Landslide Loss Reduction: A Guide for the Kingston Metropolitan Area, Jamaica

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"Our society is just beginning to understand the potentially dangerous consequences of development and urbanization in geologically sensitive areas. until recently, people were comfortable in assuming that engineering technology could overcome all environmental constraints and geological instabilities. now the public, insurers, and policymakers share a growing concern for the episodic and catastrophic damage caused by the forces of nature"

The Geological Society of America, 1997

" The nation needs environmental leadership that can make positive advances, that can encompass all of its citizens, and be open to public scrutiny. We must strive to improve the process that develops our environmental policy. Our economy must be able to support the environmental costs, and provide for standard of living in addition to the environmental quality of life. We must develop policy that reflects a consensus of the people, and that encourages enthusiastic support and compliance. Setting standards, insisting upon high standards of ethics and truth, allowing for regional differences, and providing frameworks for evaluation of issues and results are crucial to long-term success. We have not yet reached these goals."

By Lee C. Gerhard in " The dilemma of the geologist: Earth resources and environmental policy", Reviews in Engineering Geology, Vol. XII, p.7, 1998.

" … geomorphic systems are complex, because landscape systems are the product of a variety of driving forces that interrelate in different ways and to different degrees across different time frames… An understanding of this environmental complexity by environmental engineers, scientists, and managers is fundamental for the successful implementation of erosion-abatement projects and of land-use practices that reduce the likelihood of negative environmental impacts, howsoever defined."

By Paul R. Pinet, Charles E. McClennen and Laura J. Moore, in Reviews of Engineering Geology, Vol. XII, p.20, 1998.

Contents

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The primary technical and administrative (from August 1997) responsibility for the Project lies with Rafi Ahmad. He prepared the project document, compiled landslide inventory maps based on aerial photo-interpretation and field verification, collected and compiled the geological and structural data, and interpreted the data within the physical and anthropogenic environment of the study area. This work incorporates a substantial amount of Ahmad's unpublished research.

Our team effort has resulted in new data and maps that were not previously available for KMA. These maps should form the basis of an effective landuse planning. I thank all the team members for their dedication.

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Rafi Ahmad

1.0 Introduction

Purpose and scope

Hazards related to landslides are a major societal and environmental concern to Jamaica in general and the Kingston Metropolitan Area (KMA) in particular which is the main centre of the economic and industrial activity of the country. Recurrent landslide damage in KMA, caused specially by frequent rain storms, should be a growing concern to the general public, ministries of the central and local government dealing with transport, construction, housing, environment, and public utilities including water, electricity and telecommunications, policymakers, and planning agencies. It has been estimated that throughout the Caribbean some US$15m are spent annually to repair the landslide damage to roads (DeGraff *et al.*, 1989).

Economic losses from landslides have continued to increase dramatically during the past four decades throughout Jamaica. Significant landslide activity in Jamaica was recorded in 1990, 1991,1993,1994, 1996, 1997, and 1998. Most recent damages were caused by the rainfall-induced slides of 3-4 January 1998 in Portland (where a landslide claimed the lives of four persons and left several others seriously injured), and October-November 1998 rainfall related to hurricane Mitch and a frontal trough which led to widespread landslide damage in KMA. The cost of landslide damage keeps on increasing dramatically as the pace of urbanization intensifies on the geologically sensitive slopes.

Geological instabilities prevail over large sections of KMA. Many residential areas and infrastructure in KMA are located on large ancient landslides, and it is a common observation that new landslides have occurred on slopes that had previously failed. However, the real-world situation is that the small island states, such as Jamaica, have a limited land area which inspite of its natural constraints must be utilized to meet the needs of their peoples. The land area of Jamaica is some 11,000 km^2, with about 80% of the slopes being above 20^0 , and a population density of 219 persons/km^2. In KMA, which represents some 5% of the islands total area, the average population density is about 1264 persons / km^2 and it hosts some 57% (approx. 700,000 persons) of Jamaica's total urban population. In this scenario the management of landslide hazard is especially important, and is also difficult and challenging.

The answers lie in learning from the past examples of landslides that have occurred in KMA for thousand of years, in finding out why these landslides occurred and what was the direct and indirect damage they caused. Examples of some of these events have been presented in this book with the aim of making planners, engineers, and geologists aware of the geological sensitivity of the terrain. Much of the landslide damage during the last 40 years appears to have occurred on slopes that have been modified for human use. The present-day landslide hazard is therefore symptomatic of changing landuse.

"If human activities can cause or aggravate the destructive effects of landslides, they can also be used to eliminate or reduce them."

It is important that strategies be formulated and implemented to (a) reduce losses from landslides, and (b) restrict development in more dangerous areas that are prone to landsliding. It should be done in the planning stages of all new development projects. A successful landslide loss reduction programme is possible only through the active participation and cooperation of both the citizens and the elected and appointed officials of the government. The very first step in loss-reduction is the availability of landslide susceptibility maps.

In recognition of the vulnerability of the Caribbean to a variety of natural hazards, the Caribbean Disaster Mitigation Project (CDMP) (OAS/USAID) initiated the Kingston Multi-Hazard Assessment Project in 1995. Landslide hazard assessment is one of the components of this project. In 1995, Unit for Sustainable Development and Environment (USDE) of Organization of American States (OAS), who are administering CDMP, awarded contract CPR No. 13415 to the University of the West Indies, Mona to carry out "Landslide Hazard Assessment in the Kingston Metropolitan Area" including the preparation of landslide susceptibility maps at a scale of 1:50,000. Unit for Disaster Studies, Department of Geography and Geology, the University of the West Indies, Mona initiated technical studies in 1996. All the relevant data were collected by the UWI team. These were digitized and sent over to Dr. James P. McCalpin (GEO-HAZ Consulting, Inc., USA) who carried out susceptibility analysis using digital techniques on behalf of UWI. Landslide Susceptibility Maps for KMA were completed in February 1998.

The purpose and objective of this book are as outlined in the project Terms of Referencd:

"Since the objective of this activity is to identify which relative susceptible areas are suited for what types of development activities, the consultant is required to produce a *Landslide Reduction Manual* to serve as a companion to the Annotated Landslide Susceptibility Map which will provide:

a. Guidelines for planners, developers and engineers on how to use the landslide susceptibility information.
b. Recommendations for reducing and controlling landslides, referring to cut-slope design and hillslope land-use practices.
c. Guidelines for site-specific studies to be carried out for project assessments.

Guidelines for the use of the maps, as in (a) above, are contained in Publication No. 5, Unit for Disaster Studies, 1999.

This book addresses "(b) and (c)" within the framework of the very limited geotechnical data that are currently available for the KMA project. Geotechnical testing of rocks, soils and landfill materials is beyond the scope of this project. The analysis contained here is to a large extent driven by the geologic data and hence its importance in understanding constraints on landuse in KMA.

This document is based on unpublished results of the research carried out by Rafi Ahmad, James P. McCalpin and Jerome DeGraff and all such data are protected under copyright laws.

The information is presented in a format that is intelligible to non-geologists.

We have included an extended discussion on the history of landslides in KMA with the aim that it must be demonstrated that damaging landslides have actually occurred, have been occurring and will continue to occur, perhaps more frequently because of building activity in geologically sensitive areas. There is a real hazard, which makes residents of KMA vulnerable and therefore there is a risk. This book will help in readers deciding on their acceptable risk from landslides and if there is a need for loss- reduction and risk -reduction.

It is not possible to include here in detail all the landslide loss-reduction techniques, both structural and non-structural, that are currently available in the literature. There are excellent texts available on the subject to which references have been provided.

DISCLAIMER

ALTHOUGH EVERY POSSIBLE CARE HAS BEEN TAKEN IN THE PREPARATION OF THE ACCOMPANYING LANDSLIDE SUSCEPTIBILITY MAPS, USERS GUIDELINES, AND LOSS-REDUCTION MANUAL, THE USERS OF THIS INFORMATION MUST BE AWARE OF THE INHERENT LIMITATIONS IN THE COLLECTION AND PROCESSING OF THE DATA, AND ALSO OF THE METHODOLOGY. THE INFORMATION PRESENTED IN THESE DOCUMENTS SHOULD ONLY BE USED WITHIN THE GUIDELINES CONTAINED IN THIS REPORT.

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WE RESERVE THE RIGHT TO REVISE THIS DOCUMENT FROM TIME TO TIME PURSUANT TO THE AVAILABILITY OF NEW INFORMATION.

2.0 Location and Geologic Setting

The modern Kingston Metropolitan Area (KMA) is spread over a mosaic of coastal plains, reclaimed land, gravel fans, and steep slopes totaling some 554 km^2 in the parishes of Kingston, St.Andrew, and Portmore in St.Catherine (Figure 1).

Munich Re (1988) includes Jamaica in the Earthquake Exposure Grading Zone 3 (a probable maximum MMI VIII once in 50 years for average soil conditions, firm sediments); the entire coastline is shown exposed to *tsunamis* and the frequency of Atlantic Hurricanes is 1.0 to 2.9 per year. Slope instability is an active geomorphic process in KMA being primarily controlled by the nature of the bedrock, its structure, and the overall location of the island within a seismically active plate boundary zone.

Geologic history and structure profoundly influence landforms and active processes on the island of Jamaica. Therefore, inherent factors related to bedrock and rock discontinuities provide a basis for understanding landslides and also in the formulation of long- and short-term pro-active responses to natural hazards from slope instability. The regional tectonic location of Jamaica is described first, followed by a summary of the geology and structure of KMA.

The island of Jamaica evolved some 124 million years before present (early Cretaceous) as an island arc terrain, an environment that was somewhat similar to the present-day volcanic arc of the eastern Caribbean. At the present-time, Jamaica is located within the central section of the plate boundary zone separating the North American and Caribbean plates. This plate boundary is a geologically young and seismically active fault zone having come into existence some 23 million years before present (Neogene). It is some 200km wide and comprises two major strike-slip boundary faults. The Oriente-Septentrional fault is the northern of the two faults, while the southern throughgoing fault is known as the Enriquillo- Plantain Garden- Duanvale- Walton- Swan Islands- Motagua Fault Zone (EPDWSM Fault) (Prentice *et al.*, 1993; Rosencrantz and Mann, 1991). Caribbean-North American relative plate motions during Neogene are distributed across major boundary faults and are manifested as compression and uplift in the Jamaican region. The minimum rate of offset across the left-lateral faults on Jamaica has been estimated at about 4mm/year by Burke *et al.* (1980).

Robinson (1994) has described the geological framework of Jamaica. Vertical and horizontal displacements along northwest-southeast and east-west aligned faults have resulted in the present-day mountainous topography manifested as a " block and belt" structure of Jamaica in a morphotectonic sense. From east to west, the three structural blocks are Blue Mountain, Clarendon, and Hanover Blocks, which are separated by two structural belts referred to as the Wagwater Belt and Montpelier Newmarket Belt respectively. The belt boundaries are delineated by major faults. The Port Royal Mountains of St.Andrew, which dominate the landscape of KMA, incorporate the rock strata of the Wagwater Belt. The Wagwater Fault and Yallahs Fault delineate the western and eastern limits of this mountain belt.

The Wagwater Belt represents a Paleogene intra-arc rift that formed between the elevated blocks, and was a site for the accumulation of approximately 7km thick sequence of sediments and volcanics (Mann and Burke, 1990). The uplift and doming of the sediments in the rift is a consequence of compression at a right-stepping bend on the throughgoing Enriquillo-Plantain Garden-Duanvale fault. In other words, the uplift of the Port Royal Mountains is a result of block convergence and has occurred during the last 5 million years (Mann and Burke, 1990). The Wagwater fault has been active since Paleocene and field evidence indicates that movements have continued into the Quaternary (Horsfield, 1974).

The city of Kingston is located on the Holocene (?) gravel fan of Liguanea at the base of the faulted mountain front of the Port Royal Mountains. A ring of low hills of Tertiary limestones (Long Mountain, Dallas Mountains, and Stony Hill) borders the fan. Overlooking these hills are the Port Royal Mountains, which is a 10km wide belt of northwest-southeast aligned sharp ridges, maximum elevation 1,539m at Catherine’s Peak, and deep fault-controlled valleys. The bedrock is comprised of some 7km thick sequence of highly faulted and jointed conglomereates, sandstones, shales, andesitic volcanics and granodiorites of Cretaceous to Paleogene age. A majority of slopes are over 30° and are underlain by intensely jointed, faulted and weathered bedrock. Neotectonic uplift has enhanced chemical weathering and mass movements.

Box No. 1: Landslide Fundamentals

The landslide process

1. Mass movement is one of the erosional processes shaping hillslopes. Landslides are the principal forms of mass movement.
2. Mass movement involves the downslope movement of slope materials under the influence of gravity.
3. Landslide is a general term equivalent to slope movements.

Types of landslide movement

1. Landslides may occur as falls, topples, lateral spreads, slides, or flows.
2. Falls are masses dislodged from very steep slopes or escarpments which then free-fall, bounce, or roll downslope. Falls usually move very to extremely rapidly.
3. Topples are a forward rotation around a pivot point low or below one or more masses.
4. Lateral spreads are the result of movement involving lateral extension accommodated by shear or tensile fractures. This type of movement is earthquake-induced.
5. Slides displace masses along one or more discrete planes. Slides may either be rotational or translational in their movement. Rotational movement is where the plane is curved. The mass rotates backwards around a common point with an axis parallel to the slope. Translational movement is where the plane is more or less planar or gently undulating. The mass moves roughly parallel to the ground surface.
6. Flows are masses moving as a deforming, viscous unit without a discrete failure plane.
7. More than one form of movement may be represented in some landslides. Movement in this case is often described as complex.

Landslide materials

1. Landslides may involve displacement of either rock, soil, or a combination of the two materials.
2. Rock refers to hard or firm bedrock, which was intact, and in place prior to slope movement.
3. Soil is used in the engineering sense to mean loose, unconsolidated particles or poorly cemented rock or inorganic aggregates. The soil may be residual or transported material.
4. Soil may be described as either debris or earth. Debris is engineering soil with 20 to 80 percent of the fragments larger than 2mm in size and the remainder smaller. Earth is when 80 percent or more of the soil consists of fragments 2mm or smaller.

Box No. 2: Parts of a Landslide

A. Landslide Nomenclature

1. Because a landslide involves a mass of soil or rock moving downslope, a landslide can be described in terms of differences between the mass forming the landslide and the unfailed slope.

    - The unfailed slope can be termed the original ground surface. This is the slope that existed before the movement that is being examined took place. If this is the surface of an older landslide, that fact should be noted.
    - The mass that moved is the displaced material. It is the material which moved away from its original position on the slope. It may be in a deformed or undeformed state.
    - The displaced material overlies two distinct zones. The zone of depletion is the area within which the displaced material lies below the original ground surface. The surface of rupture where the mass detached from the slope defines this zone. Where no displaced material remains over the surface of rupture or where flowage rather than rupture occurred, it may be more suitable to call this the source area. The zone of accumulation is the area within which the displaced material lies above the ground surface. This zone is defined by the underlying surface of separation which separates the displaced material from stable material but is not known to have been a surface on which failure occurred. In some instances, it may be more useful to call this zone the depositional area.

2. Parts of a Landslide

- Crown - unfailed area of slope above the landslides. May contain ground cracks called crown cracks.
- Main scarp - a steep surface on the margin of the slide caused by the movement of displaced material away from the neighboring, unfailed slope. By projecting this scarp under the displaced material, it would become the surface of rupture.
- Minor scarp - a steep surface on the displaced material produced by differential movement within the displaced material.
- Toe of surface of rupture - the intersection (sometimes buried) between the lower part of the surface of rupture and the original ground surface. It marks the point separating the zones of accumulation and depletion.
- Head - the upper part of the displaced material along the contact between the material and the main scarp.
- Top - the highest point of contact between the displaced material and the main scarp.
- Main body - the part of the displaced material that overlies the surface of rupture between the main scarp and the toe of the surface or rutpure.
- Flank - the side of the landslide.
- Foot - that portion of the displaced material that lies downslope from the toe of the surface of rupture.
- Toe - the margin of displaced material most distant from the main scarp.
- Tip - the point on the toe most distant from the top of the slide.

NOTE: Not all parts of a landslide may be present due to past movement deformation or the nature of the slope movement.

B. Terms Used to Describe Other Characteristics of a Landslide

1. **Movement terms**

    - It may be necessary to describe the enlargement of a landslide from its beginning at a local area. Different terms are suggested depending on how the failure enlarged in relation to the direction it moved.

        1. Retrogressive failure is enlargement of the landslide in the opposite direction in which it is moving.
        2. Advancing failure is enlargement in the direction of movement.
        3. Where enlargement involves enlargement in both directions relative of the direction of movement, it is termed progressive.

    - It may be useful to indicate whether a landslide involved one or more movements. A single movement is one in which a single mass involving either rotational or translational movement occurs along a particular surface or zone of surface rupture. A multiple movement is one in which one or more masses occurred involving the same mode of movement along two or more distinct surfaces of rupture. If multiple movement develops over time, it is termed successive movement.

2. **Water Content terms**

    - Dry - contains no visible moisture.
    - Moist - contains some water but no free water and may behave as a plastic solid but not as a liquid.
    - Wet - contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water.
    - Very Wet - contains enough water to flow as a liquid under low gradients.

3. **Terms for speed of movement** range from extremely slow (less than 1 ft/5 yrs - 0.06 m/yr) to extremely rapid (more than 10 ft/sec. - 3 m/sec).

Box No. 3: Landslide Classification

1. **Landslide Classification**

   - Landslides are classified on the basis of different characteristics. There are various classification schemes which have been proposed. In general, schemes vary because of the purpose for classification.
   - Applying the terms from an accepted landslide classification facilitates communication and aids in developing valid generalizations about the occurrence of different classes of landslides.
   - Some researchers question the usefulness of classification given the variation between individual failures or the lack of quantitative measures to define different types.
   - One of the most commonly used landslide classifications is Varnes (1978) which primarily uses the type of movement and nature of the material. Geometry, movement, and other characteristics are employed to further define discrete subcategories.

2. **Field Evidence for Classification**

   - Field classifying should always employ a standard classification scheme which is clearly identified. Varnes (1978) is widely applied for this purpose.
   - The type of material involved in the movement is the initial evidence needed.
   - The nature of the movement and the effect on the slide mass is also primary information needed in classification.

3.0 A Model for Landslides in Eastern Jamaica

Jamaica is especially subject to slope movements because of particular combinations of geological history and rock type, its tectonic setting and the geographic location. The presence of mountains extending along the path of moisture-laden winds facilitates heavy and often intense orographic rainfall. Inherent slope stability factors include fault scarps, altered bedrock, caps of competent strata, alternating permeable and impermeable rocks, gypsum and lignite along formational contacts, and abundant discontinuities that daylight in slope cuts. These variables combine to produce a sensitive terrain where hydrologic and seismic factors are particularly effective in producing high rates of landslides. Slopes are covered with colluvium.

A majority of the slopes are unable to sustain high relief under these conditions. Notwithstanding local variations, the landslide landforms are essentially ubiquitous; streams are choked with landslide debris (often forming landslide dams) and debris flow deposits appear to dominate alluvial fans where a majority of human settlements are located.

This tectonic setting and geographic location favours a propensity to multiple seismic, atmospheric, landslide and flood hazards. A scientific understanding of the physical environment and geodynamic processes are considered essential as guides to the formulation of public policy on the sustainable use of the limited land resources of KMA.

4.0 Landslide Hazard and Damage in the Kingston Metropolitan Area

Scale of the landslide problem Landslides must have occurred for thousand of years in the Kingston Metropolitan Area (KMA) and rank high on the list of *geohazards* that affect this area. Landslides triggered by the 1692 Port

Royal Earthquake is the earliest, and perhaps the best known, historic record of a widespread landslide activity on the island.

A landslide inventory of KMA prepared in this study contains some 2,321 landslides (Map 1, KMA landslide inventory map). These landslides and their deposits cover 19.786 km^2 (or 3.57 %) of the entire study area. Excluding the Liguanea Plain, landslides cover some 4.77 % of the mountainous area (Table 1).

Table 1. Statistics of Landslide Types

GROUP STATISTICS

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

INDIVIDUAL LANDSLIDE AREAS (sq. meters)

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

PROPORTION OF AREA COVERED BY LANDSLIDES

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

Hillslopes in eastern Jamaica in general, and of KMA in particular, are prone to landslides because of the specific combinations of: the nature of bedrock, including its highly weathered state; geologic structure, dominated by throughgoing faults which are responsible for a large-scale vertical and horizontal displacements of bedrock units; abundant discontinuities in rocks due to an intense development of faults and joints along which alteration and mineralization are common; steep valley slopes, often fault controlled, in the mountainous landscape; earthquake ground shaking, due to islands' tectonic location in the seismically active plate boundary zone; geographic location in the path of tropical storms and hurricanes which provide periodic heavy and intense orographic rainfall leading to water saturation of slope materials; and deforestation as a result of large-scale human interference of slopes to facilitate agriculture, road building and housing needs. Landslides in this area occur both in bedrock (deep landslides) and also in the colluvium that overlies deeply altered bedrock (shallow landslides). The triggering mechanisms include rainfall associated with tropical storms, often-reaching hurricane force and/or earthquakes.

Historic records suggest that landslides in Jamaica, as is the case in other areas also, occur simultaneously with other hazards or, in some cases one hazardous phenomenon trigger another. For example, precipitation associated with hurricane Mitch in November 1998 caused widespread debris flows in KMA. The M5.4 earthquake of 13th January 1993 triggered landslides which, according to available records (Ahmad, 1996), caused more damage than the other hazardous processes. A sum of J$ 2.0m was expended by the Ministry of Construction to clear the roads that were blocked by the landslides triggered by this earthquake.

An extensive landslide activity and related erosion of hillslopes are evident in the landscape of KMA (Ahmad *et al.*, 1993a; Ahmad, 1995). The evidence includes: (1) a majority of steep hillslopes and fault scarps are decorated with old landslide scars; (2) spectacular landslide landforms are preserved; (3) disturbed natural vegetation in unhabitated areas; (4) colluvium covered slopes are common; (5) water courses are strewn with large rock blocks which have created small rapids; (6) relatively wide flood plains are found in the upper reaches of the montane streams suggesting the occurrence of natural landslide dams; and (7) gravel-boulder fans at the mouth of many dry/seasonal streams which may represent deposits of long run-out landslides.

These features are a record of "active tectonic" events, and have developed over a long period of time and may include both pre-1692 events as well as those modifications that have occurred during the last 306 years.

Although landslides are a major geomorphic process in KMA, being primarily controlled by the underlying geology and active tectonics, the landslide hazard is to a large extent a consequence of changing landuse (Ahmad, 1995).

While not every landslide that has occurred in KMA since the time for which historic records are available can be classified as spectacular and catastrophic, the cumulative damage from many relatively small-scale recurrent landslides, especially those along the roads, is more costly than a major slope failure.

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

It has been estimated that during the period 1910 to 1965, some 7.3% of the total expenditure of the Public Works Department, Govt. of Jamaica, accounted for damage-repair costs related to landslides and flooding (Naughton, 1984).

However, information on landslides in KMA is limited, and the significance of landslide activity and its societal impacts on the residents of KMA has not been fully appreciated.

5.0 Existing Landslide Information

Prior to this study a systematic evaluation of the landslide susceptibility at a scale that may be used in landuse planning in KMA was not available. Regional geological maps of the area, Geological Sheets 13 and 18, scale 1:50,000 (Geological Survey Division, 1994 a &1994 b) show a few major landslides and provide information on lithology and structure that may be used to indirectly assess landslide susceptibility. However, these special purpose maps are complex, include a variety of other geologic data, and are, therefore, of limited use to non-geologists. The Engineering Geology Section, Geological Survey Division of the Government of Jamaica (presently known as Mines and Geology Division) has, since its inception, investigated a number of specific landslide events and continue to provide information and advise to the relevant governmental agencies and others concerned. An islandwide identification of areas prone to landslides has been shown on two general hazard maps prepared by Geological Survey Division at a scale of 1: 250,000 (Presson, 1984a and 1984b). Detailed studies on landslides were initiated in 1980's (Ahmad, 1995).

Landslide susceptibility maps have been prepared for only two small areas in St.Andrew by the graduate students at the Department of Geography and Geology, the University of the West Indies, Mona (Naughton, 1976; Maharaj, 1992 & 1993). Since 1990, a number of publications have dealt with landslides (Ahmad, 1989 &1991;McGregor and Barker, 1991;Manning, McCain and Ahmad, 1992; Eyre, 1992; Ahmad and others, 1993; Dalling and Irenmonger, 1994; Ahmad, 1995).

6.0 History and Impact of Landslides in KMA

This section traces the history of significant landslide events in KMA and brings observation upto the present-day. We have found that in Jamaica historical records are indispensable for expanding the temporal window on landslide phenomenon beyond the limited period for which specific data on landslides are available in the scientific literature. The present account is by no means complete and includes only those events for which the available historic data is amenable to verification

The history of landslides and their impact are described with respect to the broad physiographic areas of KMA. In the following description, various lithological units hosting landslides have been identified by symbols used on Map 1, e.g., andesite (EA).

Port Royal Mountains and the Liguanea Plain

An 1827 panoramic view of the St. Andrew's and Port Royal Mountains prepared by De la Beche (1827) clearly shows many landslide landforms in the study area. De la Beche (1827) also recognized that the Recent alluvial sediments of the Liguanea Plain (FD), on which the city of Kingston is located, do not represent a cycle of normal fluvial deposition. Based on the age, thickness, and texture, he classified the sediments of the Liguanea Plain as "*diluvium*" indicating catastrophic depositional events related to large-scale landslides and floods in the Port Royal Mountains and the drainage of the Hope River. Robinson (1963) and Ahmad and Robinson (1994) have also suggested that much of the sediments and boulders on the Liguanea Plain represent extensive slope failures in the catchment of the Hope River, Port Royal Mountains. Matley (1951) has mapped the extent of boulders on the Liguanea Plain. These rock blocks and boulders show little effects of fluvial transport and are generally rhomb shaped. Their present location is either due to very long run-out flow landslides or they are debris flows which were a result of the mobilizing of sediments that had accumulated in the drainage channels as a result of landslides, or a combination of both of these processes. In terms of their composition, the rock blocks and boulders comprise andesites and conglomerates. These rocks are to be found in the Hope River catchment, east of the Liguanea Plain. The following explanation of the origin of Liguanea sediments is by Robinson (1963): "The top beds of the Liguanea gravels are characterized by the presence of enormous boulders, weighing upto 600 tons, many of which have been transported four miles across the Plain from Papine, where the river leaves the mountains. Some of these boulders are striated, and the theory was put forward by Raw (Matley, 1951) that they had been transported by glacial action. However, this is not proven, and the most reasonable theory to explain the presence of the boulders is that they were affected by the three agencies of landslides, storm waters and mudflows. It is more likely that boulders of such a size would become striated through friction with other rocks and boulders."

Lyell (1873), in describing the effects of the 6th June 1692 Port Royal Earthquake in Jamaica has noted:

> "*Mountains shattered.* -- The Blue and other of the highest mountains are declared to have been strangely torn and rent. They appeared shattered, and half-naked, no longer affording a fine green prospect, as before, but stripped of their woods and natural verdure. The rivers on these mountains first ceased to flow for about twenty-four hours, and then brought down into the sea, at Port Royal

> and other places, several hundred thousand tons of timber, which looked like floating islands on the ocean. The trees were in general barked, most of their branches having been torn in the descent."

The anomalous occurrence of thick alluvial deposits and terrace deposits (AT) containing extremely large rock blocks in the upper reaches of the Hope River, Mammee River, Hoghole River, Cane River, Trumpet Tree Gully, and Wagwater River may represent landslide deposits (Map 2, Geology and structure of KMA). A detailed study of these deposits, including age determinations, will perhaps allow for the reconstruction of landslide history and triggering mechanisms.

Landslides in the mountainous terrain of KMA triggered by the 1692 earthquake have been recorded in Sloane (1809):

> "As to the mountains in Leguanee, they fell in several places, and in some very steep; but the steepest mountain that we heard fall, was that at Gallowes, which occasioned much damage."

Although this statement does not mention the specific landslide locations on the Liguanea Ridge, the latest Geological Map of Kingston area, scale 1:50,000, prepared by the Geological Survey of Jamaica (Jamaica Geological Survey Division, 1994a and b) shows that in the same area of Liguanea, as mentioned in Sloane (1809), landslips cover some 0.8 km^2 (80 ha) of the southern slopes of the Liguanea Ridge between Papine and Jacks Hill. Landslides and their deposits cover some 16.89 % of the total slope area of 4.75 km^2. The sub-urban growth, especially upper-income housing, is increasingly taking place in the mountains of Liguanea historically subject to landsliding and major landslide disasters are known.

The landslide at ‘Gallowes’ refers to the spectacular Judgement Cliff Landslide in the Yallahs Valley, St.Thomas.

The M6.5 Kingston Earthquake 14th January 1907 triggered a widespread landslide activity in the Port Royal Mountains and the Tertiary limestone hills bordering the Liguanea plain. These have been mentioned in Fuller (1907), Brown (1907), Cornish (1908), and Taber (1920).

Ground deformation following the earthquake of 1907 was particularly significant in the entire stretch of the land between Downtown Kingston (Railway Terminal) and Harbour Head along Kingston Harbour front where ground water table is shallow. Liquefaction, ground cracks and fissures occurred in the Liguanea Fan sediments. The area around Rockfort experienced landslides on the steep limestone slopes in the Old Prison Quarry. The flow in the natural spring at Rockfort was considerably increased. It is likely that submarine slides have occurred in this area which has led to the lowering of ground surface and hence coastal flooding. This geomorphic change has been documented in all the contemporary historical accounts of 1907 earthquake as "submergence around the Kingston Harbour".

Ahmad (1996) has described the landslides triggered by M5.4 Jamaica earthquake of January 13, 1993. These have been included on Map 1.

This account of earthquake-induced landslides leads to the following conclusions:

i. Earthquakes with magnitudes >M6 affecting eastern Jamaica have a potential to trigger a widespread destructive landslide activity,
ii. Landslide-related natural erosion and deforestation had occurred and,
iii. Formation of natural landslide dams in the mountainous terrain.

Some of the major landslides in the northeastern part of KMA in the Port Royal Mountains and northwestern part of the Blue Mountains in the catchment of Yallahs River are tabulated below. The landslides included in this list were initially reported by Champion (1966) and were verified in the present study and are included in the landslide inventory map of KMA (Map 1). Most of these slides are still active although some are being colonized by vegetation. It would have been possible to determine the rate of landslide erosion and sediment generation in this section of the Yallahs valley if the time period over which these landslides were developed were known. However, landslides along the road cuts are active and contribute a large supply of sediments annually, with slopes underlain by shales and sandstones (ESS) supplying the most.

Table 2: Some major landslides in KMA, based on the data from Champion (1966). Landslide inventory (Map 1) includes these landslides.

Locality	Bedrock	Slipped Material	Approximate Volume (Cubic metres, $m^{3)}$	Probable Cause
1. Strawberry Hill Road	CV, Cretaceous Volc & Metam.	Bedrock	3,058	Oversteepening and road excavation
2. Pottsdown River, East of Halls Delight	CV, Cretaceous Volc & Metam	Old slide deposits	114,690	Oversteepening and earthquake
3. Content Gap	EA, Andesite	Bedrock	1,529	Road excavation
4. Content Gap, St. Peter's Road	Colluvium on EA, Andesite	Colluvium	3,823	Debris flow
5. Yallahs River below Halls Delight	ESS, Shales & sandstones	Shales & sandstones	11,469	Undercutting by Yallahs River
6. Yallahs River below Mavis Bank Fording	ESS, Shales & sandstones	Shales & sandstones	34,407	Undercutting by Yallahs River, fault zone
7. Clydesdale-Cinchona-Westphalia Road	ESS, Shales & sandstones	Shales & sandstones	7.646	Road excavations
8. Other minor slips in ESS, Shales & sandstones	Mainly in ESS, Shales & sandstones	Shales & sandstones	15,292	Mainly road excavations
Total			191,914	

Newcastle, Irish Town, Woodford, Liguanea Ridge and Jacks Hill areas

Following the precipitation associated with hurricanes Flora, 4-7 October 1963, and Gilda, 16-18 October 1973, widespread debris flows and mudflows occurred in the area of Liguanea Ridge (G). The 1973 debris and mudflows caused extensive damage to houses and roads.

On 14th November 1988, an engineered house in Jacks Hill, Upper St. Andrew, and a section of the Jacks Hill Road including a culvert were destroyed by a deep-seated landslide following a brief spell of heavy rainfall and earthquake shaking. The road remained closed for more than six months. The house is located on old debris flow deposits that were probably triggered by the June 1692 Earthquake. In November 1998, a landslide occurred along the road cut immediately southeast of the 1988 failure. It has not been possible to check if there has been any damage to the property. The winter rains of 1998 caused an extensive landslide activity throughout the Jacks Hill area.

Spectacular slope failures are common in the Hope River Valley. In the Enfield area, Gordon Town, large-scale rock falls have occurred in andesites (EA). A large section of slopes in the upper section of the Trumpet Tree gully are disturbed by slope failures. The time of initial occurrence of these landslides is unknown. These are examples of landslides away from the road cuts and are related to natural causes.

Debris flows and rock avalanches have frequently block roads in northeastern St.Andrew. Debris flow resulting from 1988 hurricane Gilbert rainfall that blocked the Newcastle Road below Irish Town. Debris flows originating in the sheared and weathered granodiorites on Norbrook-Woodford Road during 1997 rainfall traveled some 1km downstream into the Sandy Gully. Such long-runout landslides are known in KMA.

In October 1950, Woodford School was extensively damaged by landslides triggered by heavy rainfall and had to be relocated. Landslides at Woodford Hill had previously occurred following 1907 earthquake and rainfalls in 1933 and 1944 (Chubb, 1952). Rockfalls also occurred in this area following the earthquake of 13th January 1993 (Ahmad, 1996).

Stony Hill, Red Hills, Wagwater River and northwestern St.Andrew

In the limestone hills west and northwest of the Liguanea Plain, large-scale landslide features have been mapped. A spectacular old landslip covering an area of some 30ha has been mapped on the northern slopes of Stony Hill (Geological Sheet 13, Jamaica Geological Survey Division, 1994a). In the present study, landslide deposits comprising Tertiary limestone rock blocks and boulders covering an area of some 58ha have been mapped as exotic blocks on a basement of granodiorite (G) and Cretaceous sediments (CV). These occur infront of the Cavaliers fault scarp in northwestern St.Andrew (Map 2). The sources of these deposits are the Tertiary limestone (EL) exposed on the northern slopes of Red Hills. The stability problems associated with the fault scarps in the Tertiary limestone (EL) are best illustrated in the geological sections across Rio Pedro in the Harkers Hall area . This area is some 6km west of Rock Hall in St.Andrew. Geologically, it is the westward continuation of the Cavaliers Fault zone mentioned above. These sections are based on subsurface drilling information and were prepared by the Geological Survey of Jamaica (Dixey, 1954) in connection with the construction of a dam to impound the waters of Rio Pedro. The Rio Pedro valley section exposes a cap rock of relatively competent, but highly fractured and therefore permeable, massive Tertiary limestones (EL) overlying incompetent layers of gypsiferous and lignite bearing clays (ELC) and deeply weathered granodiorite (G). These slopes are prone to failure as limestone slabs slide on the incompetent clays and weathered granodiorite which loose strength following saturation due to heavy rainfall.

Rainfall associated with the passage of hurricane Flora, October 1963, triggered a widespread landslide activity that resulted in serious damage to watersheds, housing and road network. An extract from the Annual Report of the Geological Survey Department (Hughes, 1964) on this damage is as follows:

> "One of the most seriously affected routes of communication was the Junction Road which traverses the island from south to north between Kingston and Annotto Bay: landslides occurred at intervals along the whole length of this road and in some cases there were complete wash-outs. The most spectacular wash-out occurred at Money Hole Corner where a considerable length of the roadway was completely destroyed. An examination of the geological setting of this failure was carried out and it was confirmed that the instability at this point results from the extreme crushing and shearing of the rocks along the Wagwater Thrust which crosses the road at this point. There seems to be no practicable method of stabilizing this corner and the only long-term solution is to re-route the road

> away from it either by means of a viaduct or a causeway across the neck of the corner or by combination of both methods."

Recurrent landslide activity along this road was observed during the tropical storms of 1991(Ahmad, 1991) and winter rains of 1998 which led to road blockages. Landslide on Junction Road that were first triggered by the heavy rainfall associated with 1963 hurricane Flora are still active.

Low-income housing is often severely affected by landslides. A house was destroyed by debris flows near Temple Hall (Ahmad, 1991). The storm of 1991 caused widespread debris flows throughout northwestern St.Andrew. Some of these blocked the roads and also affected the slopes where electricity transmission poles are located.

An example of hurricane rainfall–induced landslides in northwestern St.Andrew is provided by 1988 hurricane Gilbert (Manning *et al*., 1992). Some 478 landslides, ranging in area between 53- 214 m^2, were mapped along 108km of accessible roadway. Most of these slides were debris flows. Landslides with 11% total blockage and 89% partial blockages affected approximately 4% or 4.3km of the total road length surveyed. Debris flows resulted in the removal of some 20,000 m^3 of sediments from an approximately 49,169m^2 of failed slopes along the roads during a period of five days (September 10-14, 1988) in a section of the Rio Pedro drainage basin. This gives a rate of about 4,000m^3 per day.

Landslides have seriously affected the domestic water supply infrastructure in KMA and it appears that excessive siltation in the reservoirs is related to shallow landslides in the deforested watersheds. In some instances water pipelines have been damaged (Ahmad, 1996; Ahmad and others, 1993).

Submarine landslides along the coastal areas of KMA

Indeed the impact of the catastrophic landslides in the coastal areas of the capital city of Jamaica is best illustrated by the spectacular *submarine landslide*, which destroyed the buccaneer town of Port Royal in the aftermath of the MMI X, June 6, 1692 Earthquake. A localized tsunami also occurred following this landslide. The city of Kingston was founded in 1692 on the coastal plain of Liguanea following this earthquake.

The M 6.5 Kingston Earthquake of 1907 caused *liquefaction* and *submarine landslides* in the coastal areas and triggered hundreds of landslides throughout eastern Jamaica including the Port Royal Mountains. A major submarine landslide occurred off the coast at Seven Miles in St.Andrew that caused the breakage of several submarine cables. Submarine landslides were also reported in this area following the M5.4 earthquake of 13th January 1993 causing breakages to TCS-1 digital Cable System and Jamaica-Panama Analogue Cable System some 2km offshore from the Seven Miles Cable Station (Ahmad, 1996). A fish kill was also reported from the Greenwich area of Kingston Harbour following the 1993 earthquake and it has been suggested that this might be due to localized submarine slumping (Ahmad, 1996).

Landslides and siltation in the reservoirs

The reduction in the storage capacity of the Hermitage Reservoir appears to be related to the sediments generated by landslides in the catchment of the Wagwater River. Matley (1951) has shown that the site of this reservoir is underlained by boulders and rock blocks, which appear to be old landslide deposits.

7.0 Perception of the Landslide Hazard

The destructive potential of landslides, damage caused, and their role in the degradation of the watersheds have been summarized above. Sediment supply as a consequence of landslides has reduced the storage potential of water reservoirs. During the rainy periods the water intake for the Mona reservoir is always choked with fine landslide debris. Landslides frequently damage water supply pipeline. Road cuts are prone to slope failures. Slopes made bare by landslides are the sites of accelerated soil erosion and appear to be a major cause of *watershed degradation. Landslide debris frequently chokes the rivers which results in overbank flow and flooding. Landslides recurrently affect agricultural lands, fruit trees and crops. It follows from the above discussion that in KMA landslides are a force to reckon with and should be considered as a serious and recurrent natural hazard in KMA***.**

The general perception of the urban population living on a relatively flat area, however, is that following heavy rainfall landslides will occur on the mountainous roads and are regarded as erosion due to flooding. As far as we know, there is no insurance cover available for landslides.

If a landslide blocks a road, it is the job of the Public Works Department to get the blockage cleared and depending upon the funds available carry out repairs. Since individual landslides are not spectacular events such as a hurricane or an earthquake and only directly affect a small section of the population at any locality, they are regarded as an inconvenience. Moreover, since the indirect effects and economic costs of landslides are not visible to a majority of population, landslides are not regarded as a serious hazard. The society, therefore, tends to follow the NIMBY approach when dealing with this hazard, which is- as long as it is not in my backyard, why bother.

Public interest in landslides is aroused only in the cases of spectacular events that make news headlines because people are killed, injured or buried under the debris. This happens frequently in areas with a high population density. In Jamaica, although landslides are frequent, fatalities and injuries are low because of low population density in hills. However, this picture is changing rapidly. People are moving into hills because of the high rentals in the relatively flat areas of the Liguanea Plain. Traffic congestion has forced people to use hilly roads such as Jacks Hill Road and Skyline Drive. This has resulted in a significant increase in the number of motor cars on the landslide-prone roads. During the October-November 1998 rainfall, it was a common sight to observe road-users greatly inconvenienced by landslides, some were unable to make it to their workplace. In some cases, public and private passenger vehicles were observed to negotiate through active landslides while the road crews were removing landslide debris. Since the public is now more exposed to landslides, the potential for injuries and fatalities has also increased.

Since 1991, death and injury as a result of landslides on the island seem to be a regular news feature.

8.0 Determining the Significance of Landslide Activity

A. Significance of landslide activity

1. Significance is the degree to which a specific hazard has impacted on natural and man-made environment. It would include loss of life, property damage, affect on critical infrastructure, and interference with economic production.

a. The period of time over which the losses from a hazard are examined will influence significance.
b. Some individual landslides can clearly represent significant losses - Nevado Huascaran avalanches (Peru) and Nevado del Ruiz lahars (Columbia).
c. More often, individual landslides are not very significant. It is easy to be unaware of a significant loss over time due to the cumulative or additive effect of losses from smaller landslides.

2. Significance permits differentiating between future actions which may save lives compared to actions which may protect property or preserve essential services. The benefits of applying resources to avoid a future landslide can be compared to those for using the same resources in another economic function.

3. Public action to reduce losses from landslides starts with a fuller understanding for cost of failing to take action. When studied, the losses due to landslides:

a. are much greater than expected for both the private and public sectors.

  b. public officials are commonly unaware of the magnitude of these losses. The absence of any centralized recording of such information seems often to be the reasons for this lack of awareness.
  c. Landslides often coincide with other hazards such as floods, earthquakes, and volcanic eruptions. Much landslide damage is under-reported because it is attributed to these other hazard events.
  d. incompleteness or unavailability of records will result in lower estimates of losses than are actually incurred. Where this problem with records exists, the losses need to be identified as being the minimum losses.

B. Elements defining the significance of landslide activity

1. The toll in terms of human life lost to landslides represents a special element to significance. It is a cost which should be represented in addition to monetary costs to define significance. Injuries due to landslides should be represented along with fatalities.

2. Direct costs are those which involve actual physical damage and (or) are related to restoration costs to structures and land impacted by a landslide.

  a. Physical damage would include the loss of agricultural crops as well as the value of destroyed structures.
  b. Restoration costs are limited to the reestablishment of structures, other improvements, and the land to the same conditions and degree of usefulness as prior to the landslide.

3. Indirect costs are any costs associated with the landslide which are not direct.

  a. Relocation of structures or roads would be an indirect cost as would measures taken to prevent or mitigate additional damage.
  b. A major indirect cost is the effect on economic production. Lost wages due to the inability to reach work due to a landslide-closed road, tax losses due to decreased property value, secondary physical effects such as reduced crop production of affected slopes or silting of irrigation systems are all indirect costs to economic production.

C. Methods for determining significance

1. For the area being examined, significance should be assessed in conjunction with an inventory of past landslides or after such an inventory is completed.

2. Government agency personnel should be contacted. Through interviews and review of records, costs can be compiled for public works, agriculture, and other affected sectors.

3. Historical records held by churches, community groups, and private companies should be consulted as well as old newspapers. It may be worthwhile to interview residents where a landslide occurred to find out about unrecorded affects or details.

4. Developing a complete cost accounting may require estimation. The value of a specific crop may be generally known. By finding out the amount of crop damaged by landslides and relating that to the typical or average value for that crop, the crop loss can be determined.

5. Report the economic impact of individual landslides according to the IAEG format (Cruden, 1989).

9.0 Landslide Loss-reduction Strategies

Interpreting landslide susceptibility maps and implementing landslide risk

reduction

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

1. Landslide Susceptibility Classes- Deep Landslides (Map A), and
2. Landslide Susceptibility Classes- Shallow Landslides (Map B).

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

Landslide susceptibility analysis has been performed using the susceptibility matrix approach of DeGraff and Romesburg (1980). This technique relies on an inventory map of past landslides, and man-made factors that may contribute to landsliding. All the data were analyzed by the geographic information system (GIS) software IDRISI for Windows v. 2.0, running under Windows NT 4.0 (See UDS Publication No. 5).

A. Applying the landslide hazard zonation produced by factor analysis (Maps A and B) requires an appreciation of its advantages and limitations.

1. The zonation discriminates between areas of differing landslide-susceptibility or hazard.
2. The compilation of this map uses data which is readily available or obtained with a moderate amount of effort.
3. The zonation can be completed early in the development process permitting changes in the development planning to avoid costly delays or changes.
4. The zonation is only applicable to regional planning and unsuitable for siting or engineering design. More site-specific and detailed studies are required for these latter purposes.
5. Like all maps or generalizations, the zonation is only as good as the data from which it is compiled. The generalization required to delineate map units means locations with degrees of hazard different from that identified for any particular units are likely to be present.
6. The map does not predict where landslides will occur during a specific triggering event. It represents the differences in the chance of landslide occurrence which can be expected over the long-term.
7. While the differences in degree of landslide-susceptibility are represented by the map units, the reasons why one unit has a certain degree of hazard may be different than for another unit with the same degree of hazard.

B. Role of landslide hazard zonation in regional development planning.

1. Landslide hazard zonation permits landslide risk reduction at a regional level.
2. Regional planning efforts can reduce risk by: a) discouraging new development in hazardous areas, b) removing or converting existing development, c) regulating new development in hazardous areas, and d) protecting existing developments. All of these efforts require knowledge of where the landslide hazard exists.
3. Existing development may be identified within areas of higher hazard. The greater risk of losses posed by this situation makes these areas prime candidates for remedial action to reduce this risk.

    a. Reduced risk can be achieved by changing the existing development. For example, converting residential to warehouse or industrial uses.
    b. Reduced risk can also be achieved by protecting the existing development. Structural strengthening of slopes by walls, deflection dikes to channel debris flows away from vulnerable areas, and regrading slopes is among the measures available for this purpose.

4. Areas where development will proceed despite higher degrees of hazard can include counter-measures or alternative types of development to limit the risk of losses. Requiring these counter-measures has proven effective in reducing future losses to landslides.
5. The cost of landslide risk reduction can be compared to other priorities.
6. Often, landslide hazard information will be combined with other information defining land capability or suitability for regional development.
    a. A variety of ways exist to combine such information into meaningful maps.
    b. Geographic Information systems (GIS) permit rapid analysis of possible combined maps and the opportunity to include non-map information.

C. There are five essential components for an effective and comprehensive landslide risk reduction program: a) conducting studies, b) translating results, c) transferring translated results, d) selecting and using appropriate techniques, and e) evaluating effectiveness.

1. First, scientific and engineering studies are conducted. These studies focus on the physical process of landsliding ranging from where they occur to why and when they will occur. Studies should also examine the impacts of landslides including the effects on human activities and structures.
2. The results of these studies must be translated into reports and/or maps. This shows the extent and nature of landslide hazard and its impacts in a form understandable to non-technical users. The scale of maps should be appropriate to user needs.
3. This translated information must be transferred to those who will or are required to use it. This may mean more than making copies of reports and maps available. It should involve assisting and encouraging use of translated material by participation in educational, advisory, and review services to users.
4. Selecting and using appropriate landslide risk-reduction techniques will implement risk reduction. Techniques will vary from physical changes in construction design to policy changes promoting lower risk. Policy change results from regulation, financial incentives, or education.
5. Evaluating the effectiveness of the risk reduction is the final necessary step. Over time, it should become clear thought monitoring which policies are working, what techniques are effective, and whether additional studies or data are needed for further reduce landslide risk.
6. As part of a landslide risk-reduction program, factor analysis: a) develops scientific data on the landslide process, b) translates this information into a map showing the nature and extent of the landslide hazard, c) facilities transfer through the regional development planning process.

10.0 Construction Effects on Slope Stability

A. The influence of construction activity on slopes results from altering the shape of the slope, changing the groundwater regime of the slope, or altering the character of the soil. Construction capable of inducing landslides may be limited to a site such as for a building, extend along a road, or involve an entire hillslope being modified for mineral extraction.

1. Excavation into a slope removes lateral support to the slope. This may induce a landslide by exceeding the strength of a uniform soil or rock mass exposed or by exposing a rock structure unfavorable to stability. This excavation may be the result of construction of roads or buildings or excavation for mineral extraction such as at a quarry.
2. Placing of fills or structures surcharges the slope. A landslide can result from the inability of the slope to resist this additional force.
3. Compaction of slope materials or placement of structures, which are barriers to groundwater movement, can lead to increases pore-water pressures capable of inducing landslides. Constructed works such as cesspools or poorly connected water lines can also produce this effect.
4. The character of soil used in construction can be altered so that landslides result. A common way this happens is by failing to compact or improperly compacting fills. Another way this can occur is by failing to remove vegetation on a slope prior to placing a fill or allowing vegetative material to be incorporated into the soil fill during placement.
5. The altering of surface drainage on or above part of a slope or a dormant landslide can trigger movement

by influencing water within the material present.

6. In weak, sensitive soils, blasting or equipment vibration can induce at least partial failure.

B. Construction activity can destabilize old landslides. In many cases, the danger is not reactivation of the existing landslide but creating new landslides within the older feature by destabilizing the weak landslide material.

C. Reservoir construction presents a unique means for inducing landslides. The filling of the reservoir will increase pore-water pressure in the material on the reservoir slopes and possibly cause failure. Rapid drawdown of the reservoir due to pumped storage use or dam failure can cause landslide at the reservoir's edge as lateral support is removed faster than pore-water pressures decrease in the soil or rock.

BOX 4: Slope Stability Principles

A. Development of Slope Instability

1. Gravity is the agent or driving force producing slope instability. It acts at a constant rate at all times on slopes. When slope instability is produced by gravity, landslides are the result.
2. The strength of the material making up the slope resists the action of gravity. This prevents landslides from occurring.
3. The balance between gravity acting on the slope and resistance by the slope material usually favors the resisting slope material. When this balance shifts to being equal or slightly favoring gravity, a landslide is imminent.
4. While gravity acts at a constant rate, changes happen which increase the shear stress of gravity as it acts on the slope, reduce the resisting strength of the slope material, or a combination of both. This alters the balance between driving and resisting forces. If the change is sufficiently great, it may trigger a landslide.
5. Slope instability requires triggering mechanisms. These include intense rainfall which temporarily alters the strength/stress relationship in the soil or rock, earthquake ground motion which alters the stress on the slope, or mechanical reshaping of the slope by factors such as river erosion at the base of slopes, human excavation such as quarries, and human loading of slopes by placing materials such as mine spoils.

B. Characterizing slope stability

1. Engineers describe slope stability using the term factor of safety. Factor of safety is the ratio of resisting forces to driving forces.
2. A slope is stable when the balance between driving and resisting forces favors the resisting forces. The slope would have a factor of safety greater than 1.0.
3. A slope is unstable when a slope movement or landslide occurs or is imminent. This happens when the balance between driving and resisting forces shifts to being equal or slightly in favor of the driving force. The slope would have a factor of safety of 1.0 or less than 1.0.

C. The resisting strength of slope materials

1. The resistance or strength of soil or rock materials on a slope are derived from different components.
2. Soil mass strength is usually dependent on two components: the internal angle of friction and cohesion.
3. The internal angle of friction is the steepest angle at which friction between adjacent particles prevents their movement. The size distribution of particles, as well as shape, packing, and mineralogy, present in a particular soil dictates the angle of friction.
4. Cohesion is an attractive force between fine-grained particles. It is especially strong for clay particles

which may have an electric charge.

5. Coarse-grained soils with little or no fine-grained particles derive their strength solely from their internal angle of friction. Their lack or limited amount of strength attributable to cohesion leads to their being termed cohesion-less soils.
6. The binding effect of root masses from vegetation growing on a slope provides a pseudo-cohesion. This may be significant to the strength of coarse-grained soils.
7. Desiccation can impart apparent cohesion to soils due to negative pore pressures.
8. Particle shape, particle roughness, and the distribution of particle sizes present in a coarse-grained soil increase the packing or density of the soil which, in turn, increases its strength.
9. Rock mass strength is derived from the nature of the intact rock and the presence and nature of discontinuities.
10. Intact rock which is composed of fine, interlocked grains or well-cemented particles will be stronger than large, interlocked grains or poorly cemented particles. Rock strength generally decreases as the degree to which a rock is weathered increases.
11. Most rock masses have discontinuities. Typical discontinuities are joints, bedding planes, and fault fractures.
12. The strength of a rock mass will only be equal to the strength of intact rock where discontinuities are absent. Discontinuities cause rock masses to have less strength. They provide planes of weakness in the mass that become surfaces upon which blocks will fail.
13. It should be recognized that strength of rock or soil is estimated in the field based on the classification of the material or values from simple devices. Actual measurement of strength values is done in the laboratory. (Note: It may be valuable to visit a laboratory with geotechnical measurement devices in association with this unit).
14. While generalization always have exceptions, the following generalization relate the effect of discontinuities on rock mass strength: a) filled will reduce rock mass strength less than those which are unfilled, b) open will reduce strength more than those which are closed, c) smooth-surfaced will reduce strength more than those which are rough-surfaced, and d) closely spaced will reduce strength more than those which are widely spaced.

D. The role of water in slope stability

1. Water within slope material can induce instability in a slope. No other condition is more important to the balance between gravity and resisting soil or rock.
2. Water may reduce the strength of the slope materials. Water filling the voids may produce a positive pore-water pressure. The water will force the individual particles away from each other. The reduced grain-to-grain contact decreases the friction resisting gravity. The water has no ability to resist the gravitational force transferred to it under these circumstances. This means an overall reduction in strength for the water-filled mass.

E. Factors producing changes in slope conditions favoring instability

1. Some changes can increase the force, or stress, acting on slope material. This means the driving force is greater after the change than before.

   a. Removing lateral support to part of the slope is one factor. This may result from active downcutting by a stream or erosional oversteepening of a valley sideslope by glacial ice. These represent long-term changes leading to removal of lateral support. Short-term removal of lateral support can result from cutting a road into a slope or an excavation for extracting materials.
   b. Another factor is surcharging the slope. This can result from natural processes such as a landslide depositing on a slope or human activity such as piling of material in mine spoils or fills or placing of a structure.
   c. Increasing water in slope materials by adding water to the slope through irrigation or during intense rainfall or by affecting subsurface drainage by blocking subsurface flow.

   d. Dynamic stress can result from ground shaking during an earthquake, operation of heavy equipment, or use of explosives.

2. Other changes reduce the strength of slope materials.

   a. Most slope materials lose strength from natural weathering processes such as wetting and drying, disintegration of granular rocks, hydration of clay minerals, dissolution of cementing agents and other long-term physical or chemical weathering processes.
   b. Increased water may raise pore-water pressure within materials. This can be the consequence of intense precipitation or snowmelt. Diversion of surface flow or reservoir filling can produce the same affect.
   c. Increased water may result from conversion of vegetation from higher to lower transpiration rate plant cover, leaking water transmission systems, and sewage disposal.

BOX 5: The Role of Vegetation in Slope Stability

A. The role of vegetation in slope stability

1. All vegetation types may have an effect on slope stability, but woody vegetation such as trees is the main type affecting landslides.
2. Vegetation influences slope stability by either affecting the hydrology or mechanical properties of the slope.
3. The slope steepness of landforms undisturbed by land use activity has developed with vegetation being a factor.

B. Vegetation's influence on slope hydrology

1. Vegetation can have a beneficial effect on slope stability by: 1) reducing the amount of precipitation available for infiltration through interception by the foliage and 2) lowering pore-water pressures by roots extracting moisture from the soil.
2. Vegetation can have an adverse effect on slope stability by: 1) increasing infiltration capacity through increasing ground surface roughness and soil permeability, and 2) increasing infiltration capacity by enhancing soil moisture depletion leading to greater desiccation cracking in the soil.

C. Vegetation's influence on soil mechanics

1. Vegetation can be beneficial to slope stability by: 1) increasing shear strength of soil by the reinforcement of root networks, and 2) buttressing the slope by roots anchoring into firmer strata or acting as piles supporting arching in the soil upslope.
2. Vegetation can adversely affect slope sability by: 1) being exposed to wind on the edge of forest openings transmit dynamic forces into the slope.
3. Vegetation can place a surcharge on the slope increasing downhill force. This is usually an insignificant component but can in special cases lead to either a beneficial or adverse effect on slope stability.

11.0 Site-specific Landslide Investigation

A. Successful site-specific landslide investigation begins with pre-field work. This includes gathering existing information about the landslide and site conditions. Geologic maps, aerial photos, and previous field reconnaissance notes which may be available would be examined. The other pre-field works is to gather the proper equipment needed for the investigation. This may be as simple as getting a notebook and arranging for transportation or as complicated as getting seismic and survey instruments and arranging for a several day field camp.

B. There are two main objectives for site-specific landslide investigation: a) to define the landslide feature, and b) to define the environmental factors influencing its development.

1. The amount of detail will be governed by the need.
2. A preliminary investigation or reconnaissance may be sufficient for an overall understanding of landslides in an area. The field study will be largely based on visual evidence with selected surface measurements.
3. An intensive study is more appropriate in defining the means for stabilizing a landslide or determining whether further movement is likely. More detailed surface measurement will be coupled with subsurface investigation by indirect (geophysical methods) or direct (excavation/drilling methods) examination.
4. The extent of the area to be studied will be larger than the actual landslide. This permits the landslide to be referenced to the stable area surrounding it. It may be necessary to examine a larger area around a landslide because:

    a. conditions on the slope next to or above the landslide may be important to understanding why it developed;
    b. if it is active, over time it may enlarge. Studying an area two to three time wider and longer than the feature is a useful rule of thumb.

C. There are several key elements common to defining an existing landslide.

1. One element is the surface expression of the landslide. This would include the boundaries of the feature, the parts of a landslide present, and the nature of ground disturbance in the landslide mass.
2. Second element would be the material involved in the landslide and the nature of its movement. This information in conjunction with the surface expression evidence will permit identification of the landslide type.
3. The third element would be the inferred depth to the failure plane or zone of rupture. The angle of the zone of rupture exposed at the headscarp, thickness of the material at the toe, and angle of crack surfaces within the landslide mass provide information which can be interpreted to infer the depth to the failure plane.
4. The state of activity of the landslide or parts of a landslide if it is very large should be another element.

D. Investigation should identify environmental conditions bearing on the development of the landslide and influencing its future activity.

1. The bedrock at the site should be determined. Its lithology, nature of discontinuities, inclination, and stratigarphy are all relevant factors.
2. If the failure is wholly within soil, the nature of the soil should be examined. Items such as the particle sizes present, absence or presence of buried soil horizons or stratification, and relationship of bottom of root zone to failure plane are worthwhile to note.
3. The steepness of slopes above and below the landslide and the probable slope steepness prior to the landslide are valuable to know.
4. Surface and subsurface water often have a bearing on the existence of a landslide. Whether surface water was directed into the failed area and whether springs or seeps are present within or outside the landslide give some indication of its role in the landslide.
5. Evidence suggesting past instability at this site or human-caused ground disturbance which may have contributed to the failure are worth noting.

E. Investigating the nature of a landslide and environmental factors influencing its development depends on careful ground survey.

1. Site information should be collected and related to a topographic map of the landslide and adjacent area.
2. The boundaries of the landslide, cracks, seeps, and bulges can all be noted on the map.
3. Environmental factors such as outcrops of local bedrock, drainage, and human-related disturbance can also be noted.
4. Excavation of pits or trenches and drill hole information can be located on the map.
5. Cross-sectional profiles from the map can project the angle of exposed rupture surfaces to infer the failure plane. Ground water levels noted from springs, seeps, and poorly drained area can be related to the likely water table within the landslide and surrounding area. Subsurface information gained by trenching or drilling can be used to show the subsurface conditions of the landslide and neighboring slope.

12.0 Site-specific Hazard Reduction

A. Reducing site-specific hazard should involve a close coordination between the geologist and the engineer. The need for site-specific hazard reduction arises from the need to place new development where higher degrees of hazard exist or the presence of an existing development within an area newly recognized as landslide-threatened.

1. Limiting the hazard posed for new development is achieved through the design of soil or rock slope.
2. Reducing hazard to existing development requires stabilization of landslides or control of potential failure activity.

B. Three basic strategies exist for designing slopes in soil and rock to limit the hazard posed to the new development. Both the nature of the development (road, structure, dam) and site conditions will dictate the suite of measures capable of producing stable cut and fill slopes.

1. First, avoid the problem by changing the location or the design aspect which creates the increased hazard, remove the unstable materials, or bridge over the unstable area.
2. Second, reduce the driving forces. Changing the grade, draining surface or subsurface water, and reducing weight are typical actions.
3. Third, increase resisting forces. Draining subsurface water, installing buttress or counter-weights, and installing strengthening elements are common measures to accomplish this result.

C. The geologist must provide site-specific information on the potential for landslides to ensure the engineer chooses an appropriate strategy. In some cases, this information may be collected under an expert systems approach where the availability of technically trained personnel is limited.

D. Where landslides threaten existing development or landslides have occurred, remedial measures are necessary. A variety of remedial measures exist to reduce hazard to existing development. The appropriate actions to take are highly dependent on the nature of the particular landslides and associated site conditions.

1. Selection of an appropriate remedial measure depends on: a) engineering feasibility, b) economic feasibility, c)legal/regulatory conformity, d) social acceptability, and e) environmental acceptability.

    a. Engineering feasibility involves analysis of geologic and hydrologic conditions at the site to ensure the physical effectiveness of the remedial measure. An often-overlooked aspect is making sure the design will not merely divert the problem elsewhere.
    b. Economic feasibility takes into account the cost of the remedial action to the benefits it provides. These benefits include deferred maintenance, avoidance of damage including loss of life, and other tangible and intangible benefits.
    c. Legal-regulatory conformity provides for the measure meeting local building codes, avoiding liability to other property owners, and related factors.
    d. Social acceptability is the degree to which the remedial measure is acceptable to the community and neighbors. Some measures for a property owner may prevent further damage but be an ugly eyesore to neighbors.

   e. Environmental acceptability addresses the need for the remedial measure to not adversely affect the environment. De-watering a slope to the extent it no longer supports a unique plant community may not be environmentally acceptable solution.

2. Landslide mitigation measures generally fall into four major categories: a) avoidance, b) water control, c) excavation and d) retaining structures.

   a. Avoidance is the best means for mitigating landslides. However, it usually is best applied prior to development. As a remedial measure, it would mean not rebuilding or restoring an area damaged by a landslide. The Mameyes area of Ponce, Puerto Rico had the houses and debris removed after the 1985 disaster and the area left as a park and memorial to the victims.
   b. Water control is often critical due to the role of water in slope instability. It may involve surface water only, groundwater only, or both. Surface water can be kept from a landslide of unstable slope by diverting surface flows, conducting them through in a pipe or lined ditch. Sealant such as swelling clays, concrete, or similar material can prevent infiltration of surface water. Mitigation seldom involves only one category of control. Regrading of the landslide surface to seal cracks and eliminates depressions which collect surface water may be combined with the measures previously mentioned. Groundwater can be controlled by longitudinal trench drains which intercept groundwater flow above the site or drain the landslide. Some trench drains may be counterfort or perpendicular to the slope direction. Horizontal wells, vertical pumped wells, and vertical drains are also used to remove groundwater from a landslide.
   c. Excavation following a landslide is often confined to removing slide material affecting use of a site. It can be an effective means of stabilization, too. Complete removal of the landslide is a drastic but effective excavation. One of the less expensive excavation methods is to remove the head of the slide to reduce the driving force on the remainder of the slide mass. Regrading and slope reduction is another alternative. This places the slope at angle suitable to the angle of repose for the material. Benches on a hillside can provide stabilization in a similar manner to regrading.
   d. Retaining structures are usually restricted to the toe of a landslide. One type of retaining structure is a wall. They come in a wide variety including gravity walls, cantilever walls, counterfort walls, buttressed walls, concrete or timber crib walls, gabion walls, and sheet pile walls. Compacted earth butresses may be placed at the toe of a landslide to prevent further movement. Fills may be reconstructed with reinforcing material ranging from welded-wire elements and geotextile elements to geotextile-wrapped.

3. Debris flows require special remedial measures due to their rapid movement and tendency to impact area far removed from their source. Remedial measures can be applied to debris flow source areas, transportation zones, or deposition areas. In source areas, removal of material or water control similar to that applied to other landslides is the general approach. In the transportation zone, debris flows may be diverted by deflection walls, channeled into other areas, or conveyed over critical structures. Debris catchments are the common methods to remediation in the deposition areas. Sabo dams and similar structures are used to protect structures by slowing down or stopping flows.

E. The geologist must provide the information on the nature of the landslide hazard (whether potential or existing) and other geologic site condition to ensure a stable design or suitable counter-measure is developed for a site.

1. Landslide information important to the design is the type of movement to be expected, the depth of the failure plane, the nature of the failure plane, the geometry of the landslide, the location and probable movement of subsurface water near and within the landslide, the role of surface water in the failure, the triggering action, and the probable failure sequence and likely recurrence.
2. Site information would include the nature of soil and rock, the nature of surface and subsurface water, the existence of other slope-forming processes, and topographic controls on remedial actions. While detailed study is desirable, simple methods may prove adequate for some less-demanding designs.

13.0 Post-disaster Assessment and Monitoring

A. Post-disaster assessment is needed to: a) determine whether additional danger or damage is posed in landslide-affected areas after a triggering event, and b) identify conditions associated with landslides which might provide more information on how the process operates in a specific area.

B. Site inspection immediately following a landslide disaster is needed to determine whether to evacuate individuals or property threatened by the existing failure or its expansion and to determine if conditions are safe enough to permit previously evacuated individuals to return.

1. This evaluation must consider the type of landslide, the physical extent of the failure, the presence of ground cracks or other features indicating additional areas capable of failure, whether movement has ceased, and whether the triggering mechanism is still acting at that location.
2. The potential area affected must consider the area immediately affected by the existing failure and any likely expansion as well as possible secondary effects at some distance from the landslide site. For example, a landslide damming a stream in an unpopulated valley may pose more danger by causing flooding downvalley than a landslide which has impacted an industrial area in an urban setting.
3. Post-disaster assessment of landslides identifies the extent of damage attributable to this hazard which better defines its significance.
4. Establishing a monitoring program may be necessary to establish the long-term threat posed by large, slow-moving landslides or where only partial movement has occurred in the slope.

C. Examination of landslides caused by a specific triggering event can provide data for establishing specific relationships between site characteristics and the likelihood of failure.

1. This is especially important for identifying ways in which human activities may be altering the nature landslide-susceptibility of the area.
2. The depth to failure plane, speed of movement, size of displaced material, areas of deposition and runout and other data on recent landslides serves as a basis for better predicting the effects and affected sites of future landslides.
3. The performance of site-specific practices to prevent landslides or stabilize slopes can also be assessed to see whether changes in design criteria are needed.

14.0 Assessment of the Seriousness of Landslide Damage to Buildings; Advise on the Safety, Evacuation and Relocation of the Occupants of a Building

In Jamaica, landslide hazard is widespread. However, prediction of landslides is very difficult, as the processes that cause landslides are many and variable. Slopes with apparently no landslide activity at the present time may become unstable in response to human interventions and natural processes, such as, earthquake ground shaking and/or heavy and persistent rainfall which are a common feature in Jamaica. Therefore, it is extremely important for individuals to become familiar with the ground conditions and telltale signs that may indicate future landslide problems.

House owners, occupants of public buildings, and local civil authority (Parish Disaster Coordinators, ODPEM) may use a landslide damage intensity scale to assess the seriousness of landslide damage to a building, threat of landslides, and to guide them in making decisions regarding the safety of the occupants. The importance and need for this type of decision making became obvious, for example, during the landslide damage in Kingston related to the earthquake of January 13, 1993, and January 4-5, 1998 landslides in Port Antonio. On both of these occasions, a quick decision was needed to advise the residents to vacate houses/ buildings and the extent of such relocations and evacuation.

Alexander (1986) has proposed the intensity scale given below. It is generally applicable to ground movements resulting from subsidence, and rotational and translational landslides. The various features indicating ground movements may easily be observed in built areas. This scale should not be used to assess damage resulting from debris/mud flows, debris avalanches, and rock falls, which are generally fast-moving landslides, and may overwhelm a building in relatively short time. Once the seriousness of damage has been established, repairs/reconstruction/relocation may be undertaken on the advice of a qualified geotechnical engineer. Local disaster preparedness authority may use this scale for their routine hazard assessment and also encourage managers of public utilities/schools/hospitals/police stations/private house owners/businesses etc. to check their interests as a routine practice. This exercise should be mandatory for the official disaster shelters. The data on types of repairs, expenditure incurred on repairs, and monitoring of post-repair building performance should also be recorded. The completed forms may be stored in a digital database for further analysis, and an evaluation of advice.

This format may be modified to suit the individual needs.

Intensity Scale for Landslide Damage to Buildings (Modified from Alexander, 1986)

The following data should be collected.

A. Date of inspection; grid reference based on 1:50,000 Jamaica metric topographic maps; name and affiliation of person completing the form.
B. Details of the building; including name and address of the owner; use; age of the building, value of the property; type of construction; location of the building in relation to the slope; insurance on building and contents.
C. Details of the damage. Use photographs/ sketches in support.
D. Details of the landslide. Use photographs/ sketches in support..

Monitoring activities

E. Details of repairs carried out, cost of repairs.
F. Reoccupation of the building and subsequent problems, if any.

Intensity Scale for Landslide Damage to Buildings: Grade Damage Level Explanations

0	None	Building and surrounding ground intact.
1	Negligible	Hairline cracks in walls or structural members; no distortion of structure or detachment of external architectural details.
2	Light	Building continues to be habitable; repair not urgent. Minor cracks, especially around door and window frames. Minor settlement of foundations and retaining walls, distortion of structure and inclination of walls are not sufficient enough to compromise overall stability.
3	Moderate	Walls out of plumb; or substantial cracking has occurred to structural members, or foundations and retaining walls have settled during differential subsidence, state extent and amount; floor appears tilted, apply rolling marble test; doors and windows jammed; some damage to surrounding ground and car parking facilities; building requires evacuation and rapid attention to ensure its continued life.
		Walls out of plumb; open cracks in walls; fracture of structural members;

4	Serious	fragmentation of masonry; differential settlement compromising foundations; floors ruined by heave; retaining walls, boundary walls and fences may have collapsed; surrounding ground and car parking areas severely affected; overhead water tanks cracked; drainage pipes choked. Door and window frames too distorted to use; internal partition walls will need to be replaced; occupants must be evacuated and major repairs carried out.
5	Very Serious	Walls out of plumb by 5 to 6 degrees; structure grossly distorted; differential settlement has seriously cracked floors and walls or caused major rotation or slewing of the building; wooden buildings are detached completely from their foundations and ground buckled. Partition walls and brick infill will have at least partially collapsed; roof may have partially collapsed; outhouses, porches, and patios may have been damaged more seriously than the principal structure itself. Occupants will need to be rehoused on a long-term basis, and rehabilitation of the building will probably not be feasible.
6	Partial Collapse	Requires immediate evacuation of the occupants and cordoning of the site to prevent accidents with falling masonry.
7	Total Collapse	Requires clearance of the site.

15.0 Landslide Monitoring Techniques

A. Monitoring may be part of post-disaster assessment or it may be an activity associated with other landslide investigations. In either instance, monitoring attempts to gather information useable for avoiding or reducing the impact of landslide activity.

1. Successful monitoring requires defining several elements of the program.

    a. The objective of the monitoring must be identified. Is monitoring merely to establish whether the landslide is moving or is the question really how fast or when is the landslide moving?
    b. The data to be collected needs to be specified. This follows from the objective. If the objective is determining the speed of movement, it is necessary to collect how much movement over certain periods of time to establish the rate of movement. If the objective is knowing when the landslide moves, it is sufficient to know whether movement occurred or did not occur at certain time intervals. It is also necessary to decide the units of measurement and the degree of accuracy needed.
    c. Completing the objective and specifying the data needed narrows the choice of instrumentation. Other considerations such as expense, location, availability, and reliability will influence the final choice.
    d. The final program element is assigning responsibility for the installation and data collection. This should include deciding the period of time over which this monitoring will occur. Documentation of the program and the installation and measurement is vital to ensure changes in personnel will not result in lost or incorrectly obtain information.

2. Monitoring need not require expensive of technologically sophisticated equipment. Simple and inexpensive methods exist for obtaining most measurements which can be made using sophisticated equipment.

    a. Establishment of permanently marked points for repeated photography of surface changes is a very inexpensive monitoring method.
    b. Other devices involve measuring displacement between stakes or other stable makers or the change in orientation or tilting of trees or buildings on the landslide.
    c. Some monitoring may involve using standard techniques for monitoring rainfall or groundwater level changes at the landslide site.

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