designing changes to counteract the impact that development may have on slope integrity. This might take the form of permitting only warehouses and storage facilities in higher hazard areas, to reduce the vulnerability to the population should a landslide occur.

Other mitigation approaches include avoidance of the highest risk areas, especially in terms of road construction and residential areas. Insurance and taxations can be applied specifically for natural hazards since the probability of its occurrence is high. Planners should always take into account the landslide susceptibility map(s) when making development plans.

3.4-2 Possible measures of control of landsliding in Dominica

There are several possible measures of control which can be applied to the island of Dominica to control the effects of landslides. Three measures are described below:

1. **Changing the geometry by means of excavation**
    - Reduce the slope height by excavation at the top of the slope

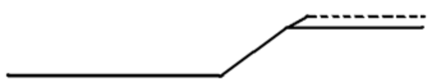

Figure 3d excavation of slopes

- Flatten the slope angle

Figure 3e flattening of slopes

- Excavate a bench in the upper part of the slope.

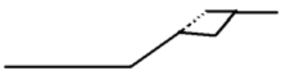

Figure 3f Excavation of bench in upper part of slope

In order to do this the area has to be accessible to construction equipment, a disposal site has to be available for the excavated soil.

2. **Earth berm fill**

- Compacted earth or rock beam placed at and beyond the toe, Drainage may be provided beyond the berm.

Figure 3g Compacted rock beam

3. **Retaining structures**

   - Retaining walls (costly, not very economical)

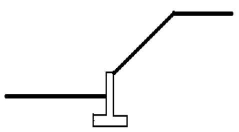

Figure 3h Example of a retaining structure

Other more complex measures may be applicable but for these more detailed geotechnical and Geomechanical studies will have to be carried out.

Conclusions and Recommendations

Conclusions

Upon completing this study, the author has gained useful professional experience in the field of natural hazard analysis. The following are the conclusions formulated upon completing the study:

- ☞ A landslide susceptibility map for landuse of the island of Dominica was created which shows that shows that according to the susceptibility of the terrain to landsliding in terms of landuse, 1.46 % of the island has a low susceptibility to landsliding, 66.43% has a moderate susceptibility and 32.11% has a high susceptibility.
- ☞ A landslide susceptibility map for geology of the island of Dominica was created which shows that shows that according to the susceptibility of the terrain to landsliding in terms of geology (rock types), 0.99 % of the island has a low susceptibility to landsliding, 88.83% has a moderate susceptibility and 10.18% has a high susceptibility.
- ☞ That generally, from the analysis of the different thematic susceptibility maps and the susceptibility map, that over 70% of the terrain of Dominica has a medium to high level of susceptibility to landsliding.
- ☞ The rock type with the highest susceptibility to landsliding on the island of Dominica is those pertaining to the Pelean domes of the Pliocene.
- ☞ The rock type with the highest number of landslide on the island of Dominica is the Assorted Volcanic rock of the Pliocene, with approximately 39% of the total landslides being associated with it.
- ☞ The landuse type with the highest susceptibility to landsliding on the island of Dominica is the elfin alpine meadow.
- ☞ The landuse type of the highest number of landslides is the mature rain forest with approximately 24% of the total landslides.
- ☞ According to the interpretation and analysis of the various susceptibility maps generated and the maps used to aid in this study; some of the principal causes of landslide activity are rock types, landuse types, precipitation, slope quality and hydrology.

Recommendations

Based on the results obtained and conclusions reached in this study, the following recommendations have surfaced, also some were made based on general knowledge of the past research done on the island and were included so as to encourage and promote studies in landsliding and other natural hazards found in Dominica:

- ☞ Due to the high number of landslides, some which are impacting or will impact in the near or distant future on the environment, on the population and the economy; on the island of Dominica it is necessary that the government take on a full scale Geotechnical-Geomechanical study of the island, to further help to curb, control and prevent the effects of landsliding.
- ☞ Make use of the maps prepared in this study and the information interpreted to help mitigation in the higher risk areas of the island of Dominica.
- ☞ If the concentration of the population is in a high risk area the authorities must develop a plan to transfer the residents to a lower risk area.
- ☞ To prevent creating more landslides, by carrying out proper preliminary studies when constructing roads, buildings e.t.c.

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Glossary of Terms

ArcView 3.2 GIS: is a desktop geographic information system which allows the creation of intelligent, dynamic maps using data from virtually any source and across most popular computing platforms.
Buffer: A buffer refers to the area contained within a specified distance from an object in space.
ARC/INFO: a vector and raster based GIS software developed and distributed by ESRI.
Crown: The material that is still in place, practically undisplaced and adjacent to the highest parts of the main scarp.
Debris Flows: a mass moves downslope with a fluid motion. A significant amount of water may or may not be part of the mass.
Displaced Material: The material that has moved away from its original position on the slope. It may be in a deformed or unreformed state.
Flank: The side of the Landslide
Foot: The portion of the displaced material that lies downslope from the toe of the surface of rupture.
Debris Slides: a mass displaces on one or more recognizable surfaces, which may be curved or planar.
GIS (Geographical Information System): A GIS is an information system designed to work with data referenced by spatial / geographical coordinates. In other words, GIS is both a database system with specific capabilities for spatially referenced data as well as a set of operations for working with the data.
Geologic map: a geologic map shows the distribution of geologic features such as faults, rocks etc.
Head: The upper parts of the slide material along the contact between the displaced material and the main scarp.
Isopleth map: An isopleth map generalizes and simplifies data with a continuous distribution. It shows the data as a third dimension on a map, thus isopleth maps are more common for mapping surface elevations, amounts of precipitation, atmospheric pressure, and numerous other measurements that can be viewed statistically as a third dimension. Isopleths never cross or divide and always form enclosed circles, however, this occurrence may not be in the mapped area.
Landslide: downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing.
Landslide Hazard: as represented by susceptibility, which is the likelihood of a potentially damaging landslide occurring within a given area.
Landslide hazard map: a map showing different zones of landslide hazard, usually the zones are classified from low to extremely high hazards.

Landslide hazard zonation: the division of the land surface into homogeneous areas or domains and their ranking according to different degrees of hazard due to mass-movement (see Varnes et al , 1984).
Landslide inventory: the systematic mapping, through various techniques (i.e., field surveys, aerial-photo interpretation, site measurements, historical records)
Landslide susceptibility (or propensity): an estimate of the slope-instability conditions of a region mainly based on the qualitative judgment of the investigator eg. of past and recent landslides in a region.
Left and Right: Compass directions are preferable in describing a slide, but if right and left are used they refer to the slide as viewed from the crown.
Main Body: That part of the displaced material that overlies the surface of rupture between the main scarp and toe of the surface of rupture.
Main Scarp: A steep surface on the undisturbed ground around the periphery of the slide, caused by the movement of slide material away from undisturbed ground. The projection of the scarp surface under the displaced material becomes the surface of rupture.
Mass Movement: is defined as the down slope movement of rock and regolith near the Earth's surface mainly due to the force of gravity
Minor Scarp: A steep surface on the displaced material produced by differential movements within the sliding mass.
Original Ground Surface: The slope that existed before the movement which is being considered took place. If this is the surface of an older landslide, that fact should be stated.
Risk (specific): the expected degree of loss due to a particular landslide phenomenon.

Rock Falls: a mass detaches from a steep slope or cliff and descends by free-fall, bounding, or rolling.
Vulnerability: the level of population, property, economic activity, including public services, etc., at risk in a given area resulting from the occurrence of a landslide of a given type.
Surface of Separation: The surface separating displaced material from stable material but not known to have been a surface of which failure occurred.
Tip: The point on the toe most distant from the top of the slide.
Toe: The margin of displaced material most distant from the main scarp.
Toe of Surface of Rupture: The intersection (sometimes buried) between the lower part of the surface of rupture and the original ground surface.
Top: The highest point of contact between the displaced material and the main scarp.
Vulnerability (V) : Vulnerability can be described on the one side as being a propension to undergo damages, i.e. a state of fragility: a set of conditions that raise the susceptibility of a community to the impact of a damaging phenomenon.
Zone of Accumulation: The area within which the displaced material lies above the original ground surface.
Zone of Depletion: The area within which the displaced material lies below the original ground surface.