ABSTRACT

Mapping Vulnerability of Infrastructure to Destruction by Slope Failures on the Island of Dominica, WI: A CASE STUDY OF GRAND FOND, PETITE SOUFRIERE, AND MOURNE JAUNE

by Zachary Dean Andereck

This thesis examines slope failure probability and the infrastructure at risk from slope failure on the Eastern Caribbean island of Dominica. Through a case study of the villages of Grand Fond, Petite Soufrie and Mourne Jaune, various landscape indicators are utilized in multiple logistic regressions to calculate landslide probabilities. Infrastructural components are examined in relationship to a landslide probability map developed for the research area.

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Wai'tukubuli

Isle of beauty, isle of splendor,
Isle to all so sweet and fair,
All must surely gaze in wonder,
At thy gifts so rich and rare.
Rivers, valleys, hills and mountains,
All these gifts we do extol.
Healthy land, so like all fountains,
Giving cheer that warms the soul.

Dominica, God hath blest thee
With a clime benign and bright,
Pastures green and flowers of beauty
Filling all with pure delight,
And a people strong and healthy,
Full of godly, rev'rent fear.
May we ever seek to praise.
Thee for these gifts so rich and rare.

Come ye forward, sons and daughters
Of this gem beyond compare.
Strive for honour, sons and daughters,
Do the right, be firm, be fair.
Toil with hearts and hands and voices.
We must prosper! Sound the call,
In which ev'ryone rejoices,
"All for Each, and Each for All."

Dominica National Anthem,
Wilfred Oscar Morgan Pond
1967

Chapter One

Introduction

When the unpredictable manner of nature collides with humans, the result is often disastrous. Natural hazards are a constant threat to many populations around the world. In many areas, particularly developing countries, economic losses due to natural hazards are increasing despite improvements in recognition, prediction, and mitigation (Schuster and Krizek, 1978; Turner and Schuster, 1996; Cutter et al. 2000; Bankoff, 2001; White et al, 2001). Losses are increasing, apparently due to the expansion of populations and development into unstable areas (Schuster and Krizek, 1978; Turner and Schuster, 1996; Bankoff, 2001).

Some argue that these losses are increasing because the relationship betweens humans and nature has changed dramatically over the past 300 years (Locke, 1965; White, 1967; Williams, 1980; Redmond, 1999), while others argue that the approach to understanding hazards is fundamentally flawed (White and Hass, 1975; Burton et al, 1993; Kusler and Larson, 1993; Hewitt 1995). This study looks beyond simply mapping natural hazards, but adds a human component to the hazard. Through the ascription of vulnerability, natural hazards become more than just a natural event.

Dominica

Dominica is an Eastern Caribbean volcanic island approximately 47km (29 miles) long and 26km (16 miles) wide located in the in the Lesser Antillies (See Figure 1.1). Formally known as the Nature

Figure 1.1
Dominica and the Eastern Caribbean/ Lesser Antilles (www.dominica.dm, 2006)

Island of the Caribbean[1], Dominica has one of the most pristine ecosystems in the world. The people of the island appreciate and understand the intricate balances of the natural systems at work on the island. They posses a knowledge or a connection to the land that is almost foreign to westerners, as the relationship between humans and nature is closely interwoven. The natural environment is not been significantly altered as it is in many western regions. The land has more than monetary value, it is the provider for all that people need, but this is rapidly changing.

Dominica, a moderately poor Caribbean Island, is faced with the task of developing its economy. With recent economic setbacks after the collapse of the banana industry, Dominica has tried to assert itself economically through new development partnerships with Venezuela, China, and Japan. Dominica is also increasing its role in developing the growing ecotourism industry. Being the backdrop for Disney's Pirates of the Caribbean II and III enhanced the appeal of the island. This exposure has caught the attention of foreign developers and investors and has the potential to change the face of the island. Local land owners are selling their land for more money than they could have ever imagined, leading to ownership by individuals who are most likely unfamiliar with the land.

This new ownership and development has the potential to lead to undesirable results in areas at great risk for slope failure. This risk derives from the volcanic soils that are dominant on Dominica. These soils are known for their unstable properties, especially in areas of intense rainfall and steep slopes, both common on Dominica.

Landslides

Losses attributed to slope failures are increasing around the world and in Dominica, despite significant advancement in knowledge. The term landslide is used to denote the rapid movement of rock, soil, or debris down a slope (Crunden, 1991; Varnes, 1978). Landslides are a common occurrence on Dominica. They are most often associated with significant precipitation events and have disturbed nearly two percent of the island's land surface (DeGraff, 1987a). Loss of life due to landslides does occur, but is currently not a significant problem. Infrastructural damage such as damaged or destroyed roads, buildings, and utilities is the primary effect of the slope failures.

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[1] Dominica adopted the new tagline "Defy the Everyday, The Nature Island of Dominica" in November, 2006. This was done to remove association with "typical" Caribbean destinations that boast Sun, Sea, Sand. Dominica hopes the new tagline draws visitors who seek a more ecological friendly getaway (Caribbean Net News, 2006).

Statement of Research Purpose and Questions

This study provides an improved understanding of the spatial distribution of slope failures and the vulnerability of infrastructure to slope failures on the small Eastern Caribbean island of Dominica. Through a case study, the local communities of Grand Fond, Petite Soufriere, and Morne Jaune are examined to gauge the likelihood of slope failures and potential infrastructure at risk from slope failures. Located on the southeast coast of Dominica, these villages are susceptible to landsliding (Figure 1.2). In the event of major slope failures, these communities are vulnerable to being isolated from relief because of limited access to the villages. These villages have the potential to also experience considerable damage to infrastructure. My field work and resulting analysis is guided by the project framework (Figure 1.3).

The project framework consists of two principal research questions:

1. What is the spatial distribution of potential slope failures in terms of probability?

    a.) What is the spatial extent of past and present failures within the research area?

    b.) What landscape characteristic/parameters affect the likelihood of slope failures within the research area?

2. What is the vulnerability of infrastructure in the research area to slope failure?

    c.) What is the spatial distribution/location of infrastructure within the research area in relation to landslide probability?

In answering these questions, I investigate the spatial extent of slope failures and the landscape indicators that potentially contribute to slope failures through field mapping and satellite image interpretation. The landscape indicators, such as slope steepness, slope aspect, soil, land cover, and distance to nearest road are used to determine the probability of slope failure using a multivariate statistical approach known as multiple logistic regression. I also investigate the spatial distribution of infrastructure in relation to potential slope failures, from which infrastructure vulnerability to landslides is assessed.

Presentation of Study

This study is presented in six chapters. Chapter two is an in-depth examination of humans' perspective of nature and the contextual generation of natural hazards. A historical perspective of hazards research and landslides is also examined. Chapter three examines the area of study by providing descriptions of the local history, economy, physical nature, and historical landslide studies. Chapter four presents the methodology in which the landslide inventory is constructed, landscape indicators compiled, and statistical analysis performed. Chapter five provides the results of the analysis including the resulting landslide probability and infrastructure vulnerability maps. Chapter six concludes with a discussion of the results the exploration of the various landscape indicators and their influence on landsliding in the research area. It concludes with a discussion of potential paths for future research.

Figure 1.2
Research area on Dominica

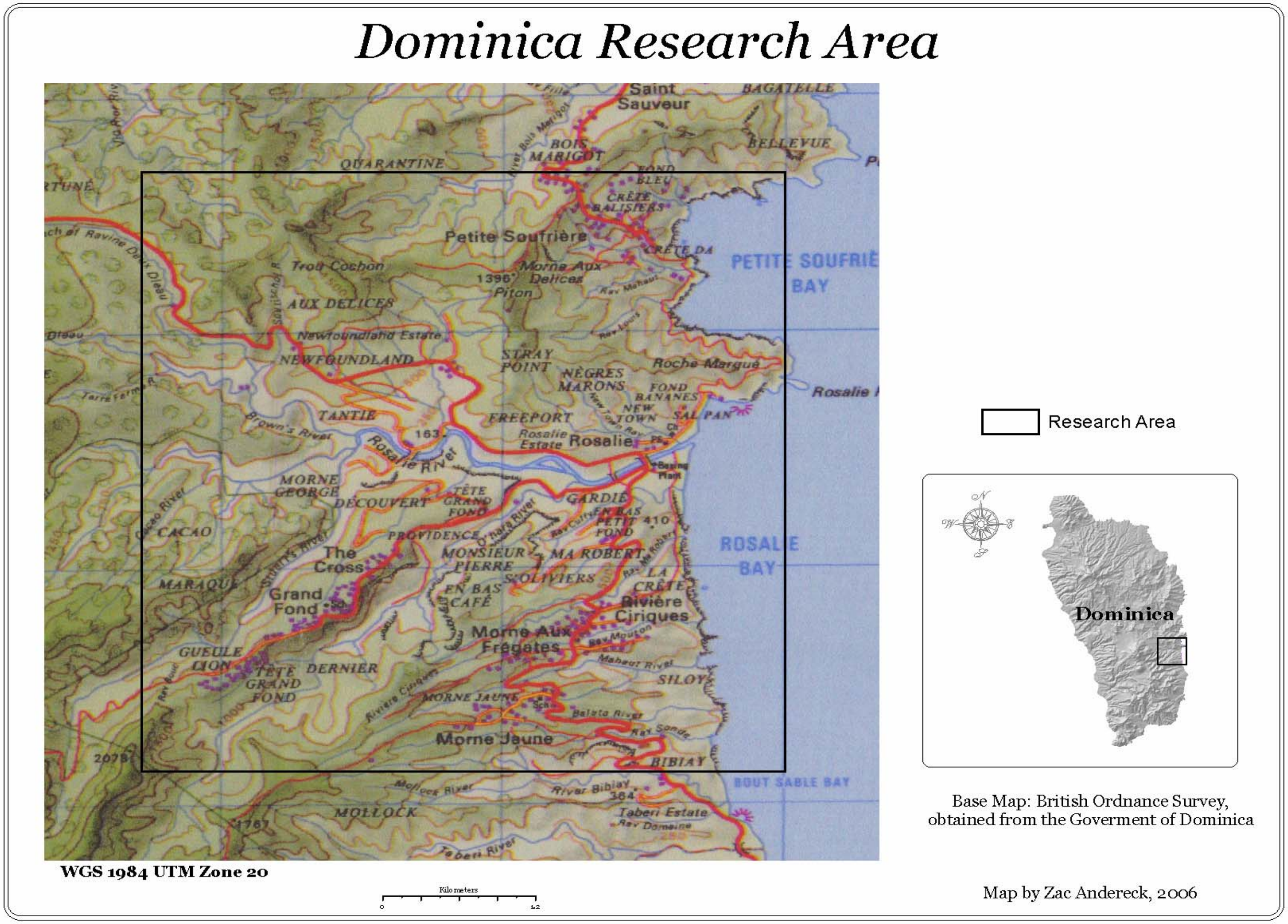
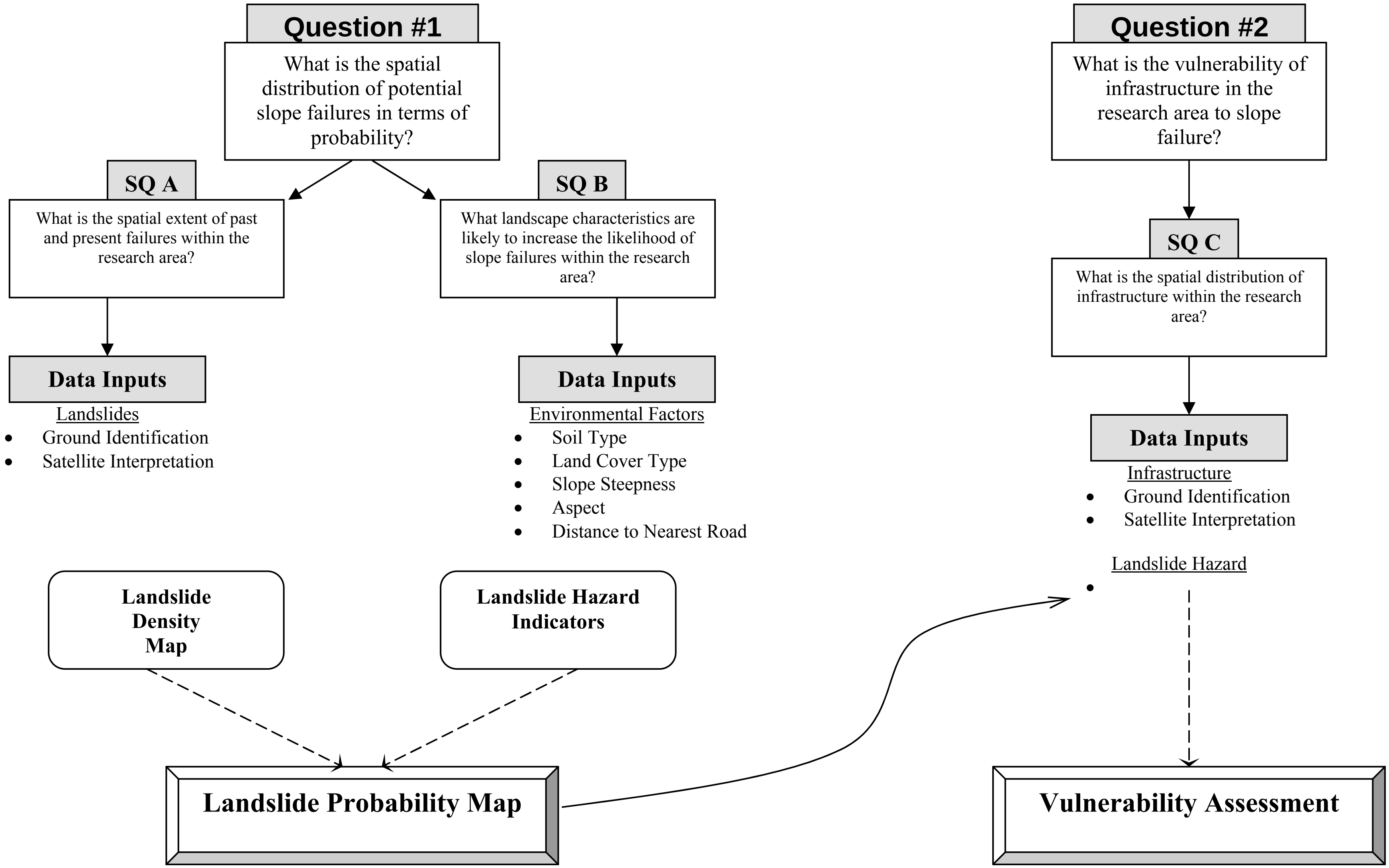


Figure 1.3:
Research framework used to investigate the
spatial and vulnerability components of landslides.



Chapter Two

Literature Review

2.1 Natural Processes and Humans

The earth's crust is continually changing due to normal physical processes operating in the earth's interior, surface, and enclosing atmospheric envelope (McGuire et al, 2002, p.1). The majority of physical processes can be classified within three categories, geological, hydrological, and atmospheric (McGuire et al, 2002). Extreme events such as lightening and flooding can be a valuable resource and a hazard at the same time. A lightening strike can kill an animal, but the resulting fire replenishes the forest ecosystem (Burton et al., 1993; White et al., 2001; McGuire et al., 2002) and a flood can destroy a farmstead but bring vital nutrients to the surrounding floodplain (Burton et al., 1993; McGuire et al., 2002). When a natural process disrupts humans, it no longer operates as a separate entity, but one that intersects and possesses a threat to humans. This intersection has been termed 'natural hazard.'

A natural hazard, broadly defined, is a natural event that has the potential threat and capable means of producing damage to physical and social spaces (Alcántara-Ayala, 2002). It is as an extreme variable in the environment that is harmful to humans (Burton and Kates, 1964); a natural process that is triggered by a climatic or geologic event beyond human control (Hewitt, 1997); an extreme natural event that poses a threat to humans, their belongings, and their property (McGuire et al., 2002); or a potentially damaging physical event or phenomenon which may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation (U.N. ISDR 2002).

2.2 Human-Nature Conflict

Lynn White Jr.s' 1967 controversial paper entitled "The Historical Roots of Our Ecological Crisis," presents the compelling argument on why humans are at odds with nature. White (1967) claims that Judeo-Christian traditions allow humans to feel separated from and superior to the natural world. This ideology begins in the early third century through promotion by the Christian church of the theological doctrine of humans' transcendence over nature. It was not immediately accepted; instead, pagan forms of reverence towards the land were common. It was believed that "before one altered anything in nature, the place spirit had to be placated." (White, 1967, p. 1207) Before many of the major anti-paganism movements, Christian believers felt that to know nature was to know thyself, as both were creations of God (Williams, 1980).

This attitude changed with the establishment of anti-pagan doctrines in the 17th and 18th centuries (Redmond, 1999). These established a state of human-nature conflict; the environment was no longer seen as an equal, but an object under humans control (Redmond, 1999). White (1967) argues the emphasis on the creation story of Genesis 1 created human-nature conflict. In Genesis 1, humans are a creation of God that named all animals; therefore meaning that humans had mastery and control over nature. White (1967) states that "no item in the physical creation had any purpose save to serve man's purposes" (p. 1205), which is reinforced by Locke (1965) who states "that God had given the Earth to humanity, and since each individual was the embodiment of humanity, each had the rights to the fruit…" (p. 327-8).

This freeing from nature created a human-centered mindset that enforced the dichotomy between humans and nature. Nature is seen as an interruption at odds with a human world and is a product which humans could control, alter, and use for their welfare (Oliver-Smith, 2004). "The reduction of nature to the status of simply ensuring human well-being, the ideological justification and the institutional means were (in place) for an unfettered mastery over, and unrestrained exploitation of, the natural world" (Oliver-Smith, 2004 p. 15).

The 'plasticity myth (Murphy 1994)' is the idea that human-nature relationships can be constructed and reconstructed at will by human reasoning because nature is malleable; to which it must be shaped to best serve humanity. Once emancipated, humans are free from the bonds of the natural world and are now "capable of manipulating, domesticating, remolding, reconstructing, and harvesting nature" (Murphy, 1994, p.5). The reduction of nature as only a means of providing for the welfare of humans led to the development of a monetary value on and exploitation of the environment (Oliver-Smith, 2004).

Degradation of the environment for development, based on linear growth indicators, accentuates vulnerability to natural hazards for those people who are subsumed in this drive for money (Oliver-Smith, 2004). This is particularly true in developing countries where "development" is based on linear western growth ideals, which lead to sectors of the population who are increasingly at risk because of migration into areas that are unsuitable for safe living (Oliver-Smith, 2004).

The drive to be "developed" as a country can create extreme levels of environmental degradation, which increases vulnerability to a natural hazard. Developing countries render pollution, depletion of resources, and other forms of environmental change subordinate to production quotas (Murphy, 1994). The implementation of western style development models continues to operate on the premise that nature is an endless and bountiful, creating a self-repeating destruction of the environment (Oliver-Smith, 2004).

2.3 Hazards Research

Human superiority to nature is expressed in early hazards research developed in the late 1950's as a means to explain increases in flood losses in the United States. Research focused on understanding and controlling natural hazards strictly through technological and engineering practices. Known as a technocratic approach, this type of management employs a mindset of applying capital and technology to mitigate outcomes, rather than understanding the underlying causes. Examples of the inherent flaws in this ideology are found throughout the last 50 years, but the effect of Hurricane Katrina on New Orleans in 2005 is the best example. The construction of levees as a means to manage flooding within New Orleans overlooked the biggest underlying problem; the city is built below sea level. This reliance on technology and engineering to control hazards in many instances led to increases in losses rather than decreases (Burton et al, 1993).

In their landmark assessment of the United States research effort on natural hazards, White and Hass (1975) concluded that:

> "Research today concentrates largely on technologically oriented solutions to problems of natural hazards, instead of focusing equally on the social, economic, and political factors that lead to non-adoption of technological findings. In short, the all-important social, economic, and political "people" factors involved in

> hazards reduction have been largely ignored. They need to be examined in harmony with (the) physical and technical factors" (p.1).

It was during this time (1970's) that social scientists began questioning whether technocratic approaches were best suited to studying hazards. "The technocratic approach permits hazards to be treated as a specialized problem for advanced research of scientist, engineers, and bureaucrats, and therefore to be appropriated within a discourse of expertise that quarantines disasters in thought and practice" (Hewitt, 1995 p.118). Technocratic approaches to hazard research are still a dominant paradigm in hazards research. Developed countries are capable of affording such practices, but for developing countries this type of mitigation is not feasible, increasing the risk of potential disasters (Kusler and Larson, 1993). Recently, sociological and physiological approaches have been incorporated into hazards research with examination of human responses to natural events. One particular area of interest is the vulnerability of populations to natural hazards.

2.4 Vulnerability

Vulnerability is a relatively new idea and is an alternative to technocratic methods of hazards mitigation. Vulnerability alters the perspective about natural hazards from merely natural/physical forces to one that incorporates elements of human interaction. The combination of various elements of society, culture, and the environment allows vulnerability to provide a framework that encompasses the multidimensionality of a natural hazard (Oliver-Smith, 2004).

Human and physical geographers differ in the use of the term. Humanistic research examines vulnerability in terms of the systems that exists within cultural, political and economic fabrics that are impacted by a natural hazard. Cannon (1993) defines vulnerability as "a characteristic of individuals and groups of people who inhabit a given natural, social and economic space, within which they are differentiated according to their varying position in society into more or less vulnerable individuals or groups" (p. 94). Deyle (1998) broadens vulnerability by stating "vulnerability (to a hazard) is constructed within the mechanisms of society, creating sectors that are capable of dealing with a hazard and sectors that are unable to cope" (p. 121).

Physically based research focuses on the physical damage, or potential damage, that a natural hazard may have on a population. May (2000) describes vulnerability as the propensity of life, property, and/or the environment to damage in the event of a hazard. Bolin and Stanford (1998) describe vulnerability as the likelihood that a person will be negatively affected by environmental hazards. Cardona (1999) ascribes vulnerability to the hazard of human settlements affected by a natural phenomenon because of the proximity of the settlement to the natural phenomenon. The National Oceanic and Atmosphere Administration (NOAA) defines vulnerability as the level of exposure of human life, property, and resources to impacts from hazards.

2.5 Hillslope Processes

A slope failure is the downslope movement of material at the moment that stabilizing factors fail. The term landslide is one type of slope failure that is used to denote the movement of rock, soil, or debris down a slope (Crunden, 1991; Varnes, 1978). The term is more inclusive than the component words, land and slide, make it seem. Landslide is used to identify falls, spreads, slides, and flows (Schuster and Krizek, 1978; Varnes, 1978; Turner and Schuster, 1996). Several authors have developed classification schemes to categorize and describe various types of mass wasting based on the material and formation process present in each movement type.

A problem with many classification schemes is that they simplify and categorize continuous processes that can span multiple categories. An example of this is a debris flow. Debris flows are landslides in which the slope forming material is permanently deformed during movement (Dikau et al, 1996). Debris flows begin as a slide and through movement downslope, transform into a flowing mass that follows pre-existing drainage paths (Dikau et al, 1996). Slope failure occurs when the gravitational stresses exceed the resisting strength of slope materials. This is expressed in the factor of safety equation:

$$\boldsymbol{F} = {}^{\mathbf{Ff}}/_{\mathbf{Fg}}$$

where F is the factor of safety, F_f is the sum of all resisting forces, and F_g is the sum of stresses acting on the material. When the factor of safety (F) exceeds one, the slope is stable, but when F equals one, slope failure occurs.

French physicist Charles Coulomb recognized that failures occur when the shear stress (driving force) exceeds the shear strength (resisting force) of a material. Shear strength, the resistance of a mass to movement over a plane, is a function of internal friction and cohesion within a mass. It is equal to the stress normal to the shear plane multiplied by the coefficient of internal friction of the material. This is expressed mathematically by Coulomb's (1776) equation:

$$\boldsymbol{\tau = c + S_n \tan \theta} \qquad \textbf{(1)}$$

where **τ**, in units of stress such as kgf/cm^2, is the shear strength, **c** is cohesion, **S_n** is normal stress, and **θ** is the angle of internal friction.

Internal friction helps to retard movement of the grains relative to each other, creating strength within the material. There are two types of internal friction, planar and interlocking. Planar friction is produced by grains attempting to slide past another along a well-defined planar surface while interlocking friction originates when particles are required to move up and over on another within the mass. Cohesion binds grains of a material by electrostatic forces between clays and/or chemical cementation. It is dependent on the pressures exerted between grain particles. Cohesion and overall shear strength is directly related; as cohesion increases the shear strength of a material also increases.

Water is a primary factor in determining internal friction and cohesion. Tiny pores between the grains of soil exist and allow water to infiltrate. The surface tension of water binds particles together helping to resist shear stress. This is why moist sand can be built into sand castles while impossible with dry sand. Too much water can have the opposite affect and cause materials to be weak. As the amount of water increases between pores, internal friction decreases. Pore pressure reduces the gravitational component that acts perpendicular to the slope on which the mass is resting. The water removes the pressure on each grain-to-grain contact, reducing internal friction. As pore pressure increases (nearing saturation) more and more of the load is transferred to the water and away from the grains. When all pores are filled, cohesion is lost. This is expressed by modifying the Coulomb equation written as:

$$\boldsymbol{\tau = c + S_e \tan \theta} \qquad \textbf{(2)}$$

where **S_e** is the effective normal stress and is equal to normal stress (**S_n**) minus pore water pressure (**S_p**). The result is a reduction in internal friction, which increases the likelihood to fail. Saturated slopes are therefore more susceptible to failure than dry slopes, as most slope failures are often associated with heavy rains.

2.6 Landslide Mapping

The key issue in predicting hazards such as landslides is the identification and collection of the relevant predictors whose nature, character, and role vary spatially. Landslides result from interactions of factors such as topography, hydrology, soil development, soil-rock interactions, and precipitation (Carrara et al, 1999). The spatial extent of the hazard determines the potential impacts on humans and infrastructure (Wang et al., 2005), therefore the development of a landslide hazard map is crucial for identifying areas susceptible to sliding.

A hazard map begins with the identification of a proper mapping scale. Scale affects the type of analysis that can be performed for landslides and can be grouped into 4 categories; regional (< 1: 250,000), medium (1: 25,000-50,000), large (< 1: 5,000-10,000), and detailed (>1:5,000) (Huabin et al., 2005). Detailed-scale analysis is used for areas with a maximum size of several hectares, with the intent of the analysis being used for a specific site. Large-scale map analysis is for areas of several tens of square kilometers with the purpose being the analysis of slope instability, the planning of infrastructure and other industrial projects (Huabin et al., 2005). Medium scale analysis is used to statistically relate the relationship between landslides and their contributing factors. Finally, regional scale analysis is used to identify broad areas that could be affected by a landslide. The intent of the regional scale would be the use by regional planners to make adjustments on a regional scale, such as regional land use planning programs. Due to the complexity of the causal mechanisms of failure, levels of uncertainty exist at each scale.

Landslide hazard maps use a variety of methods. All mapping methods share three underlying assumptions; 1) slope failures are recognizable by distinct morphological features; 2) mechanical laws that control slope movement can be measured empirically, statistically or through physical processes; and 3) future failures are most likely to occur in similar topographic, geomorphic, geologic, and hydrologic circumstances to those in which failures occurred in the past (i.e. the past and present are the key to the future). The most common methods include landslide inventory analysis, heuristic hazard mapping, statistical models, and physical processes models (Guzzetti et al, 1999). The models are qualitative, quantitative, direct, or indirect. Qualitative methods are subjective techniques that describe the hazard in qualitative terms. Quantitative methods produce probabilities of slope failure within an area. Direct methods consist of geomorphic mapping of landslides, while indirect methods conduct the hazard mapping exercise through a series of steps. Table 2.1 lists potential parameter inputs for use in landslide hazard mapping.

Landslide Inventory

Landslide density/inventory mapping attempts to predict future failures based on past and present landslide distribution. A landslide density map displays the number and/or area of landslides within a given area. Landslide density maps, in conjunction with a statistical model, can be used to determine areas that are more prone to failure based on the distribution of past failures. Remote sensing methods such as satellite images and aerial photography allows for individuals to obtain significant and cost effective information on landslides (Schuster and Krizek, 1978; Lee, 2005). Schuster and Krizek (1978) list nine advantages of using aerial or satellite images for landslide inventory mapping. They include:

1.) They present an overall perspective of large areas
2.) Boundaries of existing landslides are easily delineated
3.) Surface and near-surface drainage channels can be traced
4.) Important relations in drainage, topography and other elements can be identified and correlated properly
5.) Moderate vegetation cover seldom obscures photo interpretation
6.) Soil and rock formations can be evaluated in an undisturbed state
7.) Continuity and repetition of features is emphasized
8.) Areas for field investigation can easily be identified maximize time in the field
9.) Historical and recent images can be compared to identify progressive development of landslides

Landslides are identifiable in these types of images by breaks in the forest canopy, scarps, flow tracks, debris deposits, distinctive changes in vegetation indicative of moisture changes, and unnatural spoon shaped troughs to name a few (Schuster and Krizek, 1978; Lee, 2005).

Inventory methods are limited by their reliance on factors that attributed to failures in the past. Changing conditions in the present or future, such as deforestation or construction of a road, can change the intricate relations between properties of a slope. If the area has remained homogeneous, then this method is an accurate means to predict potential slope failures.

Statistical

Statistical modeling, usually in conjunction with an inventory map, is an indirect and quantitative approach based on contiguity analysis of observed landslides and variables that can potentially be considered instability factors (Guzzetti et al., 1999). Statistical approaches are data

Table 2.1
Potential Data Inputs for various Landslide Hazard Analysis (Turner and Schuster, 1996).

Data Layers For Slope Instability Hazard Zonation	Attribute data	Scale of Analysis		
		Regional	Medium	Large
Geomorphology				
1. Terrain Mapping Units	Terrain mapping units	3	3	3
2. Geomorphologic units	Geomorphologic description	2	3	3
3. Landslides (recent	Type, location, activity, ect	1	3	3
4. Landslide (older)	Type, location, activity, ect	1	3	3
Topography				
5. Digital Terrain/Elevation Model	Altitude classes	2	3	3
6. Slope Map	Slope angle classes	2	3	3
7. Slope Aspect	Slope direction classes	2	3	3
8. Slope Length	Slope length classes	2	3	3
9. Concavities/Convexities	Concavity/Convexity	1	1	3
Engineering Geology				
10. Lithologies	Lithology, rock strength, ect	2	3	3
11. Material Sequences	Material type, depth, ect	1	2	3
12. Structural Geologic Map	Fault type, length, dip, ect	3	3	3
13. Seismic Accelerations	Max seismic acceleration	3	3	3
Land Use				
14. Infrastructure (recent)	Roads, railway lines, buildings	3	3	3
15. Infrastructure (older)	Roads, railway lines, buildings	3	3	3
16. Land Use map (recent)	Land use types, density, ect	2	3	3
17. Land Use map (older)	Historical land uses	2	3	3
Hydrology				
18. Drainage	Type, order, size, length	3	3	3
19. Catchment Areas	Order, size	2	3	3
20. Rainfall	Rainfall in time	2	3	3
21. Temperature	Temperature in time	2	3	3
22. Evapotranspiration	Evapotranspiration in time	2	3	3
23. Water Table Maps	Depth to water	1	1	2

Note: The last three columns indicates the possibility for data collection for different scales of analysis: 3 = Good, 2 = Moderate, 1 = Poor based, 'black box' models that do not imply cause-effect relationships. Instead, these approaches examine observable relationships between instability factors and the relative distribution of landslides. Two main analysis types are used in landslide hazard mapping, bivariate and multivariate. Bivariate statistical analysis ascribes a weighted value to each stability factor of the research area based on landslide density (Turner and Schuster, 1996). Multivariate statistical analysis developed in Italy uses all relevant instability factors available in the research area to identify areas of hazard. Each sampling unit in the analysis is sampled on a large grid, or by morphometric unit. The density map is sampled, with each sampling unit including information on the presence or absence of a landslide. The resulting data layers are analyzed by either multiple regression or discriminate analysis (Turner and Schuster, 1996; Olmacher and Davis, 2003). Provided sufficient input variables, statistical models can successfully shape landslide hazards in a given area; however, its conclusions can rarely be applied to different places, or used to test simulation scenarios, which is the methods main drawback (Guzzetti et al., 1999).

Geomorphic

Geomorphic mapping is a direct, qualitative method that depends on the ability to estimate potential and actual slope failures (Guzzetti et al., 1999). This method is dependent on the physical relationships between landsliding and morphological elements (Huabin et al., 2005). The advantage of this method is its ability to be resized according to the most dominant slope failure type in an area. This allows for the subdivision of drainage areas to accommodate different scales of failure. A disadvantage of this approach, in GIS, is its heavy dependence on accurate slope information. This means that high-resolution digital elevation models (DEM’s) are needed for accurate predictions, which may not be available for all areas.

Heuristic

Heuristic mapping is based on knowledge of all instability factors present within a mapping area. It is an indirect and qualitative approach that is highly dependent on the investigators knowledge of instability factors within the mapping area (Guzzetti et al., 1999). In GIS, heuristic approaches are overlay functions that can be totally automated. The various factors are divided into a number of relative classes, then weighted and ranked according to their expected importance in causing slope failures within the mapping area. The advantage is that the degree of a hazard can be determined rapidly through automation if good geomorphologic data are available (Huabin et al., 2005). The major disadvantage of heuristic modeling is the complexity of operations involved in the weighting process, especially if it is automated. The subjectivity that arises in the weighting process hinders the extrapolative ability of a model developed for one particular area to be used effectively in another area (Huabin et al., 2005).

Physical Processes

Physical process approaches are based on basic physical principles that govern landsliding, such as the Mohr-Coulomb equation of slope failure initiation. An advantage is that findings can be applied to many different situations because the fundamental processes are the same that cause failure in one location as those that cause failures elsewhere (Guzzetti et al., 1999). Physical process models, however, usually require intensive parameterization. Many of the physical variables, such as hydraulic conductivity and soil pore pressure, which are necessary for running these models, are usually not available, and their acquisition is often costly.

This study uses a multivariate statistical approach in conjunction with a landslide inventory map. This method was chosen because it allows for several instability factors to be examined and the relationship between each factor and landslides to be assessed. The limited time and available data prevented the use of other landslide hazard mapping techniques.

2.7 Hazard and Vulnerability Assessments

Hazard assessments are a valuable tool for evaluating the affects of a hazard on an individual and/or group. They allow all sectors that could be involved in a disaster to be identified and evaluated. The Simeon Institute (1998) defines a hazard assessment as a process of estimating, for defined areas, the probabilities of occurrence of a potentially damaging phenomenon of given magnitudes within a specified period of time. Hazard assessments involve the analysis of historical records and skilled interpretation of existing topographic, geologic, geomorphologic, hydrologic, and land-use maps. These assessments are useful, but only identify areas in a community that are most susceptible to a hazard. They do not quantify the level of risk that a particular hazard imposes on infrastructure.

A Vulnerability Assessment (VA) goes beyond a hazard assessment to determine the vulnerability of infrastructure networks. The National Oceanic and Atmospheric Administration (NOAA) developed the working framework for implementing a VA. It is designed to help communities determine the vulnerability of people, property and the natural environment to hazards. The VA's include the risk/hazard information found in a hazard assessment, but also details potential populations at risk, number of structures that might be impacted, and lifelines, such as bridges and power lines that might be damaged (Hill and Cutter, 2001). The VA is a three-step process, with the first step identifying the hazards present in an area. This is followed by mapping the potential extent and magnitude of the hazard within an area. Thirdly, analysis of different components of a society is performed to assess the level of vulnerability to damage by an event. The analysis includes components such as critical facilities (hospitals), infrastructure (roads, power lines), societal (distribution of elderly), environmental (potential for pollution), and economic impacts. This step also includes the assignment of a vulnerability level to each component. The level of vulnerability is in the form of a numerical ranking usually with higher numerical values equating higher risk or vulnerability to damage.

The first step in reducing vulnerability is through the assimilation and distribution of knowledge (Tipple, 2005). The use of Geographic Information Systems (GIS) can be facilitated in the construction of the different components of VA's as it incorporates landscape characteristics such as topography, land use, vegetation, and geology as well as assessments of human systems such as population distribution, utilities (e.g. water, sewer pipes, and telecommunications), critical facilities (e.g. hospitals, emergency response centers) and access (roads, bridges, and tunnels) (Chin and Jacobson, 2003). The use of GIS allows for unique spatial integration and querying of the multiple "layers" of information available to the analyst (Chin and Rodgers, 2002). GIS also allows for this information to be easily presented in the form of maps that display the relevant information.

Chapter Three

Research Area

3.1 Dominica

The Commonwealth of Dominica (pronounced Dom-in-**eek**-a) is a small island nation in the Lesser Antilles situated between Martinique and Guadeloupe in the Eastern Caribbean (Figure 1.1). Dominica is 47km (29 miles) long, and 26km (16 miles) wide with an area of around 751 km^2 (290 mi^2). English is Dominica's offical language, but a French Patois is also spoken.

People

The majority of Dominicans are descendants of African slaves brought in by colonial planters in the 18th century. A small percentage of the total population is part of the local indigenous Kalinago, or commonly known as Carib, Indian population[2]. The presence of the Carib tribe on the island makes Dominica one of the only islands in the Caribbean to retain a pre-Columbian indigenous population (Honeychurch, 1995). The indigenous Carib Indians have their ancestral roots from the Orinoco Delta area of South America, from which the first inhabitants migrated to the island between A.D. 400 and A.D. 1000 (Quinlan, 2004). The majority of the population is located in villages along the coast of Dominica, as the rugged interior of the island

[2] Kalinago is the name that the indigenous people ascribe to themselves. The name Carib was given to them by Christopher Columbus when he first encountered them.

prevents large settlements. These villages are connected by a network of paved roads that run parallel to the coast with a few links crisscrossing the island.

History and Government

After Columbus' discovery of Dominica, Spanish ships frequented Dominica during the 16th century, but fierce resistance by the Caribs discouraged Spain's efforts to settle on the island. As part of the Treaty of Paris in 1763, which ended the Seven Years' War, Dominica became a British possession (Honeychurch, 1995). During the American Revolution in 1778, the French mounted a successful invasion with the help of the local population, but the island returned to British possession in 1783 (Honeychurch, 1995). The French attempted two more invasion attempts in 1795 and 1805, but both failed (Dominica.dm, 2006).

On November 3, 1978 Dominica became an independent country. The newly acquired independence did little to solve problems stemming from centuries of economic underdevelopment and oppression (Honeychurch, 1995). An interim government was established in mid-1979 and was replaced in 1980 after general elections. The Dominica Freedom Party under Prime Minister Eugenia Charles, the Caribbean's first female prime minister, led the newly developed government. Economic downfall was compounded by the severe impact of hurricanes David and Frederick in1979 and hurricane Allen in 1980 (Benson et al., 2001).

The end of the 1980s saw healthy economic recovery, which was short lived. The economy was weakened considerably in the 1990s by a decrease in banana prices, which is one of Dominica's primary economic sectors (Honeychurch, 1995; Benson et al., 2001).

Economy

The economy of Dominica is dominiated by agriculture with nearly one-third of the working force. The primary product is bananas, but this sector continues to be eroded by declining trade prefrence with the European Union. In response, the government has diversified the agricultural sector, with the export of small quantities of citrus fruits, exotic fruits such as guavas, mangoes, and papayas, vegetables, and fresh cut flowers. The agricultural sector is vulnerable to extreme weather phenomena and to external events affecting commodity prices.

Until recently tourism and Dominica were not synonymous. The relative isolation of the island, lack of numerous sandy beaches, and plentiful rain made Dominica unappealing to mass tourism. Ecotourism, the fastest growing sector of the global tourism market, has flourished on

Dominica accounting for nearly 18% of GDP in 2000. This tourism industry can be severely impacted by a natural disaster and/or its affects. Ecotourism vulnerability arises from its dependency on destination reputation and image. It is also a function on seasonality issues, global issues, and disaster recover and mitigation (Meheux and Parker, 2006). One example of tourism vulnerability is Montserrat after the Soufriere Hills Volcano eruption in 1995. The volcanic flows destroyed the capital city, vital sea ports, and the international airport. The majority of the infrastructure of the tourism industry was destroyed or made inaccessible resulting in a decrease of 85% in international tourism receipts (MVO, 2006).

Physical Environment

The Lesser Antillies are comprised of two arcs, the oldest comprised of heavily eroded islands. This erosion created shallow waters around which significant coral reefs could form (Honeychurch, 1995). The presence of reefs gives these older islands the white sandy beaches synonymous with the Caribbean. The younger arc, which includes Dominica, is rugged, volcanic, and geothermally active. This is evident on Dominica with its crater lakes, fumeroles, Boiling Lake, Champagne Beach, and Valley of Desolation (Honeychurch, 1995). The two highest peaks, Morne Diablotins and Morne Trois Pitons, both dormant volcanoes, rise to 4381 (1447m) and 4221 feet (1394m) above sea level.

The geology of Dominica includes deposits of andesite, dacite and basalts of Pleistocene age (Rouse et al., 1986). This is a result of the volcanic origin of the island that is due to the subduction of the Atlantic plate beneath the Caribbean plate (Honeychurch, 1995). As the remnants of the Atlantic plate dive deep into the warmer mantle, the material becomes buoyant which adds an upward force on the edge of the Caribbean plate creating weak spots through which molten rock is able to pass (Honeychurch, 1995). Most of the volcanic rocks occur as pyroclastics, including coarse agglomerates and breccias, tuffs, and fine ashes. Basalts are often seen as flows, especially in the north and central parts of the island.

Dominica's climate is tropical and marine, a result of the prevailing Northeast Trade winds. Precipitation occurs year round, but on average the wet season is from June to December, with July being the wettest month (Honeychurch, 1995). The steep terrain of Dominica disrupts the Northeast Trade winds by forcing the moist air up over the high peaks of the island resulting in significant precipitation. As the air descends on the leeward side, moisture has been removed from the air, and the western side of the island is relatively dry as a result of the rainshadow effect (Honeychurch, 1995). Average precipitation on the windward side is between 254-386 cm (100-152 inches), the interior highlands routinely exceed 762 cm (300 inches), and the leeward side gets around 127 cm (50 inches) (Honeychurch, 1995; Quinlan, 2004). As a result of such significant rainfall, hundreds of small streams and rivers flow through the deep narrow valleys of Dominica. The coolest month on average is January with temperatures between 20º-29º C (68º-84º F), and the warmest being June with temperatures between 23º-32º C (73º-90º F) (Honeychurch, 1995). A significant threat of tropical disturbances, storms, and hurricanes occurs between June and November.

Dominica is susceptible to a variety of natural hazards that include volcanic and seismic activity and tropical disturbances. The most common and historically significant are hurricanes and tropical storms. Between 1979 and 1999 Dominica experienced ten tropical disturbances, seven hurricanes and three tropical depressions (Benson et al., 2001). The most significant was a direct hit by Category 4 Hurricane David in 1979. Packing 240 kph (150 mph) winds , David caused massive devastation, including the loss of thirty-seven lives, 5000 people injured, and three quarters of the population left homeless (Honeychurch, 1995). There have only been two previous hurricanes of a magnitude similar to David to strike the island, one in 1806 in which 131 people perished, and in 1834 in which over 200 lives were lost (Honeychurch, 1995).

3.2 Dominica Landslides

Dominica's steep topography, volcanic parent material, and high annual precipitation are conductive of landslide development. Volcanic bedrock in tropical climates is susceptible to deep weathering and mass wasting (Prior and Ho, 1972; Hartford and Mehigan, 1984; Rouse, et al. 1986; DeGraff, 1991; Larson and Torres-Sánchez, 1997). Weathered volcanic soil is weaker than the original bedrock and the high precipitation on the island increases pore-water pressure within discontinuities decreasing soil shear strength. The loss of shear strength generates zones of failure in which the mass destabilizes in the form of a landslide or debris flow (Faugeres, 1966; Walsh, 1982; DeGraff, 1991). DeGraff (1987a) estimates nearly two percent (15 km^2/ 5.8 mi^2) of the land surface on Dominica has been disturbed by debris flows.

Significant damage to infrastructure on Dominica results from the flows. The most common is damaged or destroyed buildings, roads, and utilities. Human fatalities do occur, but are not common. The community of Bagatelle suffered eleven fatalities in 1977 when a landslide inundated four homes. The total number of deaths as a result of landslides is not available for Dominica.

Damage is enhanced in part by the steep terrain of Dominica. The steepness limits viable routes throughout the island, leading to the development of roads on unstable and unfavorable slopes (Anderson and Kneale, 1985). Blockage of transportation networks severely hampers transportation in Dominica, as few alternative routes exist. This is significant in the event of a major disaster, in which emergency relief would be delayed. Other vital infrastructure, such as electricity, telecommunications, and water, are in close proximity to the road network (Benson et al., 2001). Loss of this infrastructure not only compounds the immediate affects of a disaster, but also exerts tremendous financial pressure on repairing and maintaining them. Between 1983 and 1987 Dominica spent and estimated at 497,000 EC$[3] on road clearing and repairs resulting from landslides. Damage and repairs after these major tropical storms since 1979 has cost an estimated 380 million EC$ (Benson et al., 2001) (See Table 3.1).

Temporary or permanent damming of rivers is also a consequence of landsliding on Dominica. The most recent and significant event occurred on November 18th, 1997. A large debris flow from an unstable valley wall within the Matthieu River Valley passed down the gorge and into the Layou river channel forming the dam (CDMP, 1999). The dam was approximately 15 meters (50 feet) high at its highest point and formed a solid plug in the river. The following morning the landslide dam breached, with an estimated 1.1 million m^3 (300 million gallons) of water released (CDMP, 1999; DeGraff and Rogers, 2003). The following week another series of landslides occurred in the same area as well as blocking the Matthieu River, which flows into the Layou River. Water overtopped the dam on the Layou River, with the dam on the Matthieu River still remaining. Though landsliding is frequent on the island, this incidence is the only known landslide dam to occur on the island in recent times (DeGraff et al., 1989; DeGraff and Rogers, 2003).

The Caribbean Disaster Mitigation Project (CDMP) assisted the Dominican government in analyzing landslide dam. In early 1998, it was found that the dam had stabilized and the water stored behind the dam was seeping into the ground without any noticeable affects (CDMP, 1999). It should be noted however, that the dam still poses a significant threat to those

[3] The Eastern Caribbean dollar (EC$) exchange rate is: $1US = 2.7EC$

Table 3.1
Hurricane Damage and Rehabilitation Costs to Infrastructure and Buildings (Benson, 2001).
(EC$ Constant 1999 Prices)

	Buildings	**Utilities/Infrastructure**	**Total Cost**
Hurricane David, 1979/80	136.8	72	208.8
Hurricane Hugo, 1989	6.7	20.1	26.8
3 Storms, 1995	13.5	40.9	54.4
Hurricane Lenny, 1999			
a. Excluding full upgrading	11.6	76.2	87.8
b. Including full upgrading	11.6	(130.7)[a]	(142.3)[a]
Total: 1979-99	170	210	380
	(347)[b]	(522.3)[b]	

Notes: The estimates of damage and rehabilitiona costs were converted to 1999 constant prices using the 1990 GDP deflator. Buildings include housing, public and private offices and housing, schools, and hospitals. Utilities and infrastructure include roads, sea defenses, electricity, water, sewage, telecommunications, ports, and airports.

a. Excludes full reconstruction costs of roads including upgrading sea defenses
b. Includes full cost of upgrading sea defenses

downstream. Landslide dams elsewhere have appeared stable, but failed with catastrophic results after significant influxes of water in the impoundment (Costa and Shuster, 1988). The seasonal passages of tropical disturbances have a high potential to bring significant precipitation and large influxes of water behind the Matthieu Dam that could result in failure (DeGraff and Rogers, 2003).

Hartford and Mehigan (1984) first documented landslides on Dominica. They performed lab tests on the residual soils and found that the high plasticity of the soil and angle of internal of friction were conducive to failures when saturated. They also found that failures tended to occur on slopes greater than 31 degrees (Hartford and Mehigan, 1984). Walsh (1985), examining landslides following Hurricanes David and Frederic in 1979, documented that a majority of the landslides involved failures at depths of approximately two meters, while Prior and Ho (1972) found that greater occurrences of landslides on nearby St. Lucia occur on slopes greater than 35 degrees. Jerry DeGraff performed the most in-depth study on Dominica in 1987.

DeGraff (1987a) inventoried 980 identifiable landslides compiled from air-photo interpretation and ground verification. DeGraff (1987a) calculated a landslide density of 1.3 landslides per square kilometer (3.4 per sq mi), with nearly two percent of the island being affected by a landslide. A heuristic mapping approach was used to account for instability factors on the island. The landslide hazard map is based on geomorphic, geologic and topographic factors represented by slope, preexisting landslides, and geology (DeGraff, 1987a). From the input layers, heuristic determination of individual bedrock-slope relational units was developed. Finally, the total area of landslides within each bedrock-slope unit was calculated and divided by the total area of the bedrock-slope unit. This calculation gives a proportion of each bedrock-slope unit subject to landslide disturbance. DeGraff (1987a) found the proportions on Dominica to range between 0.01-0.11. He the divided those proportions into four (4) categories. Bedrock-slope units with no landslides present were marked as low hazard areas. Proportions between 0.01-0.03 constituted moderate hazard areas; 0.04-0.07 constituted high hazard areas; 0.08-0.11 constituted areas of extreme hazard (See Figure 3.1).

In 1990, DeGraff revisited the 1987 study with a post-1987 landslide assessment. The 1990(a) paper examined post-1987 landslides to find if his initial landslide hazard zonation (See DeGraff 1987a) accurately coincided with the recent landslides. One hundred and fifty-two new landslides were identified, with slide occurring on slopes of greater than 10 degrees and less than

70 degrees. Along with new landslide identification, DeGraff (1990a) utilized Lang's (1967) soil map (See Figure 3.2) and Earth Satellite Corporations (1986) vegetation classification, to perform an initial assessment of the influence of these two factors on slope stability. The final analysis only postulates on the influence each of these factors and makes no recommendations or conclusions about soil and vegetation. It did mention however, that soils appear to be influenced to slide by hydrological more so than mechanical mechanisms (DeGraff, 1990a). This was the case of similar soils types under different vegetation types. The best example of this is the occurrence of landslides on similar soils, but on different vegetation such as managed vegetation, i.e. tree crops, versus montane rainforest (DeGraff, 1990a). DeGraff concludes that soils in managed vegetation have more infiltration of precipitation resulting in greater occurrences of slides.

Few other studies have been performed since the two by DeGraff (1987a, 1990a), with those that have focusing on small, isolated slides or the financial impacts of all natural hazards on Dominica (DeGraff, 1987b, 1989, 1990b, 1991; CDMP, 1999; Benson et al., 2001; CDERA, 2003; DeGraff and Rogers, 2003).

Figure 3.1
DeGraff (1987a) landslide inventory and hazard zonation map.

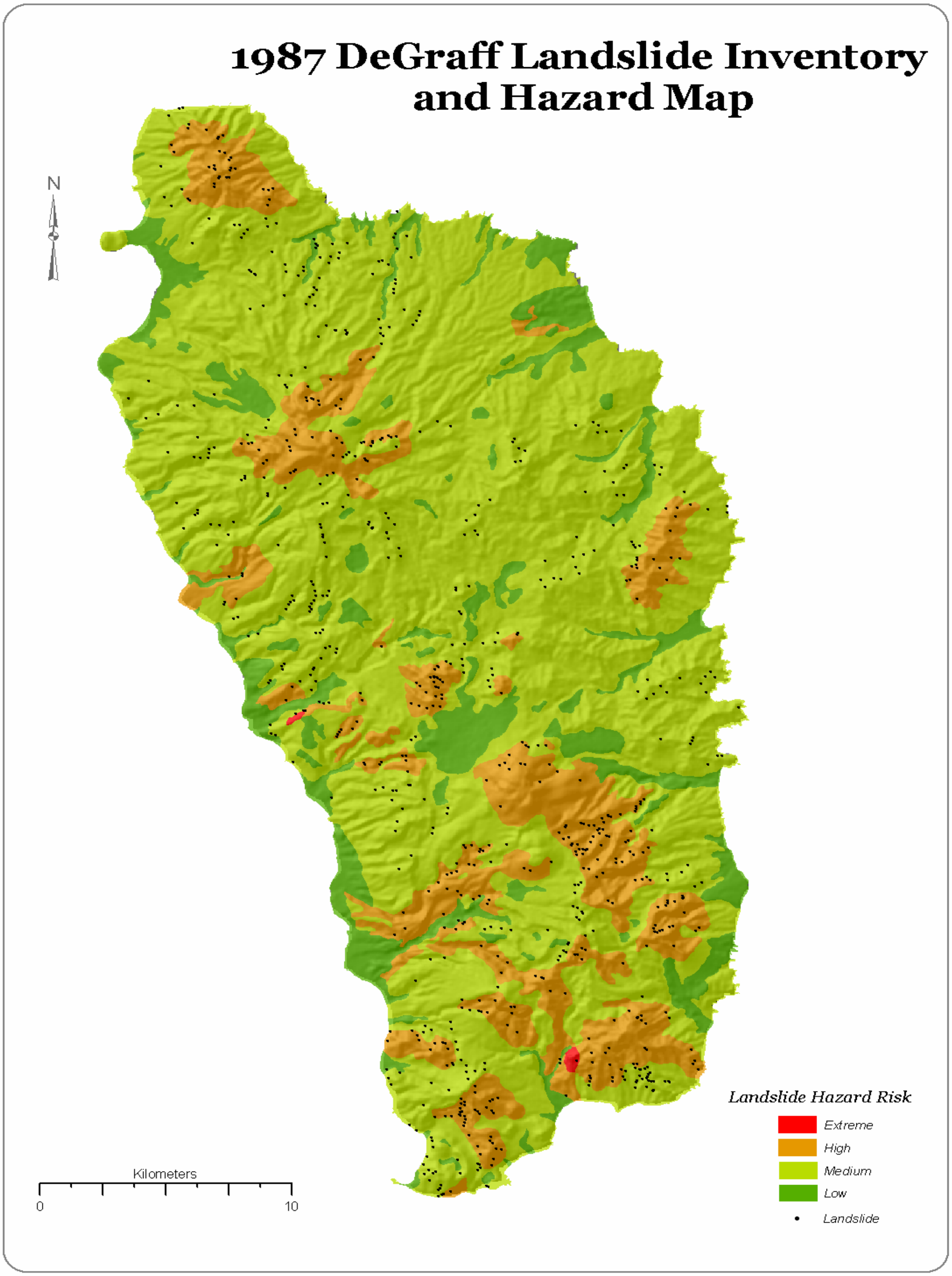
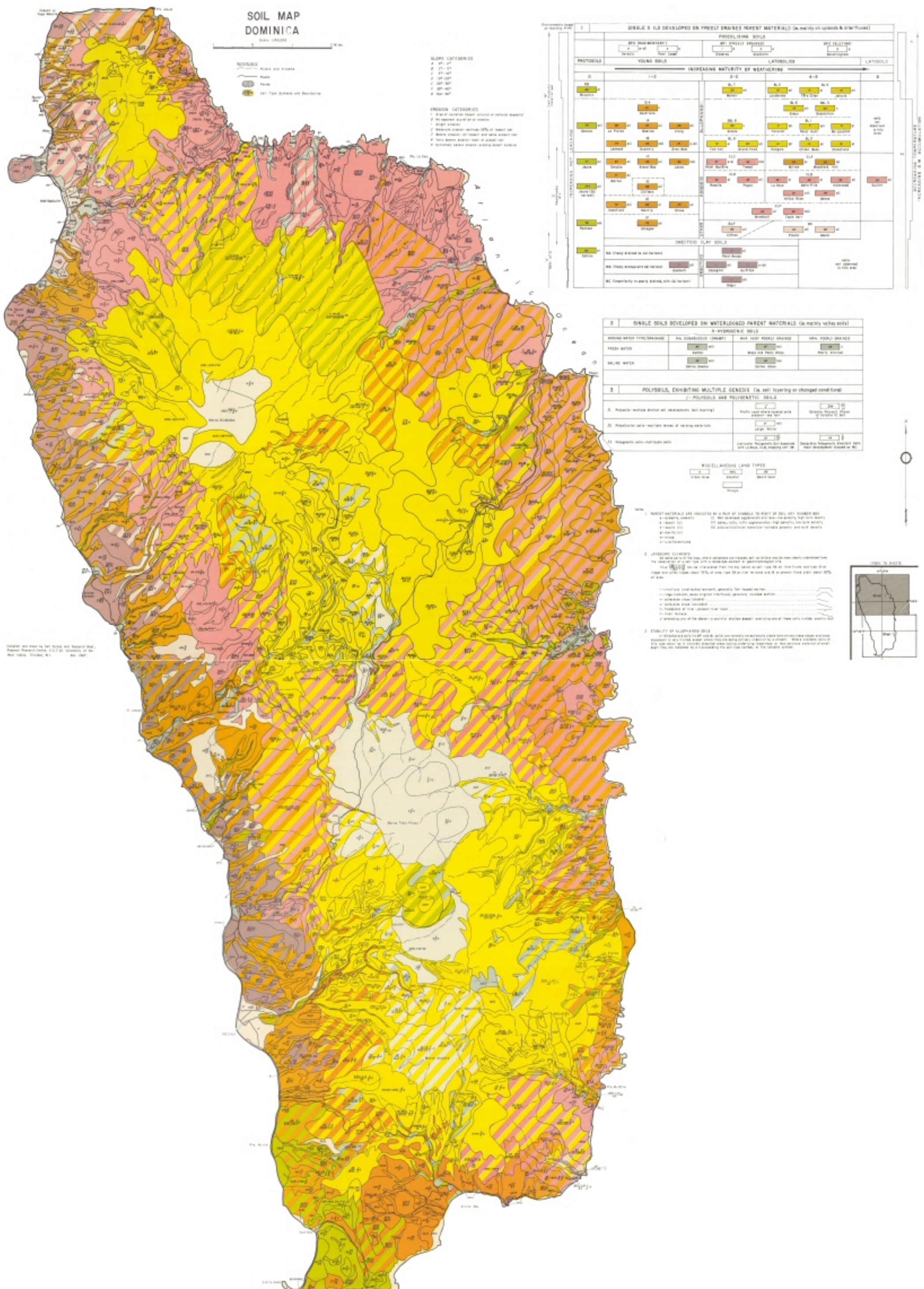


Figure 3.2
Dominica soils by Lang (1967)



Chapter Four

Data and Methods

4.1 Research Area

The research area on Dominica is a 25-km^2 area on the southeast coast of the island (See Figure 1.2). The research area contains the main villages of Grand Fond, Petite Soufriere, and Morne Jaune. This research area was chosen because of its proximity to 3Rivers ecolodge, which provided room and board for thesis research at a discounted rate by owner Jem Winston. The research area is a mix of forest and agricultural plots comprised mostly of bananas and dasheen. This is typical for most of Dominica except near the larger cities of Roseau and Portsmouth. The study area is rugged with elevation at sea level along the eastern coast of the image to 673 meters (2200 feet) in the southeast portion of the research area. Rainfall is significant in this area, which is similar to the interior and east sides of the island.

4.2 Data

The initial step in this thesis involved obtaining and assessing necessary data for the project. In March of 2006, a reconnaissance trip was conducted on Dominica to evaluate the extent and availability of data and project feasibility. Key data for the project include a reliable digital elevation model (DEM) and slope instability indicators such as soil and land use. Contacts were established in governmental and local agencies that were eager to exchange data (See Table 4.1).

Various data layers are used in this project; they include a Quickbird image of the research area with 60cm pixel resolution, a resampled 90m SRTM, a land cover/land-

Table 4.1
Dominica Research Area Original Data Inputs

Classification	Sub-Classification	GIS data type	Scale
Geological Hazard	Landslide	Point/Polygon Shapefile	1:1,500
Basic Map	Satellite Image	GRID	60cm x 60cm
	Digital Elevation Model	GRID	50m x 50m
	LCLU	GRID	30m x 30m
	Soil Type	Polygon Coverage	1:40,000

use raster with 30m pixel resolution, and a 1:40,000 soils map. GIS layers obtained from the government of Dominica included roads, electrical generation facilities, power transmission lines, soils, catchments, rivers and streams, village census data, and precipitation data.

The infrastructural component layers, roads, power lines, and electrical generation facilities were not used because of inaccuracies in the data or lack of coverage in the research area. No information was available on when, where, or by whom the digital coverage's were made, so locating the original base maps was not possible. The roads layer had multiple discontinuities and did not match up with the Quickbird image. The power line coverage only included main transmission lines, many of which were shown to be located in the Atlantic Ocean, which is not the case. Electrical generation facilities do not exist in the research area and the layer was not used.

The catchments, rivers and streams, and precipitation data were also not used. The catchments data were examined and it was found that the catchments did not accurately portray the drainage in the area. Several catchment divides were found to pass through the middle of valleys. Similar to the road coverage, the rivers and streams coverage had several discontinuities and no attribution as to the type, length, or name. The precipitation data consisted of 18 collection locations around the island. The data points were interpolated and it was found that the rainfall amounts for the research area were not significantly different, therefore it was not used.

The QuickBird image was obtained from DigitalGlobe (www.digitalglobe.com). The image is a georeferenced natural color image for January, 2005. The image is georeferenced and pan-sharpened to UTM Zone20. Aerial photographs could not be obtained for the research area; therefore, the high spatial resolution of the QuickBird image was desirable, as it offered similar resolution to that of aerial photographs.

The DEM was obtained from Ian Stewart of Stewart Geophysical Consultants Pty. Ltd. based in College Park South Australia. The DEM was created from Shuttle Radar Topography Mission (SRTM) data. This data, a three second geographic grid with an approximate pixel size of 90m available from NASA, was converted to UTM coordinates and resampled to 50m using cubic convolution by Ian Stewart. Accuracy is usually good in flat areas without vegetation, but over hilly regions such as Dominica, the original pixel size of 90 meters means that each pixel may represent a large range of actual elevations locally. Even so, the detail is much better than anything else available.

The land cover/land use raster was developed by the USGS EROS Data Center in 2005, as part of a joint project between the International Institute of Tropical Forestry, USDA, USFS, TNC, NASA, and CSU-CEMML. USAID-Caribbean Program Office, NASA GOFC program, with the collaboration of the Forestry, Wildlife and Parks Division, and the Lands & Surveys Division, Commonwealth of Dominica, and the Rare Species Conservatory Foundation. Landsat imagery for the classification was provided by NASA-GOFC and the USGS-Center for EROS (Coan et al., 2006). The raster has a pixel resolution of 30 meters and the classification of land cover was conducted in 2001 with the help of local individuals and the government. There are 14 land cover/land use classifications in the dataset.

The digital soils data layer was obtained from the Planning Division of the government of Dominica. The original version from which the digital version was constructed was a published 1:40,000 map by Lang (1967) (See Figure 3.2).

Field Mapping

Field mapping of the research area took place in June and July of 2006. The research area was hiked on foot and landslides catalogued using a notebook and GPS unit. Whenever possible, the incorporation of knowledge from local individuals was utilized to help identify areas of past sliding. The scarp of the landslide is key in distinguishing the presence or absence of a landslide. A basic physical description of each slide, photograph, and slope steepness was all cataloged. Slope was measured using a Brunton compass with a slope indicator and measured to the nearest degree. Due to the rugged terrain, most landslides identified were within short distance from a road.

Digitization

Accurate detection of landslide presence is highly desirable for use in statistical probabilistic hazard analysis (Lee, 2005). After completion of the field mapping, data analysis using GIS began. The January 2005 image is the best cloud free image closest to a major sliding event in the research area. It is desirable to locate an image with an acquisition date as soon as possible following a significant sliding event so as to sample an atypical event. Through personal correspondence with local residents, I learned that a large number of slides occurred on November 21st, 2004 as a result of several days of intense precipitation followed closely by a magnitude 6.3 earthquake.

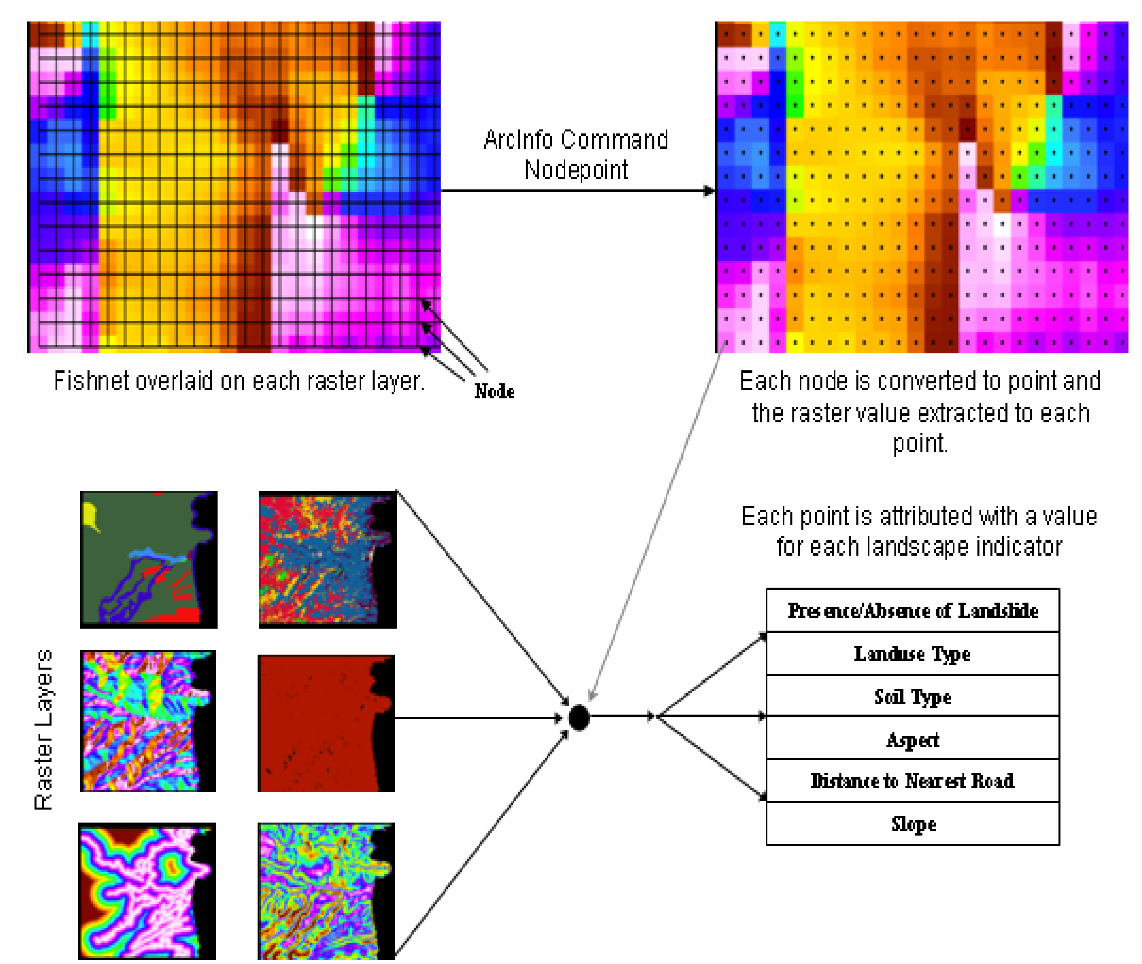
Landslides were identified and digitized at 1:1500 scale. Recent landslides were observed in the image by recent breaks in the forest canopy, identifiable head scarps, flow tracks, and road repairs. Landslides were first digitized as points so that verification of landslides could be performed. This verification was done using ESRI ArcScene, which allows for images to be draped over a digital elevation model. When draped, the image appears in 3-D and allows for visual verification of landslides based on the virtual topography. After this was completed, aerial extent of landslides was digitized as polygons.

Digitization of all visible infrastructure was done at 1:1500. This is comprised of residential and non-residential buildings and linear road features. Residential and non-residential features were digitized as points, though no differentiation between residential and non-residential buildings was made. Linear features were digitized as lines, with each feature being attributed with a road type; paved road, unpaved road, or footpath.

Landslide Characteristics

Raster transformation was performed in ArcGIS 9.1 using Spatial Analysis. Each data layer used in the study was converted to raster, if not already a raster, and resampled to a cell size of 20.164 meters. This smaller cell size was chosen to ensure an adequate sample size. The DEM was resampled using cubic convolution from which slope steepness and hill slope aspect were calculated using Spatial Analysis. The land cover/land use raster was resampled using nearest neighbor, and the landslide raster was reclassified so that landslide presence equaled 1 and the absence of a landslide resulted in a 0. For the statistical analysis, a cell-by-cell breakdown of each raster was performed in a procedure I call “raster coring.” Using ArcInfo, a fishnet was generated to create a 20.164 m grid on top of the existing raster data. It is assumed that the center of each cell represents the value within each cell of the raster. Based on this assumption, the fishnet grid is offset so that each intersection, or node, of the fishnet occurs in the center of each raster cell. The fishnet intersection points, or nodes, are converted to points resulting in a centroid for each grid cell. Each raster layer value is extracted to the centroid and input into a database for use in a statistical package. The Dominica research area contains 55,268 cells, each with a variable indicating the presence or absence of a landslide, a landcover type, a value for slope steepness and aspect, a soil type, and distance to the nearest road (See Figure 4.1).

Figure 4.1
"Raster Core" procedure for attribution of each cell with the various landscape indicators.



Statistics

Logistic multiple regression was used to develop the landslide hazard map for the research area. Similar landslide studies utilize this method to develop hazard maps on varying terrain (See Carrara et al., 1999, Olmacher and Davis, 2003, Lee, 2005, Gorsevski et al., 2006). The goal of logistic regression is to find the best model to describe the relationship between a dependent variable and multiple independent variables to be identified (Olmacher and Davis, 2003; Lee, 2005). Logistic regression proceeds by discovering the estimates that maximize the resulting likelihood function for a set of observations (Olmacher and Davis, 2003). It forms a multivariate regression relationship between a dependent variable and several independent variables (Lee, 2005). Logistic regression generates the coefficients of a formula to predict a logit transformation of the probability of the presence of the dependent variable which in the present study is the presence or absence of a landslide. Five independent variables are used; slope (continuous), distance to nearest road (continuous), aspect (categorical), landcover (categorical), and soil type (categorical). The dependent variable, the presence or absence of a landslide, can be represented as a binary value where 1 is the presence of and 0 is the absence of a landslide (Olmacher and Davis, 2003; Lee, 2005). Quantitatively this means that the relationship between the dependency on several variables and the occurrence of a landslide can be expressed as:

$$P = 1 / (1 + e^{-z}) \qquad \textbf{(1)}$$

where P is the maximum probability of a landslide, or portion of a landslide, occurring in a given cell (Lee, 2005). The probability will vary from 0 to 1, and z is the linear combination that follows the fitting of the logistic regression equation (Lee, 2005). Therefore:

$$z = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n \qquad \textbf{(2)}$$

where b_0 is the intercept of the model, the b_i (i = 0, 1, 2, …, n) are the slope coefficients of the logistic regression model, and the x_i (i = 0, 1, 2, …, n) are the independent variables predicting the occurrence of landslides (Lee, 2005).

Chapter Five

Results

Digitization resulted in 903 visible buildings, 55 linear kilometers of road features, and 246 landslides. Table 5.1 shows all landscape indicators used in the study and include indicator area, percentage of total area, frequency of landslides, and percent of total landslides within each indicator. Figure 5.1 shows the percentage of area for each indicator variable and the percentage of total landslides within each indicator variable.

5.1 Landscape Indicators

Landslides

246 landslides were identified with a total area calculated to be 26.1 hectares, or 1.2 % of total land area (2248 ha). The largest landslide is 1.6 hectares, the smallest is 0.0069 hectares, and the average is 0.11 hectares, with landslide density being 10.9 $^{LS}/_{km2}$. Figure 5.2 is the resulting landslide inventory for the research area.

Soils

The research area contains seven soil types. The largest soil type is Latosolics with 79% (1783 ha) of the total research area and contains 72% (177) of the landslides present in the research area. Skeletal and Young soils contain 16% (369 ha) of the total area but 27% (86) of total landslides. No landslides are present within the Hydrogenics, Protosols, or Soufriere, which occupy 2.4% (54 ha) of the total area.

Table 5.1
Landscape indicators for the research area.

Soils

Soil ID	Soil Type	Area (ha)	% Area	LS Frequency	% Landslide
1	Latosolics	1783	79.3%	177	72.0%
3	Skeletal	227	10.1%	41	16.7%
4	Young Soils	142	6.3%	25	10.2%
5	Allophanoid Podzolics	43	1.9%	3	1.2%
7	Hydrogenics	46	2.0%	0	0.0%
8	Protosols	6	0.3%	0	0.0%
9	Soufriere	2	0.1%	0	0.0%
	Totals:	2248	100.0%	246	100.0%

Land Cover/Land Use

LCLU ID	LCLU Name	Area (ha)	%Area	LS Frequency	% Landslide
4	Submontane Rainforest	673	29.9%	74	30.1%
5	Disturbed Submontane Rainforest	81	3.6%	4	1.6%
6	Lowland/Submontane Seasonal Evergreen Forest	246	10.9%	45	18.3%
8	Lowland Drought Deciduous Shrub	172	7.7%	24	9.8%
10	Active Agriculture	1044	46.5%	93	37.8%
11	Urban/Residential/Bare Soil/Rock	13	0.6%	2	0.8%
12	Grassland	19	0.8%	8	3.3%
	Totals	2248	100.0%	246	100.0%

Slope Steepness

Slope ID	Slope (Degrees)	Area (ha)	% Area	LS Frequency	% Landslide
1	<10	490	21.8%	41	16.7%
2	10 - 12	165	7.3%	15	6.1%
3	12 - 14	163	7.3%	13	5.3%
4	14 - 16	166	7.4%	17	6.9%
5	16 - 18	167	7.4%	19	7.7%
6	18 - 20	168	7.5%	27	11.0%
7	20 - 22	156	7.0%	22	8.9%
8	22 - 24	145	6.5%	18	7.3%
9	24 - 26	129	5.7%	13	5.3%
10	26 - 28	118	5.2%	21	8.5%
11	28 - 30	99	4.4%	11	4.5%
12	>30	281	12.5%	29	11.8%
	Totals	2248	100.0%	246	100.0%

Aspect

AspectID	Aspect Category	Area (ha)	% Area	LS Frequency	% Landslide
1	N	386	17.2%	26	10.6%
2	NE	324	14.4%	34	13.8%
3	E	367	16.3%	69	28.0%
4	SE	466	20.7%	69	28.0%
5	S	283	12.6%	25	10.2%
6	SW	122	5.4%	13	5.3%
7	W	108	4.8%	1	0.4%
8	NW	192	8.5%	9	3.7%
	Totals	2248	100.0%	246	100.0%

Distance To Nearest Road

Dist2Rd ID	Dist2Rd	Area (ha)	% Area	LS Frequency	% Landslide
1	<10	109	4.8%	26	10.6%
2	10 - 50	364	16.2%	62	25.2%
3	50 - 100	327	14.5%	40	16.3%
4	100 - 150	222	9.9%	29	11.8%
5	>150	1226	54.5%	89	36.2%
	Totals	2248	100.0%	246	100.0%

Figure 5.1

The percentage of total area of each landscape indicator and the percentage of total landslides found within each indicator variable. Refer to Table 5.1 for ID values.

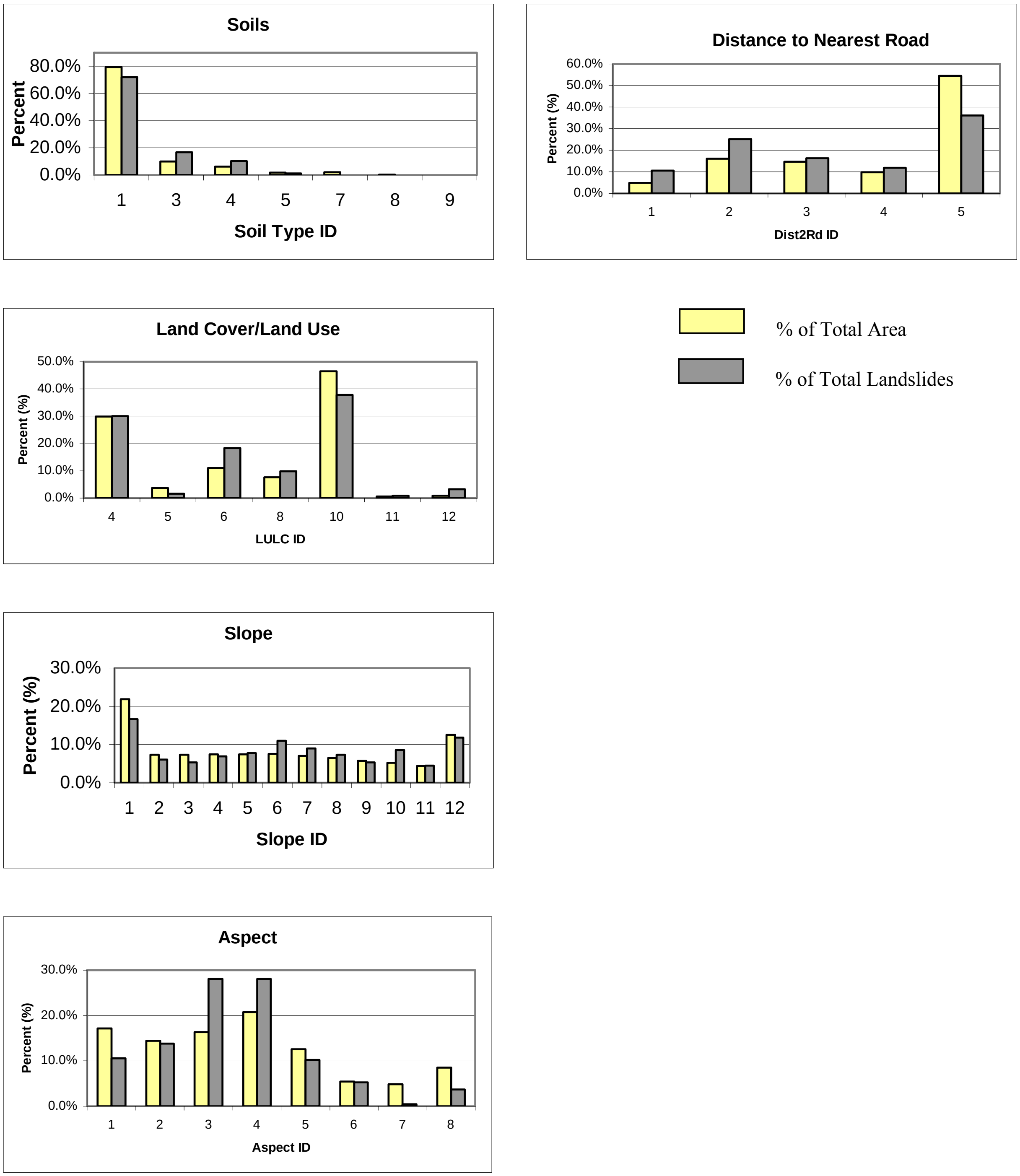
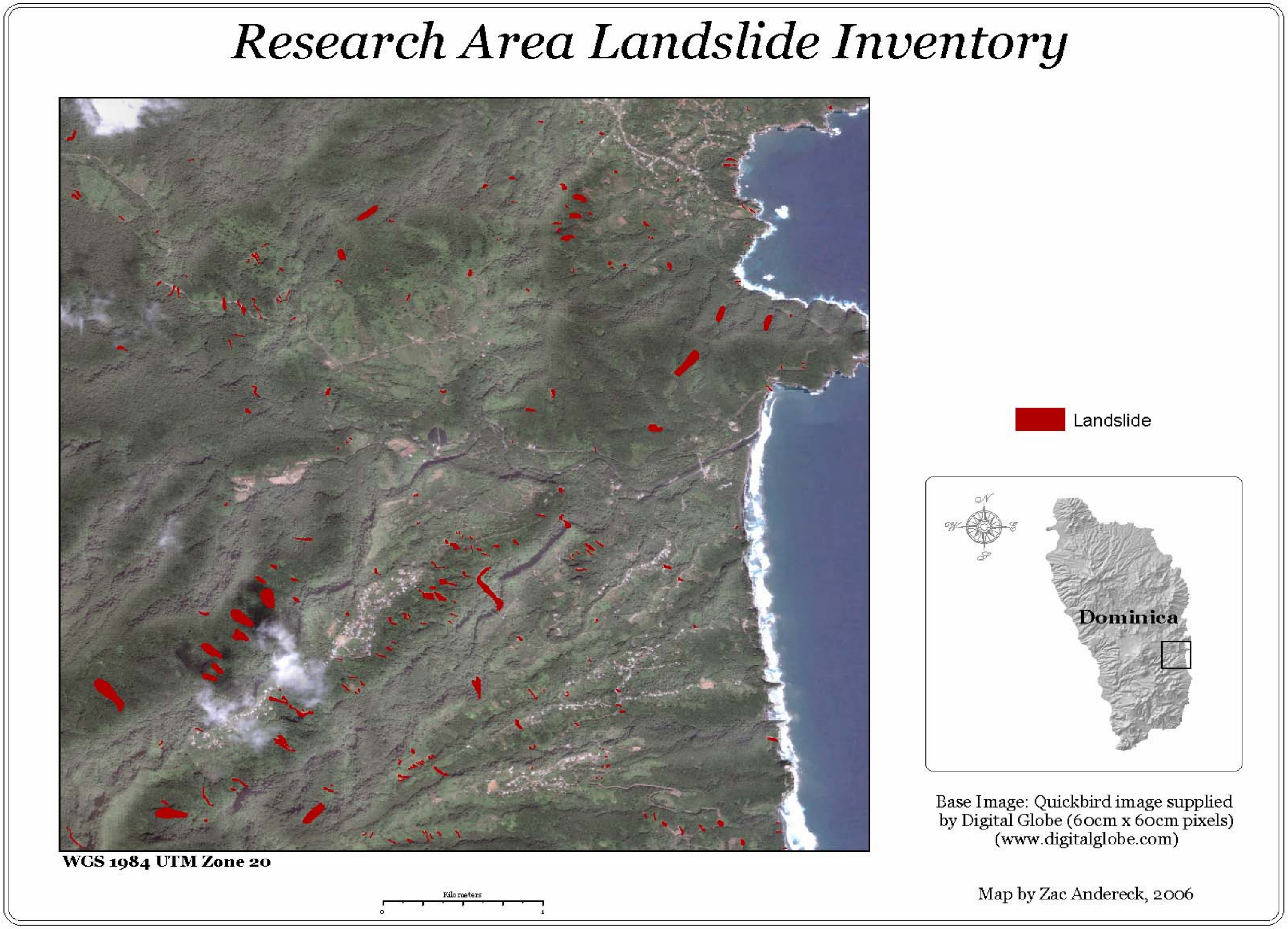


Figure 5.2
Landslide inventory map of the Dominica research area.



Land Cover/Land Use

The research area contains seven Land Cover/Land Use (LCLU) classifications. The largest classification is active agriculture with 47% (1044 ha) of the total area. Thirty-eight percent (94) of landslides fall within this classification. Active agriculture is followed by submontane rainforest with 30% (673 ha) of the total area and 30.1% (74) of landslides. Lowland/submontane seasonal evergreen forest occupies 10.9% (246 ha) of the total area and contains 18.3% (45) of total landslides. Grasslands only occupy 0.8% (19 ha) of the total area and contain 3.3% (8) of total landslides. Urban/residential/bare soil/rock occupies the smallest percentage of the research area (0.6%, 13 ha) and the fewest landslides with two.

Slope Steepness

In the logistic regression equation, slope steepness is used as a continuous variable. For Table 5.1 it is categorized into twelve categories. The highest recorded slope in the research area is 73.83 degrees and the lowest recorded slope is 0.05 degrees. Slopes of less than 10 degrees make up 21% (490 ha) of the research area and contain 17 % (41) of landslides. Slopes greater than 30 degrees comprise 13 % (281 ha) of the research area and contain 12% (29) of all landslides. In the increments between 16 and 24 degrees, landslide distribution is slightly higher than increments above and below. The range occupies 28.4% (635 ha) of the total area and 35% (86) of landslides in the research area.

Slope Aspect

Slope aspect is classified into eight categories, with each category being 45 degrees. Slopes facing southeasterly directions make up the largest portion of the research area with 21% (466 ha) of the total area, followed closely by north and east facing slopes. East and southeast facing slopes contain the largest number of landslides with each containing 28% (69) of the total. Westerly facing slopes (SW, W, NW) make up the smallest proportion of the research area with 18.7% (422 ha) of the total area and 9.4% (23) of total landslides. West facing slopes are the smallest with 4.8% of the total area and one landslide.

Distance to Nearest Road

Distance to nearest road (D2NR) like slope steepness, is used in the logistics regression equation as a continuous variable. For Table 5.1 it is categorized into five categories. The majority of the research area is at least 150 meters from a road or path, with the furthest distance from a road or path being 1313 meters. The area greater than 150 meters from the road contains

55% (1226 ha) of the total area and 36% (89) of total mapped landslides. The greatest occurrence of landslides, in terms of landslides per percentage of area, occurs within 10 meters of the road or path. This category comprise 4.8% (109 ha) of the total area and 10.6% (26) of total landslides. This is followed by the 10-50m category which contained 25.2% (62) of the total landslides, but only 16.2% (364 ha) of the total area.

Regression Results

Using the logistic regression model, the spatial relationship between landslide occurrence and potential factors that influence landslides was assessed using SAS statistical software. The software generates a logistic regression formula and calculates the probability of landslide occurrence within each cell. The parameters of the fitted model are shown in Table 4.2. The resulting logistic regression formula for the research area is:

$$P\text{ (landslide)} = \frac{1}{1+\exp[-(-6.2432+(0.064724*SLOPE)+(0.001266*D2R)+VEG+SOIL+ASPECT)]} \quad \textbf{(3)}$$

where SLOPE is the slope value; D2R is the distance to nearest road value; VEG, SOIL, and ASPECT are the logistic regression coefficient values listed in Table 5.2.

The resulting probability of landslide occurrence was input into ArcMap to create a landslide hazard map. The output was categorized into four qualitative categories for simplification; low, medium, high, and extreme hazard (See Figure 5.4). Structural and road vulnerability were assigned a vulnerability value from the hazard map (See Figures 5.6, 5.7, 5.8, 5.9). Maps constructed to show one standard error above and below the probability did not show any significant difference and are not included.

5.2 Research Area Landslide Hazard and Vulnerability

Relative Landslide Hazard

Figure 5.3 is the resulting map of the relative landslide hazard generated by mapping the probabilities calculated from the output of the logistic regression equation. The grid from which this map was constructed contains the probability that each cell contains a landslide, given the combination of slope, aspect, soil type, distance to nearest road, and land cover/land use within each cell. The highest probability of a landslide occurring within any given cell is 26.17 %, the

Table 5.2

Coefficient values for all indicators from the multiple logistic regression equation.

Parameter	DF	Estimate	Standard Error	Chi - Square	Pr > ChiSq	Sig
Intercept**	**1**	**-6.2432**	**0.1985**	**988.91**	**<0.0001**	**
Slope**	**1**	**0.0647**	**0.00452**	**205.21**	**<0.0001**	**
Distance to Nearest Road**	**1**	**-0.0013**	**0.00021**	**38.054**	**<0.0001**	**
Soils						
Skeletal**	**1**	**0.3537**	**0.1141**	**9.6118**	**0.0019**	**
Allophanoid Podzolics	1	0.2109	0.4197	0.2525	0.6153	
Young Soils	1	-0.0558	0.161	0.1201	0.7289	
Hydrogenics	1	-12.9596	265.5	0.0024	0.9611	
Protosols	1	-12.3964	754	0.0003	0.9869	
Soufriere	1	-12.7657	1489.7	0.0001	0.9932	
Land Cover/Land Use						
Lowland/Submontane Seasonal Evergreen Forest**	**1**	**0.7084**	**0.1096**	**41.771**	**<0.0001**	**
Disturbed Submontane Rain Forest**	**1**	**-0.6297**	**0.3136**	**4.0336**	**0.0446**	**
Active Agriculture**	**1**	**-0.2124**	**0.1125**	**3.5628**	**0.0591**	**
Lowland Drought Deciduous Shrub	1	-0.1833	0.1584	1.3393	0.2472	
Grassland	1	0.2891	0.3733	0.5998	0.4387	
Urban/Residential/Bair Soil/Rock	1	-13.3249	484.4	0.0008	0.9781	
Aspect						
SE**	**1**	**1.1565**	**0.1541**	**56.309**	**<0.0001**	**
E**	**1**	**1.04**	**0.1629**	**40.762**	**<0.0001**	**
NE**	**1**	**0.7706**	**0.1821**	**17.909**	**<0.0001**	**
SW**	**1**	**0.5273**	**0.2342**	**5.0701**	**0.0243**	**
S**	**1**	**0.4282**	**0.1906**	**5.0455**	**0.0247**	**
W**	**1**	**-1.284**	**0.4046**	**10.069**	**0.0015**	**
NW	1	0.2665	0.1969	1.8323	0.1759	

Statistical significance is indicated by **bold** and **. These parameters are used in the final logistic regression equation (**Eq.3**) lowest is 0.000004%, and the average is 1.21%. Figure 5.4 classifies the probability of failure into four categories; Low (0 – 0.5%), Medium (0.5 – 2%), High (2 – 5%), and Greatest (> 5%). probability map (See Figure 5.4**)**, Medium landslide probability occupies the greatest area with 55% (1243 ha) of the total area (See Table 5.3). Low landslide probability occupies 31 % (692 ha) of the total area, while High landslide probability occupies 13.5% (303 ha) of the area. Greatest probability is the smallest, with only a half of a percent of the total research area.

Linear Road Feature Vulnerability

Fifty-five kilometers of roads and footpaths crisscross the research area (See Table 5.3). Paved roads cover 14.1 kilometers and unpaved roads accounts for 21.4 kilometers. Footpaths traverse approximately 20 kilometers throughout the research area (See Table 5.3). Footpaths and unpaved roads account for 75% of total linear distance, with 41.2 kilometers.

Vulnerability to landsliding for the total length of all linear features was found by extracting the probability of landslides to the linear feature. Of the 55 kilometers, 63% (35 km) of them are within the Medium probability category (See Figure 5.5). Low probability follows with 28% (16 km) of the total, followed by High and Greatest with 8% and 0.1% respectively (See Table 5.3 and Figure 5.5). This is also evident in each category of linear road feature as all three types, paved, unpaved, and footpaths, has their greatest percentage of total length within the Medium category (See Figure 5.5). Figure 5.6, 5.7, and 5.8 shows the distribution of probability to being affected by a landslide for each of the three linear features.

Structure Vulnerability

903 structures were mapped within the research area. Vulnerability to landsliding was found by extracting the probability of landsliding for each structure. Of these, 64% (573) occur in the Medium category. 35% (316) of structures occur in the Low category and 1.6% (14) occurs in the High category. No structures occur in the Greatest category. Figure 5.9 is a map of structures in the research area attributed with their potential probability of being affected by landslides.

Figure 5.3
Uncategorized landslide hazard map derived from probabilities calculated in the logistic regression equation (Eq. 3).

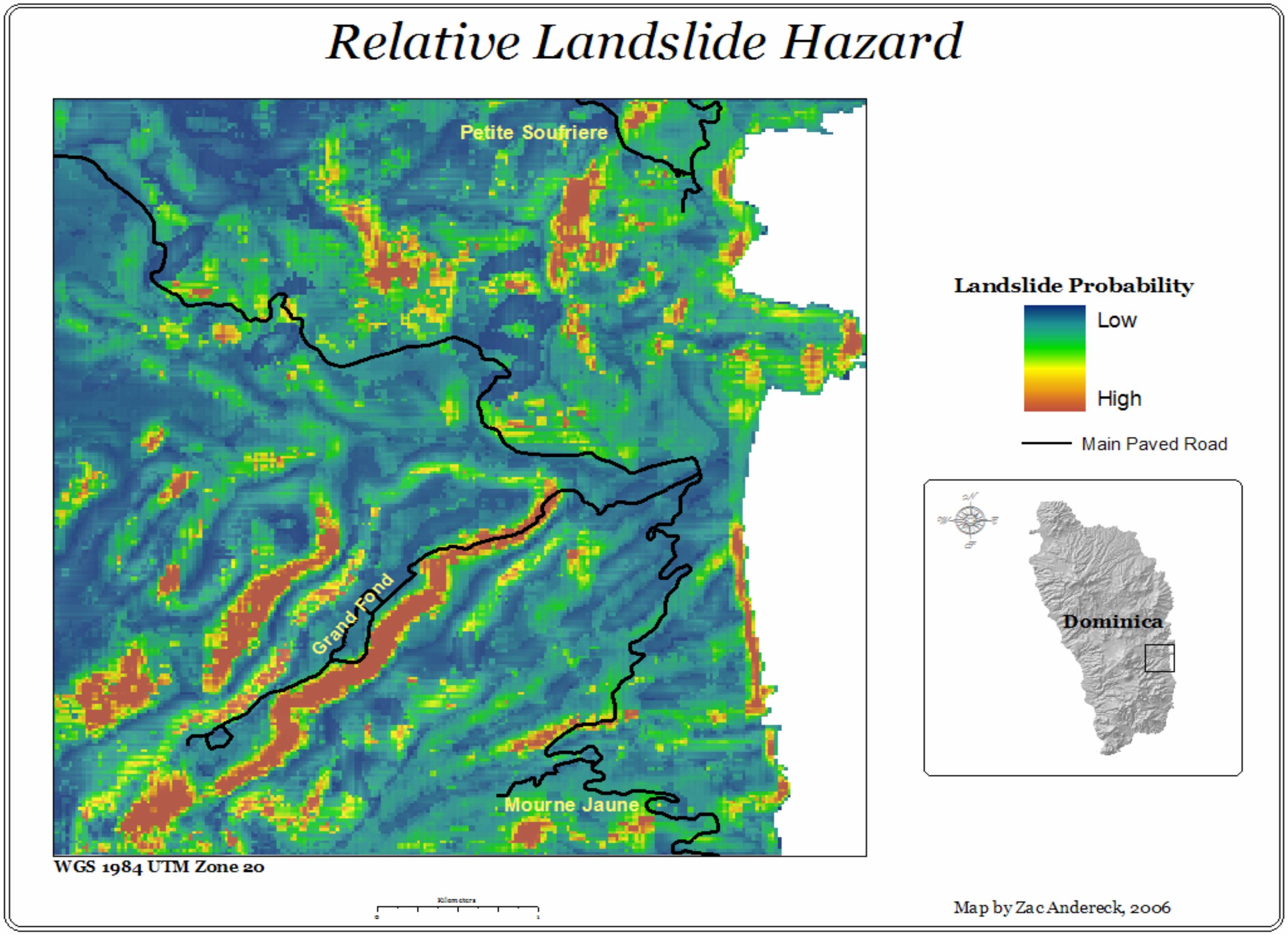


Figure 5.4
Classified relative landslide hazard map derived from classifying the probabilities calculated in the logistic regression equation (Eq. 3).

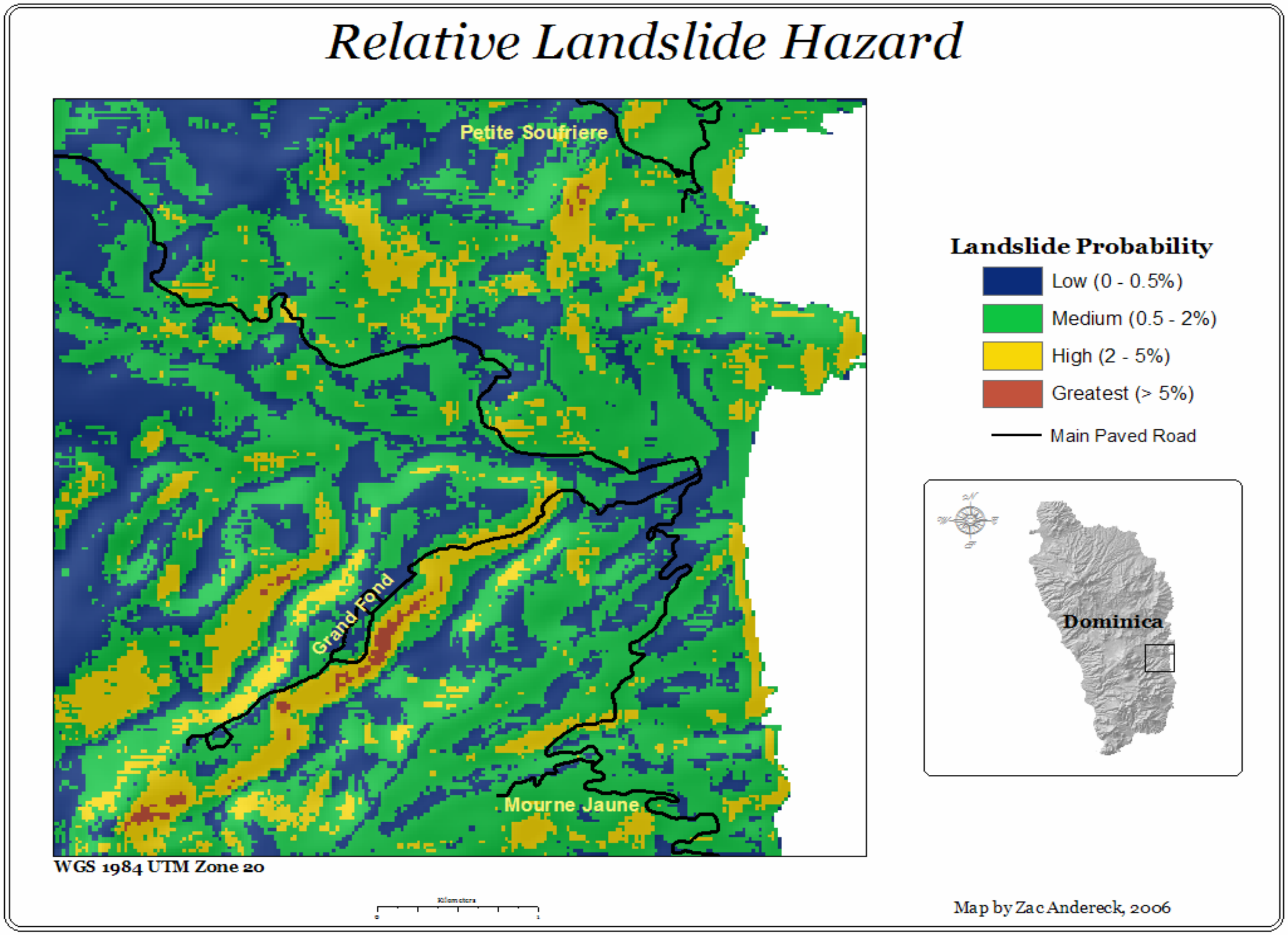


Table 5.3

Tables showing categorized landslide hazard area, road length, total road vulnerability, road type vulnerability, and structural vulnerability.

Relative Landslide Hazard Areas

Hazard	Area (ha)	% of Total Area
Low	692	30.8%
Medium	1243	55.3%
High	303	13.5%
Greatest	10	0.4%
Totals	2248	100.0%

Road Length

Type	Length (km)	% of Total Length
Paved	14.1	25.5%
Unpaved	21.4	38.7%
Path	19.8	35.8%
Totals	55.2	100.0%

Total Road Length Vulnerability

Vulnerability	Length (km)	% of Total Length
Low	15.97	28.9%
Medium	34.91	63.2%
High	4.33	7.8%
Greatest	0.03	0.1%
Totals	55.2	100.0%

Road Type Vulnerability

Vulnerability	Length (km)	% of Total Length
Paved		
Low	6.4	29.7%
Medium	13.2	61.5%
High	1.9	8.7%
Greatest	0.0	0.0%
Totals	21.38	100.0%
Unpaved		
Low	5.1	35.9%
Medium	8.8	62.7%
High	0.2	1.4%
Totals	14.1	100.0%
Path		
Low	4.6	23.1%
Medium	12.9	65.4%
High	2.3	11.5%
Greatest	0.0	0.1%
Totals	19.77	100.0%

Structural Vulnerability

Structure Vulnerability	Count	% of Total
Low	316	35.0%
Medium	573	63.5%
High	14	1.6%
Total	903	100.0%

Figure 5.5

The percentage of each infrastructure within each vulnerability classification and the percentage of total research area within each classification.

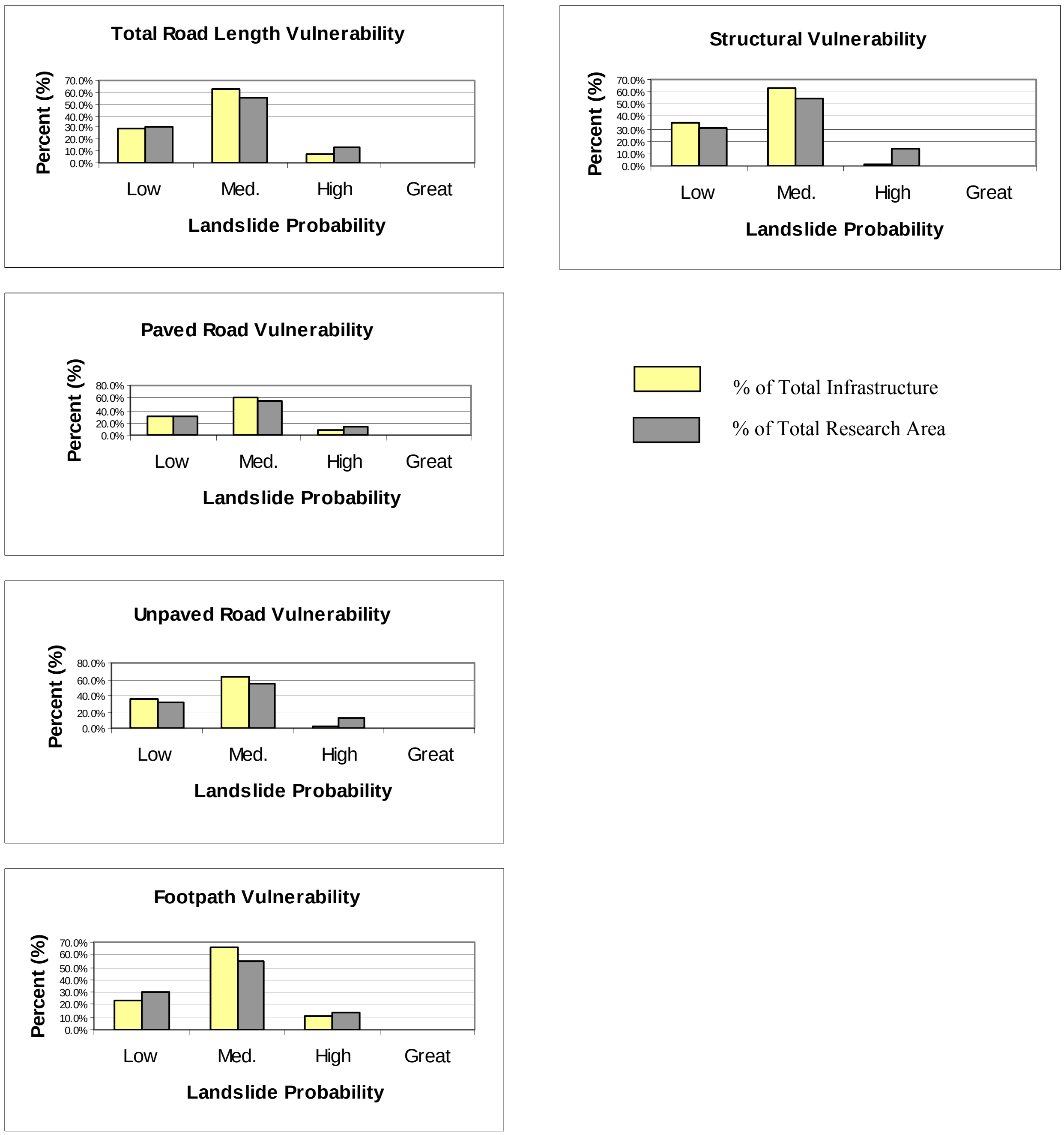


Figure 5.6
Paved road distribution in relation to vulnerability of landslides.

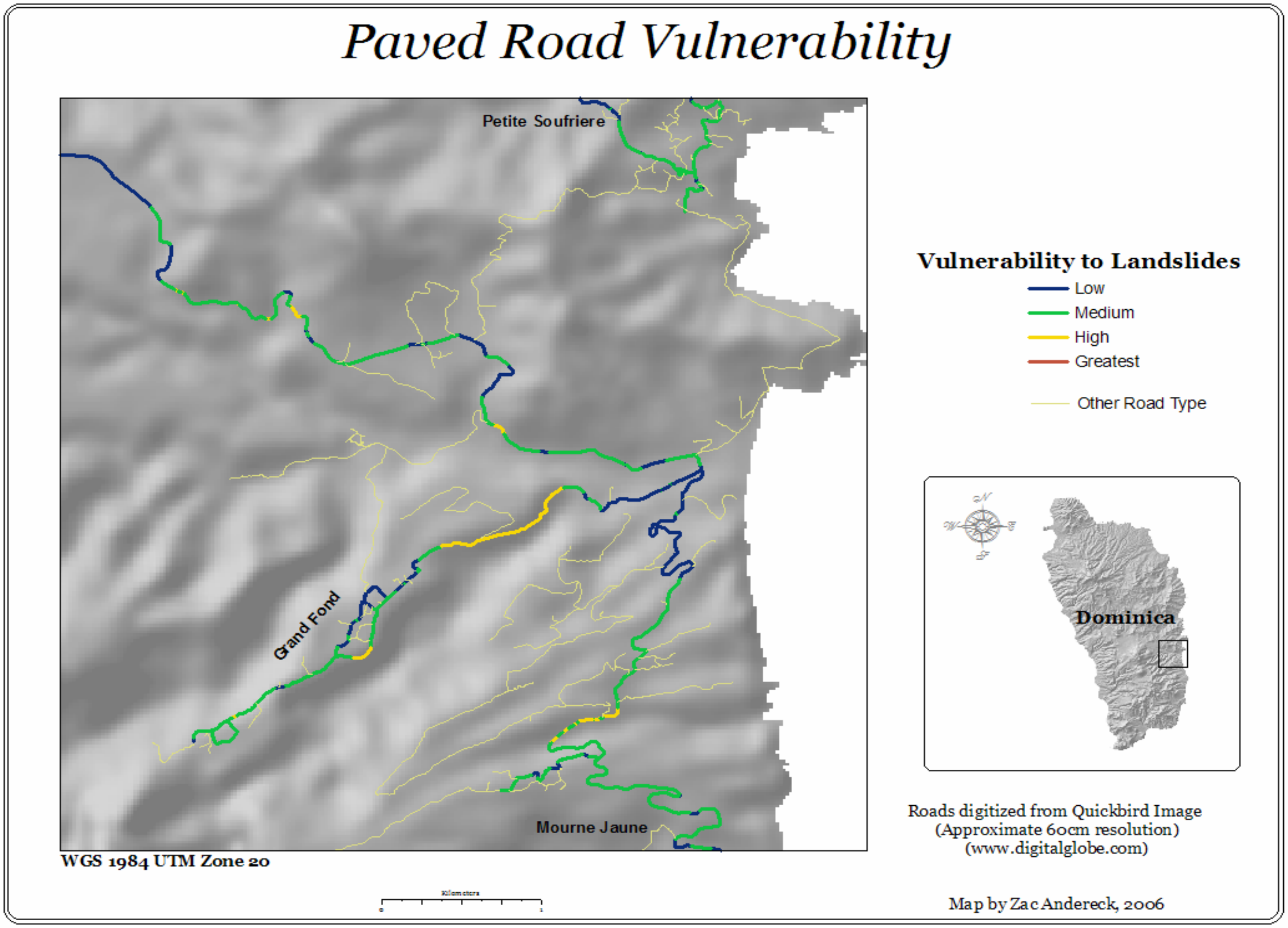


Figure 5.7
Unpaved road distribution in relation to vulnerability of landslides.

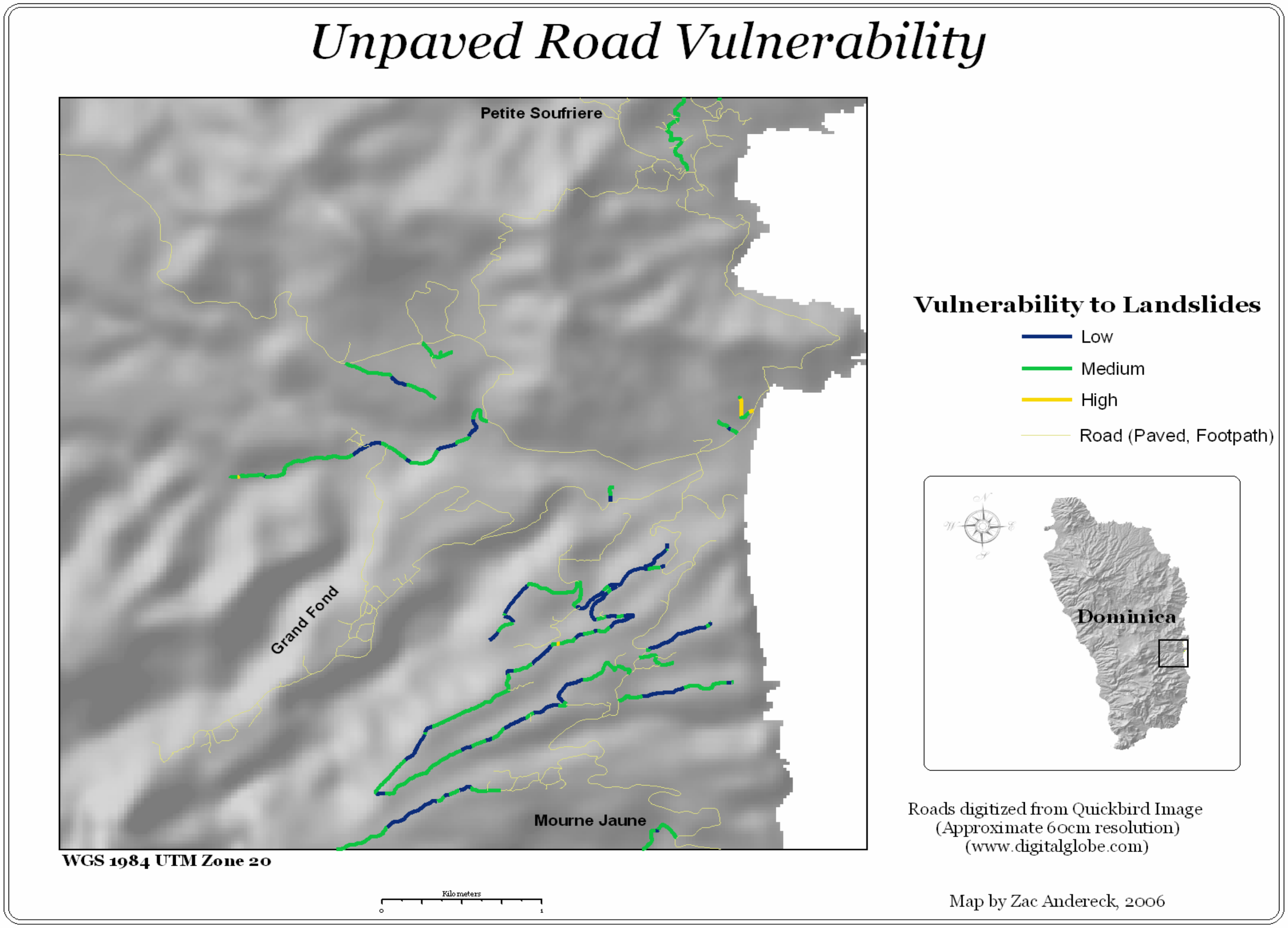


Figure 5.8
Footpath distribution in relation to vulnerability to landslides

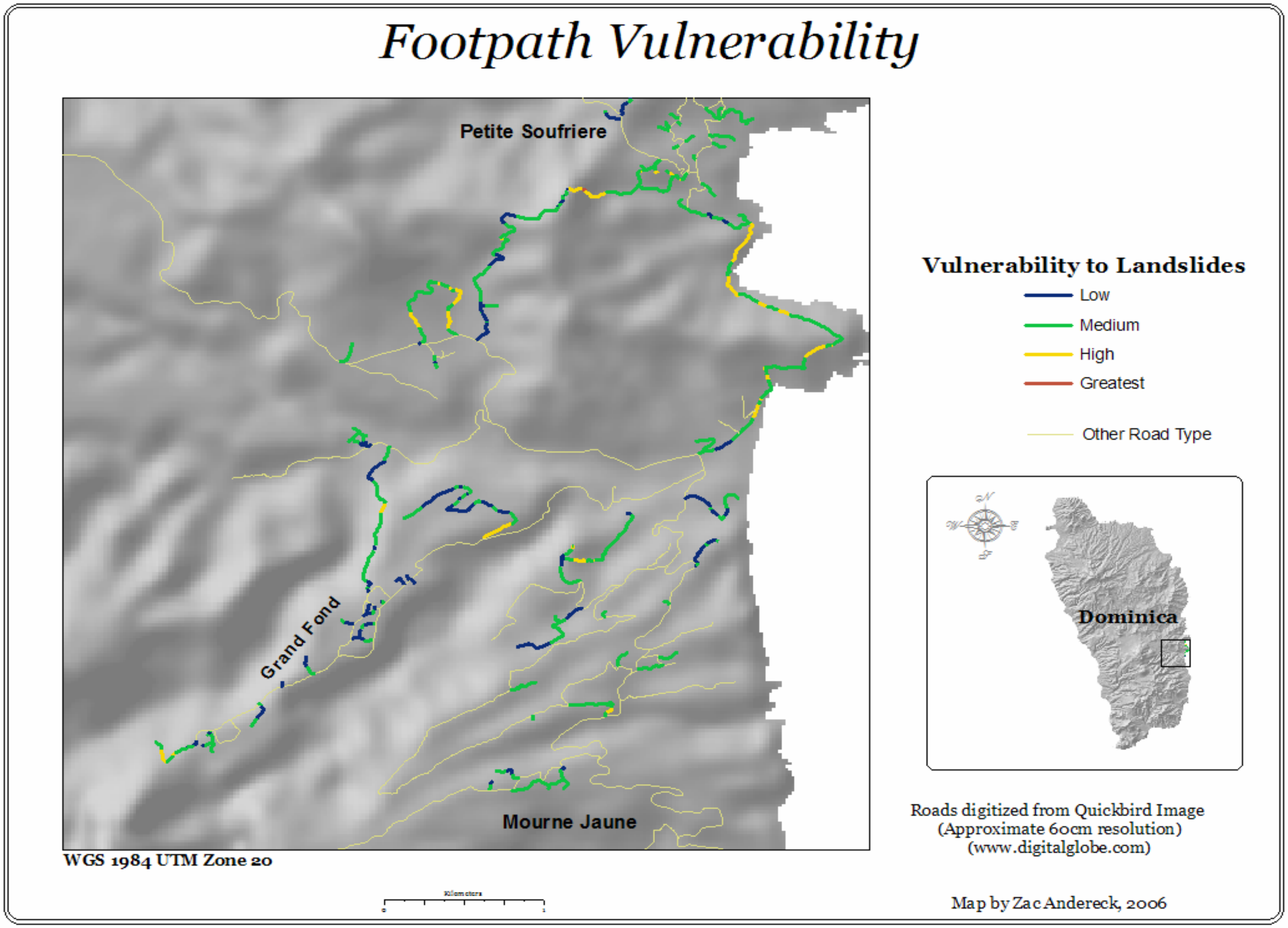
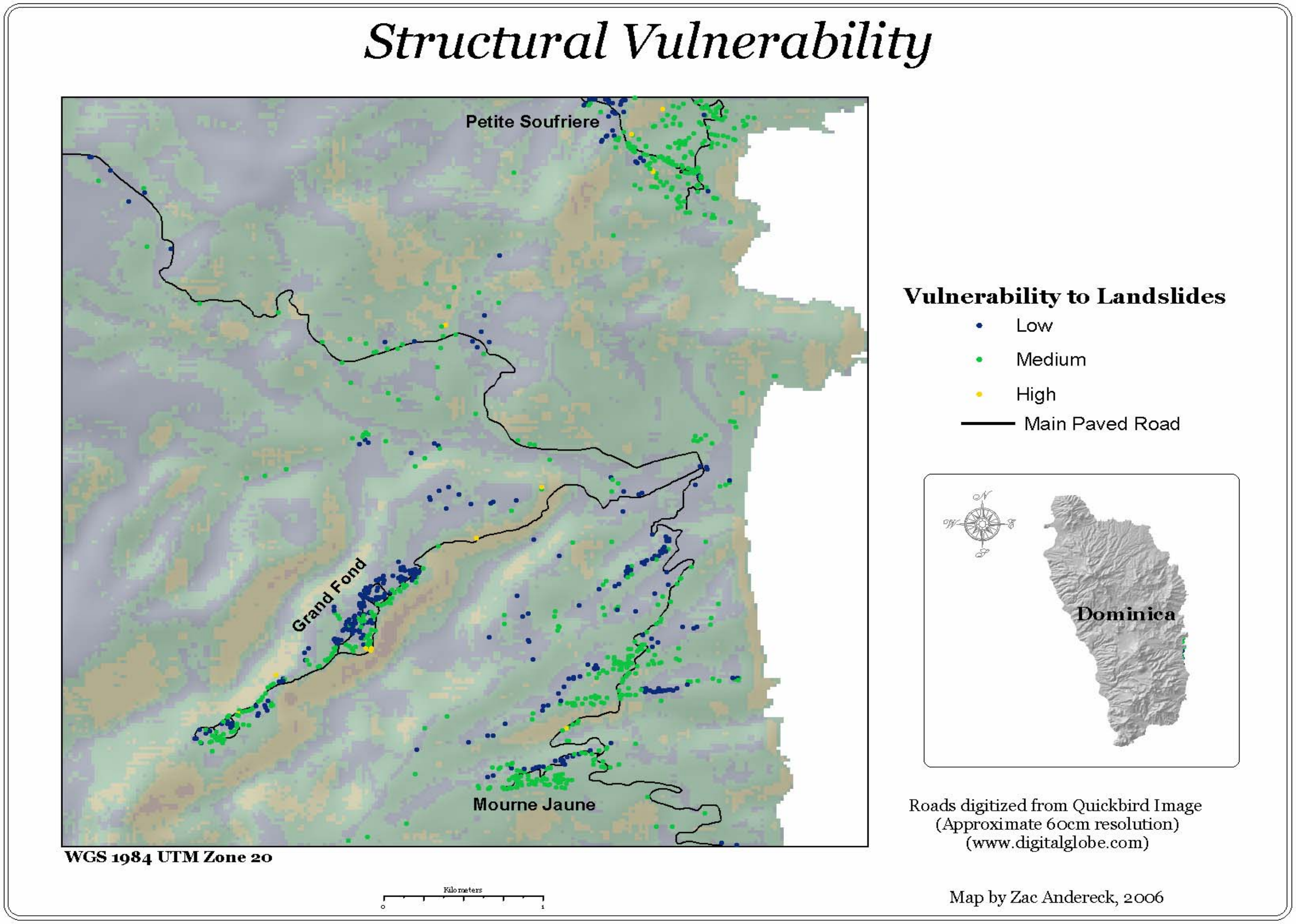


Figure 5.9
The distribution of structures within the Dominica research area.
Each structure is coded with its vulnerability to landslides.



Chapter Six

Discussion and Conclusion

Landslides are common on Dominica and can significantly disrupt daily life. In this study, a probabilistic approach is used to estimate susceptible areas to landslides using a GIS landslide inventory, and multiple logistic regressions. These areas of hazard are then extrapolated to various types of infrastructure on the island to assess infrastructure vulnerability to landslides. Like other landslide hazard methods, this study uses the three basic assumptions used in constructing landslide hazard maps; 1) slope failures are recognizable by distinct morphological features; 2) mechanical laws controlling slope movement can be measured empirically, statistically, or through physical processes; and 3) future failures are likely to occur in similar topographic, geomorphic, geologic, and hydrologic circumstances to those in which failures occurred in the past (i.e. the past and present are the key to the future) (See Guzzetti et al, 1999).

The accuracy of the landslide hazard maps, and subsequent vulnerability maps, is contingent on the accuracy of the input variables. In this study, the contingent variables are soils type, land cover/land use, DEM derived slope steepness and aspect, and distance to nearest road.

6.1 Slope Indicators

Landslides

The majority of the landslides identified in the research area were found using visual image interpretation. Verification of landslides was done in ESRI's ArcScene. Slope position of the landslide was used to determine the validity of landslides through visual interpretation. The landslide density map was also checked by another individual trained in landslide interpretation. Some difficulty arose in the analysis due to areas that could possibly be subsistence farming plots. These plots do exist on steep slopes and could be mistaken as landslides in each of the verification steps without field verification.

Soils

The soil data are originally from Lang (1967) which is the only known soils data for the island (See Figure 3.2). The soils were mapped at 1:40,000 scale and are highly generalized in the research area. The largest soil type present is latosolics, highly weathered and fragile soils due to the intense precipitation. This weathering may result in increases in landslide hazard of latosols, but in terms of percentage of landslides per percentage of area, it is not the most susceptible soil.

Skeletal soils comprise 10% of the research area but contain 17 percent of the landslides. These are poorly developed soils primarily found on steep slopes. The steepness of the slope inhibits formation of well defined soil profiles. Instead, the soil is thin and highly susceptible to erosion. Table 4.2 indicates that skeletal soils have the highest statistically significant coefficient, meaning a strong correlation with landslides, also indicated in Figure 5.1. Therefore I speculate that in locations where skeletal soils are present, landslides have a higher probability of occurring than on other soil types.

Young soils comprise 6% of the research area, but contain 10% of landslides (See Figure 5.1). Young soils have some soil development, primarily the weathering of clay minerals. I speculate that of internal weathering has changed the internal soil structure as such to increase landslides. Young soils were not statistically significant in terms of the logistic regression and should be evaluated more in future research.

Land cover/Land use

The land cover/land use raster is the most recent available data for Dominica. The raster was obtained from the USGS, which is working on developing a standard classification scheme for all Caribbean islands. Transformation of the research area by development and/or agriculture could impact the results of the study. It may be possible to assume that deforestation from development or further agricultural development could potentially influence landslide behavior. This assumption is not explored in the analysis because land cover was only available for one point in time. This assumption is questioned though by the statistical results. It was found that

Urban/Residential/Bare Soil/Rock is not significant statistically. In answering this argument, the differentiation in area between each of the four included land use/land cover is not available and therefore can not adequetly explain which of the land uses influences or inhibits landslides, and also needs further exploration.

Lowland/submontane seasonal evergreen forest (L/SSEF) comprises only 11% of the total research area but contains 18% of total landslides (See Figure 5.1). The distribution of this vegetation type is found primarily on latosolic soils, higher elevations, and east facing slopes in the research area. The most statistically significant land cover/land use is L/SSEF. It has a positive correlation with landslides. Though the probability coefficient is independent of slope and soil, I speculate that the location of L/SSEF on latosolic soils and east facing slopes plays a role in the probability for failure, but needs to be explored further in future research.

Active agriculture occupies 47% of the research area and contains37% of the landslides. Active agriculture is statistically significant, but the coefficient is negative. This means that there is an inverse relationship between the active agriculture and landslides. The presence of active agriculture decreases the probability of landslides occurring (See Table 4.2). I feel that this aspect needs to be evaluated in future research because active agriculture in the research area includes banana and dasheen cultivation. These crops have poor root systems and expose soil leading to increased infiltration into the soil changing the factor safety within the soil leading to failure (DeGraff, 1990a). DeGraff (1990a) speculated that cultivated lands may increase the likelihood of failure. The conversion from deep, strong rooted plants to shallow, weak rooted plants lead to slope failure (Mongomery et al, 2000; Gabet and Dunne, 2002). This is because shallow, weak roots do not have the root structure to hold and secure the soil in place. I also speculate that grassland, though only a small fraction of the research area is affected by this principle. It has been shown that areas of grassland have significantly higher occurrences of landslides than do forested areas (Mongomery et al, 2000; Gabet and Dunne, 2002). Table 4.2 however, does not support this assumption, as it is not statistically significant.

Slope Steepness / Slope Aspect

Slope steepness and slope aspect are derived from the initial digital elevation model. The original DEM had a cell resolution of 90m and was resampled by Ian Stewart to 50m prior to being obtained for the study. Once obtained, the DEM was resampled to match the raster cell size used in the study, 20.164m. Depending on the resampling method, i.e. nearest neighbor, bilinear interpolation, or cubic convolution, the resulting values for the DEM can vary significantly from the original pixel value. The DEM in the study was resampled using cubic convolution, which uses the nearest 16 cells to calculate the resulting value.

For Dominica, the original pixel size was 90m that was obtained by the SRTM program. The topography of Dominica is such, that within each 90m pixel, the topography can vary significantly and not be accurately portrayed. The subsequent resamplings of the DEM and the resulting products (slope steepness and aspect) have the inaccuracies built in, which is expected. This could potentially influence the results of the study by assigning inaccurate slope values for each landslide, potentially skewing the influence of slope on landsliding. Unfortunately this problem could not be overcome in the timeframe of the project. The DEM in this study was the best available product at the time. An accuracy assessment of the DEM, therefore slope and aspect, was not performed for the study area.

Slope is used as a continuous variable in the logistic regression. However, for the purpose of comparison with landslide probability, I have classified it into 12 categories (See Figure 5.1). Slopes of 16 to 24 degrees have more landslides per area than most other categories. I speculate that these slopes allows for enough soil weathering and chemical alteration to occur so that the resulting soil properties, such as the development of certain clay minerals, are unstable enough to generate slides. This is because the slopes are gentle enough to allow for soil development, but steep enough to slide easily when the conditions are favorable. Slope values above this threshold may not have enough soil alteration to influence sliding. An increase in slide activity does occur in the 26-28 degree range and could be related to the occurrence of skeletal soils, but this was not explored. A significant number of slides do occur in relatively flat areas, but as mentioned above about the inherent flaws of the DEM, I feel it is not entirely representative of the research area and needs further study.

Aspect also influences landslides. The majority of the research area and landslides are found on slopes having an easterly component (NE, E, and SE) (See Table 5.1). The location of the research area in relationship to the island offers the explanation. The prevailing winds in this area are from the east. Like the influence of sunlight on a valley, rainfall from the trade winds impact east facing slopes harder than west facing slopes. It should be noted however, that in the event of a tropical disturbance, such as a hurricane, winds may come from a different direction.

For example, a greater occurrence of landslides on west facing slopes could be possible if the eye of the storm passes to the north of the island.

Distance to Nearest Road

Distance to the nearest road does have a positive influence on landsliding (See Table 5.1). It appears that the influence of roads on landsliding diminishes as the distance away from the road increases. The areas closest to the roads had the highest landslide per area ratio for the research area (See Table 5.1). These results were expected due to limited suitable locations for the construction of roads in the research area (See Anderson and Kneale, 1985; Greenburg, 1998; Chang and Slaymaker, 2002).

6.2 Landslide Hazard and Vulnerability

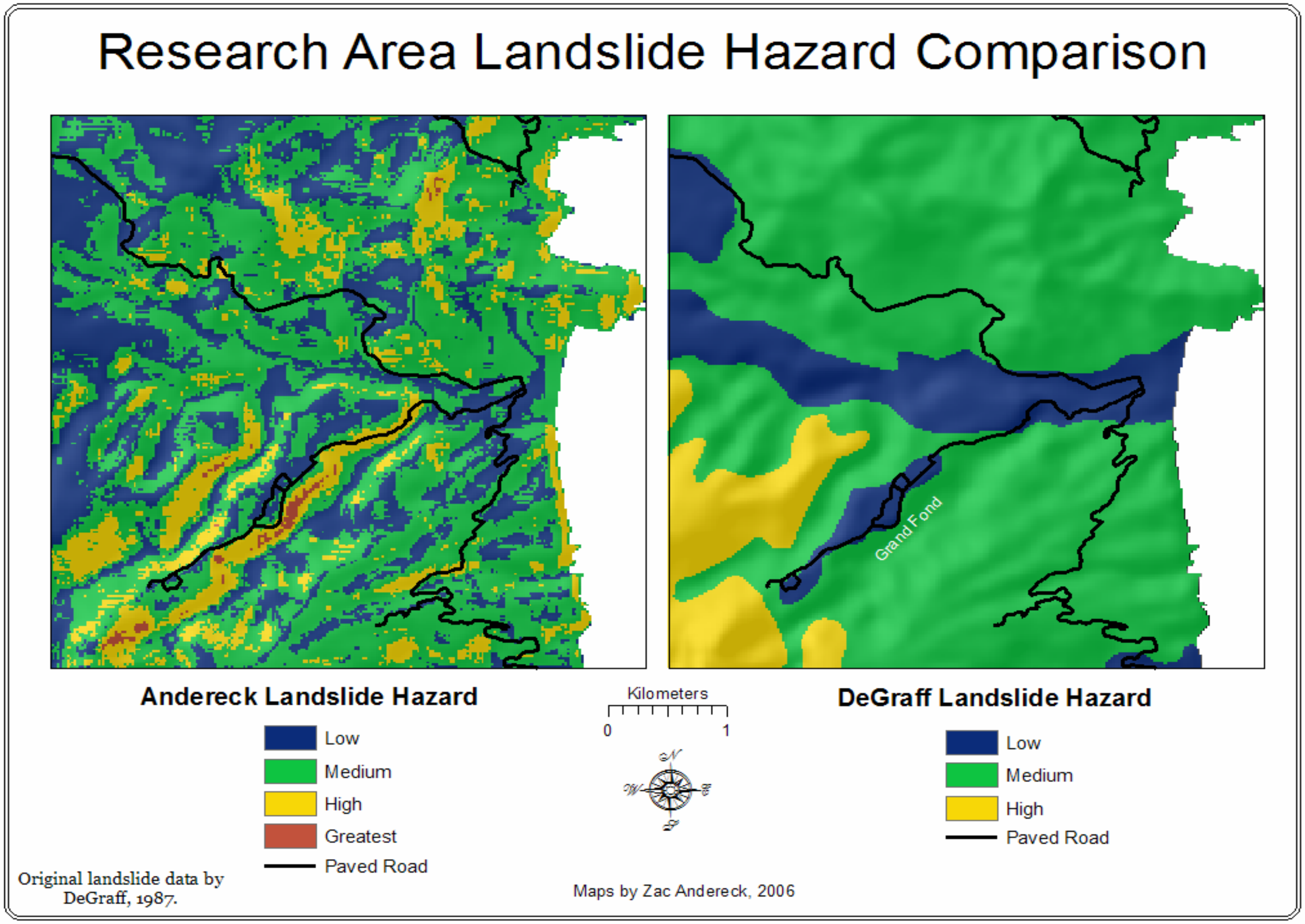
The spatial extent of a landslide hazard determines the potential impacts on humans and infrastructure (Wang et al, 1999). The hazard map for the research area is based on similar assessments of landslide hazard (See Olmacher and Davis; Lee, 2005), but goes beyond by examining the vulnerability of human infrastructural components to landslides (Hill and Cutter, 2001). This type of assessment has not been performed on Dominica except for localized, landslide specific instances (See CDMP, 1999), or vulnerability assessments that do not include landslide hazard (See OAS, 1998)[4].

The main landslide hazard investigation on the island is by DeGraff (1987a, 1990a). In this study's research area, DeGraff (1987a) identified 17 landslides, compared to 246 landslides I have found. Of the four hazard zonations present in DeGraff (1987a), three exist in the study area; Low, Medium, and High (See Figures 3.1 and 6.1). Low hazard occupies 330ha (15%), Medium occupies 1709ha (76%), and High occupies 208ha (9%) of the research area. DeGraff (1987a) and this study have the highest proportion of total research area in the medium hazard category, but differ by 455 ha (See Table 5.2).

Similar hazard zonation exists between DeGraff (1987a) and this study. The Low hazard area that spans the village of Grand Fond is similar in both studies as is the Low hazard area in the northwest corner of the research area (See Figure 6.1). DeGraff (1987a) does not identify the High hazard area to the southeast of Grand Fond. In this study, this area has the highest

[4] DeGraff (1987a) does mention ways of reducing losses to landslides through improved remediation practices but does not investigate the islands infrastructure to landslide vulnerability.

Figure 6.1
Comparison of landslide hazard between DeGraff (1987a) and this study.



probabilities for failure (See Figure 6.1). The area west of Grand Fond, classified as High by DeGraff (1987a), has large areas of low in this study.

Discrepancies in hazard area and number of landslides identified are likely due to three factors. The first is the use of different mapping scales. DeGraff identified landslides from aerial photographs at 1:20,000 scale, in this study landslides were identified at 1:1,500 scale. At the 1:1,500 scale, smaller landslides not identifiable at 1:20,000 can be identified and included in the hazard zonation process. Second is that bedrock was not included in this research and could cause some discrepancies between the two studies. Finally, the biggest difference is the methodology employed to discern landslide hazard. DeGraff used three parameters, slope, preexisting landslides, and bedrock. The proportion of landslide area to bedrock/slope unit area was used to determine the relative landslide hazard. In the categorization of landslide hazard by DeGraff, Low hazard areas were defined as having no landslides present at the time of analysis. In this study, areas that are deemed low probability to failure do include some landslides. This is evident in Figure 6.1 where the Low hazard defined by DeGraff near the village of Grand Fond had significant slides in this study (See Also (Figure 5.2). The difference in the parameters used to identify areas of increased susceptibility to hazards and the difference in the mapping scale used are why these two maps look so different.

One crucial issue in using GIS to perform hazard assessments is its reliance on suitable input data, which is often inadequate in quantity and quality (Huabin et al, 2005). Nearly all of the instability factors collected and used in this study have inaccuracies whose magnitude cannot be controlled or estimated in successive data analysis (Huabin et al, 2005). A high level of uncertainty exists in this study due to the heterogeneity of input variables spatial scale. This difference in scale significantly limits the detail to which the assessment can be performed by reducing the level of detail needed in such a small research area.

In the regression model, violations of regression model assumptions exist that make the accuracy of the output suspect. The biggest violation is the assumption that the observations are independent. Logistic regression assumes that each cell is independent from other cells, which is not realistic. This is because the surface of the earth is continuous and each cell value (in the data raster) is strongly related to and influenced by neighboring cells. Therefore, the proper analysis for a statistical regression would be properly done from a geostatistical perspective, which has yet to be developed (Olmacher and Davis, 2003).

It must be noted that the prepared relative landslide hazard and vulnerability maps cannot predict or specify the size or magnitude of landslides. The inherent errors built into the analysis do not allow the prediction of specific locations or times when landslides will occur. The maps only show the relative difference in the probability to landsliding that exists in the research area. This distinction is important to understanding the confines of these maps, as landslides can occur in areas deemed as having low landslide hazards (Figs. 5.3 & 5.4). Future changes in land use and/or development can significantly alter the stability of slopes, which these maps do not take into consideration. A reevaluation of the landslide hazard risk would need to be performed to address future changes.

If assuming that major sliding events occur only following significant precipitation events, in this case tropical disturbances, storms and hurricanes (See Table 3.1), then the recurrence interval of major sliding events on Dominica would be seven years. This is calculated by taking the number of storms since independence (See Table 3.1) plus the November 2004 storm, divided by 28 years. This is only a rough estimate and is not intended for any type of recurrence interval reference to sliding on Dominica.

6.3 Return to Dominica

In December of 2006, the results of this study were given back to the peoples of the study area. One step in reducing vulnerability is the distribution of knowledge to those who are affected by and can use the data to mitigate the hazards (Tipple, 2005). The results were in form of maps (See Figures 5.3, 5.4, 5.6, 5.7, 5.8, 5.9) given to the village council leaders of each village. Discussion of the maps was done with one village council leader, Shirley George of Grand Fond. I explained to Mrs. George what each map showed, how it was constructed, and the accuracy of the map. The villages were grateful for the maps, not so much in terms of the landslide information as was expected, but of having a map of the village. All individuals who viewed the maps expressed their excitement in being able to locate and view their houses, farms, and businesses. Prior to this, only hand drawn maps of the villages existed, with most of the information contained in mental maps.

Individuals from the Environmental Coordinating Unit, which is part of the Ministry of Agriculture, Fisheries and the Environment of the Government of Dominica, also examined the maps. Through discussion of the methods of the project and how the results were generated it was expressed numerous times that this type of work (not just for landslides) is needed on Dominica. They expressed that they would prefer to be taught how to do it, rather than researchers coming, researching and then leaving. They wanted to learn the methodology and techniques of the research so that they can perform and cater the research to their needs.

The trip also allowed for a brief assessment of some of the landslides mapped during the initial field mapping in the summer of 2006. Three landslides were observed as having reactivated since the summer of 2006, and one is currently being mitigated (Figure 6.2). Time did not permit a more detailed examination of any significant portion of landslides mapped in the project. Mitigation of the one landslide appeared to be through the construction of a retaining wall using sheet piling. This particular slide has been eroding the roadbed for some time and threatens water and sewage utilities (Figure 6.2).

Development in the research area has not been an issue thus far. But elsewhere on the island, potential future impacts of development in the research area are evident. On the Imperial Highway, northeast of Roseau, in the Roseau River Valley, urban development has severely impacted the area in the last nine months. Ron Viveralli, owner of Crescent Moon Cabins, located in this area, indicated that 22 new houses have been built in the last year alone. Water supply and quality have become an issue.

Recently, a developer illegally used an earthmover to flatten a location for a property. The person using the equipment did not have a permit to build and was forced to shut down operations (Figure 6.3). Unfortunately the debris from this illegal work was dumped into the local stream clogging the flow of water. Ron Viveralli uses this water supply for use in his greenhouse and for livestock, primarily goats. The reduction of flow and the sedimentation in the water caused the Ram pumps and mini hydroelectric systems used for water and electricity at Crescent Moon Cabins to become virtually useless because of clogging from sediments and reduction in flow velocity. In a nine month span, a local organic garden near Crescent Moon Cabins has been transformed into a housing development (See Figure 6.4). This housing development lies on the boundary of the Morne Trois Pitons National Park, a World Heritage Site. This push of development is primarily by individuals either working in Roseau or Dominicans who have lived abroad and are returning to the island and investing.

Figure 6.2

Landslide that has been active for several years. It has slowly eaten away at the roadway and exposed water and sewage lines, visible in the middle of the picture. In December of 2006, mitigation of this landslide was started through the installation of a retaining wall using sheet piling.

Photo by Andereck, 2006

Figure 6.3

The site of illegal clearing near Crescent Moon Cabins that has since been the cause of significant sedimentation in the stream that runs by Crescent Moon Cabins.

Photo by Andereck, 2006

Figure 6.4
These three pictures are a nine month time series of an organic garden near Crescent Moon Cabins. Note the change in the upper left of each image.

March 

July 

December 

If this type of illegal building and rapid development evident in the Roseau River Valley continues to expand, significant loss of infrastructure and lives to landslides and other natural hazards is a possibility.

Degradation of the land from development in this area is clearly evident in just nine months since the first observations were made. This means that the mindset of the people in this area have shifted and is reflected in the shift from a lifestyle in harmony with nature to one opposed, or in conflict with nature. The placing of monetary value of the land above the well being of the land, and the people linked to the land, puts these areas at a greater vulnerability to landslides and other natural hazards. This shift in values from a more holistic lifestyle to one driven by capital creates the conflict between humans and nature (White, 1967; Murphy, 1994; Oliver-Smith, 2004). This is because the people settling in these areas are not knowledgeable of the potential risks because of a lack of knowledge about the risks and degradation to the environment.

6.4 Future Research

This vulnerability assessment needs continued input and refinement beyond the completion of this project. It needs to be continually updated as new information becomes available through new research and discovery of other historically significant data (Huabin et al, 2005). Historical landslide information is of particular importance. The landslide inventory for this study only includes those landslides that most likely occurred within the previous year leading up to the reference image.[5] This one snapshot in time does not allow for the development of a landslide hazard map similar to modern flood hazard maps. The inclusion of historic landslides into the landslide inventory would help identify areas of greater historical landslide occurrence within the research area. This information could then allow for the designations of not only hazardous areas, but areas with a specified recurrence interval, such as a 10-year slide, or 50-year slide.

Improvements in the quality and detail of the DEM, soil, and land cover/land use present in the research area can greatly improve the accuracy of the study. Improvements on all three can improve upon or nullify the influences of these factors (Slope, Aspect, Soils, LULC) used in this study. Improvements in the quality of the DEM will allow for better slope and aspect predictions

[5] The 17 DeGraff (1987a) landslides are included in this study, but only make up 7% of the landslides used in the analysis.

for the research area. This would allow a better understanding of the influence of slope, potentially leading to a critical slope threshold. Improvements of the soils map could greatly increase the accuracy of the assessment by allowing greater detail in the spatial extent of the various soil types found in the research area. Also, the influence on geology in the development of the residual soils in the research area could offer insight into geological controls on landsliding, which was not done for this study. With potential increases in development in the research area, the influence of land cover/land use could be altered. Verification and continual updating of this data is crucial to maintaining the significance of this study.

Finally, cooperation with individuals on the ground is vital to the distribution and local understanding of the information in this study. The results found in this research have been dispersed to the villages in the study with the hopes of allowing people to have a greater understanding of the risks of landslides. Local contacts offer insight to the accuracy of the research and can contribute to the refinement and upkeep of the data. Simply marking the location of historical or present landslides can increase the spatial and temporal extent of the landslide inventory. This involvement will also alleviate any misrepresented areas that may have been identified in this research. This includes areas that appear to be landslides but are really subsistence farming plots.

The involvement of local individuals through this type of participation can increase the awareness to landslides that the people may not have had. At the national scale, the methods of the research can potentially be extended to the entire island. It would require significant improvements to currently available GIS information, but upon completion can be used as a national development and planning tool to reduce losses.

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