British Geological Survey

University of the West Indies

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Overseas Geology Series

DFID Project No. R6839

Landslide hazard mapping: Jamaica case study

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Front cover illustration: Small landslide along mountain road, Jamaica

Keyworth, Nottingham, British Geological Survey, 2000

EXECUTIVE SUMMARY

The British Geological Survey has undertaken a programme of research on landslide hazard mapping under support from the Department for International Development. The aim of the studies has been to develop a generic approach to landslide hazard modelling that can be applied and adapted in developing countries worldwide. The overall goal of the research is to prevent or minimise the loss of life and damage to property, infrastructure and livelihoods caused by landslides. To this end, case studies in four countries have been used to develop a rapid, inexpensive method for the production of regional landslide hazard maps. This report presents specific results and findings from the Jamaican study area in the Rio Minho.

Conventional landslide hazard mapping involves expensive, time-consuming ground surveys and sub-surface investigations. It is essential for site specific studies that support new infrastructure development, but cannot be justified for wider regions. This report describes an alternative approach that does not provide site-specific information but instead depicts broad zones of hazard for a whole region. The resulting hazard maps do not show the actual hazard for any particular location, but they can be used as a guide to planning and to help select sites for detailed follow-up studies. The method is based on the principle that the past is the key to the future. It uses a landslide inventory for the study area that shows where landslides have already occurred. This is compared to a range of possible controlling factors, depicted in a series of thematic maps. The degree of control exerted by each factor, such as geology or elevation, is evaluated. The thematic maps are then reclassified in terms of landslide susceptibility and combined to produce the final hazard map.

The method achieves savings in time and costs through the use of remote sensing and Geographic Information Systems (GIS). The landslide inventory is created through the interpretation of aerial photographs or satellite images, with a minimum of necessary field checking. The manipulation of the thematic map data and its statistical analysis is carried out in a GIS. Developments in computing and Earth observation systems mean that these methods can now be used on inexpensive personal computers affordable in development projects. In Jamaica, the small scale of the landslides that occur means that only aerial photography can be used to produce the inventory. Satellite data with sufficient resolution are now becoming available, such as those from the Ikonos satellite, but this was not the case during the main phase of this study. The most important controlling factors on landslide occurrence are the geology, depth of weathered material, slope steepness and faulting. Most slides are shallow debris slides involving weathered bedrock material over certain lithologies. It is therefore probable that these formations possess lithological characteristics that promote deep weathering and make them vulnerable to landsliding when triggering events such as intense storms occur, particularly in areas with steeper slopes.

This report is aimed at people and organisations in Jamaica that are concerned with, or affected by, landslides. It discusses local issues that affect the development of landslide hazard preparedness strategies in individual countries. The accompanying map is a first attempt at mapping the regional landslide hazard in this part of Jamaica. It can be improved through additional local knowledge and the incorporation of more data on possible controlling factors, for example. Ultimately, the success of the project can only be judged by the take up, use and development of the hazard map in Jamaica.

CONTENTS

1 INTRODUCTION

1.1 Background

This report is one of four resulting from a research project on landslide hazard modelling undertaken by the British Geological Survey with support from the Department for International Development (DFID). It describes work undertaken in Jamaica in order to develop a methodology for mapping landslide hazards rapidly and cost effectively over wide areas. Parallel development work on a contrasting style of landslide in Slovakia is described in a separate report (O'Connor *et al.*, 2000). The resulting strategy for landslide hazard preparedness is set out in Greenbaum *et al.* (2000) and summarised in Marsh (2000).

Landslides are a common natural hazard throughout much of the developing and developed world. They occur when extreme events such as heavy rainfall or earthquakes trigger mass movement of ground that is only marginally stable. On a human time scale, landslides occur infrequently and tend to be regarded as unusual occurrences. However, from a geological perspective they are nothing exceptional and probably form the main erosional process in many regions. This makes it possible to examine their distribution in space and time in comparison to a range of triggering factors and potentially unstable surface materials. Statistics can then be used to predict the likelihood of such events occurring in the future in a particular location. This is the rationale behind landslide hazard modelling.

In conventional landslide hazard modelling, expensive and time-consuming ground surveys and sub-surface investigations are used at the local level to produce detailed, site-specific maps for use in planning. These are essential where major new infrastructure or other developments are planned in a region prone to landslides. However, the approach is too expensive and slow to be used over wide areas. This research project has developed an alternative approach aimed at producing regional landslide hazard maps quickly and at low cost. It uses information that is either readily available for many countries, or can be easily obtained. The approach is based on the principle that the past is the key to the future; landslides are most likely to happen in areas where the conditions that caused past landslides pertain today. Remote sensing is used with limited field surveying to map existing landslides. Their distribution is then compared to that of a range of ground conditions and triggering mechanisms to understand why they occurred where they did. Finally, this understanding is used to classify a map of these same factors over a wider area in terms of landslide hazard.

The resulting maps may not be as reliable as those produced by conventional ground surveys but they at least provide a preliminary indication of hazard over a whole region. They can be used for general planning purposes, and to guide the siting of more detailed, local ground investigations. This report details the application of the hazard modelling approach to the landslides in the Jamaican study areas, the Rio Minho. It gives the regional setting, describes the type of landslides that occur, sets out the remote sensing methodology used to map them and the GIS methodology used to model the hazard. The resulting hazard map is also presented.

1.2 The Impact of Landslides in Jamaica

Landslide hazards are a major societal, economic and environmental concern to Jamaica. Natural geological, geomorphological and climatic conditions (principally rainfall events associated with tropical storms and hurricanes) act in combination to cause the widespread development of landslides across the island. The landslide hazard is also likely to be exacerbated in future years because of changing land use. For example, the encroachment of building and infrastructure development on ever-steeper marginally stable land, and continued clearance of natural vegetation cover to yield increased productive farmland, is a natural response to increasing population pressure. However, these factors are likely to go hand-in-hand with increased problems of slope instability.

In Jamaica, landslides have caused death and injury and have damaged or destroyed rural settlements, public and private property, roads, bridges and culverts, water pipelines, electricity and telecommunication transmission lines and cables, and agricultural land and crops. The causes of accelerated soil erosion on the island are also intimately linked to landslide-related mass wasting of slopes (Gupta, 1975; Manning *et al.*, 1992). Due to a lack of information, the cumulative direct and indirect economic cost and social impact of Jamaican landslides cannot be easily quantified, and much of the damage attributable to landslide movements remains undocumented (Ahmad, 1995). Since landslides are often the secondary consequence of triggering events such as hurricanes, severe storms or earthquakes, their damages and costs tend to be subsumed within the effects of these often more dramatic and conspicuous events. However, the cost of landslide-related damage is likely to be high. For example, Hubbard and Fermor (1972) and Naughton (1984) noted the extent of rainfall-induced landslides and pointed out that the cost of repairing damage is a significant burden on the country's economy. It has been estimated that throughout the Caribbean, some US$15 million are spent annually to repair the landslide damage to roads alone (DeGraff *et al.*, 1989).

1.3 Landslide Hazard Maps

As in many other parts of the world, landslides constitute one of the most common and important erosional processes that shape Jamaica's landscape. Science and technology are some way from allowing us to forecast when and specifically where, a particular landslide will occur. However, we do have a sound understanding of the factors (such as geology and lithology, slope steepness, rainfall, etc.) which control the general development of landslides. Using appropriate analytical techniques, this knowledge can be used to identify those areas or zones in any given terrain that are most susceptible to slope movement. The regional occurrence and distribution of existing landslides will reflect the occurrence of the combination of factors that resulted in the slope failures. If those causal factors can be identified, recorded, measured and mapped, then comparison of the distributions of different factors allows the identification of areas with varying potential for, or susceptibility to, future landsliding. This is the logic of the approach to regional landslide hazard assessment and the preparation of regional hazard maps. Landslide hazard maps display the extent of potentially threatening landslide events across a region by showing divisions or zones reflecting the scale or intensity of the landslide hazard (hazard zonation). This zonation is based on statistical analysis of acquired, areally distributed base-line data (the landslide inventory and identified controlling factors). These maps are also referred to as landslide potential or susceptibility maps.

A variety of hazard assessment techniques exist that should prove suitable to a wide range of situations, depending on the extent of the area under consideration, the type of landsliding and available base-line data. In the present study, and of particular relevance to developing countries, methodologies for the rapid assessment of landslide hazards have been developed. These are suited to a variety of terrain conditions and enable preliminary hazard maps to be prepared quickly at reasonable cost. Using these methodologies, a landslide hazard assessment and hazard map was prepared for an area of some 375 km^2 in the landslide-prone terrain of the Rio Minho basin, in Jamaica's Central Inlier.

1.4 A Hazard Preparedness Strategy

Although earth scientists and engineers may undertake assessments of landslide hazard, the responsible government authorities or departments must apply the available information through appropriate planning policies and other precautions. Sensible planning in hazardous terrain involves developing policies and practices that mitigate the effects of the hazard. In areas affected by slope instability problems, landslide hazard assessments and the preparation of landslide hazard/susceptibility maps provide a sound basis for strategic and regional planning aimed at mitigating the effects of threatening landslide events. Landslide hazard maps are of great value to development planning as they present a spatial division of the ground into areas of different levels of potential threat (landslide hazard zones). It is these divisions which provide essential frameworks for land-use planning, building regulations and engineering practices.

A landslide hazard preparedness strategy requires government administrators and the general public to appreciate two things: the scale of the existing landslide problem; and the potential for hazard assessment to assist in dealing with the problem. The Office of Disaster Preparedness and Emergency Management (ODPEM) is the agency mandated by the Government of Jamaica to execute all disaster management activities within the island. Through the offices of ODPEM, the Government has recently carried out a review of the policies regarding hazard mitigation, with a view to developing a comprehensive and regional policy. To date, there are a number of on-going initiatives but currently no structured framework that guides mitigation approaches. However, continuing efforts are being directed towards this aim. The reports and maps derived from the current study are aimed at providing information of assistance to those charged with incorporating landslide hazard mitigation into a planned comprehensive hazard mitigation strategy for Jamaica (and other countries with similar landslide hazards). The objective is to increase awareness of the methodologies for rapid, landslide hazard assessment as an aid to assessing and planning for landslide hazards, and the relative cost-benefits of these techniques. The landslide hazard map of the Rio Minho study area accompanying the report may also be used to guide development and land use planning in this part of the Central Inlier.

The study findings for the Rio Minho basin may be viewed as a source of information to complement the comprehensive analysis of landslide hazards in the Kingston Metropolitan District completed in 1999. This was undertaken as part of the Caribbean Disaster Mitigation Project (OAS/USAID). Maps and publications related to the Kingston (KMA) study can be found on the Caribbean Disaster Mitigation Project (http://www.oas.org/en/cdmp/) and the University of the West Indies, Unit for Disaster Studies (UDS) (http://isis.uwimona.edu.jm/uds/index.html) web sites. The KMA maps, reports and information on landslides throughout the Caribbean area are also available there. Landslide hazard maps, and seismic and flood hazard maps, have also been prepared for an 11 km stretch of a land corridor lying inland from the south coast of Jamaica between Kingston in the east and Negril in the west. Further information and contacts (Mr Rafi Ahmad) may be found on the UDS web site.

2 JAMAICAN GEOLOGY, LANDSCAPE AND LANDSLIDES

2.1 Regional Setting and Climate

The island of Jamaica lies within the Caribbean region, between latitudes 17½° and 18½° north and longitudes 76½° and 78½° west. It forms part of the Greater Antilles, whose other major islands are Cuba, Hispaniola and Puerto Rico. Jamaica occupies a central location with respect both to the Caribbean islands and the mainland of North and South America.

The island has a tropical maritime climate, modified by land and sea breezes such as the north-east trade winds. Temperatures are warm and equable throughout the year and rainfall is relatively high; however, the distribution of average annual rainfall is strongly influenced by terrain. The primary rainfall peak is October/November with a secondary peak in May/June. Heavy rainfall often occurs in the summer and autumn months when the rains brought by the trade winds are augmented by convectional storms generated during these hotter periods. The major dry period is from January to March. The north-east, windward side of the island receives most rain with an average of over 250 cm per year, with the high exposed slopes of the Blue Mountains experiencing over 500 cm annually. Areas in the west-central part of the island also experience annual average rainfalls between 180-250 cm per year. These figures contrast markedly with those of the southern coastal lowlands that receive less than 125 cm per year, being in the rain shadow of the central mountains and uplands.

Jamaica's geographical position also makes it very vulnerable to hurricanes and other tropical depressions, especially during the hurricane season from August to November. The great majority of recorded hurricanes tend to track WSW to ENE, or SW-NE across the island from origins in the mid-Atlantic. Hurricanes and tropical storms may bring rainfall of over 30 cm in a 24-hour period. The rainfall is generally of short duration and high intensity; however, rainfall associated with stationary weather systems and tropical depressions may be intense and prolonged. On 12 September 1988, the most devastating hurricane of the century, Hurricane Gilbert, tracked across the length of the island, slightly south of centre, at a more-or less constant speed of 24 km per hour. Wind speeds reached 184 km per hour with a maximum recorded 24-hour rainfall of 45 cm. The hurricane caused widespread flooding, landsliding, extensive damage to property and infrastructure and 45 hurricane-related fatalities. Approximately 1 million people were evacuated from their homes and the resulting damage and economic loss was estimated at $J4 billion.

2.2 Geological Framework

Tectonically, the island is located within the central section of a 200 km wide, seismically active, left-lateral strike-slip Neogene deformation zone that marks the plate boundary separating the North American and Caribbean Plates. The relative motions of these plates since the Neogene (c.23 million years before present) are distributed across major boundary faults and are manifested as compression and uplift in the Jamaican region.

Geologically, Jamaica evolved in the early Cretaceous period (124-65 million years before present) as an island arc terrain, an environment that was somewhat similar to the present day volcanic arc of the eastern Caribbean. At the end of the Cretaceous, the sedimentary, volcanic, metamorphic and igneous rocks of this period underwent uplift and subsequent submergence. This resulted in the deposition of fine and coarse clastic sediment and an impure yellow limestone (Yellow Limestone Group) during the early Tertiary (Table 3.1). As submergence continued, this was followed by extensive deposition of a pure, white limestone (White Limestone Group) during the middle to late Tertiary (mid Eocene-mid Miocene times, c.50-10 million years before present). After this period, extensive uplift followed by folding and faulting affected the entire island. Following uplift, most of the White Limestone areas underwent dissolution weathering, giving rise to distinctive karst topography which reaches its fullest development in the Cockpit Country of west central Jamaica, and the development of associated bauxite-rich 'terra rossa' soils. The coastal formations, deposited around the still-submerged margins of the island during the Pliocene and Pleistocene, comprise marls, limestones, sands, gravels and reefs. Some of these have been elevated up to 200 metres above sea level by subsequent folding and faulting during the Quaternary. The coastal plains are covered with loose sandy, gravelly and deltaic deposits derived by erosion from the high ground of the interior. Some of these Quaternary deposits, that today make up the coastal plains, are derived by large debris flow fans incorporating material eroded from the elevated formations inland.

Vertical and horizontal displacements, resulting from neotectonic uplift and compression, along the northwest-southeast and east-west aligned faults have resulted in the present-day mountainous topography, manifested as a complex " block and belt" structure (Robinson, 1994). Faulted and dissected Tertiary White Limestone hills and plateaux dominate two thirds of the land surface of the island. However, the uplift and erosion has resulted in exposures of the older Cretaceous/early Tertiary rocks (comprising volcaniclastics, limestones, andesites, mafic rocks, low-grade metamorphics, serpentinites and granodiorites) which form the mountainous spine of the island. The early Tertiary rocks occur in a tectonic belt (the Wagwater Belt) in eastern Jamaica, with the Cretaceous rocks exposed in a number of inliers scattered across the island. Geological complexity and uplift are both greatest in the Blue Mountain Range at the eastern end of the country. In the middle of the island, Cretaceous rocks exposed in the 'Central Inlier' give rise to east-west trending, generally rugged and deeply dissected mountain ridges. It is within this zone that the study area for the present project is located.

Faults are the most prominent structural features in Jamaica. In the Tertiary White Limestone cover they produce spectacular escarpments and control the orientation of karst features. These features are more difficult to delineate within the other lithological units, particularly where weathering has resulted in the rounding of major topographic features, and few escarpments are observed. Therefore, it is likely that fault structures in the Cretaceous inliers may be far more complex than are presently indicated on available geological maps (Fenton, 1979).

2.3 Seismicity

Earthquakes are a sporadic but constant threat to Jamaica and some 400-500 shocks each year are recorded by the University of the West Indies (National Atlas of Jamaica, 1989). Although lying in a seismically active region, the majority of the earthquakes are usually of low intensity. However, two devastating earthquakes have occurred in historic times. The first was in 1692 and resulted in the virtual destruction of Port Royal, when most of the town slid underwater and 2000 persons were believed killed. The second occurred in 1907, destroying much of Kingston with the loss of 800 lives. Other earthquakes of lesser magnitude, whilst not catastrophic, have also resulted in damage and disruption to infrastructure. For example, Ahmad (1995) describes more than 40 landslides in the parishes of Kingston and St Andrew being triggered following an earthquake of Duration Magnitude 5.4 in January 1993.

Seismic hazard zonation maps are prepared by the Seismic Research Unit, and are accessible via the World Wide Web (http://www.oas.org/en/cdmp/document/seismap/jamaica.htm). They indicate that an earthquake of expected Maximum Mercalli Intensity 7-8, with 10% probability of exceedance, is likely within any 50-year period. The hazard probability zones increase from MMI 6-7 in the western half of the island to MMI 8+ around Morant Bay near the easternmost edge of the island.

2.4 Landscape and Landslides

Jamaica has geologically young landforms, steep hillsides, high annual precipitation and periodic short-duration/high-magnitude rainfall from tropical storms and hurricanes. These factors, in combination with the geology and tectonic setting of the island, give rise to a landscape prone to a high incidence of landslides. The landslide distribution pattern is not a random one. Rather, it reflects those areas where particular lithological, structural and topographical influences act in combination to promote slopes susceptible to movements when triggered by excessive rainfall events, earthquakes and/or disturbance by human activity. Landslide occurrence may be described broadly in terms of the three major neotectonic landforms (or morphotectonic units) which characterise the island, namely:

a) the Alluvial Plains;
b) the highly dissected Limestone Plateau; and
c) the Interior Mountain Ranges.

Quaternary alluvial deposits mainly occur as narrow alluvial plains fringing the upland landforms, chiefly along the south coast, or along the interior river valleys. Landslide incidence in these essentially flat-lying areas is low and generally restricted to small slides and slumps associated with undercutting of the riverbanks. However, the Quaternary deposits may be prone to liquefaction, as was evident during the earthquakes of 1692 and 1907.

The highly dissected and faulted Tertiary limestone plateau forms most of the central and eastern parts of Jamaica, covering 60-65% of the island's surface area and lying between 700-1000 metres in elevation. Common failure types in this terrain include rock falls, rock topples, rock slides, debris flows and debris slides. The plateau fringes the interior mountain ranges. Some of the most spectacular and damaging landslides in the island have their origin in the faulted contact between the plateau-forming Tertiary limestones and the underlying, less competent Cretaceous and early Tertiary rocks. In these localities, slope movements may involve the deep-seated failure of large limestone blocks (block slides), sliding along planes of weakness at their basal contact with the weaker underlying strata.

The interior mountain ranges comprise the most landslide-prone terrain in Jamaica. The Blue Mountains dominate the eastern end of the island and reach elevations of over 2000 m within 20 km of the coast. The central and western mountain areas are lower, with only a few peaks above 900 m. However, the terrains are both rugged with steep slopes, prominent ridges and fault-controlled incised river systems. The Cretaceous-early Tertiary sediments and volcaniclastic rocks of these areas comprise a range of lithological types, which can vary markedly over small areas, and are generally deeply weathered. Slope movements are dominated by landsliding in the zero-order drainage basins characteristic of the neotectonic landforms (Ahmad, 1995). Common failure types are rotational and translational slides involving weathered bedrock and shallow debris and earth slides and flows. Rock and debris falls are also often encountered, particularly where disturbed by the building of access roads. The generally steep slopes are also very prone to landslide movements following removal of the natural forest cover.

For detailed information on landslide hazards associated with the mountainous eastern zone of the island, the reader is referred to the comprehensive series of maps and reports prepared for the Kingston Metropolitan Area (KMA). These form part of the Caribbean Disaster Mitigation Project (UDS Publications 4 & 5, 1999). The focus of the present study is the occurrence and assessment of landslide hazards in the interior mountain ridges of the Central Inlier, centred on the Rio Minho basin. This is discussed in the following sections.

3 THE RIO MINHO STUDY AREA

3.1 Local Setting of the Study Area

The Central Inlier extends across the parishes of Trelawney, Upper Clarendon and St. Catherine; its length is 54 km from west to east, with a maximum width of over 12 km. The area under study forms part of this Central Inlier and extends some 34 km from Spaldings in the west to Bellas Gate and Juan de Bolas in the east. The study area, approximately 375 km^2 in extent, encompasses exposed Cretaceous rocks bounded by Tertiary limestone hills and drained principally by the Minho and Thomas rivers (Figure 3.1).

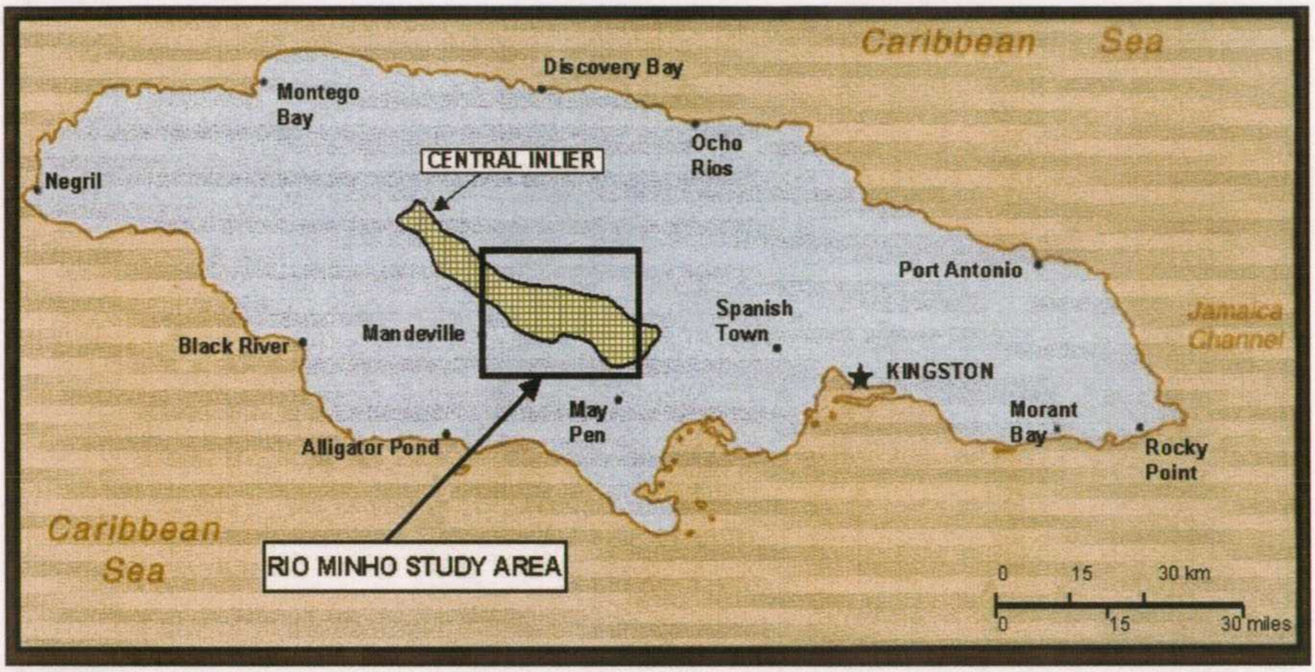

Figure 3.1 Location of the Rio Minho study area, central Jamaica

An estimated 40,000 people live and work within the study area boundary, the majority being engaged in agriculture. Small individual farmsteads and rural settlements of less than 500 persons (e.g. Guinea Corn, John's Hall, Nine Turns, Colonels Ridge, Crawle River and Connors) are scattered throughout the area. Larger settlements of between 500 and 2500 persons extend along major access roads, or have developed at major junctions. These include Beckford Kraal, Pennants, Kellits and Rock River. The bustling town of Chapelton (population 5000-10,000) near the confluence of the Minho and Thomas rivers and Frankfield (population 2500-5000) on the main May Pen-Chapelton-Spalding road, are the major settlements in the area.

3.2 Local Geology and Landscape

The Rio Minho basin is enclosed by a high plateau region formed by the Yellow and White Limestone Formations of Tertiary age. It is incised into a WNW-trending ridge and valley system underlain by fault-bounded Cretaceous volcaniclastics and sediments subdivided into six stratigraphic formations (Figure 3.2, Table 3.1). A significant strike-slip fault line, the Rio Minho/Crawle River fault zone, bisects the inlier (Draper, 1987). The topography of the limestone varies from undulating to hilly with sinkhole structure and escarpment terrain in the Yellow Limestone (Mid-Eocene) to 'cockpit country' karstic landscape in the overlying White Limestone zone (Mid-Eocene-Mid Miocene). The Yellow Limestone fringes the major part of the study area to the north and south with elevations generally averaging between 600-700 m, rising to over 900 m at the south-western margin. A small area of the White Limestone outcrops near Spaldings at the western end of the study area, reaching elevations in excess of 900 m. It also occurs in the south-east where elevations are much lower (>300 m). The volcaniclastic terrain is highly dissected with a mainly dendritic to trellis-type drainage system, giving rise to a rounded and angulate ridge and slope physiography. The ESE-WNW trending elongate ridges of Bullhead Mountain (845 m), Main Ridge (c 7-800 m) and Juan de Bolas (833 m) form the highest ground within the study area. First order rivers and, to some extent, secondary river systems are highly meandering whilst third order tributaries are generally rectilinear. Flat-lying alluvial deposits are concentrated in the confluence zone of the Minho and Thomas rivers and the Trout Hall area along the Minho River.

The generalised geology of the study area presented in Figure 3.2 shows the extent and distribution of the major stratigraphical formations and significant faults. The distribution of landslides, identified from aerial photographic analysis, in relation to the geological units is also indicated. Summary lithological descriptions of the stratigraphical formations are given in Table 3.1.

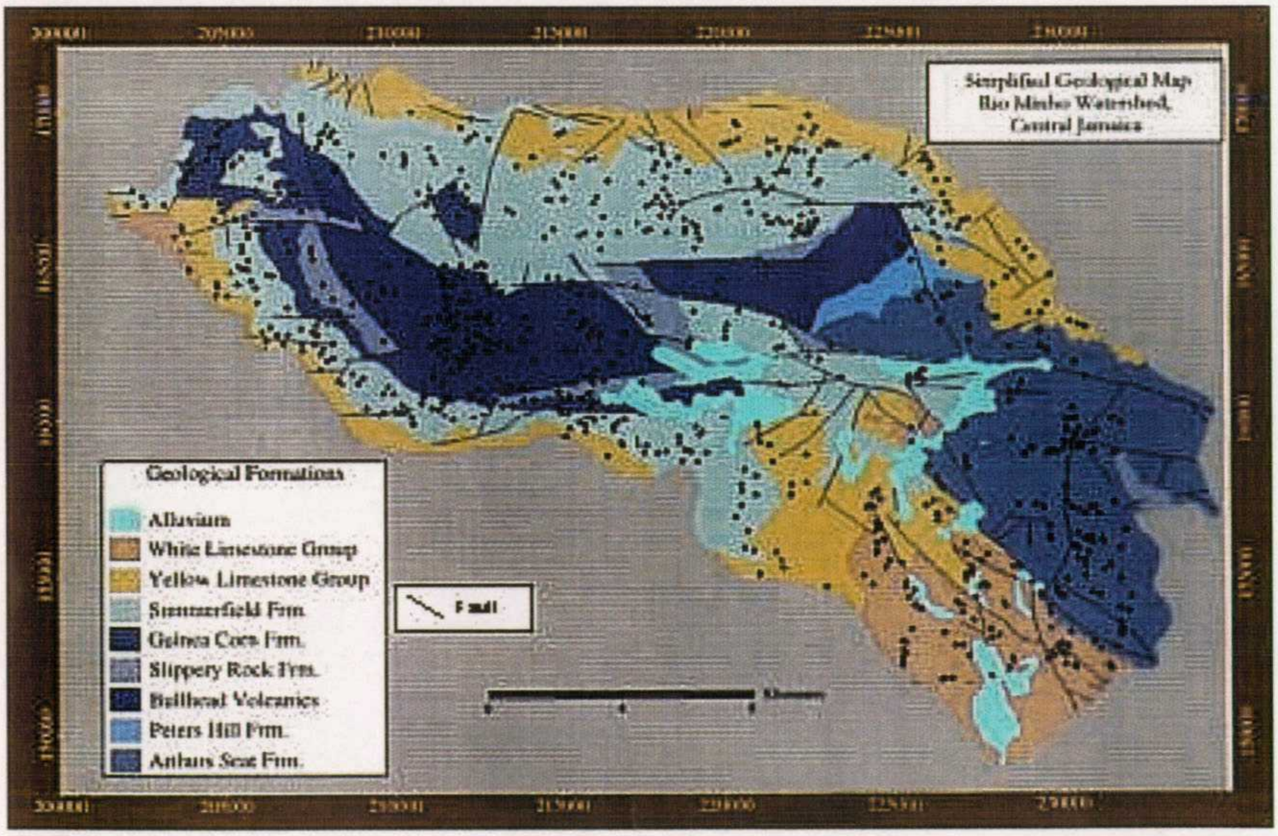

Figure 3.2 Simplified geological map of the Rio Minho study area; landslide occurrences are denoted by the cross symbol

Table 3.1.

General lithological descriptions of the geological formations in the Rio Minho study area

Geological Formation	Age	General description
Alluvium	Quaternary	Generally comprises gravels, sands and silts with subordinate, impersistent silty sandy clay layers and lenses. Main development occurs on flat-lying floodplains of principal rivers.
White Limestone Group	Tertiary	Generally well-bedded, well-jointed, buff coloured to white, hard recrystallised limestone.
Yellow Limestone Group		Complex sequence of moderately to well-bedded sands and sandstones, mudstones, tuffs, marls, red clays, cream coloured bioclastic calcarenites and marly limestones. Many limestone exposures with large limestone blocks and boulders occur within red clays and fine clastic sediments and do not appear to be *in situ* outcrops.
Summerfield Formation	Cretaceous	Thick sequence of alternating, generally regularly-bedded, ignimbrites, volcanic grits, sandstones, and laminated shales, overlain by very coarse, bedded conglomerates alternating with grits and sandstones. Devitrified tuffs occur in two horizons. Rocks are massive to thinly-bedded and moderately to deeply weathered. Steep faults and joints are present throughout the sequence.
Guinea Corn Formation		Limestones, dominantly massive in the upper part, with frequent silts, siltstones, sandstones and shales intercalated with more rubbly limestone in the lower section.
Slippery Rock Formation		Variegated, mainly red conglomerates with clasts of andesitic and basic volcanic rocks, showing channelling and cross-bedding, overlain by a sequence of more evenly bedded siltstones and mudstones, with subordinate sandstones and limestones. Often intensely weathered with colluvium cover of variable thickness containing stones and boulders in sandy, silty matrix with subordinate clay.
Bullhead Formation/ Main Ridge Volcanics		Volcaniclastic rocks and lavas. Intensely weathered and altered andesitic volcanics and volcaniclastics are common, often with colluvium cover of variable thickness.
Peters Hill Formation		Siltstone/mudstone sequence with subordinate sandstones and basal limestone beds. Yellow- and red-weathering shales and grey calcareous shales are common. Some mineralized zones are present along fractures.
Arthurs Seat Formation/Eastern Volcanic Group		Poorly bedded, unsorted epiclastic volcanic conglomerates and breccias, with subordinate lavas, laminated volcanic grits, sandstones and shales with rare basalt dykes and flows. Often deeply weathered.

3.3 Weathering and Soil Development

The bedrock formations in the study area are deeply weathered with the depth of the weathered zone extending up to, and in places probably exceeding, 30 m (Ahmad, *et al.*, 1997). The more competent strata are, for the most part, well-jointed, often with closely spaced, steep joint sets, and have been highly fractured and weakened by the influence of widespread fault movements. These fractures and joints have enhanced groundwater movements and weathering effects to significant depths within the hillside strata. In addition, within the Cretaceous strata, lithologies vary markedly over short distances giving rise to markedly variable weathering depths and weathering products on both a local and regional scale. On the steeper slopes, the uppermost 1-2 m of the hillsides are often covered with a granular colluvium cover consisting of stones and boulders within a finer matrix. This colluvial cover provides a ready source material for debris slides and flows on the valley sides. Apart from the granular colluvial debris cover, which has formed largely from weathering, erosion, hillwash and downslope movement from higher elevations, the soil development on the bedrock units reflects the nature of the materials from which they are derived. Most of the lithosols in the area are residual soils developed in situ from the bedrock they overlie. These lithosols may reach up to approximately 1.5 m in depth but are often much shallower, reflecting both the resistance or susceptibility to material breakdown and soil development and the stability of the soil cover to shallow landsliding.

The distribution of soil types, based on the classification of Finch and Jones (1959), within the study area are shown in Figure 3.3. The general distribution of landslides in relation to the major soil units, identified from aerial photographic analysis, is also indicated in the figure.

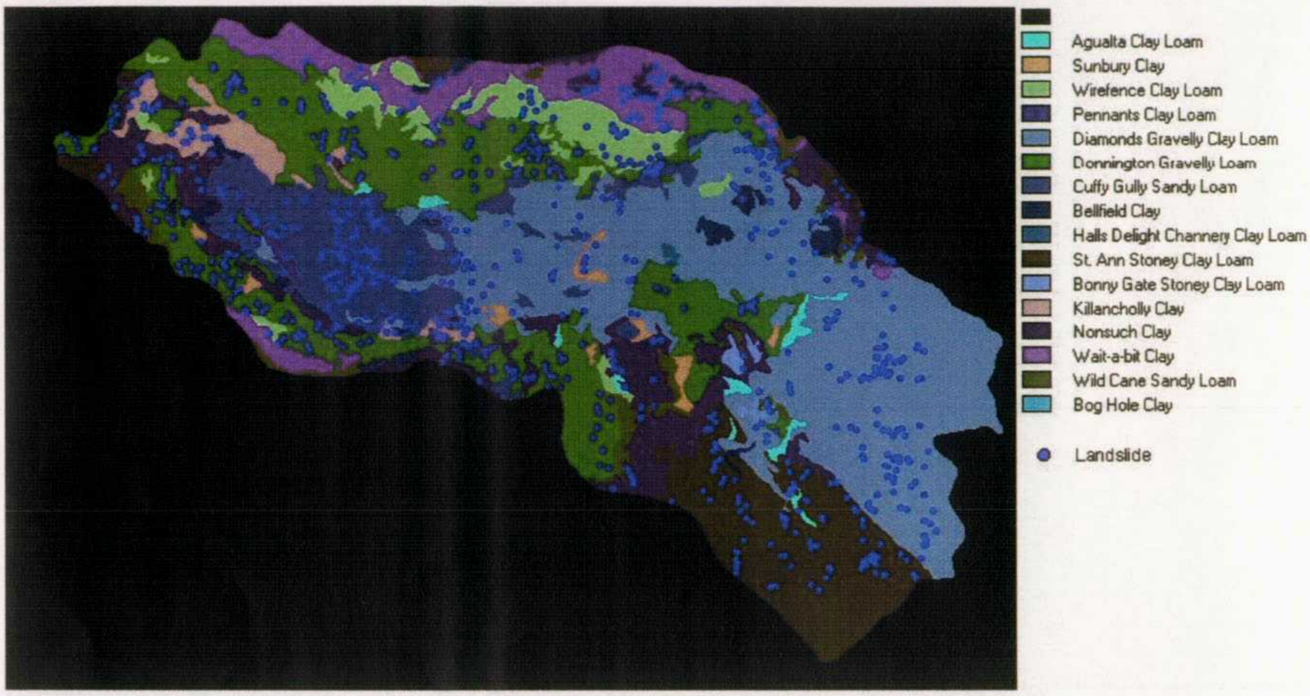

Figure 3.3 Generalised soil map of the Rio Minho area with distribution of landslides (red circles)

3.4 Landslides in the Rio Minho Study Area

3.4.1 Landslide recognition

Landslide recognition and identification for the study was undertaken mainly by aerial photographic analysis, as described in chapter 4. This was supplemented by rapid field reconnaissance of selected areas determined from the aerial photographic interpretation. Additional information was also obtained from published information and local knowledge of landslide types and localities in the area by Mr Rafi Ahmad of the Unit for Disaster Studies, University of the West Indies, the principal project collaborator in Jamaica. Of particular relevance to the current project investigations was initial survey work carried out on landslides in the Rio Minho watershed by Aiden H. Earle, during M.Phil. studies at UWI (Earle, 1991).

The use of panchromatic aerial photography, at a nominal scale of 1:15 000, was an essential tool in landslide recognition, although some difficulties were encountered in the identification of small to medium-sized landslides in thickly vegetated terrain. This was particularly acute along many road routes in steep terrain, where lush tree cover obscured many small landslides associated with the road cuttings. The field reconnaissance also identified a number of fresh landslides that post-dated the 1991 aerial photography used in the analysis. However, the photographic data allowed recognition of the majority of landslides in the study area and, importantly, a realistic pattern of landslide distribution to be obtained. This could not have been achieved by rapid reconnaissance alone due to time constraints and, more particularly, due to restricted vehicular access along suitable roads and tracks. In addition, thick vegetation poses equally difficult problems for landslide recognition on the ground. Recognising old large-scale failures also presents difficulties during ground survey, particularly in steep, rugged volcanic/volcaniclastic terrains with considerable vegetation cover. The aerial photography, allowing a much larger field of view, proved particularly suitable for initial identification of areas of existing, or potential, large-scale slope failures that could be checked during field reconnaissance. Unless confined to important road routes, additional detailed ground survey to enhance details of landslide occurrence, over and above that derived from aerial photographic analysis and rapid, focused field checking, cannot be justified in cost-benefit terms.

The main types of landslides identified during the study are described below. However, no distinction of landslide types was made when compiling the landslide inventory used as a basis for subsequent landslide hazard analysis. This was due to: (i) the difficulties encountered in assessing accurately the aerial extent of the dominantly small to medium-sized landslides in the vegetated, hilly terrain of the study area; and (ii) the emphasis of the project on developing and assessing the technique for rapid landslide hazard analysis. Accordingly, the landslides recorded on the landslide inventory were expressed as 'point source' data, representing the initiation points of individual slope failures identified mainly from analysis of the aerial photography.

3.4.2 Landslide types and occurrence

Analysis of the aerial photographs showed the presence of two major types of slope movements, namely rotational slides or slumps and translational earth/soil/debris slides. Field reconnaissance confirmed this distinction but, in addition, noted the development of rock and debris falls and debris/earth flows.

Rock falls occur most frequently where highly fractured rock occurs along road cuts with slopes greater than 30°. The discontinuity spacing controls the block size and falls are most likely where bedding and joint/fracture planes daylight into the slopes. The majority of these failures are generally no more than 5-10 m in the longest dimension, but are capable of blocking roads, restricting access and, at worse, causing injury to road users. Such failures can occur in almost all the lithological units in the area, but they are most frequently observed in the highly fractured rocks of the Summerfield formation and Bullhead Volcanics. These failures occur as a result of natural erosional processes on steep slopes, and they are often triggered by medium to heavy rainfall and/or seismic shocks. However, the incidence of rock falls has been increased by the modification of slopes for road construction (Ahmad, *et al.*, 1997). It is therefore not surprising that many of these failures can be observed on the steep upslope cuts of road routes.

Rock fall debris on a much larger scale was observed near the southern boundary of the study area where the Summerfield Formation, capped by the fringing Yellow Limestone, forms steep slopes >25-30°. Here, along the Thomson Town - Smithville road, dominantly andesitic, blocks and large boulders line the road and, in at least one instance choke an incised watercourse (Figure 3.4). It is possible that some of these large blocks have been incorporated into large debris slides, but the majority of the blocks appear to be rock falls that have tumbled down slope from failures at higher elevations. Landslide movements in this area are complex and it is likely that these rock falls are associated with large slide movements, either falling from steep unsupported scarps following initial sliding failures, or becoming detached from blocky landslide debris by erosion.

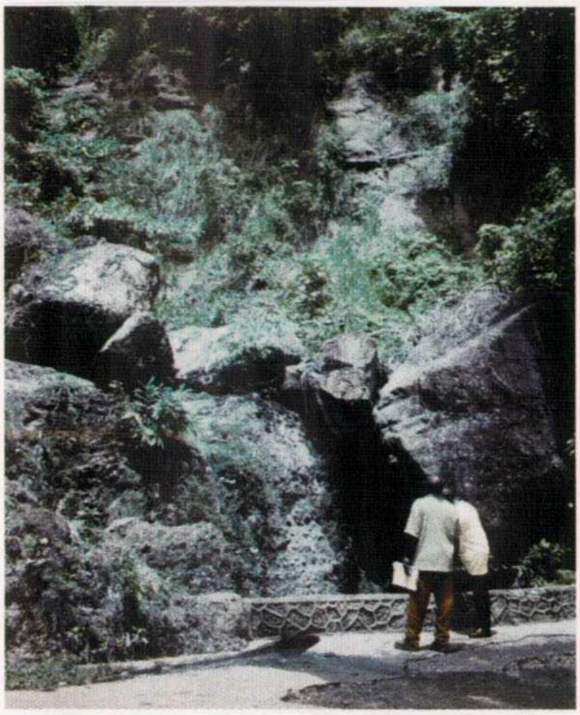

Figure 3.4 Rock fall comprising large rock blocks and boulders that choke the Plantain tributary of the Thomas River, upslope of the Thomson Town-Smithfield road. Water from blocked drainage channel flows across road leading to deterioration of road surface.

Rockfalls are also present in the fractured limestones of the Yellow Limestone Group (e.g. near Fairburn) and the limestones of the White Limestone Group (e.g. near Corner shop, both locations being near the northern boundary of the study area.

Debris falls are common across the area and can occur in weathered bedrock, lithosols and colluvial debris on virtually all lithologies. They are usually less than 5-10 m in the longest dimension and occur on slopes of more than 20°. As with rock falls, they may be triggered by rainfall and/or seismic shock. They are frequently associated with road cuts which tend to cause over-steepening, and hence instability, in the surficial colluvial debris cover which subsequently fails by falling down the face of the cut (Figure 3.5).

Translational slides in debris or earth involve slope movements along planar (or nearly planar) shear surfaces oriented sub-parallel to the slope surface. The shear surface is typically located near the bedrock/colluvium contact, the depth of the shear surface being controlled by the thickness of weathered regolith or overlying colluvium/soil cover, therefore, these failures are generally shallow in nature. With increased water content, debris slides grade into debris flows and may travel large distances. The flows may develop at the toes of debris slides or occur as narrow tongues of debris that are usually, but not always, confined in existing stream channels or gullies. Debris slides tend to occur on slopes greater than about 20° and range markedly in size; however, many have been identified from aerial photograph analysis as averaging some 100 m^2 in overall area. There are undoubtedly much larger debris slides within the study area but degradation and rapid vegetation growth has obscured these features to a considerable extent. Field reconnaissance indicated the probable presence of large debris slide/flow deposits involving weathered conglomeratic sequences of the Slippery Rock Formation near Slippery Rock River. Similar debris slide/flow deposits, largely obscured by vegetation, are also likely in the Summerfield and other formations on slopes in excess of 20° and where detrital slope deposits provide a source of debris material. The aerial photography indicates that many debris slides/flows occur close to the escarpment zone below the fringing limestone, on interfluve ridges and on the lower slopes of second- and third-order river valleys.

Figure 3.5 Small scale rock and debris fall from a steep road cut in volcaniclastic sediments of the Bullhead Formation, Main Ridge. Debris, recently cleared from road, is derived from the weathered, fractured and jointed bedrock and overlying, 1-2m thick, colluvium comprising earth and rock fragments.

Many debris slides and flows, usually of relatively small-scale, occur along road routes and appear to be associated with slope over-steepening and/or disruption of the natural groundwater regime. On the steeper mountain slopes, access roads cut into slopes of 200 or greater are particularly prone to trigger debris slides and flows. Many examples of road cutting-induced debris failures were observed, particularly, in the weathered/fractured rocks of the Summerfield and Bullhead Formations and in rubbly limestones of the White Limestone Group (Figure 3.6). A particularly good example of a debris flow developed within weathered and fractured beds of the Bullhead Formation near Main Ridge is shown in Figure 3.7. Here the cutting of an access road triggered a number of small debris falls and slides in the weak fractured rocks and overlying weathered mantle. The debris flow shown in the figure occurred where a small debris slide, triggered by slope over-steepening, interrupted a small watercourse. The initial slide deposits subsequently developed into a well-defined flow of saturated granular debris.

Figure 3.6 Translational debris slide in weathered and fractured rocks of the Arthurs Seat Formation, adjacent to the Crawle River-Arthurs Seat Road. Over-steepening and removal of support from steep sideslopes due to road cutting results in frequent slope failures of this type.

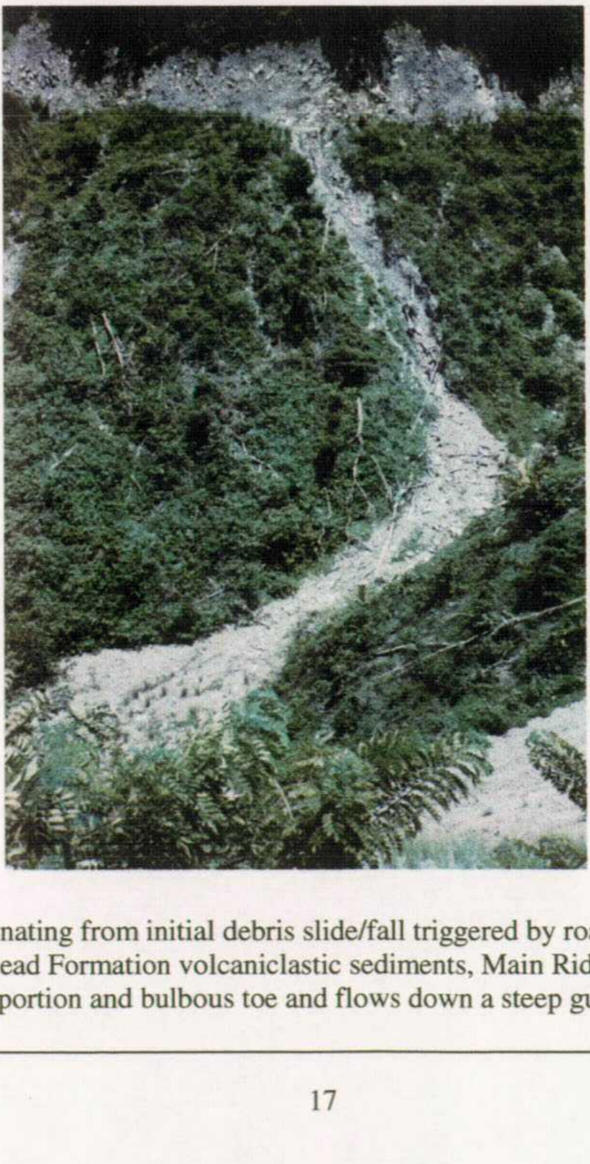

Figure 3.7 Debris flow originating from initial debris slide/fall triggered by road cutting operations in highly weathered and altered Bullhead Formation volcaniclastic sediments, Main Ridge area. The debris flow shows a characteristic narrow mid portion and bulbous toe and flows down a steep gulley leading to the Rio Minho.

Translational earth slides and earth flows occur in finer-grained weathered regolith dominated by material less than fine-gravel size, usually with significant proportions of silt and clay. As with debris slides and flows, rainfall is the most common triggering event. However, unlike granular debris, which is often fairly free draining, regolith dominated by fine material may remain saturated or partially saturated during hot dry seasons at variable depths below ground surface depth. Even during periods of prolonged drought, it is likely that seepage horizons or perched water tables within the slopes will maintain parts of the fine-grained regolith in a wet condition. Thus, movements are likely to occur following rainfall of less duration and lower intensity than that required to trigger debris slides and flows. Earth slides and flows are also prone to remain seasonally active in response to annual rainfall cycles. Earth slides are likely to occur on slopes above 10-15° but occasionally occur on shallower slopes, depending on the clay content of the slope materials and the amount of ground water available. These slope movements are particularly sensitive to removal of vegetation cover and almost all of the earth slides observed during the field reconnaissance occurred in areas where the natural tree/scrub cover had been removed for cultivation. Movements are generally shallow, not exceeding depths of about 1 m for the smaller failures and less than about 5 m in the longest dimension (Figure 3. 8). However, much larger earth slides, often grading to minor earth flow at the toes, were also observed in the Diamonds Gravelly Clay Loam. These overlie the volcanic conglomerates, grits and shales of the Arthurs Seat Formation (Figure 3.9).

Aerial photograph analysis indicated that very shallow earth/soil slides are probably the most abundant forms of slope movement in the study area. These slides probably involve less than 0.5 m of the soil cover and they are dispersed widely across the study area. They occur in regions generally devoid of wooded vegetation, such as savannah grasslands (e.g. Calabash and Longville districts) or in areas stripped of woodland for cultivation. The shallow movements are generally of small size and clustered development is common on steeper slopes (>25°) forming ridges and interfluves in the Main Ridge, Bull Head Mountain and Calabash Ridge areas. At some locations (e.g. Pennantsland, Nairn Castle and Bull Head Mountain) these clustered soil slides tend to give rise to a badlands-type landscape. Such widespread and shallow surficial failures are invariably triggered by rainfall events.

Figure 3.8 Small translational earth slide in clay-rich soil overlying Guinea Corn Formation, adjacent White Shop-Guinea Corn road

Figure 3.9 Complex earth-slide on a cultivated slope adjacent to the Crawle River-Arthurs Seat road. The slide has occurred in Diamonds Gravelly Clay Loam, overlying weathered shales and volcanic grits of the Arthurs Seat Formation. The entire slope shown in the figure shows evidence of active movement. A small, wet, active earth slide is seen in the toe area in the bottom centre of the figure. To the right, not shown, trees lean severely downslope as a result of recent movements.

Shallow rotational slides or slumps (c. 3-5 m deep) were observed at a number of locations in the study area on moderately steep slopes (c. 15°), but appeared to develop much less frequently than planar debris slides. These movements involve sliding along a curved, concave-upwards shear surface, or surfaces, such that the sliding mass sinks at the rear and heaves at the toe. The shear surface may be circular or non-circular in section, the former being more common in relatively thick homogeneous clay deposits, which are rarely encountered in the study area. These shallow slides tend to occur in the finer-grained weathered regolith with significant clay content and generally require a regolith depth in excess of about 2 m for rotational movement to develop. If sufficiently wet, the slipped material may grade into an earth flow at the toe. Frequently, these slides involve more than one phase of movement and develop as a series of multiple slump masses down the slope, yielding a set of characteristic back-tilted 'benches' or 'terraces'. A well-defined example of a shallow multiple rotational slide has occurred at Ivy Store, downslope of the road immediately south of Cross Roads. The slide, initiated in 1986, resulted in abandonment of a small dwelling that was partly engulfed by the slip toe (Figure 3.10). The material involved in the movement is a clay regolith/lithosol (Nonsuch Clay) overlying weathered Yellow Limestone strata (probably red clay and fine clastic sediments). In this instance, increased groundwater flow into the slope may have been associated with blocked drainage culverts and/or increased runoff from the road (Figure 3.11). The section of metalled road immediately west of Ivy Store is characterised by irregular arcuate depressions and cracks that may be indicative of further incipient rotational movements. In such situations it is imperative that road culverts are maintained and cleared of blocking debris so that water can be carried away in designed channels rather than infiltrate the slope materials.

Figure 3.10 Toe zone of a medium-sized rotational landslide that caused destruction and abandonment of a house in 1986 at Ivy Store, near Cross Roads, 1km south of Chapelton.. The slide has occurred downslope of the main road in a clay regolith (Nonsuch Clay) overlying weathered strata of the Yellow Limestone Group (probably red clay and fine grained clastic sediments).

Figure 3.11 Ditch and culvert choked with dirt, leaves and other debris on the upslope side of the main road above Ivy Store landslide. Increased groundwater flow into the slope due to blockage of these water channels and increased run-off from the metalled road surface, may have been critical factors in triggering the landslide downslope of the road. The people in the picture are inspecting a cracked and displaced retaining wall, indicative of further movements in the steep slope above the road.

Aerial photography indicated the presence of much larger deep-seated rotational slides within the study area. These landslides, which are generally arcuate in shape and in the order of c. 120 000 to 490 000 m^2 in area, were difficult to observe clearly during field reconnaissance due to wooded vegetation and access difficulties. These large slide areas are generally characterised by steep backscarps and irregular hummocky toe zones. In some examples, multiple failure movement is indicated by several bench-like scarps downslope of the main backscarp, frequently ending at the toe zones in the valley bottoms. The occurrence of these large slides is rare in comparison to the earth and debris slides/flows that characterise most of the study area. They are located mainly in the steep gorges of the Thomas and Minho rivers and along Moore's Gully tributary. A small number of medium-scale rotational landslides occur on the watershed escarpment zones, in the Calabash Ridge area at the eastern end of the Minho basin. Although generally arcuate in shape, one large slide showed a backscarp section lying parallel to a straight section of the Minho River, suggesting that the movement may be fault-controlled. Indeed, it is likely that the presence of faults, in conjunction with the undercutting erosive action of the major rivers, played an important role in the initiation of these large slides along the main valleys. All of these large landslides are heavily vegetated and are probably currently inactive. Their age is uncertain but the presence of thick a regolith/soil cover able to support a tree canopy implies a considerable time gap since major movements of these features occurred. However, secondary, smaller-scale slump movements at the toe zones of these landslides is likely where river erosion continues to undercut the slide toes.

3.4.3 Landslide distribution

The distribution of landslides, identified primarily from aerial photographic analysis and rapid field checking, was assessed for landslide hazard in relation to six themes: the geology of the study area (Figure 3.2); soils (Figure 3.3); elevation (Figure 3.12); slope angle (Figure 3.13); slope aspect (Figure 3.14); and distance from faults (Figure 3.15). In total, 827 landslides were identified over the study area, representing about 0.55% of the total ground area. Due to the small map scale, the points of landslide occurrence shown in Figures 3.2 and 3.3 do not depict all landslides identified within the study area. Only a representative general distribution of landslide occurrence is indicated. The rapid landslide assessment undertaken for this study did not attempt to distinguish between different types of landslide movements. Because of the steep topography and vegetation cover in the study area, such a distinction could not be accurately made from aerial photographic analysis and rapid field checks alone. This is an important constraint to the study results. Systematic field mapping to accurately determine the distribution of different movement types would be an important next stage in upgrading the preliminary hazard analysis undertaken in the present study.

Landslide distribution and geology (Figure 3.2)

The relationship between landslides and geological units, assessed from statistical analysis within the GIS, is shown in Table 3.2.

Table 3.2
Relationship between landslide occurrence and geology in the Rio Minho study area.

Geological unit	Number of landslides identified on aerial photography	Total area of geological unit (10^6 m^2)	Approximate percentage of landslide area relative to geological unit area
Alluvium	6	19.03	0.08%
White Limestone Group	13	30.95	0.11%
Yellow Limestone Group	86	68.31	0.31%
Summerfield Formation	398	110.3	0.89%
Guinea Corn Formation	34	17.62	0.48%
Slippery Rock Formation	35	14.42	0.60%
Bullhead Formation	123	46.79	0.66%
Peters Hill Formation	19	4.52	1.05%
Arthurs Seat Formation	113	61.68	0.45%
Total	827	375.54	0.55%

Figure 3.2 and Table 3.2 show that although landslides occur widely across the study area, there is a tendency for increased occurrence in certain geological units. Most landslides are developed within the Summerfield, Bullhead and Arthurs Seat Formations with a significant number also identified within the outcrops of the Yellow Limestone Group. However, the number of landslides developed also reflects the areal extent of the formation. When expressed as a percentage of outcrop, the geological units with the most concentrated landslide development are the Peters Hill, Summerfield, Bullhead and Slippery Rock Formations. Many other factors, such as topography, structure (e.g. faults) and lithology and depth of weathering also effect the development of landslides across the area, and areas of landslide concentration (high landslide density) within each formation. As many of the landslides in the area are shallow debris slides involving weathered bedrock materials and colluvium, it is speculated that the aforementioned formations possess lithological characteristics that promote deep weathering and development of a significant colluvial cover.

Very shallow surficial earth slides, usually triggered by intense rainfalls, occurr widely across the area on the steeper (25-45°) and higher slopes of ridges within the Summerfield, Bullhead and Arthurs Seat Formations. On these steeper, higher slopes, the colluvial cover may be expected to be less well developed than at lower elevations, with movements being restricted to the overlying soil cover. In these situations, factors other than the underlying geology are likely to exert more influence over the development of these landslides. These include the depth of soil cover, the development of savannah or scrub vegetation rather than a dense protective and anchoring tree cover, and slope steepness.

Landslide distribution and soils (Figure 3.3)

The soils developed on the weathered bedrock reflect the nature of the parent material from which they are derived. As such, most landslides have developed in, or involve, soils formed over the geological units noted above. Landslide occurrence is very well marked on six of the sixteen soil units developed across the area. These are:

Waitabit Clay	Mainly developed on weathered clays and fine-grained clastics of the Yellow Limestone Group, fringing the northern and southern boundaries of the study area, to elevations of 600-800 m; occurs on slopes ranging from <5 to 20°.
Cuffy Gulley Sandy Clay Loam	Mainly developed on weathered and altered andesitic volcanics and volcaniclastics of the Bullhead Formation in the Main Ridge area to elevations up to 700-800 m. Occurs on moderate to steep slopes generally >20-25°, and present on slopes of 30-45°.
Donnington Gravelly Loam	Widely developed on weathered volcaniclastic sediments of the Summerfield Formation in the Bullhead Mountain to Frankfield areas and in the southern parts of the study area from south and west of Chapelton to the White Shop area; occurs at elevations ranging generally from 200-500 m on a wide range of slope angles form 15-20° to >35°.
Diamonds Gravelly Clay Loam	Mainly developed on epiclastic volcanic grits, conglomerates, sandstones and shales of the Arthurs Seat Formation in the east of the study area, and on volcaniclastics of the Bullhead Formation in the area around Johnnies Hill; occurs at elevations up to 600-700 m (e.g. Calabash Ridge) and on slopes up to 35-40°.
Pennants Clay Loam	Mainly developed on conglomerates, siltstones and mudstones of the Slippery Rock Formation in the Slippery Rock River area to elevations of 500-700 m; present on many slopes ranging from 25 –45°.
Wirefence Clay	Mainly developed on fine-grained volcaniclastics of the Summerfield Formation in the Bullhead Mountain, Nairns Castle areas and, sporadically, on fine-grained clastics of the Yellow Limestone Group; occurs at elevations up to 700-800 m and on slopes up to 25-35°.

The composition and thickness of the soil cover and slope steepness will influence the development of shallow surficial slides. Apart from the Pennants Clay Loam, all of the above soil types occur in areas associated with widespread very shallow earth slides, triggered by high rainfall events (e.g. Main Ridge, Calabash Ridge, Bullhead Mountain, Pennantsland and Nairn Castle areas). These areas are characterised by steep sided ridges of relatively high elevation. The Cuffy Gulley Sandy Loam in the Main Ridge area showed a strong association with the development of these surficial slides. The Pennants Clay Loam also showed a particularly strong association with landsliding. This soil is developed chiefly over the deeply weathered mudstones and conglomerates of the Slippery Rock Formation. Larger debris/earth slides tended to occur in this outcrop in the region around the Slippery Rock River.

Landslide distribution and elevation (Figure 3.12)

The majority of landslides occur at elevations between 370 m and 660 m, with the highest association at elevations in the 730 m to 970 m range. It is appears likely that this high association of landslides with higher elevations is due to the development of widespread, shallow surficial earth slides, because colluvial cover at increasing elevations and steeper slopes is likely to be less well developed. To some extent, this association also reflects the development of the old, large-scale rotational landslides that also tend to occur at the higher elevations and on steeper slopes.

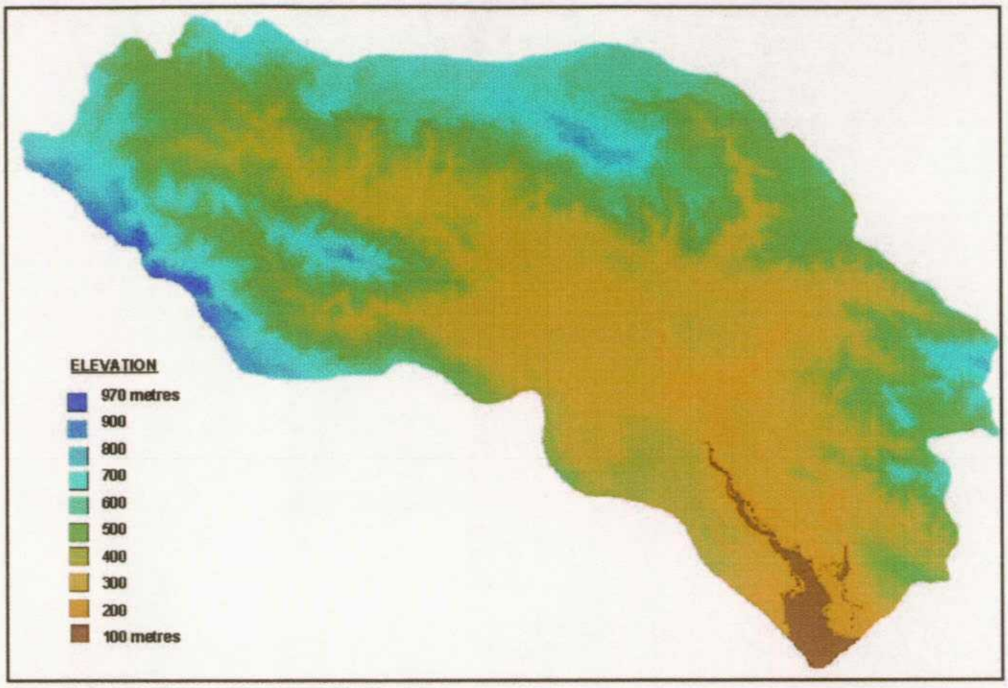

Figure 3.12 Elevation map of the Rio Minho study area.

Landslide distribution and slope angle (Figure 3.13)

The majority of landslides occur on slopes between 10° and 25°, although the areas of highest association occur on slopes between 40° and 45°. Again, the high association of landslides with steeper slope angles is likely to be a reflection of widespread shallow surficial earth slide development on the steeper exposed slopes. The depth of the weathered colluvial cover may be expected to decrease with increasing slope angle, thus promoting shallow surficial slides in a thin soil cover. As with elevation, this association may also reflect the development of old, large-scale rotational landslides on steeper slopes at high elevations.

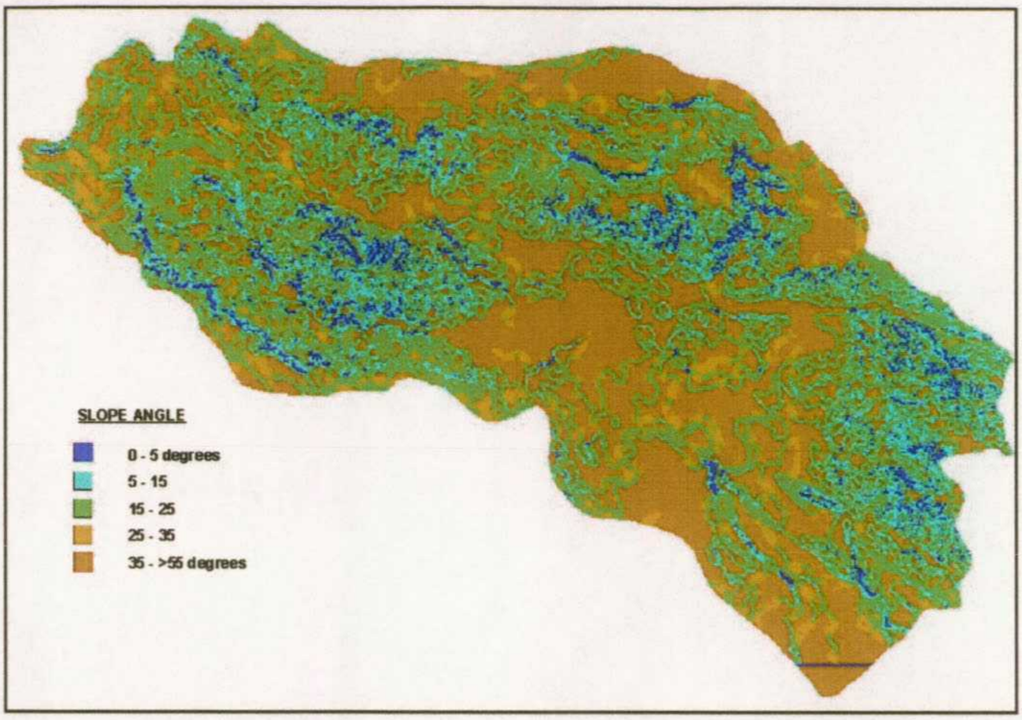

Figure 3.13 Map showing distribution of slope angles in the Rio Minho study area (Calculated from digital elevation model)

Landslide distribution and slope aspect (Figure 3.14)

There is some association of landsliding with slope aspect, with a tendency for landslides to develop preferentially on southeast to east-facing slopes. This is consistent with a directional trigger mechanism such as intense rainfall from tropical storms and hurricanes that most frequently track across the island from the ESE or SSE. This association may be related, in part, to the development of very shallow earth slides in thin soil mantles, which would undoubtedly be triggered by directional rainstorms. The tendency for greater landslide densities on the more easterly-facing slopes is also consistent with observations in more northerly latitudes. In these regions, slopes that face the hotter afternoon sun tend to have higher soil temperatures, lower soil moisture, often less vegetation, and thus more erosion and thinner colluvium (UDS Publication No.5). A reasonable explanation of this pattern may be that slope aspect affects the density of shallow debris slides by limiting the development and thickness of colluvium on the drier slopes. To some extent, this interpretation may also be applicable to the development of debris slides on Jamaican slopes. Deeper-seated landslides are less likely to be influenced by slope aspect, due to the over-riding controls of lithology and structure.

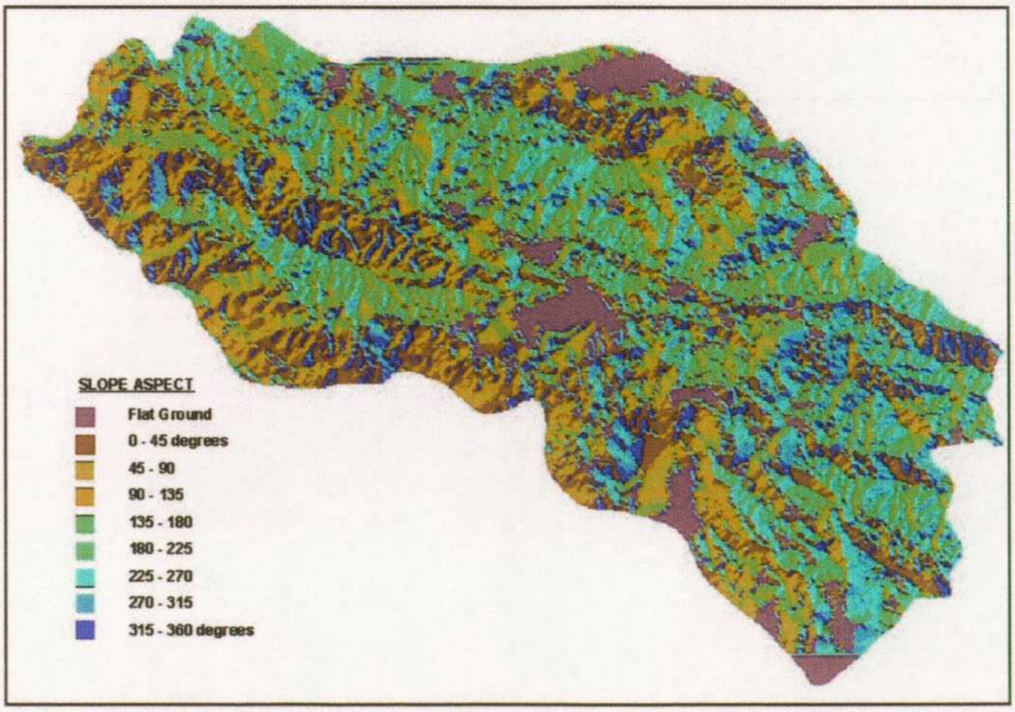

Figure 3.14 Map showing slope aspects in the Rio Minho study area (Calculated from digital elevation model)

Landslide distribution and faults (Figure 3.15)

Throughout the area, the majority of landslide initiation points are less than 1500 m from a mapped geological fault, or structural lineation observed from aerial photography. Faults are abundant within the central inlier and influence landslide development by fracturing and weakening the rock mass, channelling water into the slope materials and enhancing the extent of weathering. No analysis was undertaken to assess variations in landslide densities at specific distances from observed faults. However, it is highly likely that many, if not the majority, of the old, deep seated rotational landslides observed on mountain ridges are closely associated with faults. This was evidenced in at least one landslide by a steep, linear, fault-controlled backscarp paralleling a straight section of the Minho River. Although indicated on geological maps as discrete linear or curvilinear features, faults are usually associated with a fault zone rather than a fault line. Shattered rock and deep weathered bedrock profiles within the fault zone may extend hundreds of metres either side of a mapped fault. Thus faulting controls on landslide occurrence may occur over a more extensive area than generally anticipated. In the Kingston Metropolitan Area (UDS Publication No. 5), a positive correlation was observed between increasing landslide density as faults are approached. Fault controls on shallower debris and earth slides are less clear. By promoting weathering profiles and fractures that can channel water into the slope colluvium, faults may influence the development of debris slides. However, the extent and of this influence within the area is currently not clearly understood.

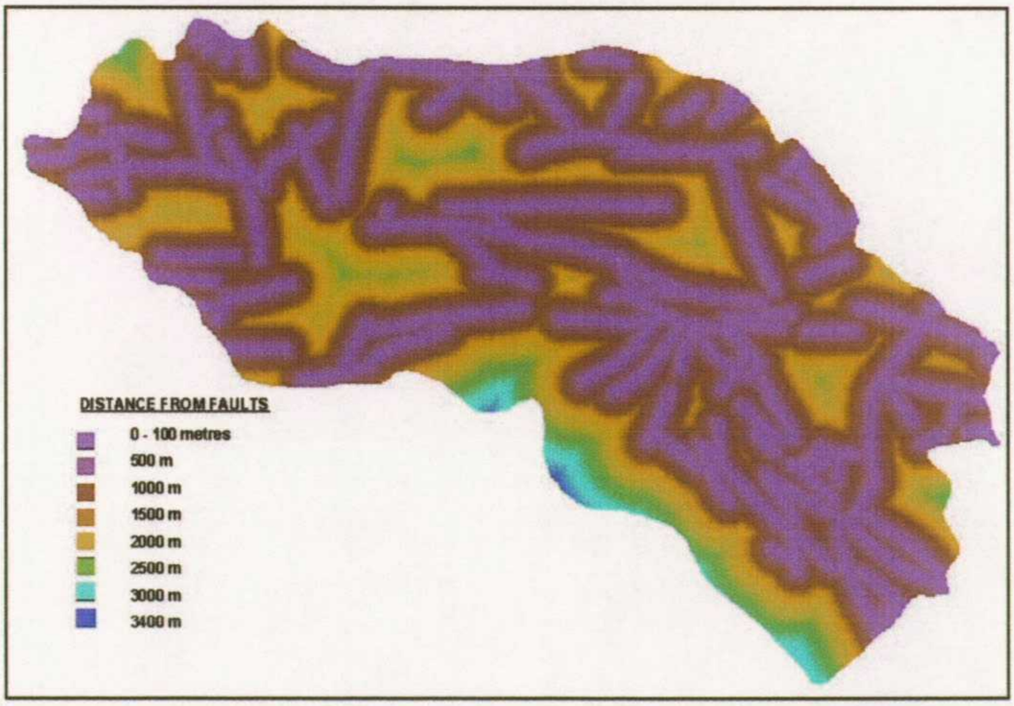

Figure 3.15 Map showing distances from identified faults, Rio Minho study area.

Landslide distribution and roads

Many small-scale landslides (mainly shallow debris slides) recorded on the landslide inventory occur along road routes. During field checking it was clear that many more failures associated with road cuttings were present than could be identified from the aerial photography. This was primarily due to heavy vegetation cover obscuring landslide details. In addition, the field reconnaissance, undertaken in June 1999, confirmed that a number of roadside failures had occurred after the aerial photography was flown (December 1991 – February 1992). As the focus of the present study was on the rapid assessment of landslide hazards, detailed field survey of all roadside landslides was beyond the scope (and funding) of the investigation. However, the landslide inventory compiled during the study was considered to meaningfully represent the general areal distribution of landslides across the study area, and, as such, form a suitable basis for assessing landslide hazard.

Small debris slides, debris falls and minor and rockfalls appear to be closely associated with roads throughout the area. The majority are small failures on the upslope side of roads and tracks cut into steep hillsides or near valley bottoms. Where the roads follow ridge crests, landslides often occur on the hillslopes downslope of the road level. It appears that human actions have caused these landslides mainly by over-steepening of the sideslopes. Ahmad *et al.* (1997) have also noted that unchannelled water flow along the inner shoulders of the road also causes erosion at the base of these cuts to further reduce their stability. In some cases, the debris from these small failures blocks small watercourses or roadside ditches that have subsequently initiated failure downslope of the road/track. On some roads (e.g. near Ivy Store) increased runoff from the road surface and/or blocked drainage culverts has concentrated water flows into the slope materials and initiated movement downslope of the road grade. Arcuate subsidence hollows and small cracks in the metalled road surface immediately east of Ivy Store, appear to signal further incipient movements related, probably, to increased water runoff and blocked ditches and culverts along this stretch of road.

Landslides and vegetation

Hillside vegetation cover, although not assessed in the analysis of landslide hazard in the study area, plays a significant role in hillslope stability. Vegetation enhances slope stability, particularly against shallow landsliding, by mechanical (root strengthening) and hydrological effects (extraction of soil water, increasing soil suction, rainfall interception). Some argue that trees tend to loosen and destabilise the soil slopes due to rocking by winds. Although this may apply in some situations, it is usually far outweighed by the stabilising effects due to enhanced hydrological conditions and anchoring root systems. Removal of natural vegetation, particularly woodland, from hillside terrain will increase the susceptibility of the slopes to erosion and mass movement in the form of debris and earth slides and flows. Many small-scale earth slides were observed to be associated with land cleared for cultivation, and the removal of vegetation for agricultural purposes is likely to increase in future years. Although the increased development of shallow slides in these areas is probably inevitable, the situation can be improved considerably by controlled selective removal of trees and sensible re-planting. For example, well-rooted thick hedges or thickets planted at suitable intervals across cleared slopes can reduce erosion and enhanced stability. On all slopes, but particularly steeper areas, the integration of permanent tree crops such as timber trees and/or potential fodder trees, could contribute significantly towards enhancing stability on cultivated slopes. It would both stabilise the soil and increase the value of the farmed area.

4 THE REMOTE SENSING AND GIS METHODOLOGY

4.1 Rationale

The ability to map landslide hazards rapidly over wide areas relies on a combination of remote sensing and spatial analysis techniques, performed using image analysis and geographic information systems (GIS) software.

Firstly, appropriate remotely sensed data must be acquired for the study area. This is then interpreted to produce a landslide inventory, taking into account any existing information on their distribution and with a minimum level of field checking to support the interpretation. Maps of potentially unstable ground conditions and possible triggering mechanisms are digitised ready for analysis in the GIS. The inventory is then compared statistically to each digitised layer and a weighted significance attached. This is a measure of the association of each surface material with the existing landslides. The weighted layers are then reclassified in terms of landslide susceptibility, before they are combined to form the overall susceptibility map. The hazard can be presented to the target audience in a variety of ways. The risk posed to infrastructure can be assessed qualitatively by including key roads, railways, settlements and other cultural features of interest on the final hazard map.

Image analysis and GIS software is increasingly available at low cost and can be run on inexpensive personal computers. The two methods of analysis are converging, so that image analysis software often contains GIS functionality and vice versa. Both types of software also include sophisticated cartographic output capabilities. Because of the need to know the hazard value at every point on the surface, the hazard analysis is best performed using a raster GIS. These systems operate on grids of contiguous data values recorded for every point in each digitised file. Vector GIS is less suited to this type of spatial analysis because it divides the surface up into a series of discrete vectors and polygons. It is, however, useful for the production of final map output because roads and other important elements of infrastructure can be conveniently displayed as vectors.

4.2 Remote Sensing

Remote sensing covers a range of systems that can be used to provide information about the Earth's surface from satellite or aircraft platforms. The most familiar types of data are colour and black and white aerial photographs. These have been a valuable source of data in geological studies since at least the early-1940s. Similar optical imagery, albeit with much reduced spatial resolution, became available from satellite platforms in the early 1970s. For over 15 years, affordable repeat coverage from optical and radar sensors in Earth orbit has been available to scientists. As sensor technology has advanced, so spatial resolution has increased.

Two main factors guide the selection of data for landslide hazard studies; the scale of the landslides to be mapped and the climate of the study area. Until recently, only the largest landslides could be studied using satellite data because the resolution of the systems in orbit was insufficient. For most of the smaller landslides, data from photographic aerial sensors had to be used in order to resolve the features of interest. New high-resolution satellite systems such as IKONOS are slowly changing this, but for many regions aerial photography are readily available and will remain a key information source for years to come. The main problem with optical imagery is their unsuitability for tropical regions with persistent cloud cover. In such regions radar data, which penetrate cloud, are a valuable additional information source.

Although remote sensing offers a convenient way to map disturbed ground over wide areas, the methodology contains certain assumptions. These are: (1) that landslides can be reliably identified and in a consistent fashion by all researchers in a team; (2) that triggering mechanisms remain the same over time; and (3) that the ground conditions that were previously susceptible to landsliding continue to be so. It is therefore essential that the interpretation is checked against both the existing, local knowledge of the problem and field conditions during the study. Field checks to provide "ground truth" should be a key step in the interpretation, leading to iterative improvements in the landslide inventory as knowledge of the problem increases.

4.2.1 Applicable remote sensing data types in Jamaica

The climate in Jamaica would tend to make radar data the most appropriate data type. Modern C-band fine-beam SAR data from Radarsat was acquired over the project area on 31 January 1998. The data was georeferenced to the Jamaican Grid and processed using speckle filter and frequency domain analysis to suppress much of the noise component. The 6.25m resolution of the data allowed large-scale display and feature analysis (Figure 4.1) However, only the larger rotational landslides could be discriminated on the imagery and the small scale of the main landslide types mitigated against their detection on satellite SAR imagery. Airborne radar was not available. Aerial photography proved to be by far the most appropriate remote sensing data type in this study.

Figure 4.1 RADARSAT, Main Rdge area, Rio Minho District, central Jamaica, Fine beam mode. Approximately 6 m ground resolution. Low Pass filter and contrast stretch. Large scale rotational landslides shown by arcuate radar-shadow features north and south of the Minho river.

4.2.2 Data processing and analysis

Selection of aerial photography as the input data for the landslide inventory creation determines the processing and analysis strategy. In making this choice for Jamaica various routes were eliminated and so will not be considered further in this country-specific report.

It is possible to process the aerial photography in a digital environment. This involves scanning the images and adding information about the orientation of each image in three dimensions. Sophisticated software can then be used to remove the geometric distortions inherent in aerial photographs. This process results in orthophotographs that are true to a map base. At the same time, a digital elevation model is created and the imagery can be viewed in stereo on the computer display. Interpretation can proceed within the digital environment and map-accurate linework can be captured directly. This approach uses relatively expensive computer hardware and software, however, and so it was not followed in this project. It could be considered in the future as costs of software fall. One of the principal advantages is that the digital elevation model, created as part of the photogrammetric process, is one of the data layers that is always required for the GIS analysis.

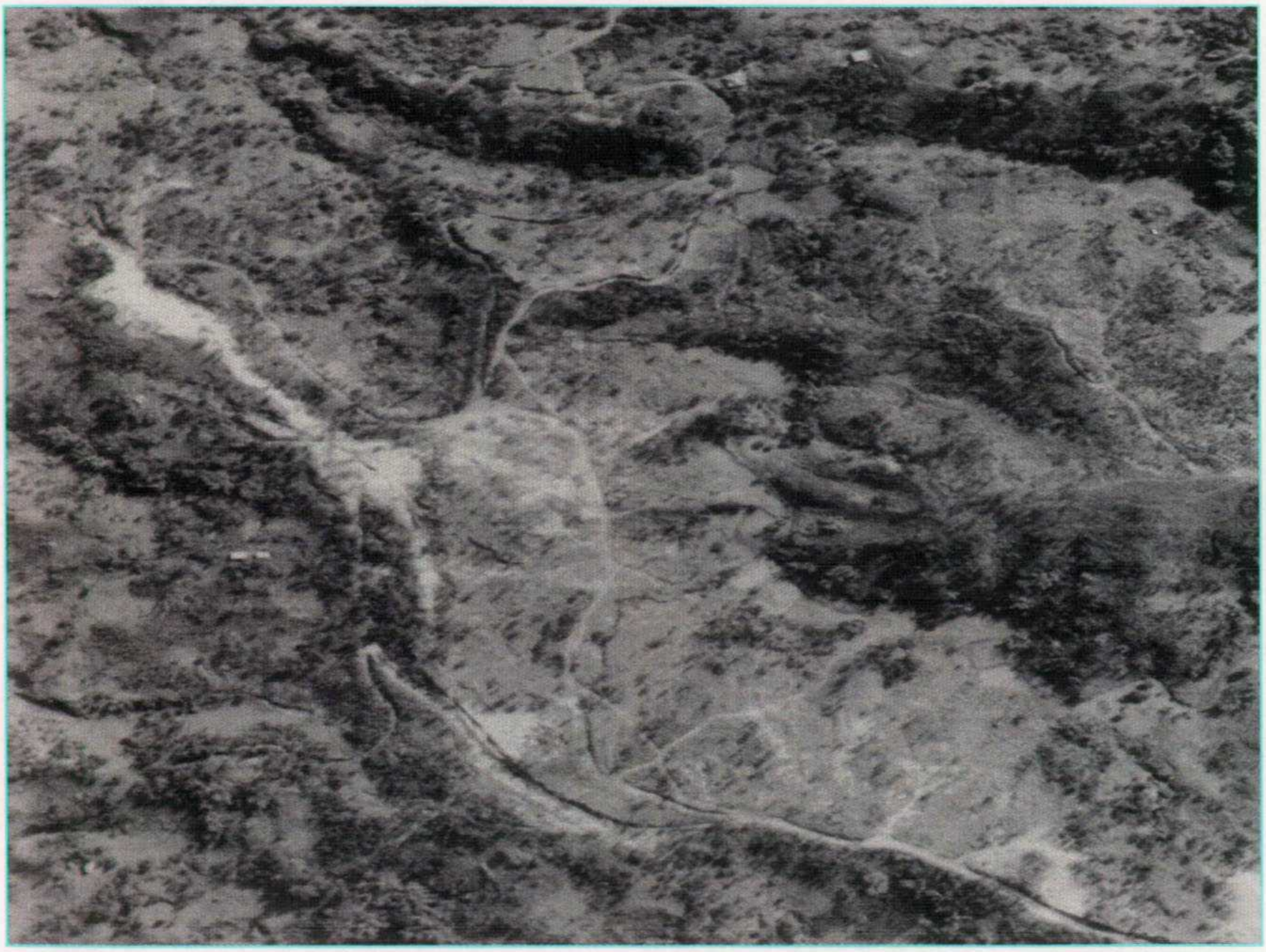

Figure 4.2 Extract from aerial photograph, Bull Mountain area Central Inlier Jamaica.
Details of road cuts and earthflow-type landslides of differing ages shown by soil and vegetation patterns

In the present study, the aerial photography was analysed in analogue form using a traditional mirror stereoscope. The photography was acquired between December 1991 and February 1992 at a scale of 1:15 000 and was purchased commercially within Jamaica for this project. The first step in the analysis was to agree on a classification procedure for the landslides. A simple approach was used in this study whereby the initiation point of each landslide was recorded, irrespective of the style of landslide or the area covered by the debris. This information was recorded manually before being transferred to a map base and digitised. More complex classification schemes can be followed that record other useful information, such as the shape of the landslides and the area covered by their debris fan. The simple approach followed here has the advantage of producing a uniform landslide inventory that is easily understood. It also makes subsequent GIS analysis relatively straightforward.

It will be clear from chapter 3 that the interpretation of these aerial photographs relied on a certain amount of field verification in Jamaica and also drew on accumulated local knowledge within the collaborating organisation.

4.3 GIS Analysis

The hazard analysis relies on the statistical comparison of the landslide inventory with various layers of information. A layer constitutes a map on a particular theme, such as geology, and is typically split into a series of classes, which could be different lithologies within the map. The analysis could be done manually in principle, but it is a much more powerful analytical method when undertaken digitally within a raster GIS environment. In this scenario, each map is digitised so that it contains *nominal* data in *raster* format; that is, a regular grid of data points within which each of the classes is represented by a particular number. Once all themes are geographically referenced, the GIS can be used to carry out complex spatial correlations so that the significance of each class within a theme, or even of multiple classes in combined themes, can be assessed objectively. No prior knowledge of the causative factors need be assumed. After this significance has been established, the layer can be reclassified in terms of landslide susceptibility and the susceptibility maps mathematically combined to give an overall susceptibility value at each point within the study area.

4.3.1 Data layers used in Jamaica

The choice of map layers to include in the analysis depends on what controlling factors are considered important in the local context. The Jamaican study used six themes in the final analysis. These were geology, soils, elevation, slope angle, slope aspect and distance to faults. Examples of each theme were given in chapter 3.

4.3.2 Analysis approach

In the Jamaican study, a simple cross-tabulation approach was used to judge the significance of each class within each theme. More complicated statistical methods can be used and are described in the full implementation strategy (Greenbaum *et al.*, 2000). In the cross-tabulation approach, the landslide inventory is considered a theme with two classes, landslide and not landslide. It is cross-tabulated with each controlling factor theme in turn and the area of landslide within each class measured. If the area is greater than the average area of landsliding in the theme as a whole, that class is considered more susceptible to landsliding than the average. This susceptibility must be assessed in a consistent way, so two other factors are taken into account. Firstly, the overall significance of a particular theme, such as geology, must be estimated. This is done using a statistical correlation co-efficient that varies from 0, indicating no correlation, to a maximum of 1. In the case of Jamaica, geology has a co-efficient of 0.038, showing that it is more significant than slope aspect, which has a co-efficient of 0.024. It was therefore given more weight in the final model. In the same way, the significance of each class within a theme must also be assessed. In the case of Jamaica, this was done using a factor called association that varies from -1 (maximum negative association with landslides) through 0 (no association) to +1 (maximum positive association). The method is explained in full in the implementation strategy (Greenbaum *et al.*, 2000).

Having assessed each theme separately, the next step is to assess their combined effect. Each theme is reclassified as an association map and then weighted by its correlation with landsliding. They are then summed and the result is normalised by the sum of the correlation coefficients. This results in a landslide susceptibility model with values of between -1 and +1 that can be interpreted in the same fashion as the individual association maps.

4.4 Outputs, Visualisation and Validation

The final hazard model should be output as a full map, depicting appropriate cultural and geographical reference information. It will depict the hazard zones calculated in the GIS, the topography as contours or as a shaded relief image, and appropriate map data such as roads and habitation. The Rio Minho hazard map is described in chapter 5.

The GIS can also be used to visualise the hazard in various other ways. It is possible to create perspective views of the hazard zones draped on the digital elevation model, for example. Fly-through movies can be generated to give a helpful perspective on the hazard in particular areas and its relationship to the controlling factors. These visualisations help get the information across to non-scientific users. They can also form part of the validation process. The final hazard map should be compared with the landslide inventory closely. If it does not predict landslides where they actually occur, the analysis is suspect. Better still, it should be compared with an independent source of information, such as a landslide inventory created by field surveying alone.

5 THE RIO MINHO LANDSLIDE HAZARD MAP

5.1 Introduction

The rationale and methodology of landslide hazard assessment leading to the preparation of the landslide hazard/susceptibility map for the Rio Minho study area are described in the previous sections of the report. Fundamentally, the hazard assessment was based on statistical correlation of existing landslide distribution with six factors, or themes, which were considered to influence landslide occurrence in the area. These factors were geology, soils, elevation, slope angle, slope aspect and distance to faults. The resulting hazard map, prepared at a scale of 1:75 000, accompanies this report. Figure 5.1 shows a smaller representation of this map. To assist in visualising the hazard zones in relation to specific topographic elements in the area, the zones are presented as a 'drape' over a shaded relief base. To enhance visualisation further, the hazard zonation is also shown as a drape over a perspective view of the shaded relief (Figure 5.2).

5.2 Use of the Hazard Map

Four levels of susceptibility to landsliding have been identified on the Rio Minho landslide susceptibility map, namely:

ZONE 1 Areas of generally **high landslide susceptibility** within which significant landslide activity is likely to occur. Although some safe locations may exist, many areas will present unacceptable risks. The vulnerability of existing buildings, infrastructure, access routes and critical services should be critically assessed as a matter of priority and specific risks identified. New building or development should be restricted and planning permission subject to expert site evaluation and approval.

ZONE 2 Areas of generally **moderate landslide susceptibility** within which local and possibly some widespread landsliding is likely to occur. This zone will contain a mixture of higher and lower risk areas. An assessment of risk to existing infrastructure is recommended. The vulnerability of access routes and critical infrastructure should be considered in regional contingency planning. Expert advice should be sought when planning new developments and restrictions should apply.

ZONE 3 Areas of generally **low landslide susceptibility** where some local landsliding is possible. The vulnerability of existing structures should be assessed where site stability gives cause for concern. New developments in this zone may be unrestricted but should take account of local site conditions and, where uncertainty exists, expert advice should be sought.

ZONE 4 Areas of **minimal landslide susceptibility**. Relatively minor failures may occur along banks of streams and road cuttings but generally, low slope angles will preclude landslide initiation across this zone. Nevertheless, the vulnerability to disruption of access routes from zones of higher landslide potential should be considered as part of the contingency planning process.

The zones imply relative (not absolute) hazard or susceptibility only and do not imply any legal restriction or regulation by zoning ordinances or laws as laid down by local government authorities.

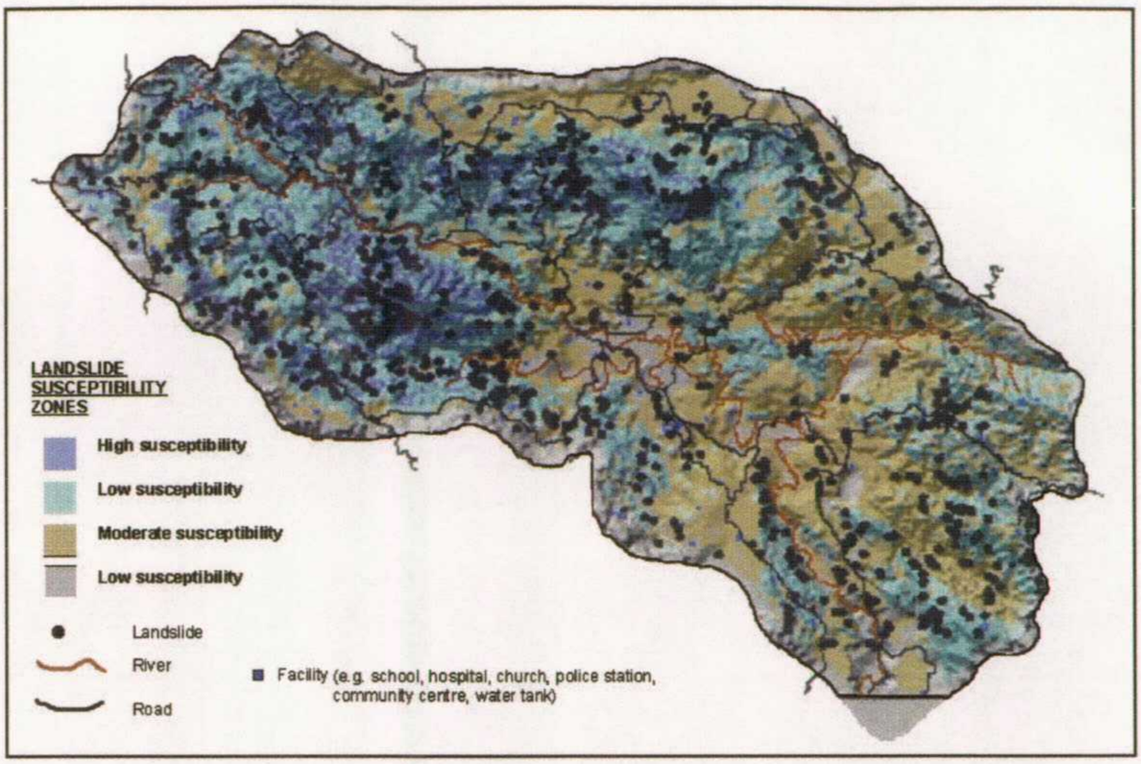

Figure 5.1 Landslide hazard map of the Rio Minho study area. Four hazard/susceptibility zones and points indicating general landslide distributions are shown 'draped' over a shaded relief base to enhance visualisation of the zones in relation to major topographic features, roads, rivers and important facilities in the area.

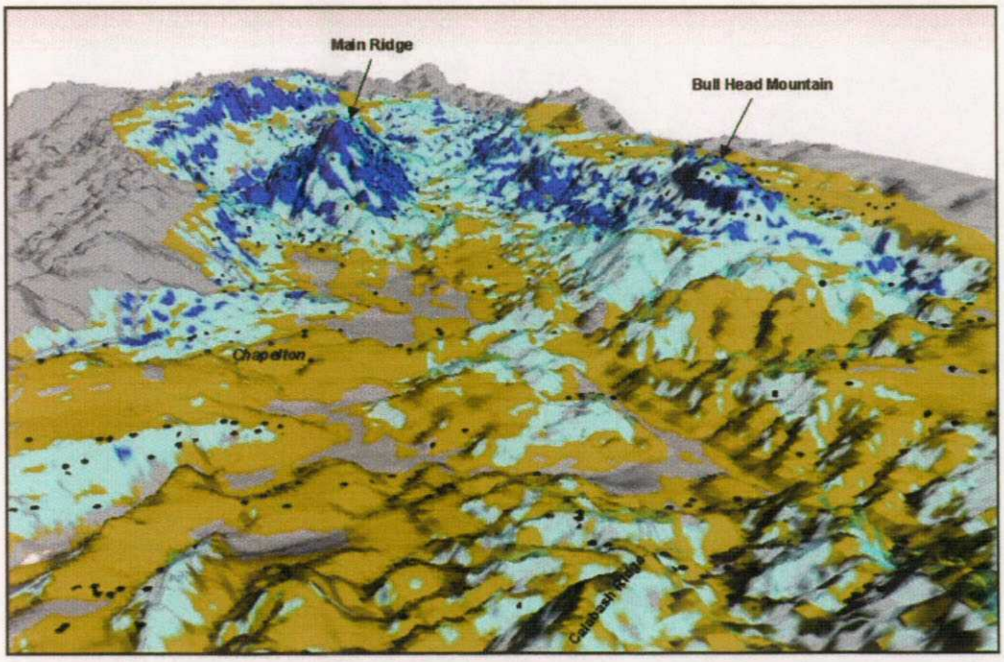

Figure 5.2 Landslide hazard/susceptibility zones and general landslide occurrences (black dots) shown as a 'drape' over a perspective view of the terrain in shaded relief. Using the Image Analysis and GIS software, perspective views from any direction may be produced to further enhance visualisation of the landslide susceptibility zones with respect to key topographic features. Population centres and infrastructure networks (e.g. roads) may also be included to assist in planning or land-use decision making.

Also shown on the main hazard map are the locations of schools, hospitals, churches, community centres, police stations and water tanks. These are essential elements in emergency relief situations and are presented on the map to enable the user to make a preliminary assessment of their relative susceptibility to landslide hazard in the area.

The map is intended primarily for the assessment of landslide hazard on a regional scale. It indicates indirectly the extent and relative severity of landslide hazard. For regional planning purposes, the map may be used as a tool to assist in:

(a) recognition of geographical areas where landsliding has already occurred and future landsliding is most likely. In other words, the maps help in understanding the constraints on land use and the scale of the landslide problem, and thus can assist in land-use planning by relating land-use zonation to hazard zonation

(b) evaluation of the likelihood of hazardous events occurring as a consequence of proposed developments *(environmental impact assessments)*

(c) assessment of hazard potential with regard to proposed developments so that future losses can be minimised by relocation (hazard avoidance) or the adoption of protection measures

(d) identification of areas where detailed geological/geotechnical investigations are desirable prior to development

(e) enhancement of public education.

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

5.3 Limitations of the Hazard Map

The landslide hazard map does not predict when or exactly where landslides will occur during a specific triggering event or events. The hazard zones represent the differences in chance of landslide occurrence that can be expected over the long-term.

The map can be used for preliminary regional assessments only, and should not be used for any purposes over and above that determined by the map scale. Specifically, the map is unsuitable for site-specific stability assessments, for the siting of individual structures, or for engineering design. More detailed local hazard assessments are required for these purposes. The map in no way replaces or reduces the need for new developments to be designed on the basis of appropriate geotechnical investigation. The map serves to focus attention on likely problem areas that should then be assessed in detail, before new developments occur, using site-specific geotechnical techniques.

Like all maps, the landslide hazard zonation is only as good as the data from which it is compiled. The generalisations required to delineate map units means that specific locations within those units may in practice have a different hazard susceptibility than that indicated.

If the limitations on use and accuracy of landslide susceptibility maps are appreciated, they can provide an extremely effective basis for landslide hazard management and land planning. Advances in remote sensing techniques and GIS technology now make rapid and cost-effective production of these maps viable. By following established methodology, rapid assessment of areas with limited existing data, leading to the production of 'preliminary' or 'first-stage' susceptibility maps, is possible. GIS capability allows map accuracy to be readily updated, or the scale of production changed, as additional data are acquired. It would be of considerable benefit to Jamaica if resources and expertise were directed toward promoting 'in-house' GIS capabilities for landslide hazard assessment and hazard map preparation. The University of the West Indies, Unit for Disaster Studies, has developed considerable expertise and experience of landslide hazards on the island. Government agencies, notably the Office of Disaster Preparedness and Emergency Management, are making determined efforts to develop a structured framework for a national hazard mitigation policy. Enhanced GIS-based capabilities for hazard assessment would complement both organisations considerably and assist in building a sound framework for developing and implementing effective hazard preparedness strategies.

6 CONCLUSIONS AND RECOMMENDATIONS

This report describes the preparation of a landslide hazard map for the Rio Minho study area in Jamaica. A rapid, cost-effective method for landslide hazard mapping has been developed. It is based on the principle that the past is the key to the future. A landslide inventory depicting past landslides in the study area was created using remote sensing. This was then used as one of several input data layers within a GIS to model the future hazard for the study area. The inventory was statistically compared to various thematic maps to establish the likely controlling factors on the occurrence of landslides in the area. These were then used to weight the input thematic map layers in terms of landslide susceptibility. The final landslide susceptibility map was created by combining six layers, of which the most important was geology.

The resulting landslide hazard map depicts broad zones of landslide hazard across the region. Validation against local knowledge of the study area and against the landslide inventory itself suggest that the map is a reasonable first interpretation on which it will be possible to build in the future as more information becomes available. It forms a useful tool to guide the planning process and the siting of more detailed ground investigations. It must be remembered that it does not indicate the actual hazard for any specific locality. There is a clear correlation between certain geological formations and increased landslide susceptibility in the area. Topography is also a controlling factor, with slides occurring on steeper slopes in many settings. Faulting and depth of weathering also appear to be important factors. Many of the slides are shallow debris slides involving weathered bedrock material over certain lithologies. It is therefore probable that these formations possess lithological characteristics that promote deep weathering and make them vulnerable to landsliding when triggering events such as intense storms occur.

The creation of the map is only one step in the establishment of a mitigation strategy. Many of the others lie beyond science, within the realms of local planning procedures and the political and legislative process. These issues have also been described and they are discussed in full in Greenbaum *et al.* (2000). The methodology described in this report is no more than a skeleton on which to build a national landslide mitigation strategy that takes into account a variety of local factors. These include:

- Differences in the local controlling factors and triggering events
- Related differences in the style and scale of landsliding
- Climatic and geographic variations
- The optimum local choice of remote sensing data type
- Availability of the necessary thematic maps layers for the GIS analysis
- The presence of an appropriate local technical skills base
- Local computer hardware and software systems and support
- Political and legislative constraints
- Adequate funding

The use of the map resulting from this study should take into account all these local factors.

The local nature of controlling factors can be illustrated by comparing the Jamaican situation with that in the other study sites used during this research. In Slovakia, geology was again very important but the majority of slides occurred on less steep slopes, and were strongly associated with a certain clay-rich lithology. The character of these earth movements was also quite different to those found in Jamaica, with more moderately disturbed ground occurring over wide areas rather than as discrete landslides. Fiji was similar to Jamaica, but the overriding controlling factor was intense rainfall events that can trigger landslides in most terrain types. These local differences in controlling factors and triggering mechanisms are perhaps illustrated best of all by the studies in Papua New Guinea. Here the slides are very large indeed, and can be mapped easily using low-resolution satellite data. The most important triggering mechanism is earthquakes and the slides are strongly controlled by the rugged terrain, with extreme elevation and very steep slopes being common.

Whilst local conditions do vary, the same approach to landslide hazard mapping has been followed with reasonable success in each country by adapting it to fit the local circumstances. This indicates that the aim of developing a generic approach has been achieved.

The map should be utilised and then perhaps developed further by all those concerned with landslide hazards in the region. The importance of collaboration between all the interested parties and the involvement of the likely users in the process cannot be overstated. This will ensure that the products are useful and understandable by those they are intended to help. It will also create a feeling of shared ownership and thus encourage take-up. The success of this project should not be judged solely on the validity of the final hazard map. A more important measure is perhaps the degree to which the map is subsequently used and built upon.

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