British Geological Survey

TECHNICAL REPORT WC/95/28
Overseas Geology Series

RAPID METHODS OF LANDSLIDE HAZARD MAPPING: FIJI CASE STUDY

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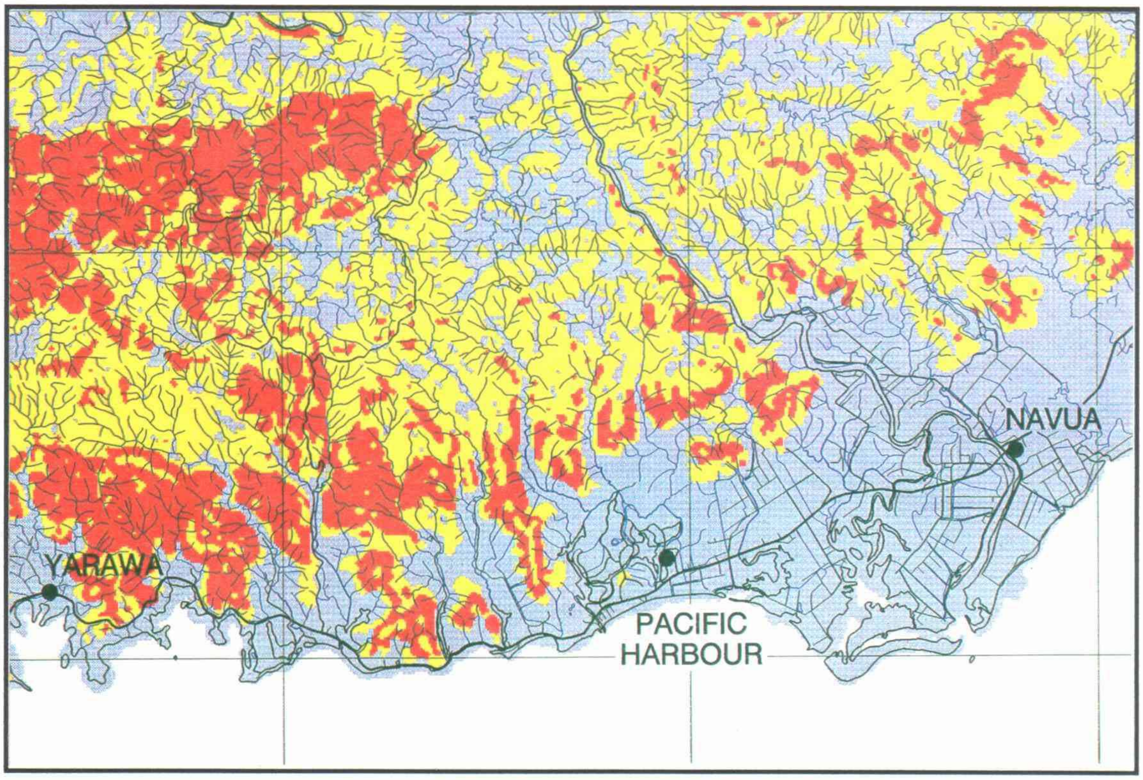

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A report prepared for the Overseas Development Administration under the ODA/BGS Technology Development and Research Programme, Project 92/7

ODA classification :
Subsector: Geoscience
Theme: G3 - Improve geotechnical hazard avoidance strategies in national planning
Project title: Rapid assessment of landslip hazards
Reference number: R5554

Bibliographic reference :
Greenbaum D and others 1995. Rapid methods of landslide hazard mapping: Fiji case study
BGS Technical Report WC/95/28

Keywords :
Fiji, aerial photography, GIS, Landsat TM, landslide classification, landslide hazard, remote sensing

Front cover illustration :
Part of the landslide hazard map for south east Viti Levu, Fiji

Keyworth, Nottingham, British Geological Survey, 1995

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Summary

A landslide hazard probability map can help planners (1) prepare for, and/or mitigate against, the effects of landsliding on communities and infrastructure, and (2) avoid or minimise the risks associated with new developments. The aims of the project were to establish, by means of studies in a few test areas, a generic method by which remote sensing and data analysis using a geographic information system (GIS) could provide a provisional landslide hazard zonation map. The provision of basic hazard information is an underpinning theme of the UN's International Decade for Natural Disaster Reduction (IDNDR). It is an essential requirement for disaster preparedness and mitigation planning. This report forms part of BGS project 92/7 (R5554) 'Rapid assessment of landslip hazards' carried out under the ODA/BGS Technology Development and Research Programme as part of the British Government's provision of aid to developing countries. It provides a detailed technical account of work undertaken in a test area in Viti Levu in collaboration with Fiji Mineral Resources Department. The study represents a demonstration of a methodology that is applicable to many developing countries.

The underlying principle is that relationships between past landsliding events, interpreted from remote sensing, and factors such as the geology, relief, soils etc provide the basis for modelling where future landslides are most likely to occur. This is achieved using a GIS by 'weighting' each class of each variable (e.g. each lithology 'class' of the variable 'geology') according to the proportion of landslides occurring within it compared to the regional average. Combinations of variables, produced by summing the weights in individual classes, provide 'models' of landslide probability. The approach is empirical but has the advantage of potentially being able to provide regional scale hazard maps over large areas quickly and cheaply; this is unlikely to be achieved using conventional ground-based geotechnical methods.

In Fiji, landslides are usually triggered by intense rain storms commonly associated with tropical cyclones. However, the regional distribution of landslides has not been mapped nor is it known how far geology and landscape influence the location and severity of landsliding events. The report discusses the remote sensing and GIS methodology, and describes the results of the pilot study over an area of 713 km² in south east Viti Levu. The landslide model uses geology, elevation, slope angle, slope aspect, soil type, and forest cover as inputs. The resulting provisional landslide hazard zonation map, divided into high, medium and low zones of landslide hazard probability, suggests that whilst rainfall is the immediate cause, others controls do exert a significant influence. It is recommended that consideration be given in Fiji to implementing the techniques as part of a national strategic plan for landslide hazard zonation mapping.

1. INTRODUCTION

1.1 Landslides and hazard zonation maps

Landslides are one of the most common natural hazards which, together with earthquakes, volcanic eruptions and floods, have a major impact on life and property. Most landslides are small and individually account for relatively few fatalities. However, the worldwide frequency of landsliding is such that the cumulative death toll accounts for around 25 per cent of the annual total for all natural hazards (Hansen 1984).

Landslide is a general term used to describe the mass movement of soil and rock downslope under gravitational influence. Landslides result from natural slope instabilities combined with various other factors. They possibly represent the single most important erosion mechanism, especially in tropical environments. The term *hazard* refers to the probability of occurrence of an event in an area within a specified period of time, although it is commonly used in a relative rather than an absolute sense. The areal distribution of landslide hazards is usually presented as a map divided into a few zones corresponding to the relative likelihood of landslide occurrence. Zones tend to be simple categories ranging from, say, 'very high' to 'low'.

A knowledge of the causes and incidence of landsliding can help planners (1) make contingency plans to prepare for, and/or mitigate against, the effects of landslide events on infrastructure, housing and people, and (2) avoid or minimise the risks associated with new developments. Such information can help identify communities at risk and can prevent new construction that would itself increase the danger of landsliding. The provision of basic hazard maps is an underpinning theme of the UN's International Decade for Natural Disaster Reduction (IDNDR). It is an essential requirement for disaster preparedness and mitigation planning.

Although many parts of the world experience significant landsliding, for relatively few areas are hazard maps available. Whereas the mechanisms of slope mass movements and the controlling/triggering factors are, in general, well understood, the required geotechnical investigations have all too often not been undertaken. The work involves the testing of materials' properties and extensive fieldwork. Such investigations are costly and time-consuming, and generally cannot be justified on a regional scale in many developing countries. Given the magnitude of the task worldwide, it is important that alternative approaches are developed that can provide basic hazard information cheaply and quickly.

This report forms part of BGS project 92/7 (R5554) 'Rapid assessment of landslip hazards' carried out under the ODA/BGS Technology Development and Research Programme as part of the British Government's provision of aid to developing countries. The work in Fiji was undertaken in collaboration with Fiji Mineral Resources Department which provided support and funding for local studies.

1.2 Aims & objectives of the study

Hazard maps based on conventional geotechnical ground survey techniques require expertise and resources that are all too often not available in developing countries. Consequently, such maps are not likely to become widely available in the foreseeable future where they are most needed. Detailed geotechnical investigations may be undertaken in urban areas or where major new infrastructure is proposed, but for national or regional planning purposes, alternative rapid and inexpensive methods are needed to provide preliminary assessment maps.

The **immediate aim** of this work is to establish, by means of studies in a few test areas, methods by which remote sensing and data analysis using a geographic information system (GIS) can provide the information needed to produce a preliminary hazard zonation map.

The **wider aim** of the research is to develop a methodology that can be implemented more generally in developing countries. The use of empirical, less rigorous techniques inevitably results in less precise and less reliable information, but there are many situations where this provides a valid and useful interim solution. In any event, even limited information is better than none at all.

The extent to which landslide probability can be determined by indirect techniques is uncertain; consequently, the present investigation is somewhat experimental. The purpose is to identify approaches that may lead to a rapid and cost-effective methodology. Consequently, the production of particular landslide hazard zonation maps is an incidental product rather than a main objective. The maps should be regarded as provisional. Information deriving from these pilot studies will help identify useful approaches, limitations and problems.

The use of a GIS has a number of potential advantages. First, the GIS and associated database can be used to store, process and output data in a range of thematic formats, designed to meet particular user needs. This is important: in order to be of practical use, a hazard map must be free from unnecessary, complicating detail, and be understandable by people who do not have a geological background, including engineers, planners and decision makers. A GIS allows the production of simple thematic maps tailored to meet particular requirements. Second, the computer database can be easily expanded as more information becomes available, so that updated maps can be provided. Finally, the GIS can be used as a convenient tool to analyse the importance of various factors and to help 'model' hazard probabilities.

1.3 Study areas

Whereas the causes and mechanisms of landsliding are in general well understood, the actual controlling factors vary from country to country depending on the local geological, physiographical and climatological conditions. The choice of study areas was determined by various considerations including: an identified landslide hazard problem; a collaborating national agency already involved in tackling the issue; and a variety of different physical situations. The extent of the investigation allowed only a limited range of environments to be studied. The scale at which a study is undertaken, and at which maps are produced, depends upon likely usage, the precision required, the existence of geotechnical and other information, and on the resources (time, personnel, equipment, money) available. Thus, the approach, the inputs, and the final map product will vary. In the present study, we have concentrated on situations requiring national to regional scale hazard maps where rapid evaluation methods are most appropriate. The type of landslide hazard analysis undertaken may be sub-divided according to the scale of the study. Table 1.1 is modified from information provided by van Westen (1993) and Soeters and van Westen (1994):

Table 1.1: Scales of hazard zonation analysis

Category	**Scales**	**Use**
National scale	< 1:1 000 000	National planning
Regional scale	~ 1:50 000-1:100 000	Regional planning in rural areas
Medium scale	1:25 000-1:50 000	Feasibility studies related to large engineering works, corridors for infrastructural development etc
Large scale	1:5000-1:25 000	Detailed planning of infrastructure in urban or industrial areas
Detailed scale	> 1:5000	Site specific investigations

Information obtained from remote sensing data (aerial photographs and/or satellite images) is an important input no matter what the scale of the study. In general, however, the larger the scale, the more information will be provided by ground based surveys and the less will be the need for remote sensing. *The role of remote sensing is mainly to provide information on the occurrence and distribution of past landslide events.* Apart from speed of coverage, its advantages over point-based ground studies are the continuous nature of the information and the ability to map old terrain features which may be difficult to recognise on the ground. The underlying assumption is that the distribution of landslides is significant either in relation to likely future events or in terms of the actual deposits.

Test sites were chosen in three countries where landsliding is a significant problem and represents a threat to life and property: Fiji, Papua New Guinea, and Colombia. In each country hazard maps are an important and urgent requirement. The national agencies in these countries are already involved in landslide hazard mapping but the size of the problem, in terms of areas to be covered, is large compared with the resources. If significant progress is to be made, this will require the use of rapid, more cost-effective techniques. The three test sites chosen provide a range of different situations requiring somewhat different approaches.

Fiji is a small south Pacific nation consisting of two main islands and many smaller ones. Though geologically young, the islands are tectonically relatively stable and the relief fairly subdued. The association of deep tropical weathering with high intensity rainfall, especially during tropical cyclones, results in mostly small, though locally numerous and damaging, landslides. In 1980, cyclone Wally caused devastation to the Serua Hills area of south Viti Levu. The requirement in Fiji is for medium to regional scale hazard maps covering at least the two main islands.

Papua New Guinea (PNG) is a large, mountainous and thinly populated country covering 462 840 km². It experiences high rainfall and seismicity. The region is tectonically very active, the Highlands recording some of the highest rates of uplift anywhere on earth. As a result, landslides in this rugged terrain are of considerable scale in terms of volume of material involved. Although most occur in sparsely populated regions, their widespread distribution and their size result in significant loss of life and damage to infrastructure. Possibly as much as one-tenth of the world's annual death toll from landslides occurs in PNG. In view of the large area concerned, the requirement is for regional to national scale hazard zonation maps at scales of 1:100 000 to 1:250 000.

Colombia has a high incidence of natural hazards, including landslides which occur regularly. High relief and steep slopes together with seismic activity and heavy rainfall, combine to produce the conditions for landsliding. In many areas, the natural hazard has been increased by man's activity such as urban development, roads and agriculture, particularly coffee growing. The national authorities take the problem of landsliding very seriously and studies of many of the important population centres have been undertaken or are planned. However, a need remains to cover many additional areas at the regional, large and detailed scales.

1.4 Dissemination and training

Project-related training in remote sensing and GIS was provided to geologists from each of the three collaborating organisations.

Mr Joe Buleka and Mr Gabriel Kuna of the PNG Geological Survey spent 4 weeks at the BGS from 8 November 1993 to 3 December 1993 During this time they received instruction in image processing, satellite imagery and aerial photograph interpretation, and GIS analysis of PNG data. The visit was funded from both external and ODA sources

Mr Satish Prasad of the Fiji Mineral Resources Department spent 4 weeks in BGS from 21 November 1994 to 16 December 1994. The visit was funded by the South Pacific Applied Geoscience Commission (SOPAC) in Suva. Mr Prasad received project training in photointerpretation of landslides, data capture and GIS using data for part of the Viti Levu test area.

Sra Liliana Marin from the Cali office of Ingeominas, Colombia spent 10 weeks in BGS from 8 January 1994 to 20 March 1994. The visit was funded by the British Council. Training involved image processing, aerial photograph interpretation of landslides, data capture, and GIS analysis using ILWIS. Despite the limited time available for the work, a full study and GIS analysis was carried out and a report completed in Spanish and English translation.

1.5 Remote sensing inputs to hazard mapping: underlying rationale

The simplest form of hazard zonation map obtained from imagery or photography is one showing the distribution of landslides, perhaps sub-divided into older and more recent events. The assumption is that past events provide an indication of what is likely to occur in the future. There are several uncertainties in this approach, and at best a landslide hazard map of this type is no better than a general guide. It assumes that (1) landslides (including landforms developed under various mass movement mechanisms) can be reliably identified using remote sensing; (2) controls and/or triggering mechanisms remain essentially constant; and (3) areas previously affected by landslides continue to be unstable. The approach does not depend on a detailed knowledge of causes, but only on observed patterns and spatial associations.

One important limitation of the remote sensing approach is that the interpreted distribution of landslides represents a snapshot in time, weighted in favour of the more recent events. For example, interpretations of the Serua Hills area in southern Viti Levu using photographs taken before and after cyclone Wally in 1980 show markedly different patterns. This bias can be overcome to some extent by attaching more weight to the distribution of older landscape features of landslide origin rather than the most recent, and perhaps most conspicuous, events. Despite its obvious limitations, the landslide distribution inventory is probably the best single indicator, and forms the basis for most remote sensing approaches. Landslides can be represented as polygon outlines or points, or the data may be converted to a contoured landslide density map. The information is usually presented on a locational base map for geographical reference.

A more informative map will include other information either extracted from the remote sensing data or obtained from other sources. In the simplest case, cause and effect relationships are not inferred, and the data sets merely depict spatial patterns of the different categories of information. These might include relief, geology, rock structures, lineaments, roads, infrastructure, population distribution, etc. Map products of this type require only a cartographic capability; a vector-based GIS provides an appropriate computer database for storing data and for outputting customised, easily-updated map products as and when required.

In such maps, relationships between variables may be visually apparent, and risks to property or lives may be readily inferred, but there is no attempt to analyse the data in any rigorous or quantifiable manner. The next stage involves ranking the different parameters according to their perceived importance. The resulting plots are, to varying degrees, landslide 'probability distribution' maps which attempt to show the likelihood of landslides occurring *given the necessary triggering circumstances*. This type of analysis can be done in various ways depending on the information held on the GIS database, the availability of supporting field or geotechnical evidence, and the analytical approach adopted.

In *qualitative analysis* the factors believed to affect the occurrence of landslides are subjectively weighted in terms of their perceived importance, and used to provide a modified distribution map, zoned in terms of landslide probability. For example, if landsliding is considered to be caused by a combination of steep slopes and volcanic-derived sediments, then the GIS may be used to identify areas where such factors occur together (and also coincide with past landslide events). In this example, the associations derive from observed relationships in the distribution patterns, but they could equally be intuitive (e.g. an assumed relationship between landslides and steep slopes) or be based on ancillary field information. Here, the GIS software may be used to produce new, weighted combinations or the probability classes may be drawn manually based on various visual on-screen comparisons. *Analytical quantitative analysis* involves using the statistical correlation capabilities of the GIS software to quantify the spatial relationships between variables. In this case, the use of a GIS is an essential requirement. The types of analysis undertaken here depend on the data types available and the scale of the study.

1.6 The south east Viti Levu study area

The location of the study area in south east is shown in Figure 1.1. From east to west it covers the coastal region extending from Veisari (6 km west of Suva) to Serua Island, and inland to Namuamua where the Navua River abruptly turns southwards. On the recently published Fiji Metric Grid (FMG) 1:50 000 topographic maps, the study area includes most of the mainland region of sheet N29 Navua (1993), with the western boundary coinciding with 1910000mE on sheet M29 Korolevu (1993).

The study area was chosen for the following main reasons:

(1) There is a history of repeated rain-induced landsliding in south east Viti Levu. Lawson (1993) records three recent extreme rainfall events that affected this region: 5 May 1979, 1-5 April 1980 (cyclone Wally), and 16-21 April 1986. Extensive damage to roads and housing between Suva and Navua was caused by landsliding related to the severe storm of 1979. During cyclone Wally, the Queens Road was blocked and undermined by landsliding in the Serua Hills requiring a repositioning of the highway. Many villages were isolated for up to four weeks, and the cost of road reconstruction was put at about $F1.6 million. Initial work on the landsliding in the Wainitubatolu catchment of the Serua Hills was described by Howorth *et al.* (1981) and Crozier *et al.* (1981). This work established that the frequency of landslides was closely related to the occurrence of red regolith. Subsequently, Howorth & Prasad (1981) mapped 28 landslides in a ten hectare area immediately south of Korovou village. Some examples of landslide damage in this part of Viti Levu are shown in Figures 1.2A to 1.2D.

    Shorten (1982) reported that the Deuba Reservoir, which is located on a 50 m high ridge 300 m north of the Queens Road and 1.2 km west of the Beachcomber Hotel (Pacific Harbour Resort), had been partly undermined by landslides and that a proposed site for a new resort was also threatened.

    The 1986 storm caused landslide damage to housing in the Veisari area.

    Howorth *et al.* (1993) reported on the severe road embankment erosion along the Queens Road from Navua Bridge to Nasasa Road junction, due to flooding associated with cyclone Kina on 2-3 January 1993. Most of the landsliding occurred in the region to the north of Suva, where it mainly affected 'cut and fill' road construction slopes. Howorth *et al.* (1993) also reported that inland access to Namosi from Nabukavesi was prevented by many landslides along the road.

(2) The south east part of Viti Levu is an economically important area of Fiji. The population in the study area is dispersed predominantly along the coastal region (Figure 1.3, reproduced from Gale and Booth, 1991); it numbered some 15 000 in 1976. The area includes Navua and the holiday resort of Pacific Harbour.

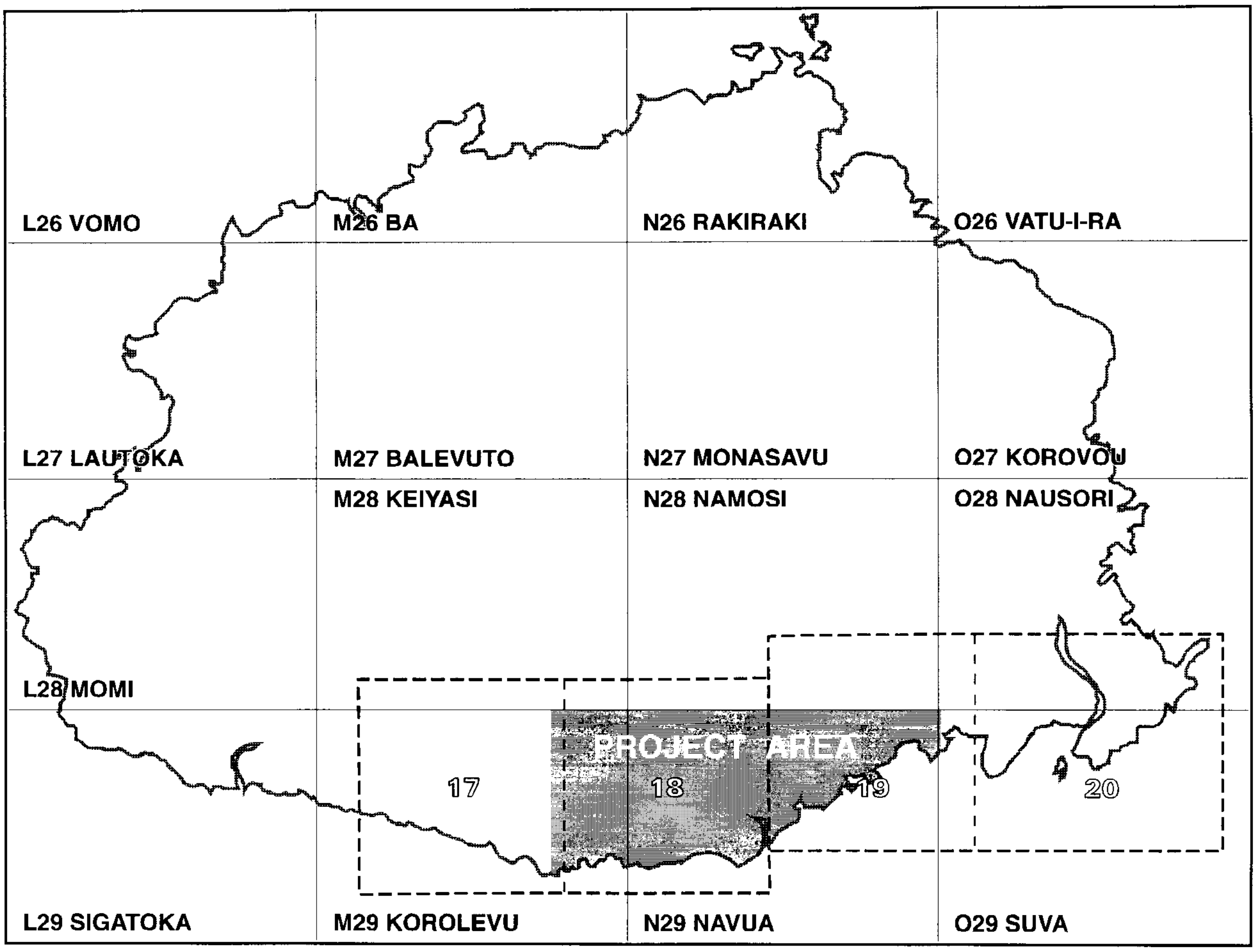

Figure 1.1 Map of Viti Levu showing the old 1:50,000 topographic series (dashed) and the new 1:50,000 series (faint). The location of the project area is indicated.

Figure 1.2 A: Recent landslides, Galoa-Korovisilou area; B: slump in natural ground, 1 km west of Korovisilou; C: landslide at Taunovo, near PWD depot; D: house built on slide debris, Korovisilou (note the 'amphitheatre' like form of old landslide).

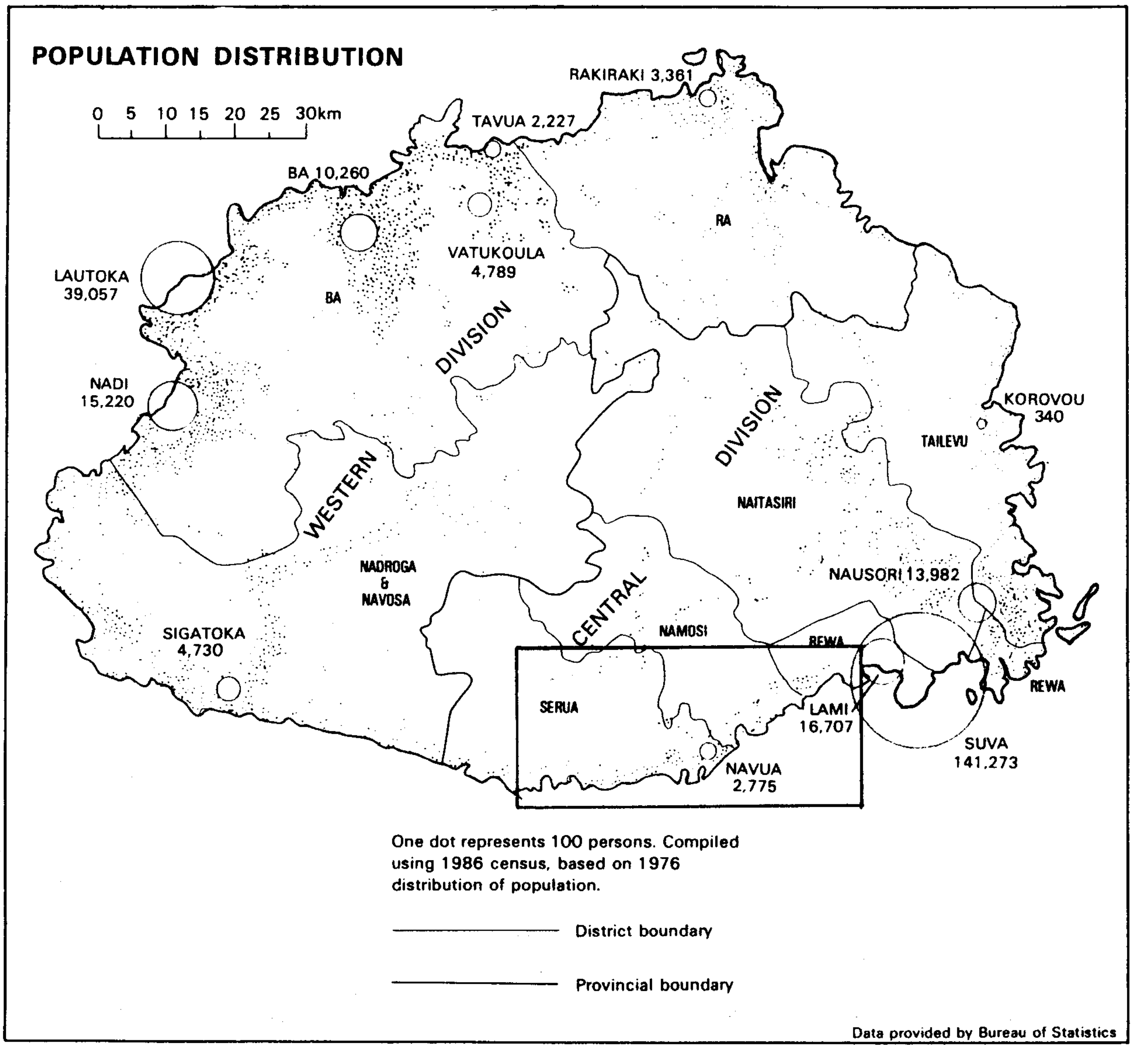

Figure 1.3 Population distribution in Viti Levu (reproduced from Gale and Booth, 1991). Study area outlined.

a few kilometres to the west. The main Suva-Nadi highway traverses this region; any disruption to this route by landsliding could have severe economic consequences.

(3) Gale and Booth (1991) noted that approximately 40% of the study area is suitable for arable/tree crops (Figure 1.4 reproduced from Gale and Booth, 1991). Possible developmental pressure on the inland regions, through logging or an expanded road network, could lead to an increased risk of landsliding.

(4) Landsliding in the study region needs to be considered in relation to the planned overland ore transportation system from the proposed Namosi copper mine to the coast.

(5) Prior to the present study, no maps existed showing the regional extent of past landsliding in south east Viti Levu. A landslide inventory was recommended as the next phase of the work in the Lawson report (1993).

(6) Several generations of aerial photographs exist for south east Viti Levu. There is thus the possibility of attributing the landslide distributions to particular time periods and hence some of the major rainfall events.

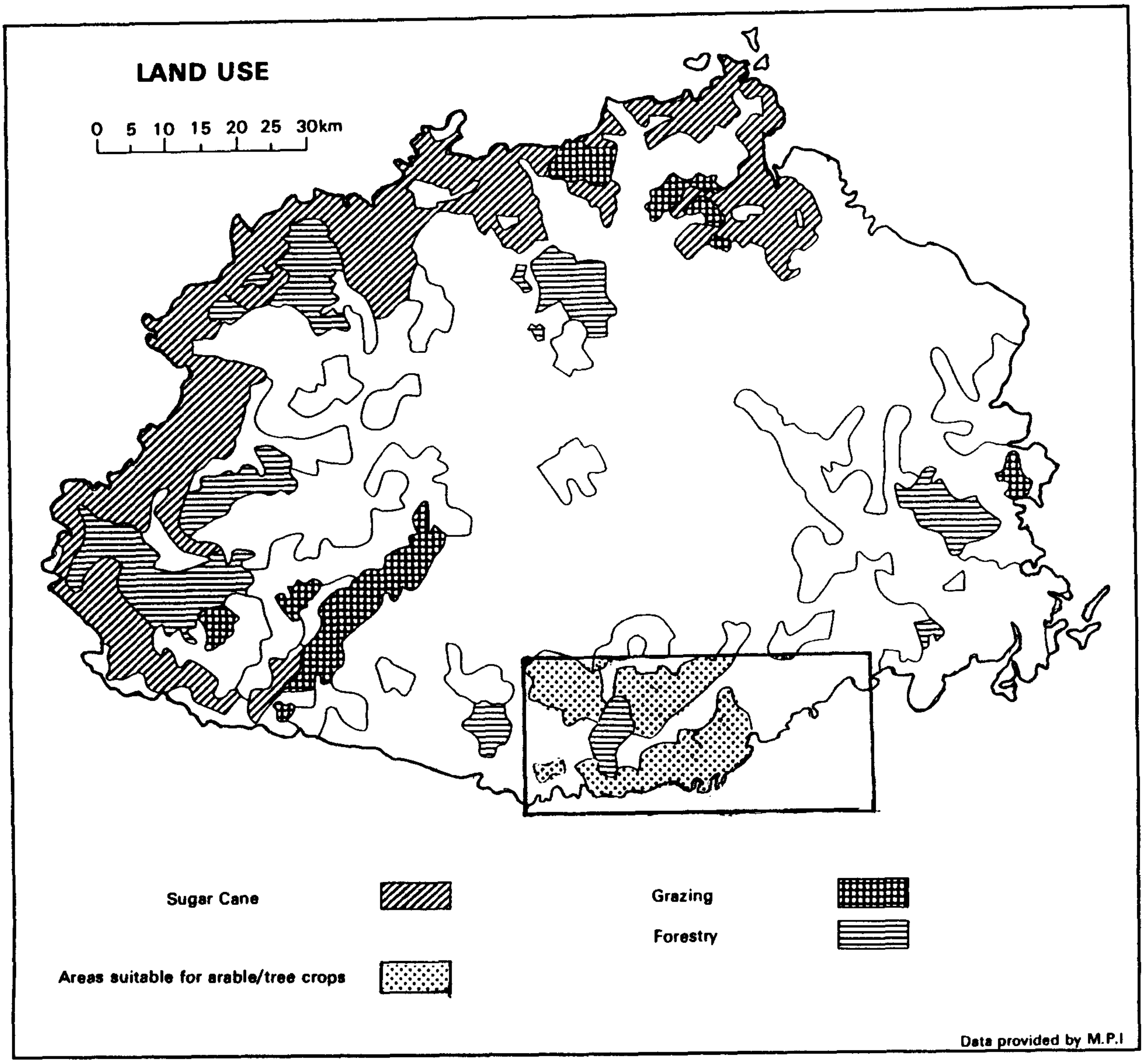

Figure 1.4 Land use map of Viti Levu showing areas designated for arable/tree crops (reproduced from Gale and Booth, 1991). Study area outlined.

2. LANDSLIDE HAZARDS IN FIJI

2.1 Regional tectonics and geological setting

2.1.1 Geology

The islands of the Fiji archipelago form part of the Fiji Platform which lies within a complex transform zone delimited by the New Hebrides Arc-Trench to the west and the Tonga arc to the east. The arc systems are driven by convergence of the Indo-Australian and Pacific Plates. The region has undergone a complex history of plate convergence, subduction and arc-volcanism from the Middle Eocene to the Early Pliocene (Figure 2.1). Recent summaries of the geology are provided by Hathway (1993) and Rodda (1994). The following is taken from these accounts.

The oldest known rocks, named the *Yavuna Group*, occur in south west Viti Levu and consist of basaltic lavas and intrusive rocks with minor epiclastic conglomerates and limestones. These are intruded by a trondhjemite stock of Lower Oligocene age. An unconformity separates this unit from the overlying Lower Oligocene to Middle Miocene *Wainimala Group* of volcaniclastic conglomerates and lavas with sedimentary units which crop out in south Viti Levu. The Wainimala Group is disconformably overlain by turbidites and conglomerates of the Upper Miocene *Tuva Group*.

A period of folding and faulting separates the Tuva Group from the overlying Upper Miocene sedimentary rocks of the *Nadi Sedimentary Group* and *Navosa Sedimentary Group* exposed in west Viti Levu. A phase of calc-alkaline volcanicity in south and west Viti Levu was contemporaneous with these sediments. In the Late Miocene to Early Pliocene, high-potash lavas of the *Koroimavua Volcanic Group* were erupted in north west Viti Levu and followed by shoshonitic and calc-alkaline volcanism of the *Ba Volcanic Group* across the northern half of the island.

Table 2.1 Stratigraphy of south east Viti Levu

Pliocene-Miocene	Mendrausucu Group	Suva Marl Veisari Sandstone Waindina Sandstone/Navua Mudstone Quartz Diorite Namosi Andesite Serua Conglomerate
Lower Miocene	Savura Volcanic Suite	Vago Volcanics
Lower Miocene-Lower Oligocene	Colo Plutonic Suite Wainimala Group	Diorite/tonalite Gabbro Tawavatu Tuff Nubuonaboto Volcanics

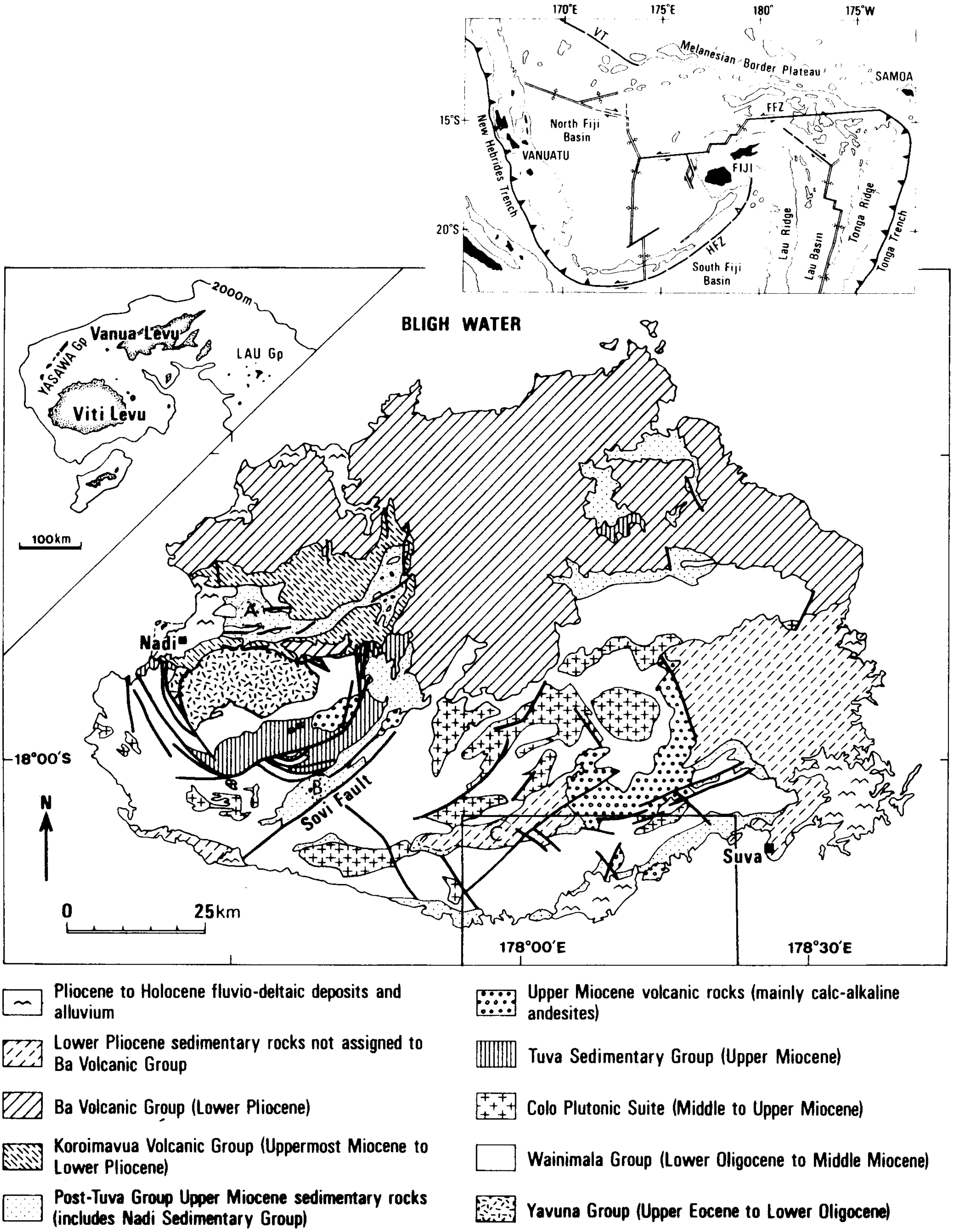

Figure 2.1 Generalised geology of Viti Levu with major faults. Late Miocene to Early Pliocene sedimentary basins shown in A, Nadi Basin; B, Sovi Basin : C, Navua Basin. Inset map of tectonic plate boundaries of the west Pacific region (reproduced after Hathway, 1993).

The stratigraphy of south east Viti Levu is summarised in Table 2.1 from published geological sheets 18 and 19 (Band, 1964; 1965). On the eastern margin of Sheet 19 (Mau area), olivine basalt flows of the *Nakobalevu Basalt Group* of Miocene/Pliocene age occur. These are correlated by Band (1968) with the *Ba Volcanic Group*.

2.1.2 Regional seismicity

The Fiji Platform lies within a triangular zone of active extension fault lines around which most of the shallow earthquakes have been centred (Louat and Pelletier, 1989). These are the Fiji Fracture zone (FFZ) to the north, the 176° Extension Zone (176°E EZ) to the west and the Eastern Seismic Line (ESL) to the east, equivalent to Hunter Fracture Zone (HFZ) of Hathway, 1993) (Figure 2.1). Lawson (1993) divided the seismicity of Fiji into seven zones most of which lie along, or near to, the tectonic lines described above. Earthquake activity is pronounced along the FFZ line with magnitudes of 6.5 to 7.0. The Suva earthquake of 1953 with a magnitude of 6.8 is known to have triggered landslides in the Navua area (Houtz, 1961 cited by Lawson, 1993). Seismicity recorded in south Viti Levu since 1979 is minor and shows no regular pattern.

2.1.3 Neotectonics

The neotectonism of Viti Levu is characterised by progressive uplift from the Late Pliocene onwards with a rate increasiMw toward the centre of the island. One manifestation of this is the uplift and dissection of the Pliocene Navua Plateau to form young narrow gorges. On Viti Levu and the other main islands, there are examples of active delta formation and coral reef building, whilst drowned coastal features are rare. Mesa-like features present on some coastal plains are thought to represent former coastal platform or alluvial deposits which now stand some 6 to 12 m above the present coastal plain (Twyford and Wright, 1965).

2.2 Landscape of southern Viti Levu

The highland area of southern Viti Levu may be divided into three topographic units:

Rama Range

Navua Plateau

Lokalevu Hills

The Rama Range in the eastern sector is formed of rugged volcanic terrain with some volcanic necks (Rama Peak 442 m) rising prominently above the landscape. Part of the Rama Range is underlain by gabbro of the Colo Plutonic Suite. The Navua Plateau is a peneplain whose base-level now stands at 150 m above sea-level. Much of this plateau is underlain by tuffs and volcaniclastics of the Wainimala Group. Changes in sea-level have rejuvenated the area resulting in the dissection and deepening of young narrow gorges (e.g. Navua Gorge). The Lokalevu Hills extend west from, and are bounded against the Navua Plateau by, the Yarawa Fault scarp.

Much of the upland relief of south east Viti Levu is carved from the Wainimala Group volcaniclastic rocks in the south sector, the Navua Basin sediments in the north, and Suva Marls in the east. The landscape shows a high density of deeply-incised small streams and many grey cliffs of 'soapstone', numerous waterfalls and occasional caves. Remnants of older plateaux surfaces rising above 1000 m and 600 m respectively are common. In the south east of the region near Suva, steep mudstone landscapes gradually give way to hilly and rolling land in Suva Marl near the coast.

2.3 Soils

2.3.1 Soil classification

The soil resources of the Fiji islands were documented in a comprehensive manner by Twyford and Wright (1965) who provided maps and a report covering Fiji. Their scheme has been modified in recent years by the Land Use Planning Section of the Ministry of Primary Industries (MPI) based on work done at the Koronivia Research Station near Nausori. The major soil groupings in the revised scheme are sub-divided into a series of range numbers corresponding to geographical and geological domains. These range numbers are further qualified by slope class symbols varying from flat to very steep.

According to Twyford and Wright (*op. cit.*), the two major groups of soil-forming materials on Viti Levu are tuffaceous sedimentary rocks and basic to intermediate volcanics. They occur predominantly in the hilly country with moderate to steep slopes. Soils derived from the intermediate volcanic rocks and their associated sediments are generally reddish-brown to red, although black soils occur where the sediments are calcareous or where the volcanics are enriched in pyroxene phenocrysts. Basaltic rocks give rise to reddish-brown, brown and black soils which vary in appearance according to age, stability and depth of weathering. The thickness of the soil profile correlates generally with the age of the parent rock i.e. younger rocks produce shallow soils, although there are several exceptions to this pattern. The colluvial, alluvial and aeolian soils prevalent on the foothills and floodplain areas are derived from a mixture of rock types but mineral grains from the intermediate andesitic types are dominant. Where siliceous rocks are prominent in the source area, the derived soils are usually rich in quartz grains.

In the Twyford and Wright scheme, the dominant soils of south east Viti Levu are classified as humic latosols derived mainly from rocks of basic to intermediate composition. In general terms, the latosols are the product of leaching in a very strong tropical weathering environment. They are ubiquitously clays in composition but behave like clay loams or loams in the field.

The following is a description of three major soil classes of the upland zones within the study area based on Twyford and Wright (1965)

The soils derived from rocks of andesitic and basaltic composition are predominant in the hilly country of the Navua and Serua Hills. These are probably synonymous with the *Serua and Lobau steepland clay and boulder clay unit* of Twyford and Wright (1965). The soil profile on moderate slopes typically shows a sequence as follows:

Reddish brown friable clay with a fine to very fine nutty structure	7 cm
Red friable clay with a fine angular fragmental structure	108 cm
Bedrock	

On very steep slopes, the soil profile is little more than 40 cm in thickness. These soils support the natural rain-forest and are locally used for subsistence cropping. A local variant on this soil type is *Batiwai clay* (Twyford and Wright, 1965, p 286) which is texturally very similar to the steepland clays above. They are invariably thicker soils, extending to 6 m, and are located on more gentle slopes to rolling hills.

A proportionally smaller area north of the Navua river within the study region is underlain by the *Naraiyawa steepland soil.* This is similar to the soil grouping derived from rocks of acidic composition and shows a typical profile as follows:

Dark brown friable stony silty clay loam with a weak blocky structure	10 cm
Light brown, friable, very stony, sandy clay with a coarse blocky structure to a fine, blocky and coarse granular structured sandy soil containing abundant weathered rock	24 cm

From the foregoing pedological descriptions there would appear to be few marked textural or compositional differences in the steepland latosolic clay soils of south east Viti Levu. However, geotechnical tests carried out on these soils indicated that, whilst there were no significant pedological differences due to parental bedrock, there were pronounced differences in engineering properties (Lawson, 1993). This highlights the difficulty of attempting to relate pedological classifications shown on regional soil maps to engineering behaviour and landslide distribution.

Differences in soil properties result from the gradational effects of weathering, both vertically and laterally within the soil profiles. For example, typical weathering profiles comprise 'mature' intensely weathered residual soil grading to successively less altered rock at depth. This gives rise to variations in material properties vertically within the profile. The intensity of the tropical (essentially chemical) weathering process is such that the physical and mechanical properties of the most highly altered surficial residual soils may bear no relation to the parent rocks from which they are deived (see above). Since weathering is increased around fissures in the parent rocks, there may also be marked lateral as well as vertical variations in the composition and physical properties of the weathering profiles. Lateral variations in properties on steep residual soil slopes may also result from surface material, which has attained near-equilibrium with the physico-chemical environment, being continuously removed by landsliding and erosion. This activity exposes less weathered, more 'immature', parts of weathering profile and thus leads to rejuvenation of the weathering process. Therfore, soils with markedly different material and engineering properties may occur in juxtaposition on the steepland slopes in south east Viti Levu. Such variations may not be indicated by the soil groupings shown on small to medium scale pedological maps.

Within the study area, the soil classification scheme of the MPI may be simplified for the purposes of description. The former soil classes have been reduced to two major groups as follows:

1.	Soils of the coastal marshes. Soils of the beach strands, dunes and estuaries. Soils of the major and secondary floodplains including terraces, fans and outwash surfaces.	Range 2-76
2.	Soils of the hill country	Range 116-243

The latter grouping is the more significant in the context of landslide phenomena and has been further divided into four sub-units based on broad compositional differences of the parental rocks, as follows:

2A	Soils from calcareous tuffs, sandstones, marls and volcaniclastic sedimentary rocks of intermediate to basic composition	Range 116-136
2B	Soils from quartz porpyhry, quartzite	Range 158-159
2C	Dacite, acidic andesite, silicified tuffs, sandstones	Range 163-182
2D	Soils from andesite and basalt and related tuffs	Range 204-243

For the purposes of GIS analysis, the MPI soil classes were modified to exclude their slope sub-category. This resulted in 43 soil types which formed the basis of the digital data. Although the use of the 5 groupings outlined above was considered for the GIS analysis, it was eventually decided to use all 43 classes so that any patterns of significance could be independently derived from the correlations with landsliding themselves.

2.3.2 Land use and soil erosion

Early accounts of soil erosion on Viti Levu focused on areas used for commercial agriculture and subsistence cropping. It was reported (Twyford and Wright, 1965, p 216) that agriculture was taking place on soils with moderate slopes which rendered the soil unstable. The degree of slope affects the amount of soil erosion, and even a slope of a few degrees is sufficient to induce severe soil loss in the wet season. Two types of soil erosion were noted: sheet and gully erosion. The former is much more subtle and is thought to be more prevalent on tuff-derived soils because these are naturally thinner in development than lava- or sedimentary-derived types. Gully-type erosion is common in the steep banks of river valleys and is expressed as large gullies or run-outs.

Since the 1960s, the woodlogging industry has grown substantially, and the clearing of trees is very evident in the south western sector of the study area. Such clearing has exposed large areas of clay soil and rendered them susceptible to sheet and gully erosion. However, the risk of soil erosion has apparently been recognised, and evidence from the 1990 aerial photography shows that most of the logged zones have been systematically replanted in an attempt to stop further soil removal.

2.4 Climate and rainfall in south Viti Levu

2.4.1 Introduction

The Fijian archipelago lies within the zone of the South East Trades and consequently there is a marked difference in climate between the lowland areas of the south and east, and those of the north and west. In the higher ground of the interior, there is a clear distinction between wet windward and dry leeward zones with substantial differences in rainfall, humidity and range of mean temperature. The mean annual rainfall on south east Viti Levu ranges from 3750 to 5000 mm per year whilst the leeward zones to the north receive only 1750 mm (Figure 2.2).

The period between mid-November and mid-April is recognised as the *hurricane* or *cyclone* season when tropical revolving storms may sweep across parts of the archipelago. These cyclone events are accompanied by violent wind-speeds in the range of 165 to 212 km per hour and cause considerable damage to property and agriculture. They also induce landsliding.

2.4.2 Tropical cyclone and storm events in the Fiji region

During the last 15 years, at least six major cyclones have either directly affected, or passed in close proximity to, Viti Levu. These are listed below and their tracks are plotted in Figure 2.3.

Cyclone	Date
Wally	1-6 April 1980
Arthur	12-15 January 1981
Oscar	28 Feb - 2 March 1981
Eric and Nigel	17-20 January 1985
Kina	26 Dec 1992 - 5 Jan 1993

In addition to these catastrophic wind/rainfall events, there were a number of other severe storms which affected Viti Levu in the 1980s and which had significant landsliding associated with them (Lawson, 1993).

A good correlation exists, as might be expected, between these cyclone/storm events and the average monthly rainfall data. The figures which follow were recorded by the Fiji Meteorological Service from five rain-gauge stations located within the study area. The figures cited below in Table 2.2 will, therefore, be somewhat representative of extreme rainfall events.

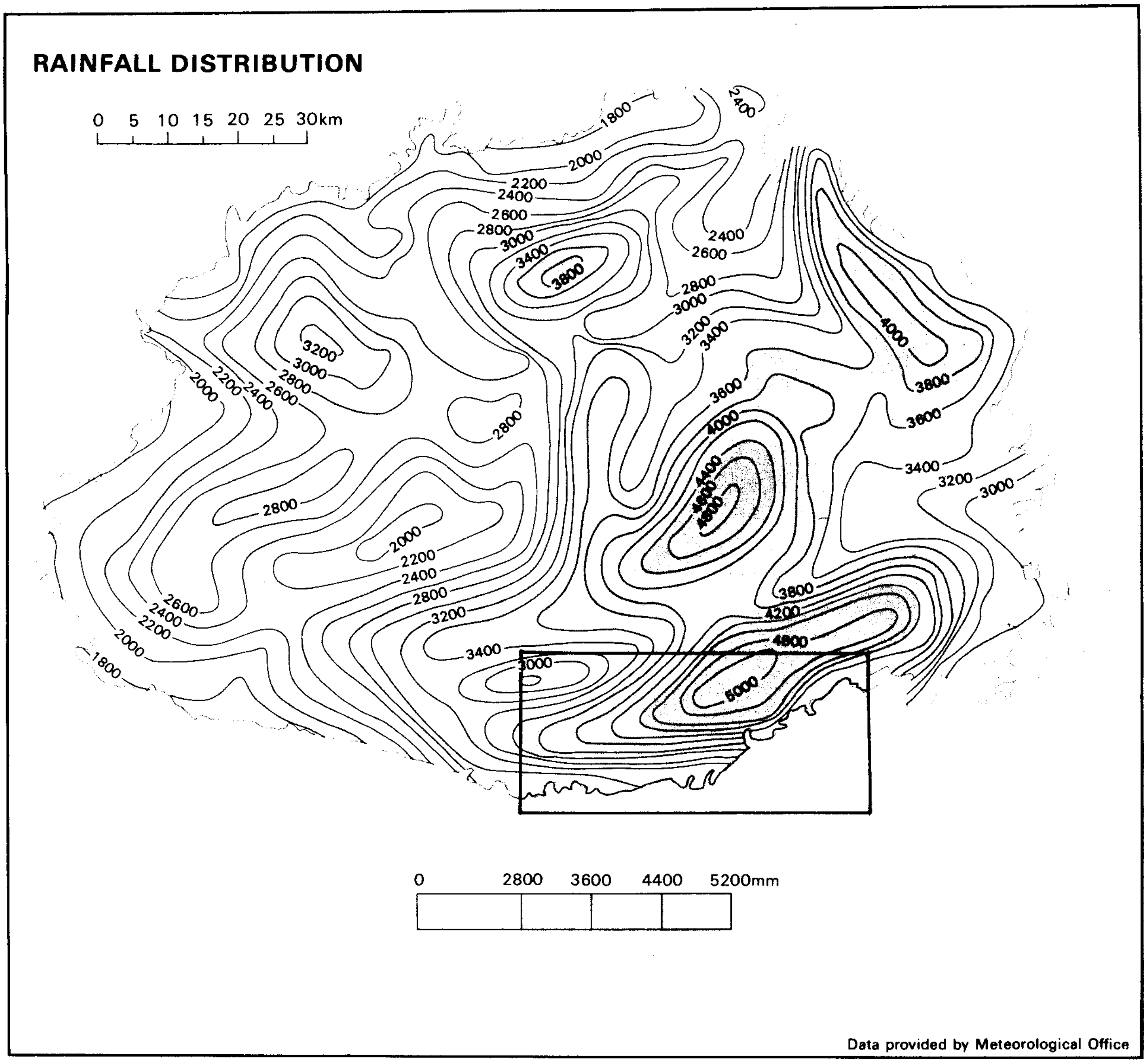

Figure 2.2 Rainfall distribution in Viti Levu. Data provided by Fiji Meteorological Service. (Reproduced after Gale and Booth, 1991).

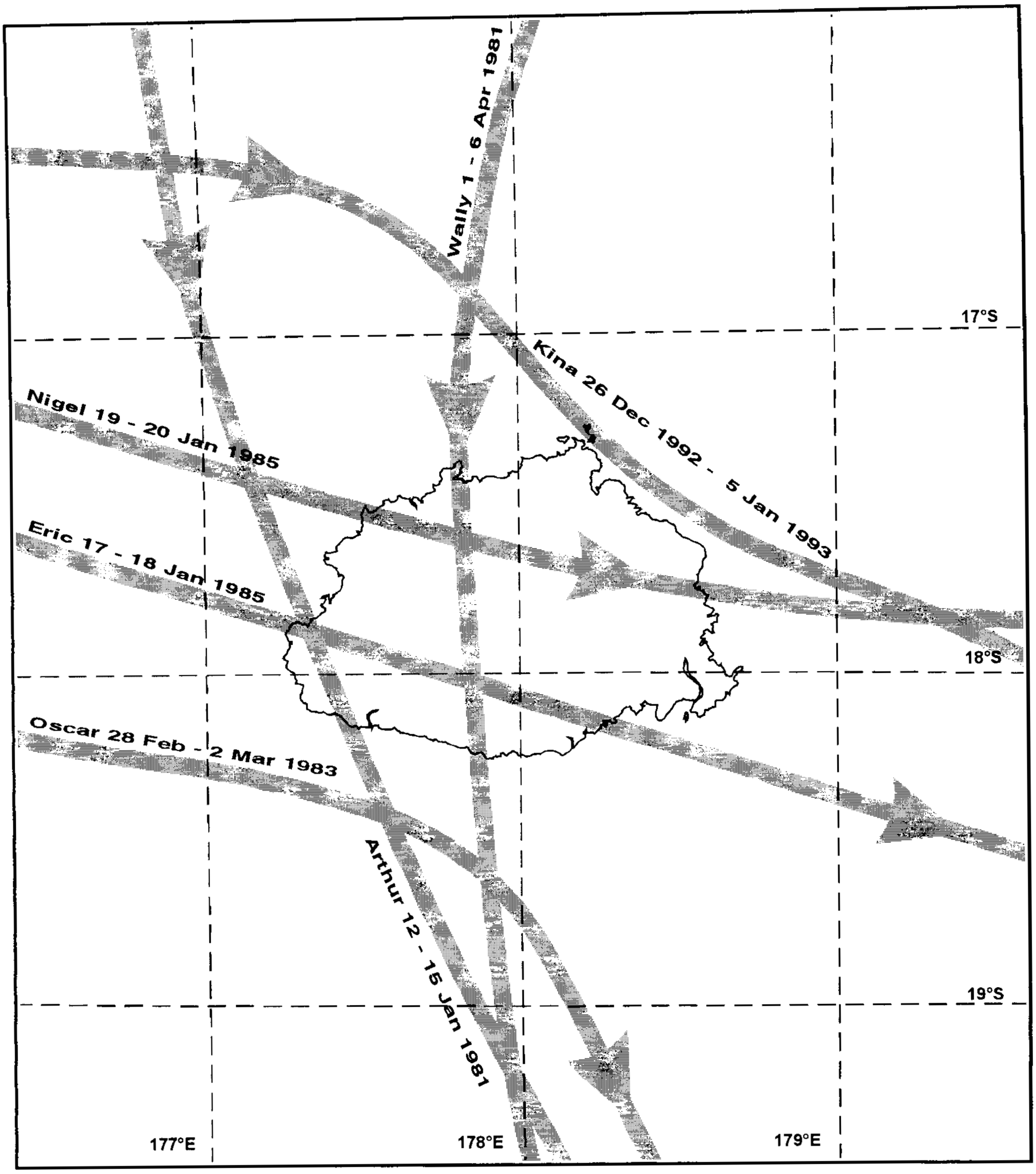

Figure 2.3 Plot of cyclone tracks in the Viti Levu area, April 1980 - January 1993. Data from the Fiji Meteorological Service.

Table 2.2 Monthly rainfall data plotted for cyclone and major storm events

Cyclone/storm	Month/year	Range in monthly rainfall (mm)	Monthly maximum (mm)
Wally	April 1980	501 - 924	1035
Storm	November 1980	310 - 576	1136
Storm	June 1984	260 - 288	790
Arthur	January 1981	273 - 452	527
Oscar	February 1983	384 - 785	1033
Storm	April 1986	966 - 1177	1422
Kina	December 1992	280 - 538	597
	January 1993	175 - 376	399

For cyclone Wally, the monthly rainfall figures for April 1980 recorded from the five stations are moderaately high with an extreme of 1035 mm. However, the storm of 24 November of the same year produced a similar volume of rain ranging from 310 mm to a record high for any single month of 1136 mm. In some years, as for example in 1984, the rainfall in autumn/winter was average. This culminated in a storm on 16 June 1984 which produced landslides observed on road cuttings (Lawson, 1993). The range in monthly rainfall figures from 273 to 452 mm for cyclone Arthur in January 1981 is atypical but not wholly exceptional.

Even though its track lay to the south west of the island, cyclone Oscar in February-March 1983 was associated with prodigious rainfall, in the 384 to 785 mm range with an extreme of 1033 mm for February recorded at the Wainikavika station. The storm of 16-21 April 1986 produced the highest average rainfall record for a single month (1422 mm) with an exceptionally higher than average range for any month in this area.

The average range of rainfall recorded at the stations for January 1993, with an above average figure of 597 mm for December 1992, is not exceptional in comparison with the above extreme rainfall events. This time-span corresponds to the passage of cyclone Kina and it illustrates that the localised effects of cyclones passing north of the island (Figure 2.3). The destructive effects of this cyclone in east and north east Viti Levu are documented by Howorth *et al.* (1993). The main impact on the south east Viti Levu area was flooding of the Rewa and Navua river valleys with associated landsliding.

An important parameter of rainfall data is the intensity of the actual rainfall over a twenty-four hour duration of a particular storm or cyclone event. According to Lawson (1993), rainfall intensity and duration data is the simplest approach to understanding the relationship between rainfall and landslide occurrence. Figure 4.1 in Lawson (*op. cit.*) illustrates this concept but data of this type was not available to the present study.

2.5 Landslides in south east Viti Levu

2.5.1 Landslide classification

Landslides are influenced by, and occur in response to, a combination of many factors (e.g. lithology, geological structure, hydrogeology, topography, climate, vegetation, seismicity and erosion). Numerous classification schemes exist, many of which were designed for a specific local purpose and are not applicable elsewhere. Of the more general classification schemes, that of Varnes (1978) is the most widely used and one of the easiest to apply. It is particularly amenable to the rapid classification of landslides assessed from appropriately-scaled aerial photography or rapid field reconnaissance.

Based on Varnes' scheme, a relatively simple classification of landslides in south east Viti Levu was devised by Lawson (1993) and is used here, with qualification, for consistency. Classification is based primarily on type of movement, qualified by descriptive terms relating to type of material involved and rate of movement (Figure 2.4).

Varnes divides material involved in landslide movements into two main types - bedrock and engineering soil. *Bedrock* is defined as hard or firm rock that was intact and in its natural place before initiation of movement. *Engineering soil* includes any loose, unconsolidated or poorly cemented aggregate of solid particles, either transported or residual in origin. It may be further sub-divided into *debris* and *earth* depending on the dominance of coarse or fine material. In south east Viti Levu, the distinction between bedrock and engineering soil is not clear-cut due to the formation of deep residual weathering profiles formed by intense alteration of the parent rocks under tropical (hot and humid) climatic conditions. Thickness of the weathering profiles varies markedly in steep volcanic terrain but *regolith* (i.e. all materials above the solid bedrock in various stages of decomposition) often extends many metres below the ground surface. For example, borehole investigations for the Suva-Nadi highway traversing the southern edge of the study area, recorded highly altered rock to depths well in excess of 15 metres (Lovegrove & Fookes, 1972).

Based on appearance, texture, and physical and geotechnical properties, a six-fold weathering classification for residually weathered rock masses, based on the recommendations of the Geological Society Engineering Group Working Party Report on tropical residual soils (Anon, 1990), is shown in Figure 2.5.[1]. In some descriptions, weathering Zones IV and IV are collectively known as '*saprolite*' (a term generally used to describe undisturbed, though wholly altered material, showing original rock textures and structures), but in this classification, Zones IV, V and VI are generally considered as 'engineering soil' and Zones I-III as 'rock'. However, since the weathering profiles tend to be markedly gradational in their characteristics, this distinction is somewhat arbitrary and may vary from locality to

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[1]This classification is similar to that developed during investigations for the Suva-Nadi highway (Lovegrove & Fookes, 1972) which also recognised six weathering zones (I, II, II, IVa, IVb, V). In this scheme, weathering zones IVa, IVb and V are equivalent to zones IV, V and VI of the currently accepted Engineering Group classification (Anon, 1990). The use of weathering zones IVa and IVb during the highway investigations, attests to the practical difficulty of distinguishing boundaries between 'highly' and 'completely weathered' zones in the field.

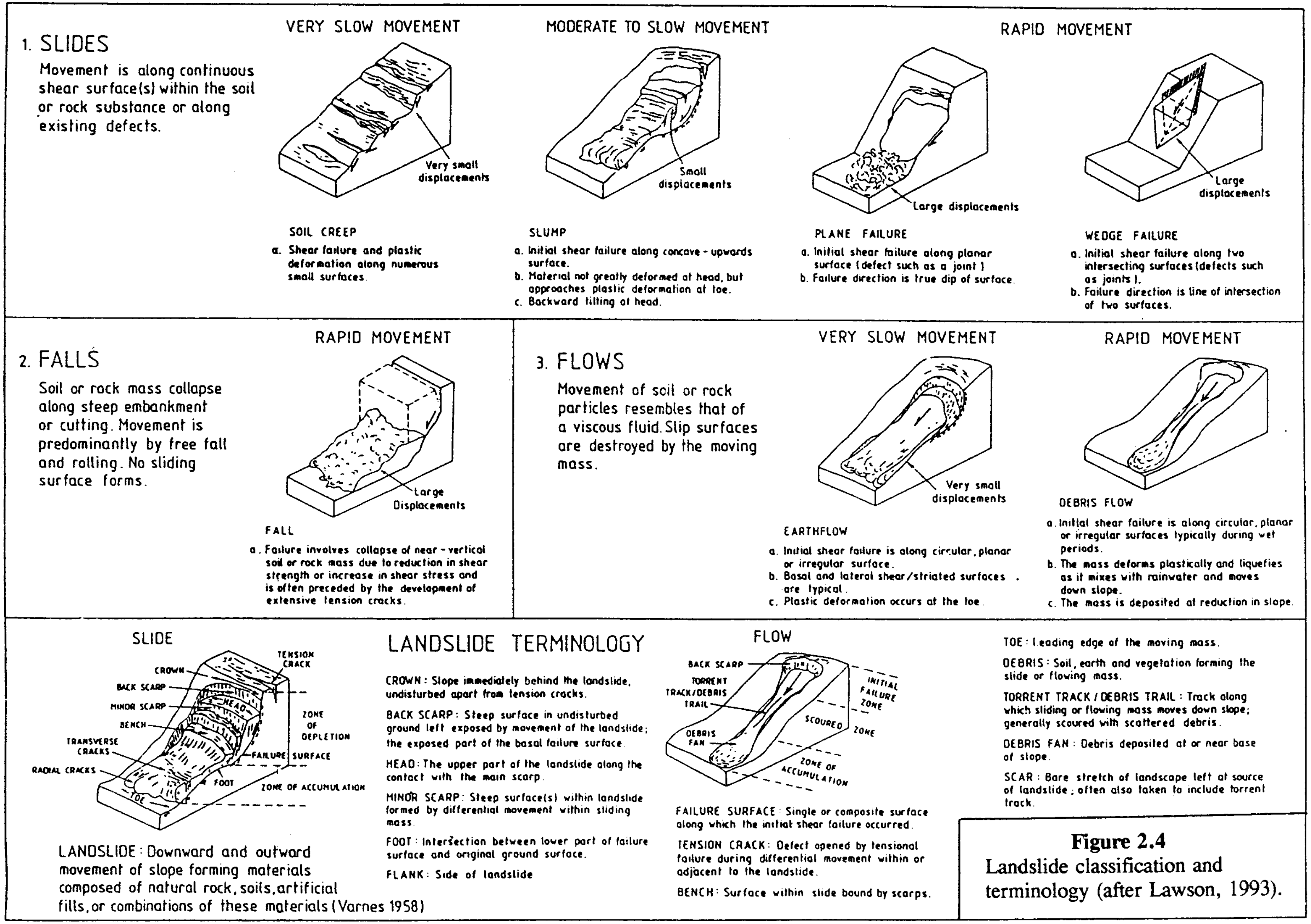


Figure 2.4
Landslide classification and terminology (after Lawson, 1993).

TERM	DESCRIPTION	GRADE
Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces.	I
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering.	II
Moderately weathered	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	III
Highly weathered	More than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	IV
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.	VI

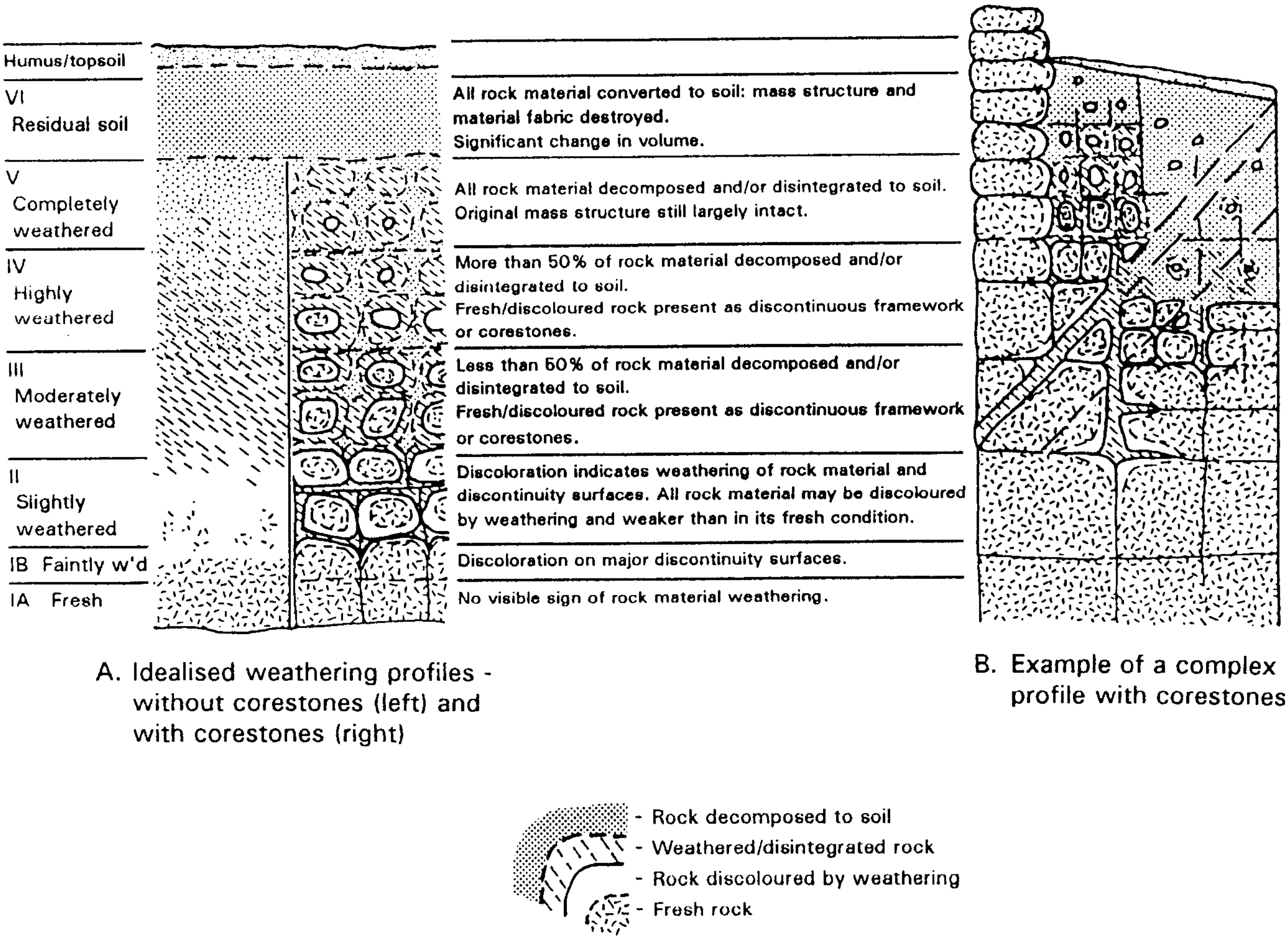


Figure 2.5 Classification of rock mass weathering zones. (after Anon, 1990)

locality. The specific term 'residual soil' is restricted here to describe material of weathering Zone VI, that is, near-surface material in which virtually all traces of the original rock mass structure are destroyed.

Rates of landslide movement are described as ranging from 'very slow' to 'extremely rapid'. Approximate quantitative movement rates pertaining to these terms are shown in Figure 2.6.

Based primarily on type of movement, Lawson (1993) recognised three main groups of landslides - slides, falls and flows - the identification of which is based largely on landslide morphology and arrangement of debris (Figure 2.4).

2.5.1.1 Slides

Slides involve the downslope movement of a rock, soil or debris mass occurring dominantly on surfaces of rupture or relatively thin zones of intense shear strain (slip, shear or failure surfaces) which may be curved or planar. Two main sub-divisions can be recognised: *rotational slides* and *translational slides*.

<u>Rotational slides (slumps)</u> are characterised by curved, concave-upward slip surfaces which impart a backward rotation or tilt to the slipping mass, which sinks at the rear and heaves at the toe. Movement typically ranges from slow to rapid. In relatively uniform materials (e.g. residual soil fills), the slip surface is generally circular. In natural slopes, the slip surface is usually controlled by lithological and strength boundaries or the presence of discontinuities such as bedding and joints, which may result in the slip surface being markedly non-circular. As a general rule, the slipped mass becomes more disrupted as the slip surface becomes more planar in character. In south east Viti Levu, relatively shallow slumps (generally less than 5 m in depth) occur mainly in thick, dominantly cohesive (clayey) sequences of residual soil or weathered regolith (weathering Zones IV-VI). Larger, deeper-seated slides may involve weathered rock (weathering Zone III). The backscarps of these slides following initial failure are usually steep, often sub-vertical, and multiple failure movements are common, resulting in a series of bench-like slip masses and scarps formed as rotational movement retrogresses upslope from the unsupported original backscarp.

Because of the concave-upward nature of the slip surface, slumps often reach a state of near-stability after only relatively small displacements. This usually results in most of the slumped mass remaining within the area of shear failure. Once stability is attained, slumps begin to rapidly degrade and acquire a vegetation cover (Figure 2.7). Shallow slumps, in particular, may rapidly degrade to innocent-looking grass or scrub-covered cross-slope hummocks or mounds which, if unrecognised, can be readily reactivated if the slope equilibrium is adversely altered by excavation or loading.

<u>Translational slides</u> involve movement along essentially planar shear surfaces, or zones, usually running sub-parallel to the ground surface and related to a layer of weakness or zone of contrasting strength within the slope. Rates of movement vary widely from very slow to rapid, depending mainly on the steepness of slope and type of material involved. In south east Viti Levu, translational slides are most frequent in the residual soils or granular weathered regolith overlying more competent rock, with the depth of failure largely controlled by the thickness of weathered debris (Figure 2.8). Howorth *et al.* (1980; 1993)

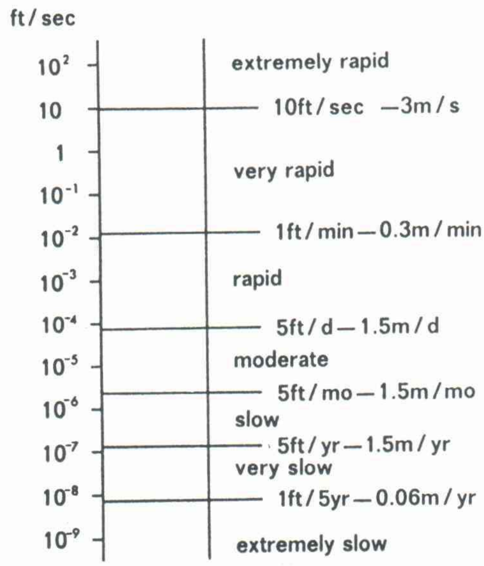


Figure 2.6 Rate of movement scale.
(after Varnes, 1978)

Figure 2.7 Multiple rotational slump in residual soil on unforested slope. The slump masses below the steep backscarp are rapidly degrading to rounded hummocks and attaining a vegetation cover. (Location: Serua Hills area)

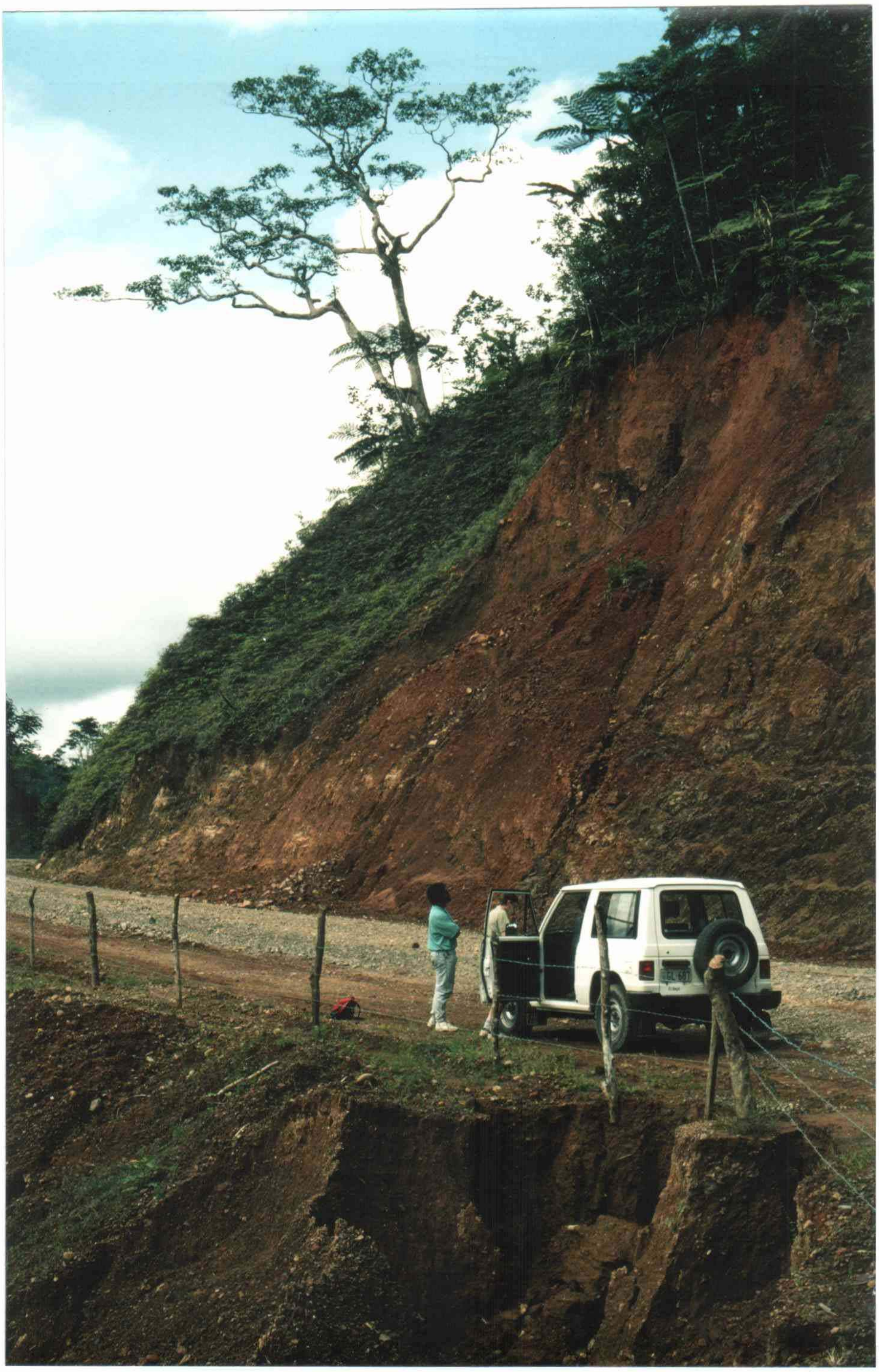


Figure 2.8 Shallow planar translational debris slide in regolith overlying more competent weathered bedrock. Slide debris spilled onto road which has beeen subsequently cleared. Erosion and minor slipping in soil road fill is visible in foreground. (Location: Waindina River catchment, north east of Waivaka village)

refer to many such slides which occurred following heavy rain associated with cyclones Wally and Kina. Discontinuities remaining as relict features within the weathered regolith also exert an important control on the development and shape of translational slides. For example, Howorth *et al.* (1993) and Lawson (1993) describe a number of slides in natural and man-made slopes where weathered debris had slid along slickensided planar surfaces related to pre-existing joint or shear surfaces within the parent rock mass. The effect of relict discontinuities was also confirmed by the limited fieldwork undertaken in the present study (Figure 2.9). *Wedge failures* are a particular type of translational failure involving a 'wedge' of rock or weathered debris sliding along two steeply-dipping intersecting discontinuities. It is possible that more extensive field surveys may show these relict discontinuities to be more significant in the initiation of translational debris slides, particularly the deeper slides, than was hitherto appreciated.

Unlike rotational slumps, translational slides will continue moving so long as the planar failure surface is sufficiently inclined and the shear resistance along this surface remains lower than the driving force. They tend, therefore, to continue moving until arrested by a marked shallowing of ground slope angle. Translational slides are frequently triggered when slopes are over-steepened by erosion or excavation, as is evidenced by many such slides associated with steep road cuts (Figure 2.10). Slides in weathered rock debris on steep mountain slopes are frequently triggered by intense rainfalls or earthquake shocks. With sufficient water content, the translational slides on these steep slopes may grade into extremely rapid debris flows.

Creep is considered by Lawson (1993) to constitute a particular category of 'slide' movement but controversy remains over its status with respect to landslide classification. It is usually defined as comprising extremely slow, spatially diffuse movements which are not concentrated on discernable shear surfaces (Hutchinson, 1988). It is not in the strict sense, therefore, a slide movement. Varnes (1978) considers it a variety of flow whereas Hutchinson considers it to be a separate category of movement and recognises four main varieties - *superficial creep*; *mass creep*; *pre-failure* or *progressive creep*; and *post-failure creep*.

Superficial creep is confined to surface layers (generally less than 1 m depth) which suffer seasonal changes in volume. In non-periglacial environments such as Fiji, these movements arise from soil moisture changes in both fine and coarse-grained regolith with movement rates generally less than 10 mm/year. Daily temperature changes may also contribute to this form of creep.

Mass creep occurs at depths below that of superficial creep in clay (including clay regolith) and rock. It is more related to the engineering concept of creep as it occurs at essentially constant stress, well below the ultimate strength of the material involved. Direct measurements of mass creep are rare.

Pre-failure (progressive) creep involves accelerating movements which reflect progressive development of shear surfaces, presaging overall shear failure (landsliding). It is of great importance as it provides a warning of impending failure and a chance of predicting it (from progressive creep curves) if identified and measured at potentially vulnerable sites. Pre-failure creep has been recognised in a wide variety of rock types including residually

Figure 2.9 Translational debris slide with movement initiated along steeply dipping planar discontinuities in highly weathered bedrock. (Location: Nambukavesi-Namosi road in Waindina River catchment)

Figure 2.10 Unstable road cutting near Galoa on the Suva-Nadi Highway. Failure is translational, involving residual soil sliding along an irregular, steeply-dipping interface with underlying weathered bedrock, and compounded by shallow rotational movements in the displaced debris mass.

weathered rock regolith. For example, Irfan (1993) described a creep-induced landslide in volcanic saprolite in Hong Kong where creep movements appear to have developed as a result of mineralogical changes. The creep occurred in part of the weathered regolith characterised by the presence of hydrated halloysite and smectite - clay minerals with relatively high values of cation exchange capacity and swelling potential, possibly produced by seasonal wetting/drying - immediately underlying the near-surface residual soils which were dominated by *non*-swelling dehydrated halloysite and kaolinite. A discrete shear plane eventually developed due to a localised rise in pore pressure, probably during an intense rainstorm. The creeping layer continued to deform until a landslide was triggered by undercutting during engineering works. Irfan also suggested that deeper creep may be initiated in the saprolite by mineralogical changes along relict joints or fissures as a result of downward-percolating groundwater. It is of interest to note that mineralogical analysis of a sample collected during the present study from a relict joint surface in saprolite exposed in the backscarp of a large landslide at Wainigasau, showed the clay mineralogy to be dominated by hydrated halloysite with subordinate smectite.

Post-failure creep involves small renewals of movement on pre-existing slip surfaces, for example, at times of seasonally high groundwater levels. Recognition of post-failure creep is extremely useful in back-analysing landslide movements as the factor of safety can be taken as unity with some confidence, enabling mass strength of the slipped material and/or pore water conditions at time of failure to be accurately calculated.

2.5.1.2 Falls

Falls involve the detachment of a mass of rock, soil or debris from a steep slope along a surface on which little or no shear displacement takes place. Failures are generally initiated by tension cracks or fissures followed by abrupt release of the rock/soil mass. The size of the falling masses is generally governed by bounding discontinuities such as bedding, joints and sheared zones, relict features of which may be present even in highly to completely weathered regolith. Falls may also occur in 'intact' residual soils particularly along river banks and coastal cliffs which are being actively eroded by stream or wave action and from over-steepened slopes formed by landslide backscarps and man-made cuts. Falls may occur from almost any steep natural and man-made slope in almost all rock and soil types, but on a regional basis are probably not as significant a hazard as other types of slope failures in south east Viti Levu. Locally, however, rockfalls comprising blocks up to 3 m in diameter have occurred in steep slopes of Suva Marl in the vicinity of Suva cemetery. Some of the falls resulted in destruction of buildings and fatalities (Keefe, 1980).

2.5.1.3 Flows

A *flow* comprises a spatially continuous movement in which surfaces of shear are short-lived, closely spaced and not usually preserved. The distribution of velocities in the displacing mass resembles that in a viscous fluid whereby inter-granular movements predominate over shear surface movements. There is a complete gradation between *debris flows* and *earth flows*, based on the predominance of coarse or fine material. There is also a gradation between debris/earth slides and flows depending on lithology, shear strength, water content and mobility of the materials involved. They tend to exhibit a wide range of movement rates from very slow (< 1.5 m/yr) to extremely rapid (> c. 3 m/sec).

A variety of terms have been used to describe flow movements which are essentially the same process but involving different materials and rates of movement. They include earthflows, mudflows, debris flows, debris torrents, debris avalanches and flowslides. In south east Viti Levu, flows involving residual soils and weathered regolith are extremely widespread. Howorth *et al.* (1980) used the term debris flow to describe flows involving regolith in the Wainitubatolu catchment near Korovou village which, in some instances on steep slopes, also show characteristics of debris avalanches. The terms earthflow and mudflow are also used by Howorth *et al.* (1993) to describe flows in residual red soil fills triggered by heavy rainfall associated with Cyclone Kina. Lawson (1993) states that most flows in the region are debris flows consisting of a wet, variable mixture of material ranging in grain-size from clay to boulders. Following this earlier work, the terms earthflow and debris flow are described in detail below.

Earthflows are slow to moderately rapid flow movements involving dominantly argillaceous debris on moderately steep natural slopes or in relatively uniform residual soil fills forming engineered earthwork slopes. They usually involve lobate or elongate masses of accumulated debris in a softened clayey matrix. They develop from an initial sliding movement in fine-grained material where water contents are sufficiently high for the sliding mass to become remoulded and flow as a viscous fluid. Movement continues until the flow material reaches a lower gradient and/or drains sufficiently for the shear strength to increase to a point where further movement is inhibited. Earthflows frequently develop at the foot of rotational slumps in both natural and earthwork slopes. Where the slide and flow components are roughly equal in proportion, they are more correctly termed slump-earthflows and represent a particularly common type of complex landslide movement. Earthflows, and slump-earthflows, are usually characterised by a steep back scarp and a more gently inclined front slope, or accumulation zone. Once initial stability has been attained, forward movement of the flow toe may recur periodically due to undrained loading of the main slide debris from falls and shallow slides at the rear scarp. Movement may also be maintained or re-activated by removal of the supporting toe material by stream erosion or excavation.

Debris flow is here restricted to rapid to extremely rapid flows involving residual soil and weathered rock debris on steep mountain slopes. They are by far the most common type of landslide in south east Viti Levu (Lawson, 1993). They may occur almost solely in the surficial residual soils (weathering Zone VI material) to form relatively shallow fine-grained debris flows (mudflows in some classifications), or involve more granular regolith down to and including weathering Zone IV. For example, in their study of typical landslides in part of the Wainitubatolu River catchment immediately south of Korovou village, Howorth and Prasad (1981) identified 28 landslides triggered by extreme rainfalls associated with cyclone Wally. Virtually all of these slides were rapid debris flows involving 'red' regolith comprising weathering Zones IV, V and VI. In the majority of these failures, shear surfaces of initiating slide movements were developed either within Zone IV material or close to the boundary with weathered rock (Zone III/IV).

The development of debris flows is favoured by abundant water, unconsolidated source material, slopes steep enough to induce flowage in the material and, in most cases, insufficient protection of the ground by vegetation cover. All these requirements are met in south east Viti Levu. Debris flows are generally initiated by a sliding failure followed by the rapid transformation of the displaced mass into a flow of wet saturated debris which can be potentially very destructive. Below the headslide source area, they are usually characterised by a narrow elongated mid-portion ('flow track' or 'torrent track') and a bulbous toe or 'debris fan' developed where the slope gradient becomes low enough to arrest movement (Figures 2.11 and 2.12). The initial slide area is usually completely vacated of debris which can move with considerable erosive power. If the supply of saturated debris is sufficient and the slope steep enough, they may travel large distances, sustained and enlarged by further slides and bank collapses generated by their own erosion. Following cyclone Wally, Howarth *et al.* (1980) and Lawson (1993) describe the widespread development of debris flows initiated on both steep planar hillslopes and within drainage lines or slope depressions. In the majority of cases, the flows developed from initial slides on upper slopes close to the ridge line. The torrent tracks of these flows often form elongate, bare stretches of soil or exposed rock of variable dimensions depending on local topography, the nature of the underlying slope materials and the erosive power of the flowing debris. Torrent tracks range from steep-sided channels eroded into underlying regolith to debris-covered stretches along which only vegetation has been stripped.

Debris flows similar to those experienced in Viti Levu have been reported from many tropical and sub-tropical regions, particularly following high rainfall events associated with cyclones or severe storms. For example, following hurricane Hugo which struck eastern Puerto Rico in 1989, Larsen and Torres Sanches (1992) describe the widespread occurrence of shallow 'soil slips' and debris flows in residual soils overlying saprolite. Rouse (1990) also describes numerous small extremely rapid 'flowslides' which occurred in Dominican residual soils as a result of two hurricanes, David and Frederick, in 1979. The term 'flowslide' (equivalent to debris flow here) is used to describe a disintegrating subaerial slide where part of the normal stress is temporarily transferred onto the fluids of the void space (liquefaction), with a consequent sudden decrease in strength. The stress transfer results directly from the initial sliding failure, after which the moving debris becomes a rapidly flowing fluid mass. It is this sudden liquefaction of the slide debris which is critical to the development of these rapid flows. However, even during extreme cyclonic rainfalls not all slides translate into debris flows.

Lawson (1993) has reviewed a large amount of available data pertaining to rain-induced landsliding and the development of debris flows in south east Viti Levu. The following general conclusions may be drawn from the data presented in his report:

- provided sufficient water is available, most of the residual soils/weathered regolith have the potential to <u>flow</u>, despite widely varying clay contents and plasticities

- the potential for <u>liquefaction</u> is not sensitive to clay content and is highest in soils/regolith characterised by an open-textured, 'bonded' fabric with high void ratios and porosities

- rapid debris flows occur most frequently on steep slopes from initial slide movements in soils/regolith prone to liquefaction

- slow earthflows develop from slides (mainly slumps) in dominantly fine-grained clay regolith characterised by relatively low void ratios and porosities due to the absence of an open-textured 'bonded' fabric

The development of particular landslide types is clearly dependent upon a complex inter-relationship between such factors as moisture availability, topography and the physical and geotechnical properties of the slope-forming materials. The effect of these factors on general hillslope stability in south east Viti Levu is discussed briefly below.

2.5.2 The Serua Hills landslides of 1980

Various mention has been made in the foregoing sections to the devastating landslides events in the Serua Hills in 1980. A summary of those events and conclusions drawn is provided below.

Extensive landsliding occurred in the southern coastal area of the Serua Hills in the period 1-5 April 1980 during the passage of, and following, cyclone Wally. This part of the Serua Hills appears to be particularly vulnerable to landsliding and was the area worst affected by this cyclone. This storm track passed from north to south centrally through Viti Levu (Figure 2.3). Up to 45 fresh landslides were reported from an aerial survey flown along the mountainous section of the highway (Lawson, 1993). The following is largely drawn from information recorded at the time and shortly afterwards by Howorth and co-workers.

A study of the landsliding in the Serua Hills by Howorth *et al.* (1980) looked at the coastal strip between Navua and Korovou. Their report gave a detailed account of the exceptionally high rainfall levels during the passage of cyclone Wally as well as descriptions of the resulting devastation to the local population, property and road system. Peak water discharge rates measured near the mouths of the Navua and Rewa rivers apparently correlated with the triggering of landslides. The great majority of the slides involved only regolith material; in only one instance was the removal of bedrock observed.

The Howarth *et al.* (1980) report also included a detailed examination of the Wainitubatolu catchment, a sub-site within the above area. This was one of the areas most severely affected by landslide activity. Their map of landslips is reproduced here as Figure 2.13. The study addressed the question of the location of slope failure and presented a model to explain landslide occurrence within the catchment. Up to 74 landslides, mainly debris flows, were recorded. In many cases, landslide depth corresponded to regolith thickness. As is characteristic of rainfall-induced surficial landslides, the mass movement occurred where the landform or configuration of the bedrock surface facilitated the concentration of slope water. More than half of the landslides originated in slope depressions or drainage lines, with initial failure taking place on an upper slope, ridge or summit.

Clues to the triggering mechanism were provided by the evidence of water seepages at the bedrock/regolith interface, along which failure tended to start. It was suggested by the authors that the intensity of rainfall was such that a perched water table was formed above relatively permeable bedrock causing pore water pressures in the regolith mantle to increase sufficiently to cause failure.

Another potentially critical condition identified from this study is the stabilizing effect of vegetation. Variations in the stability of the soil mantle appeared to be related to the density and type of vegetation cover. A forested slope with deep, penetrating root systems stabilises the surface much better than grass or crop vegetation. Evidence of this kind of control was

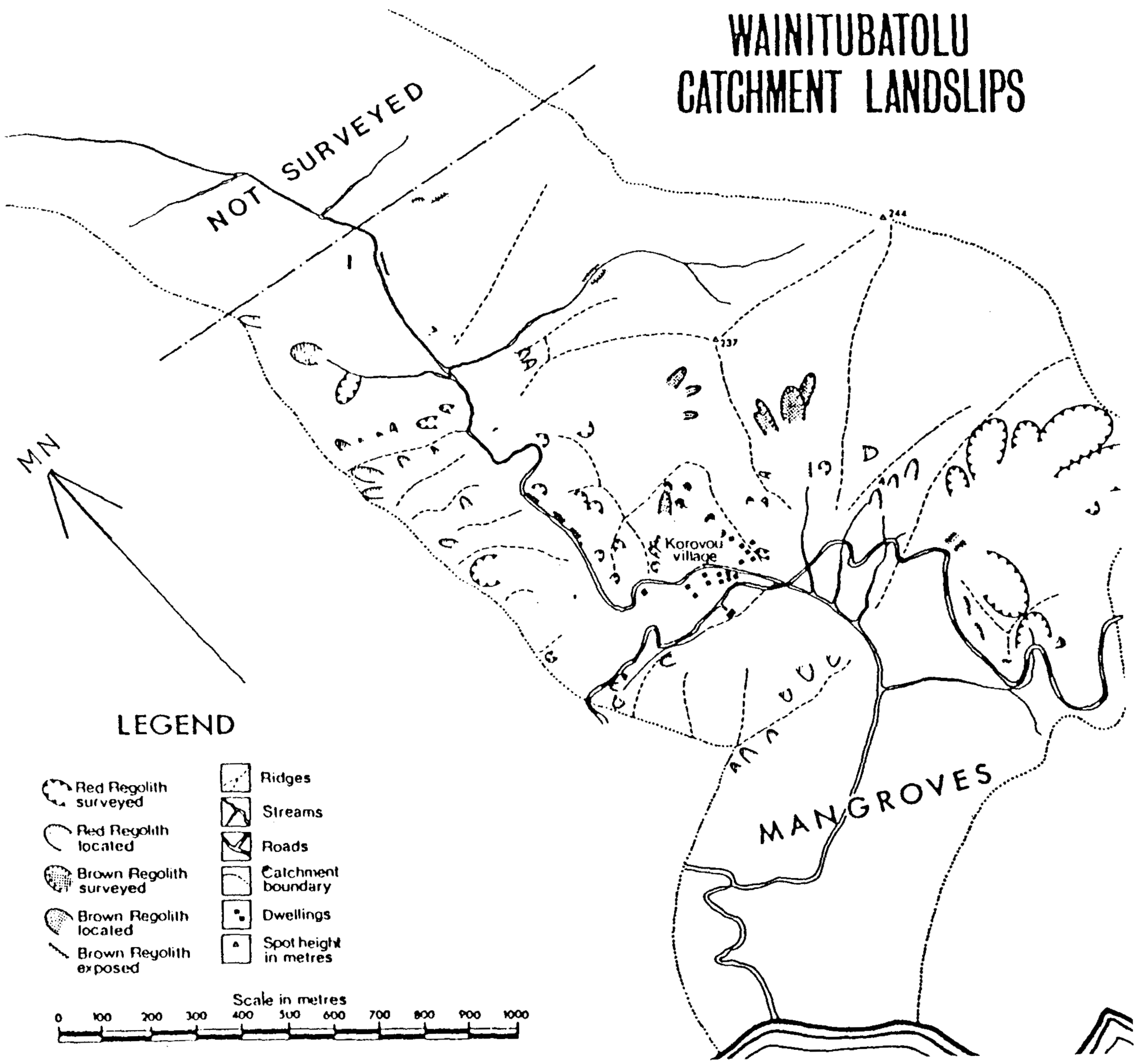


Figure 2.13 Distribution of landslides in the Wainitibatolu catchment (reproduced after Howorth, Crozier and Grant, 1981).

observed with the May 1979 rainstorm during which landslides were apparently confined to cultivation plots. However, this hypothesis is contradicted by the observation of Howorth *et al.* that landslides were equally developed on forested and grassland slopes in the Wainitubatolo catchment during cyclone Wally. The vegetation factor in controlling landslides was tested against slope angle. It was assumed that landslides in forest cover require steeper slopes than those on grassland or garden areas. However, results from two test sites showed that the mean slope angle on forest and grassland landslides were not significantly different. It was concluded that the sheer intensity of rainfall and the shallow rooting of trees (< 1 m) resulted in landslides occurring on slopes of similar gradient irrespective of vegetation cover.

The importance of soil/regolith type as a control of slope stability was addressed by Howorth *et al.* (1980). Two soil types were distinguished in their study: red clay and brown gravelly clay. A comparison of landslide distribution in the catchment showed a much higher incidence of landslides, and hence instability, within the red clay zone. The gravelly clay soils are, allegedly, more stable due to the gravel fraction with its strong internal friction and greater permeability. The brown gravelly soils are thinner than the red clay type and allow tree roots to anchor onto bedrock. However, the distribution of red and brown soils is rather localised in this study area and it is difficult to extrapolate this local classification to the scheme outlined in section 2.3.

It was concluded that the landsliding activity in the Wainitumbatolo catchment was the result of an exceptional high-intensity rainfall event. The steep to moderate nature of the slopes and the disposition of weakly-vegetated and unconsolidated landslide material indicated that the area would be highly prone to further mass movement under even a lower intensity rainfall event. An important statement in this report is that slope stability is related to the maturity or age of the regolith developed on the land surface. Thus, it was postulated that red clay soils are more mature than gravelly soils, and are more prone to rainfall-induced landsliding.

Details of the morphology and distribution of 28 landslides in the Korovou village area associated with the same cyclone event were documented by Howorth and Prasad (1981). Their map of landslides is reproduced here as Figure 2.14. The area is formed of a single ridge of volcanic bedrock mantled by thick red soils. This study is similar to the earlier one of Howorth *et al.* (1980) in that it concentrates on the detail of landslide morphology and mass movement i.e. position of failure, dispersal of debris and details of the soil (regolith) profiles.

A number of significant results emerged from this detailed study and are summarised as follows:

- Most of the slides were located at the headwaters of drainage or in interfluves close to south-facing ridge crests. Minor failures developed along drainage lines.

- Slides were mainly debris avalanches or debris flows with upper slide areas generally totally evacuated of debris, which in some cases was displaced onto the coastal floodplain.

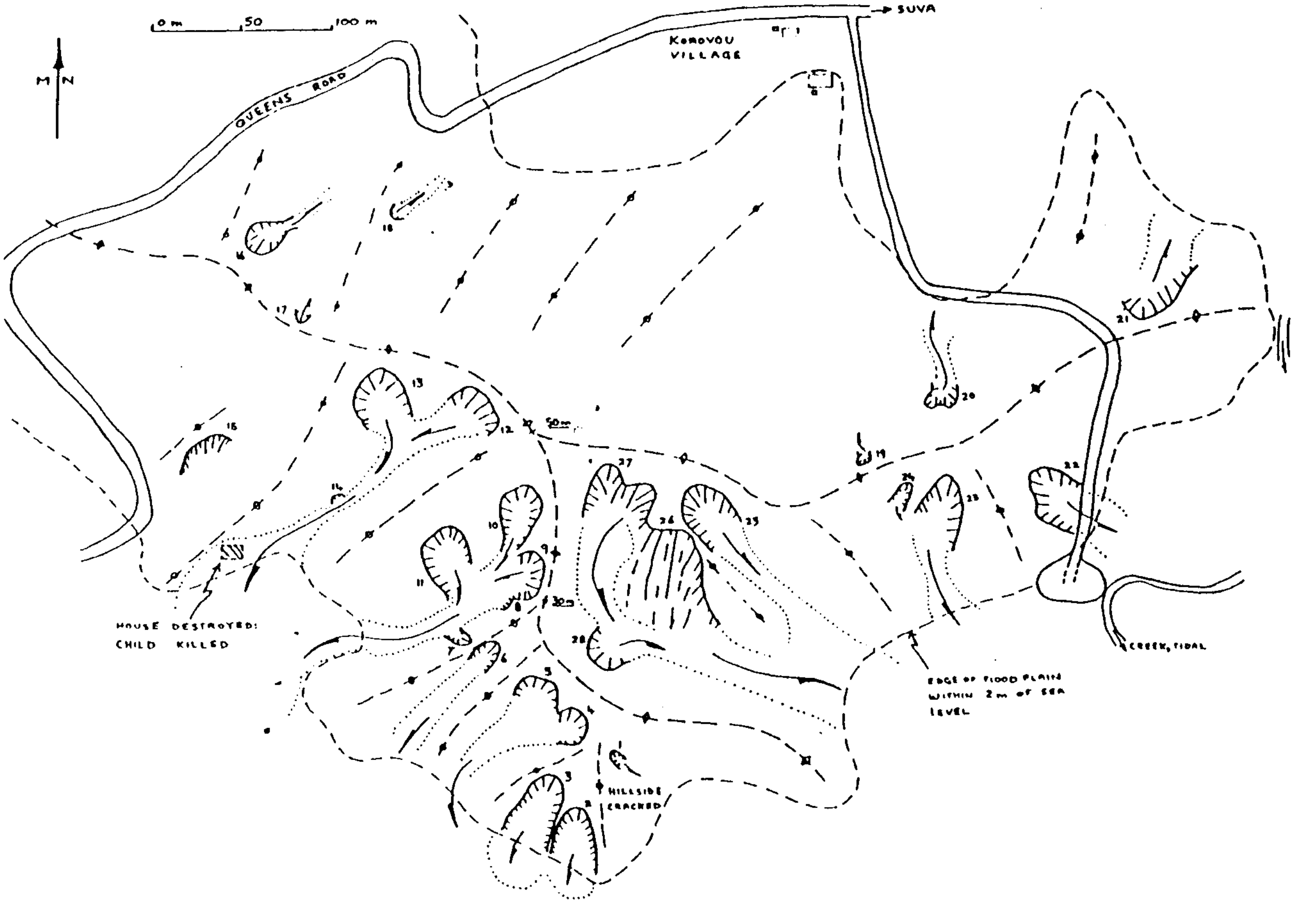


Figure 2.14 Map of landslides in the Korovou area (reproduced after Howorth and Prasad, 1980).

- The majority of slides involved regolith ranging from surficial residual soil down to 'strongly weathered' rock, with failure surfaces commonly developed at or close to moderately weathered rockhead.

- The majority of slopes appear to have been initiated on maximum slopes of between 26° and 44°.

2.5.3 Factors controlling hillslope stability in south east Viti Levu

Based on the above, and on work done in similar tropical settings elsewhere, this section attempts to summarise the main factors thought to influence or control hillslope stability and landsliding in south east Viti Levu.

The majority of landslides occur, or are at least initiated in the case of debris flows, by shear failure within the regolith. This takes place when the available shear strength of the slope materials is exceeded by the *in situ* stresses. This may occur by a reduction in shear strength due to an increase in pore water pressures, or by an increase in shear stress due to static and dynamic loads. Static stresses may be increased by over-steepening of slopes due to removal of support by erosion and excavations, or by surcharge loads resulting from engineering structures or even landslide debris. Increased dynamic loads may be caused by earthquake shocks or by the movement of tall trees during high winds where stresses are transferred to the slope material by agitation of the root system. Once failure is initiated, the shape of the resulting shear surface is largely governed by the composition and thickness of the slope-forming materials and the presence of pre-existing weaknesses or discontinuities in the slope.

That landsliding is closely related to high magnitude rainfall events is clearly indicated by the extensive slope failures which have occurred during major storms and cyclones. In the case of widespread debris flow development, exceedingly high rainfalls appear to be required before pore pressures are elevated sufficiently to induce failure and subsequent flow. During these high rainfalls, landslides occur on slopes of widely varying slope angle, but the location of these slides may in some cases be related to the nature of the surface regolith. For example, Howorth *et al.* (1980) note that in the Wainitubatolu catchment near Korovou village following cyclone Wally, five times as many slips occurred in highly weathered 'red' regolith as in less weathered 'brown' regolith, despite the latter having steeper mean slope angles (32° as opposed to 27°). It was also noted that landslides occurred in both forested and non-forested areas on slopes of similar gradient. Other records of landsliding elsewhere in south east Viti Levu note that landsliding events have involved the complete regolith cover down to weathered rockhead, or occur mainly in non-forested areas under cultivation or pasture. It is also interesting that in reports of earlier work on landslides in Viti Levu, the majority of failures are reported to have occurred or started on upper slopes at or near the slope crest. This tends to indicate that the sliding is caused by downward percolation of water rather than by a rising groundwater table, as the latter would have been likely to influence the lowest slopes first and to the greatest extent (Vaughan, 1985).

Residual red and brown soil/regolith deposits (pedologically classified as latosols) are ubiquitous in the steep terrain most prone to landsliding in the study area, and are generally characterised by high void ratios and porosities, and low saturated unit weights. Factors affecting the stability of similar latosol soils in Dominica, with respect to widespread shallow landsliding following severe rainfalls, have been described in several publications (Rouse *et al.*, 1986; 1990; Reading, 1991). In addition to instability due to severe rainfalls, these studies attempt to explain the stability of these soils on slopes of about 30° under the 'normal' very wet conditions of a humid tropical environment very similar to that found in Viti Levu. Since most of the shallow slope movements in these residual soils are essentially planar in character, and because the relatively high effective strengths of the soils were little different from residual values, the Infinite Slope Method of analysis (Skempton and De Lory, 1957) was used to determine characteristic limiting slope angles for stability. Limiting stability angles were calculated for 'wet' conditions where the water table was at the ground surface, and for 'dry' conditions where the water table was below the shear plane. The results showed that the maximum stable slope angles for the two moisture conditions were approximately 12° and 30°, respectively. When compared with a natural slope angle of 30°, this means that pore pressures would have to remain close to zero for stability. Almost identical results are obtained when this analysis is applied to slopes in south east Viti Levu. Based on soil and strength properties presented by Lawson (1993), limiting stability angles for 'wet' and 'dry' residual soils on these slopes range from 12°-16° and 30°-35°, respectively. Again, when compared to typical natural slope angles of 30°-38° in the area, pore pressures approaching zero (equivalent to unsaturated conditions) must apparently be operating for stability to be maintained.

It is known that, at least during the wet season, moisture levels in wet tropical soil and weathered rock often lie close to saturation (Brand, 1982) so that the explanation of this apparently anomalous stability must depend on additional factors related to the soil structure. Most notable of these are the high porosities, permeabilities and infiltration capacities associated with the open-textured 'bonded' structure of the residual soils and the effect of soil suction in increasing *in situ* shear strength. There is increasing evidence that even in the wet season soil suction forces play an important role in the stability of tropical residual soils. Wesley (1977), for example, notes that similar soils in Indonesia frequently have deep water tables and retain negative pore pressures (soil suction) despite being saturated almost to the ground surface. The combination of high *in situ* strengths and relatively high permeabilities in such soils means that only prolonged high intensity rainfall can elevate pore water pressures to levels capable of inducing widespread landsliding; these are critical factors controlling landslide occurrence in south east Viti Levu. Moreover, once sliding is initiated, a vast amount of soil water is available for the rapid translation of debris slides into debris flows.

In the latosol soils of Dominica, two potential saturation levels related to decreases in permeability with depth were identified (Rouse *et al.*, 1986). Firstly, a perched saturation zone may occur near the base of the highly permeable topsoil; here, perched saturation conditions occur only during heavy rainfall with sustained intensities which exceed the subsoil (weathering Zone IV-V) permeability. The cohesive strength of this layer may preclude slides if it is very shallow, and particularly if added cohesion is provided by a forest root mat. However, if this horizon is relatively thick and forest cover is absent, shallow slides are likely to occur. The second, semi-permanent, saturation zone lies at the regolith/weathered rock boundary (junction of weathering Zones IV/III) and is a critical depth for landsliding in these slopes. This saturation zone needs to expand considerably before instability occurs, and is likely to be associated with landslides triggered by prolonged high intensity rainfalls related to cyclones.

The presence of these potential saturation zones in the Viti Levu regolith, goes some way towards explaining the occurrence of landslides on mainly unforested slopes following heavy rains associated with severe storms, and on virtually any slope regardless of vegetation cover during cyclonic rainfall conditions. Clearly, a threshold rainfall effect must be associated with the onset of landsliding in the tropically weathered regolith-covered slopes in Viti Levu. Attempts to calculate this threshold value were made by Lawson (1993) using information on rainfall intensity and storm duration both resulting in landsliding and where no landsliding occurred. The results, plotted on an X - Y diagram, show that an asymptotic curve separates rainfall-related landslides from rainfall patterns not related to landslides. This curve is regarded as an empirical lower-intensity threshold above which rainfall-inducing landslide events could be expected to occur.

It is clear from this and earlier studies that landslides can be triggered by sufficiently high rainfall on virtually all slopes in the study area irrespective of slope angle and vegetation cover. The extent of this widespread landsliding has been established from aerial photograph analysis. Site specific occurrence of individual landslides appears to be controlled to a large extent by the variation in the material, geotechnical and hydrogeological properties of the regolith mantles. These factors pose particular problems in the preparation of meaningful landslide hazard maps based on rapid reconnaissance techniques.

3. REMOTE SENSING

3.1 Rationale of remote sensing approach

The combination of deeply-weathered soils, moderate to steep slopes and high rainfall associated with tropical storms (cyclones), makes the Fiji islands very susceptible to landsliding. Although the islands are thinly populated with villages and towns located mainly around the coast, scattered communities occur throughout the islands, and development is taking place at a growing rate. In 1980, cyclone Wally caused devastation over a small area of the Serua Hills in southern Viti Levu. Other cyclones regularly cause destruction and loss of life. Whilst rainfall is clearly the most important triggering event, the extent to which other controls are important is uncertain. There is a clear need to provide regional scale hazard zonation and risk maps for much of the country, both for planning new developments and infrastructure, and for establishing preparedness and mitigation procedures for vulnerable areas and populations.

Fiji has an estimated land area of 18 330 km^2 with the main centres of population on the two main islands of Viti Levu and Vanua Levu. Geotechnical investigations by the Mineral Resources Department have provided some valuable information on the nature of the ground conditions that result in landsliding (Lawson 1993: see section 2.5). However, field survey work is slow and expensive, and cannot be regarded as an approach that, by itself, is capable of covering the large areas at risk in any realizable time frame. For the foreseeable future it is probable that hazard studies will be limited to specific investigations associated with major infrastructural developments and construction, such as the transportation corridor for the proposed Namosi copper mine.

If national coverage is to be achieved, it is therefore important that a method is developed that can provide small-scale regional maps quickly and at low-cost. Such provisional maps can serve to identify areas most susceptible to landslide events and the main risks to life and property. The use of remote sensing, combined with other existing data, is a practical approach potentially capable of achieving these coverage requirements. The need, therefore, is to determine how such data may be used, and to develop an operational methodology. The output from such an analysis will initially be a landslide inventory map showing the distribution of past landslides of different ages. However, although a type of hazard map, this is merely a record of past events and says little about locations where past slides have not occurred but which may be potentially at risk. The main purpose of the present pilot study is to determine whether the landslide inventory can be used to identify basic relationships with the geology, relief etc that can be used to rank the hazard more generally both within the area of the photointerpretation and beyond.

3.2 Data types, availability and acquisition

Given the relatively small land area concerned, and the scale of most landslides, the immediate requirement is for sub-regional hazard maps at a scale of around 1:100 000. Although Landsat Thematic Mapper (TM) imagery was provided by the Fiji-German Inventory Project (a forestry land cover project), no direct use was made of this; for most purposes, the 30 m ground resolution and maximum working scale of 1:50 000 is not appropriate to mapping landslides in Fiji. The use of SPOT Panchromatic imagery (10 m resolution and working scales up to 1:15 000) is a possibility but was not available to the current project. A general problem is that all types of visible-to-infrared remote sensing data (including aerial photographs) suffer from the presence of persistent cloud cover in this tropical island situation. SPOT data has the potential for stereoscopic coverage but this requires two cloud-free overpasses on separate dates making acquisition of suitable data still more unlikely. It was finally decided to concentrate all efforts on the interpretation of conventional stereoscopic aerial photographs. These have a number of general advantages including large scale, high spatial resolution, stereoscopic coverage, low cost, ease of availability and the need of only modest equipment for their interpretation.

Various dates and scales of photographs are available for Fiji. In theory, useful information relating to individual cyclone events could be obtained by interpreting several generations of photographs for the same area. For example, such an approach could help indicate landslides which were active and others which had apparently become stable. However, for the purposes of this pilot study it was decided to use only the 1990 Agricultural Census photography. This is uniformly high-quality photography with a nominal (average) scale of 1:16 000. This scale is adequate to resolve even relatively small landslide events whilst not too large to be able to observe larger terrain features that developed as a result of landsliding over a period of time.

A major advantage of aerial photographs is stereoscopic viewing which significantly assists the interpretation and understanding of terrain features. Disadvantages at the regional scale include the large quantities of photographs needed to cover an area, the slowness of the interpretation and the difficulty of accurately transferring the information to a planimetric base map.

Aerial photographs are readily and cheaply available for Fiji, and can be ordered from the Lands Department offices in Suva.

3.3 Interpretation of aerial photographs

3.3.1 Techniques

Various types of stereoscope are available for photointerpretation, but the most convenient for systematic desk-based work is a mirror stereoscope, preferably with a parallel-motion attachment which allows roaming across the photograph pair. The mirror stereoscope enables the geologist to view the complete 'stereo model' (the area of overlap between adjacent photographs) at low magnification, or selected parts at higher magnification using a binocular attachment. It provides an appropriate working arrangement for the manual plotting of interpreted features onto a translucent overlay attached to one of the photographs.

Problems associated with the use of aerial photographs include relief-related distortions and scale variations. Relief distortions arise as a result of variations in land surface elevation across the photograph (in the same way that a tall building occurring at the edge of an aerial photograph would appear to be 'falling over'). Thus, the top of a hill will be displaced laterally outwards relative to its true, or planimetric, position. Scale changes are mainly the result of variations in flying height above the *ground surface*; thus at a constant flying altitude (i.e. above *sea level*), photo scale will change with the changing elevation of the land surface. Both these factors make it difficult and slow to accurately transfer interpreted information to a base-map. For most photogeological work, alternate photographs in a 'run' are used for annotating the interpretation (making use of the stereo overlap on either side of the central one). However, because relief distortions increase towards the photo margins, it is more accurate to use only the central portion of *every* photograph along a flight line. Even then, the subsequent transfer of interpreted information to a base map can prove difficult in areas of significant topography. In south east Viti Levu this was generally a significant, though not a major, problem.

The interpreted information was transferred to a base map using a Plan Variograph. This instrument uses a lens system to project an image of the interpreted overlay at adjusted scale onto a translucent printed map base. In this case, the map base used was 1:25 000 scale separate of the drainage network, again obtained from the Fiji Lands department. By adjusting the magnification, the projected image was matched to the map (using drainage lines also marked on the photointerpretation for reference), and the information plotted. Where such an instrument is not available, the interpreted overlay for each photograph can be reduced using a photocopier. Given the final scale of plotting or analysis, this method will still provide sufficient accuracy. Other approaches to data transfer are possible provided that appropriate computer systems exist. These include the raster scanning of the interpretation overlay (onto which the map coordinates of recognizable points have been added), and the subsequent warping and merging of the digital images to fit the base map.

3.3.2 Geological interpretation and terrain classification

Aerial photography can provide information on old and recent landslides, faults and fractures ('lineaments'), bedding and other lithological structures, recent erosional/depositional processes, habitation (including cultivation), infrastructure and roads. In the present study, the aerial photographs were used to identify landslides, lineaments, and roads although useful information relating to various development activities potentially related, or relevant, to landsliding is also evident.

The interpretation of landslides is not difficult but requires some training and experience, and an understanding of landslide mechanisms and morphology. Figure 2.4 shows the form of 'typical' landslides and Figures 3.1 to 3.3 how these appear on the aerial photographs. Since the emphasis of the project was on *rapid* techniques, the 'level' or 'detail' of interpretation is important. Ideally, the experienced interpreter should be able to interpret a stereo model (photo pair) in about an hour or so, depending on the scale and complexity. Much more time than this suggests a higher level of detail than is required.

In order to develop a scheme for mapping landslides, an initial field inspection was carried out of several areas in south east Viti Levu, and the results verified in the field with an engineering geologist from the MRD. The field appearance of typical landslides is illustrated in Figures 1.2 and 2.7 to 2.12. Based on this orientation study, a simplified scheme of terrain and landslide classification was developed for the interpretation of the main study area.

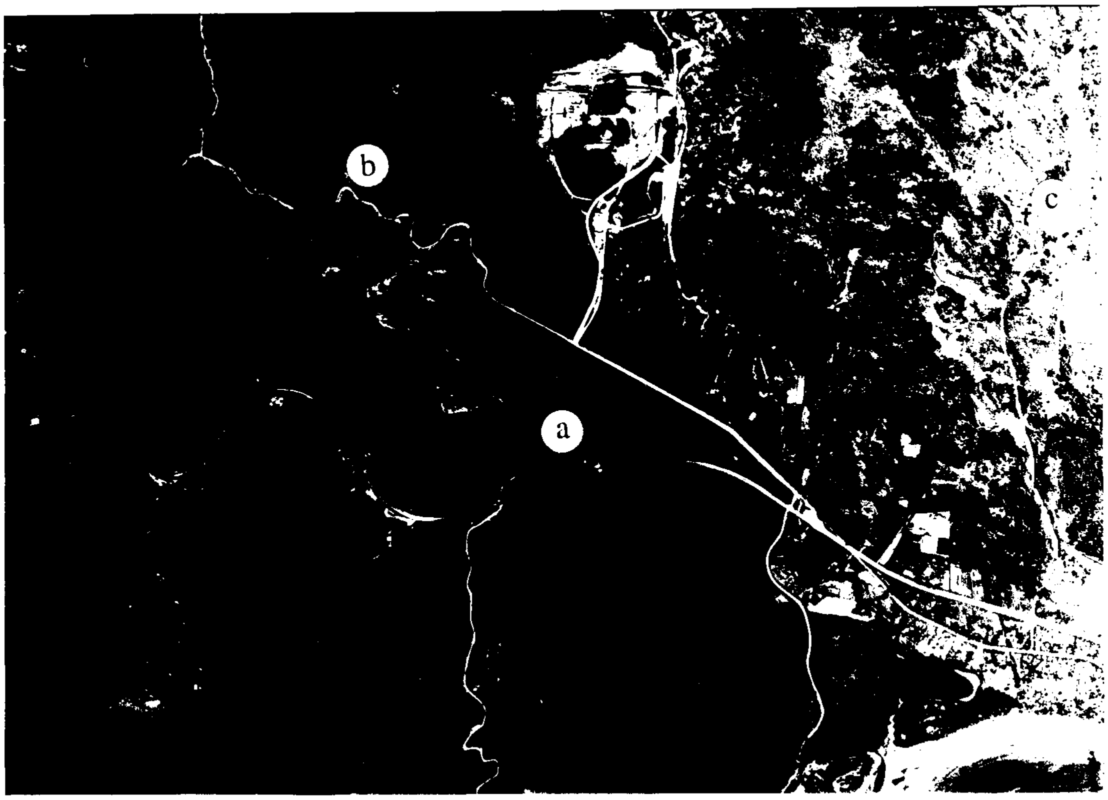


Figure 3.1 Aerial photograph (41/012) of the coastal Waivunu region, Serua Hills, showing abundant 'young' landslides between locations a and b. Many landslides of 'transitional' age occur in deforested slopes SSW from locality c, towards the main Suva-Nadi highway.

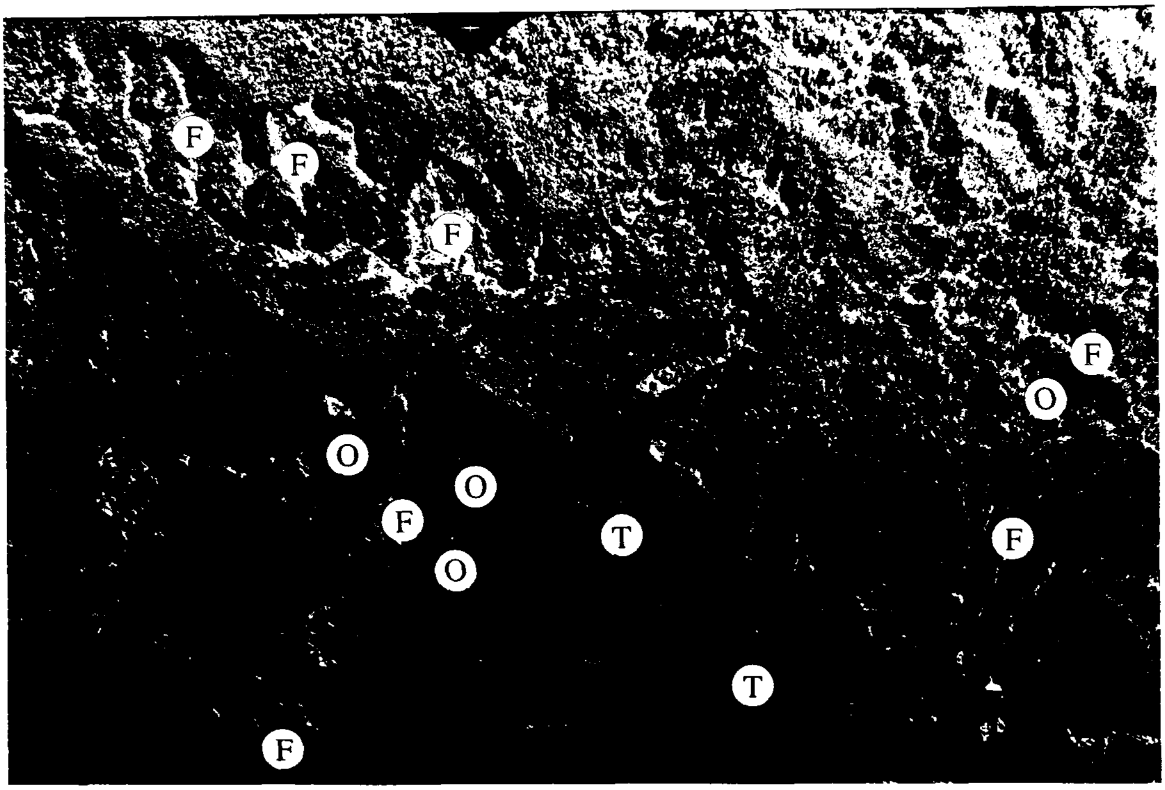


Figure 3.2 Classic appearance of landscape features due to landsliding shown on aerial photograph 39/142, 6 km NNW of Yarawa. 'Young' landslides (F) initiate new drainage, and also occur within 'transitional' (T) and 'old' (O) landslides.

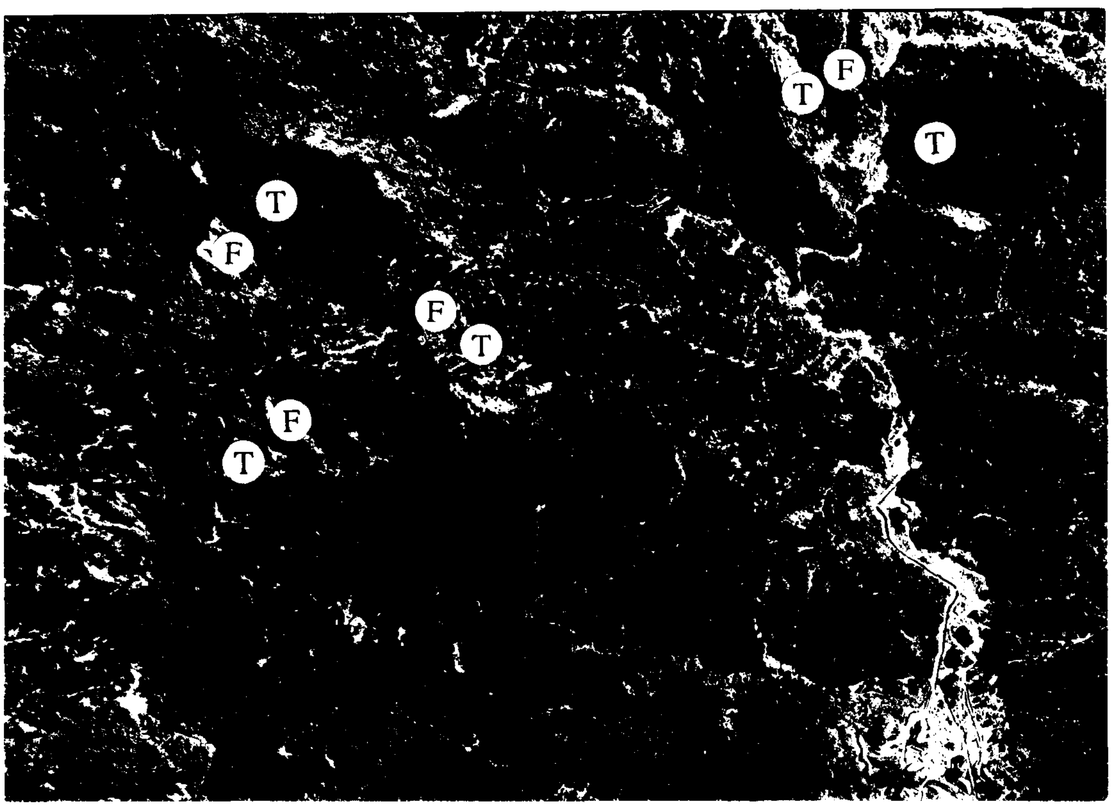


Figure 3.3 Aerial photograph (40/102) showing 'young' (F) landslide scars within particularly revegetated, 'transitional' (T) landslides, 2 km NW of Yarawa.

It was decided that three categories of landslide were recognizable and interpretable at the scale of the 1990 photography. These were categorised as: 'old', 'transitional', and 'young'. They are defined as follows.

Old Generally large landscape features produced by repeated, multiple landsliding over a long period. In their most characteristic form, they appear as large crescentic amphitheatres. Less often, they appear as large deep-seated, or small, 'single' landslides. They occupy areas completely vegetated in a manner similar in type/density to the immediate surrounding country - usually tree/forest cover in upland areas away from the coast. 'Old' landslides can be considered as 'relict' or 'mature' features which have been inactive (dormant) for many years. The age of these landscape-landslide features probably varies widely from perhaps 30 to hundreds/thousands of years. More recent slides and flows may, however, occur within the bounding areas of the larger old landslides (or 'landslide zones'). Where such younger slides occur, they are separately shown. Examples of 'old' landslides are shown in Figure 3.2.

Transitional Landslides, or landslides zones, of relatively recent origin but old enough to show significant revegetation in both the backscarp and run-out/accumulation zones. Vegetation generally consists of grasses/ferns/low scrub in contrast to the unbroken tree/forest cover in surrounding areas. They tend to be of intermediate size between old and young but show considerable variability. The backscarp of these slides is generally devoid of trees but the run-out/accumulation zones (where recognized) may show younger trees (plus older intact trees in some cases). Age is uncertain and variable, from perhaps 10 to 30 years or more. The activity state of these slides is difficult to determine. The backscarps are not as degraded as old landslides and may be more prone to further retrogressive sliding movements or to smaller 'spalls' as active degradation proceeds leading to increased instability. The transitional category covers a range of landslides and is the most vague and difficult to define. Examples of 'transitional' landslides are shown in Figures 3.1 to 3.3.

Young Generally small, individual slides showing a clear unvegetated backscarp, run-out track and accumulation zone. They appear as bright 'scars' on aerial photographs. They may occur in isolation, in groups (sometimes coalesced) or within the bounds of transitional or (more rarely) old landslides zones. Many young landslides show narrow run-outs originating in drainage headwaters and confined to (or forming) the drainage channel. All are very recent in age, generally less than 10 (in some cases possibly 15) years old. They may show signs of revegetation but retain a relatively fresh appearance due to minor spalling from, or sheetwash on, the backscarp. The accumulation zone or run-out track of these slides may have a thin partial vegetation cover of grasses/ferns/low scrub. Examples of 'young' landslides are shown in Figures 3.1 to 3.3.

Despite the apparent precision of the above descriptions/definitions, it is difficult to devise a scheme that in practice can be systematically and consistently applied *by different interpreters*. Whereas most geologists have no difficulty in recognizing and agreeing on the young category of landslides and certain obvious and major old landscape features, the less well-defined older landslides and the entire transitional category are subject to considerable variability in interpretation. This subjectivity is probably the single most serious problem to be overcome in the rapid approach to hazard mapping. It requires the setting up of a systematic 'quality assurance' procedure that can be consistently followed over a period of time by different geologists in areas with different landslide histories. This problem was recognized during the present study but at too late a stage to implement such a formal procedure. Future work must address this as a priority issue.

3.3.3 Lineaments

The term 'lineament' is used by geologists to refer to any straight or slightly curved feature, or alignment of discontinuous features, apparent on a photograph, image or map. Lineaments are particularly well-expressed on satellite images due to the oblique constant illumination, the suppression of spatial detail and the synoptic coverage, but smaller fractures traces, often representing individual faults, are also evident on aerial photographs. The size of lineaments tends to relate to the scale of the photography or imagery used. Lineaments correspond to various types of geological features including fractures (faults and joints), bedding, dykes/veins and lithological boundaries, as well as to spurious man-made features (roads, boundaries etc). In relation to landslides, fracture-related lineaments may be of significance in controlling the location or form of landslides. This is not proved but the indications from south east Viti Levu are that the distribution of landslides in some areas is structurally controlled.

In the present study, a start was made interpret lineaments, and it was clear in some instances that there was a spatial association with landslide scars. This is not surprising since fracture zones are known to influence the development of landscape through their effect on rock strength and weathering. Unfortunately, time limitations in the pilot study meant that the lineament data was not included in the eventual GIS analysis. However, it is suggested that further work on lineaments - possibly including the airborne radar (SLAR) interpretation - be included in any continuation of the work.

4. GEOGRAPHICAL INFORMATION SYSTEMS AND THE FIJI DATABASE

4.1. Principles of the geographical information system

A geographical information system (GIS) may be defined as a computer-based system (both hardware and software) for the capture, storage, integration, analysis and display of spatially distributed data. A GIS should be able to reference all data to defined map coordinates and manage changes of scale or geographic area; to transfer information to and from different sources and systems; to permit interrogation of the data (e.g. answer queries posed by the operator) usually through the use of a data base management system (DBMS), and to handle attribute information about an object (e.g. depth to named horizons in borehole logs). Importantly, it provides a means of visualising the data in various different ways and providing map outputs.

Conceptually, a GIS should be able to utilize spatial data in any form, whether raster, vector or tabular. (These are discussed further in Section 4.2). Most practical GISs, however, tend to operate predominantly with either raster or vector data, and this reflects fundamental differences in the way the GIS can be used. The benefits of both architectures are being increasingly recognized and systems are now available in which analysis and display can be performed in either mode.

By its nature, a GIS satisfies several important requirements for hazard mapping. These include:

- a database of spatially registered data which can be updated as new information becomes available;

- a capability to output simple thematic maps of selected parameters, at appropriate scales, tailored to meet particular user needs;

- an ability to compare and analyse inter-relationships between variables in order to 'model' the controls on hazards.

These will now be considered in turn.

Database: The establishment of a database, or inventory, of information relating to landslides is a major task involving various inputs. These may include remote sensing, lithological and soils information, structural, and geotechnical data, laboratory test results, and so forth depending on what data exist and are readily available. In many respects, the task of databasing is one that should be considered ongoing, more data being added as it becomes available. Given these requirements, some form of digital database is the obvious solution. However, *the size of the task involved in building a digital database should not be underestimated*. Most workers agree that more than 90 per cent of the effort in GIS-related studies is concerned with data capture (by digitising or other means), and co-registering data sets referenced in different map projections.

Maps: The hazard map is a convenient visual summary of information relating to the probability of landslides. It represents *one possible* interpretation of the data. A major advantage of a GIS is that maps/plots can be created as required, designed to answer particular needs, using the latest available information held in the database. This is particularly important where the user is a non-geologist looking for practical solutions to particular problems.

Data analysis: The visual and statistical comparison of inter-relationships between different spatial variables held in the database allows the importance of various factors to be assessed in relation to landsliding. Thus, for example, the relationship between old landslides and a lithology or soil type, or perhaps a combination of soil type and slope class, can be judged using the GIS, and the results used to help understand, or perhaps 'model', the occurrence of landslide events in general. Such an approach is not new to geologists; traditionally, maps have been overlain on a light table to identify correspondences. The advantage of the GIS is that data sets may be more easily manipulated and viewed in combination, and quantitative measures of correlation derived to measure the results.

4.2 GIS design and implementation

The large and growing range of commercially available GISs and the increasing awareness of this technology worldwide, indicate their value in environmental applications. The choice of GIS will depend on several factors, the main ones of which are: size/extent of problem; design requirements of the database; analysis needs; output formats; financial constraints; and, importantly, what computer/GIS systems are already in use and commercially supported nationally/locally. The last factor is in many respects the most fundamental as it will strongly influence the eventual choice. A community of users is important in regard to training and advice, data sharing, problem solving, and support/maintenance. None of these should be under-estimated. The choice of system may also be influenced by existing GISs within the organisation, or a need to share the eventual system with other users having different requirements. In Fiji, the GIS user community is already large and growing. Cooperation between individual organisations, such as through user groups, will lead to a sharing of data to the advantage of all.

Another important consideration is the complexity of the system chosen. The difference between a personal computer (PC) and a workstation is becoming increasingly blurred as processing power and data storage capability increase. Nevertheless, it is sensible to chose a system that is not over-sophisticated for the purpose. For example, in order to produce simple hazard maps, the output need not be cartographically very refined. Complex systems generally require considerable training and expertise, and consequently do not encourage sustained use. For some organisations, there is a danger of the system being so complex that only one specialist in the group can effectively operate it: should he leave, the system can easily fall into disuse.

The final basic consideration relates to the generic design of the system: vector or raster (Figure 4.1). In *vector* systems, map elements are represented by points, lines and polygons, the vertices of which are defined by map co-ordinate pairs. Each element may be associated with tabular attribute information describing its characteristics. Advantages of vector systems are that data storage requirements are small and the systems are well suited to cartographic plotting applications. Vector GISs are particularly useful for answering spatially-referenced database enquiries and for the analysis of networks such as drainage patterns. In the case of

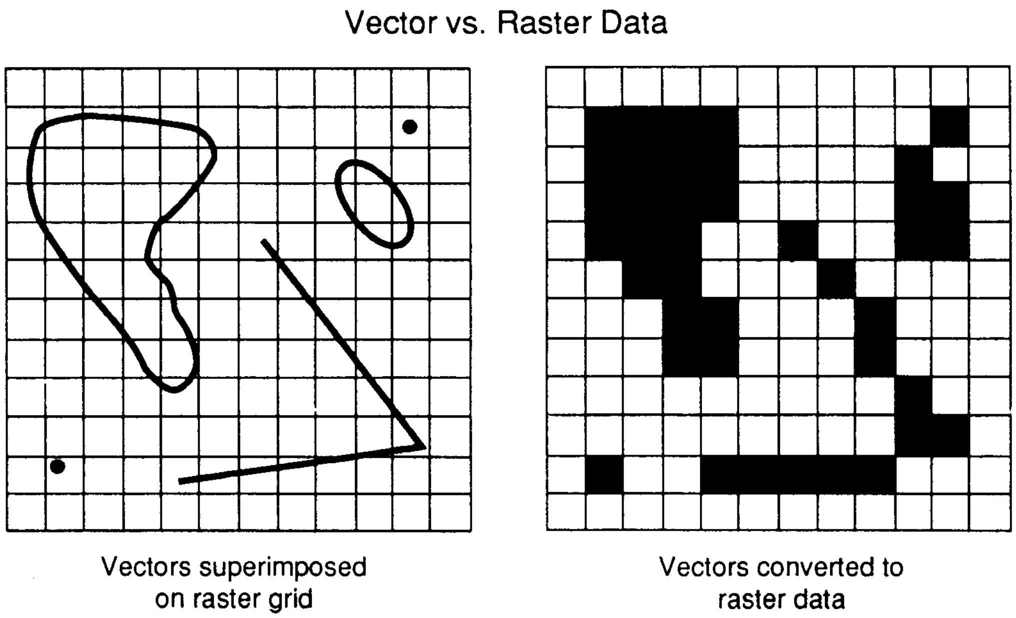


Figure 4.1 Concepts of vector and raster representations of points, lines and polygons.

raster systems, the map area is divided into a mesh of grid cells (also called 'pixels') each of which records the value of the parameter. Raster data require more storage than vectors since every pixel must have a value, even if it is a code to indicate the absence of information. They also produce less elegant map output. Their main advantage is they are better suited to analyzing spatial relationships between parameters over continuous areas.

Given the range of considerations, there is usually no simple answer to the question: 'What is the best GIS system to use?'. The final choice is usually a compromise. In the present study various systems were used to develop a methodology. The choice was based on (1) immediate and long-term project requirements and (2) existing/potential hardware/software availability in the Mineral Resources Department and BGS. The following systems were employed:

- Intergraph Modular GIS Environment
- ILWIS
- IDRISI

4.2.1 Intergraph Modular GIS Environment (MGE)

MGE is a predominantly workstation-based system comprising various software modules which can be combined for different applications and which is underpinned by the MicroStation computer-aided drafting/mapping package. MicroStation is a sophisticated vector system for data capture, editing and presentation. Once digitized, map information can be passed into other modules for analysis and modelling. Of particular use to this study were the MGE Grid Analyst and Terrain Modeller modules. The former was used mainly to convert from vector to raster formats and the latter for the manipulation of DEMs.

The disadvantages of MGE are its complexity, cost and the limited capability for converting vector data to other proprietary vector formats for transfer to other systems.

4.2.2 ILWIS ('Integrated Land & Water Information System')

Of the systems used in this study, ILWIS probably comes closest to the definition of a GIS given above. It can manage and analyse raster and vector data in combination, and link to an internal DBMS for processing information in tables. Based on an upgraded PC with dual screen capability, one for graphics the other for textual information and control, this system represents an extremely cost-effective stand-alone solution for hazard mapping. ILWIS was the system originally chosen for the project but was largely replaced by IDRISI (section 4.2.3) because this latter system is likely to become more used in Fiji and the south west Pacific region.

ILWIS is capable of transferring data to and from many different systems, of digitizing vector information and of producing output maps to specified scales with annotation. Analysis of raster maps and tabular information is achieved by treating each data set as a variable in an equation easily entered by the operator in a calculator function.

4.2.3 IDRISI

IDRISI (Version 4.0) is a very low-cost raster-based GIS which can be installed on almost any PC. Although designed as a system to provide training in GIS technology, it can, nevertheless, perform operational tasks. It provides the same analysis functions as ILWIS albeit with a less elegant operator interface and some restrictions on parameters.

The main disadvantages of IDRISI are the very limited vector and map presentation capabilities and lack of a DBMS. To overcome these, it is recommended that additional software packages are installed on the system to provide these facilities. Another disadvantage is the limited ability to read information from other systems. For example, to load vector information captured using MicroStation, the file had first to be converted to the AutoCAD DXF format, read into ILWIS (thereby converting to its internal format), converted to Arc/Info GEN format and then read into IDRISI; a total of five different formats for the same information.

Although not currently used in the MRD, there are suggestions that SOPAC will provide and support the soon-to-be-released Windows-based version of the software.

4.3 Raster GIS analysis

The tools available in the raster GIS may be divided into four basic groups, described below.

Database query: This allows simple enquiries related to the stored information, such as *..show all areas with a slope angle greater than 30°...* or combined queries such as .. *show all areas with a slope angle greater than 30° that are underlain by Veisari Sandstone..* This is done by reclassifying each layer to show the presence or absence of a condition (known as a *Boolean* or *binary* image composed of 1s and 0s), and then logically overlaying the Boolean maps using the conditional operators *AND OR* to create a new display satisfying both criteria.

Map algebra: This allows a layer to be mathematically transformed, or several layers combined, using various scalar or algebraic operators. By this means, layers can be weighted and different situations modelled. The tools also allow the more complex mathematical overlay of layers using ADD, SUBTRACT, MULTIPLY & DIVIDE.

Distance operators: These allow a *buffer zone* (or 'corridor') to be calculated around a point, line or polygon where distance is an important aspect of the analysis (e.g. to test whether proximity to a fault/lineament is significant).

Context operators: The calculation of slope from a DEM is based on the relationship between the value at a point and neighbouring points. Other examples of context operators include digital filters which allow such operations as smoothing or shaded relief.

Analytical operations carried out on a GIS using the above tools fall into a few main categories. Database enquiries may be used to look for obvious spatial patterns in the data which allow ideas about relationships to be formulated. Thus, by examining in turn the spatial occurrence of landslides within different lithologies, one can decide whether lithology is an important control on landslide occurrence. For example, the spatial association of landslide polygons with, say, volcanic breccia, might suggest that these rocks are prone to landslides, even though the precise explanation for this is not known. This can be done for all logical combinations of primary data layers. Secondary data layers may be derived from the primary information either by combining different layers or by transformation. For example, the digital elevation model may be used to generate secondary layers of slope and aspect which may be then used directly in the analysis.

4.4 Fiji database

Mention has already been made of some of the information derived from the remote sensing data. These and other inputs are further described below. In assembling a GIS database derived from maps of differing ages and content, a major task involves converting the data sets to a common coordinate and map projection system. This is no trivial exercise, and considerable effort was expended in this study to achieve this. Various problems were encountered during data conversion, and these are briefly described below.

Map base: Fiji is in the process of converting from an older mapping co-ordinate system (Series X754, Edition 6-GSGS, published by the Ministry of Defence, United Kingdom 1972), to a new one based on the Fiji Metric Grid (FMG). The former 1:50 000 series maps were based on the Cassini-Soldner projection and Clark 1880 spheroid, with the projection origin at 18 degrees south, 178 degrees east, and a scale factor of 1.0000 at the origin. The coordinates of the origin are 5440.00 chains east, 7040.00 chains north (1 chain = 22 yards).

The new FMG is based on the Fiji Geodetic Datum 1986. Its definition is the same as the World Geodetic System Datum 1972, which is often referred to as WGS-72. The semi-major axis has A = 6378135.0 m with a flattening F = 298.26. The FMG has a Transverse Mercator projection defined by the following parameters:

False Easting	2 000 000 m
False Northing	4 000 000 m
Central Meridian	178 degrees 45 minutes east
Central Scale Factor	0.99985
Origin	178 degrees 45 minutes east 17 degrees south

Problems in map data conversion: Some difficulties arose in digitising old format map information and converting it to the new projection system (e.g. geology, soils, coastline, river drainage). The coastline and drainage for old map sheet 19 (Mau) were digitised from the 1972 topographic map at the beginning of this study. The 1:50 000 topographic maps have the advantage of a UTM grid with one kilometre spacing superimposed over them, which allows the coordinates of any physiographic feature to be easily obtained. Unfortunately, the 1:50 000 geology (1967) and soil maps (1975) do not have a UTM grid, but instead a coarse latitude/longitude grid at 15 minute intervals (about 28 kilometres). This makes it difficult to obtain coordinates readings for features of interest. Before digitising, the equivalent FMG coordinates had to be obtained for the four map corners, together with some random points such as well defined physiographic features (e.g. river or road intersections).

To facilitate the digitising process, the Fiji-German Inventory Project (FGIP) at Colo-I-Suva provided BGS with calculated FMG map corner coordinates for the 1:50 000 Land Resource Division (LRD) forest inventory maps (produced in 1973 by the LRD of the ODA, UK). These maps appeared to be plotted on the same map base as the 1:50 000 geological maps. An official Cassini-to-FMG map coordinate conversion program was later (December 1993) obtained from the Fijian Land Information System Support Centre (FLIS) in Suva. This had been developed by the New Zealand Department of Survey and Land Information (September 1992). However, when the UTM coordinates of a road intersection near the top left corner of the old 1:50 000 topographic map sheet 20 (Suva) was converted to FMG coordinates using this program, its calculated position was found to be some 500 metres ENE of its location shown on the new 1:50 000 map sheet (FMS 31 O28 Nausori). Other locations tested gave similar errors.

If it is assumed that the computer program and new 1:50 000 maps are correct, this indicates that there is a serious problem with the absolute spatial latitude/longitude positions of physiographic information shown on the old 1972 topographic maps. This has important consequences when attempting to digitise information from these old maps and entering them into a GIS database.

Subsequently, the MRD provided BGS with a general purpose, PC-based, geodesy computer program developed by the FGIP (8 August 1994), called FMG.EXE. This converts geographical co-ordinates (expressed as decimal latitude and longitude) from the old map base to grid co-ordinates in the new FMG (and visa-versa). This program was compared with a coordinate transformation program available on the Erdas image processing system, using the four corner points for the old 1:50 000 topographic map sheets 17, 18, 19 and 20. Table 4.1 shows that the two programs give essentially the same sub-metre accuracy results. The Erdas program gives Easting values which are consistently about 0.5 metres greater than the Department of Forestry program. The Northing values agree to within 0.1 metre.

Another problem was that the geology maps appear to have incorrectly-labelled latitudes, the values being 12 seconds of arc too large. This can be seen by overlaying the geology (1967) and topographic maps (1972) and matching physiographic features. This procedure demonstrates that these two map bases have the same actual corner points. Thus, the southern boundary of geological map sheets 17 and 18 should be 18° 17' 48"S (not 18° 18') and the northern boundary 18° 02' 48"S (not 18° 03'). Similarly, the southern boundary for geological map sheets 19 and 20 should be 18° 14' 48"S (not 18° 15') and their northern boundary 17° 59' 48"S (not 18° 00').

However, even after allowing for the 12 second shift in latitude, digitising the old topographical and geological maps using the corner points, calculated either by Erdas or the latest computer program [FMG.EXE] (see Table 4.1), still produces a significant mis-registration between physiographic features when compared with their positions on the new 1:50 000 topographic maps (1993). For example, two river confluences from sheet 18 gave an ESE shift of about 400 m west and between 90 and 220 m south as shown on the new map M29 Korolevu. Other points gave differing shifts.

It was therefore not possible to directly transform data points analytically from the old map projection to the new one.

Table 4.1 Comparison of 1:50 000 geology map sheet corners in latitude/longitude & computer calculated Fiji Metric Grid coordinates

1:50 000 SHEET	CORNER	GEOLOGY MAP LATITUDE °S	GEOLOGY MAP LONGITUDE °E	DECIMAL LATITUDE °S	DECIMAL LONGITUDE °E	ERDAS CALCd FMG EASTINGS	ERDAS CALCd FMG NORTHINGS	FMG.EXE CALCd FMG EASTINGS	FMG.EXE CALCd FMG NORTHINGS
17	SW	18° 17' 48"	177° 40' 00"	18.29666667	177.6666667	1885475.22 E	3856171.13 N	1885474.68 E	3856171.17 N
	NW	18° 02' 48"	177° 40' 00"	18.04666667	177.6666667	1885312.04 E	3883841.57 N	1885311.50 E	3883841.61 N
	NE	18° 02' 48"	177° 55' 00"	18.04666667	177.9166667	1911780.36 E	3883978.73 N	1911779.82 E	3883978.77 N
	SE	18° 17' 48"	177° 55' 00"	18.29666667	177.9166667	1911905.88 E	3856309.93 N	1911905.34 E	3856309.97 N
18	SW	18° 17'48"	177° 55' 00"	18.29666667	179.9166667	1911905.88 E	3856309.93 N	1911905.33 E	3856309.97 N
	NW	18° 02'48"	177° 55' 00"	18.04666667	177.9166667	1911780.36 E	3883978.73 N	1911779.82 E	3883978.77 N
	NE	18° 02'48"	178° 10' 00"	18.04666667	178.1666667	1938247.32 E	3884080.10 N	1938246.78 E	3884080.15 N
	SE	18° 17'48"	178° 10' 00"	18.29666667	178.1666667	1938335.17 E	3856412.51 N	1938334.63 E	3856412.55 N
19	SW	18° 14' 48"	178° 10' 00"	18.24666667	178.1666667	1938317.51 E	3861946.21 N	1938316.97 E	3861946.13 N
	NW	17° 59' 48"	178° 10' 00"	17.99666667	178.1666667	1938229.89 E	3889613.66 N	1938229.35 E	3889613.58 N
	NE	17° 59' 48"	178° 25' 00"	17.99666667	178.4166667	1964703.36 E	3889679.09 N	1964702.82 E	3889679.01 N
	SE	18° 14' 48"	178° 25' 00"	18.24666667	178.4166667	1964753.42 E	3862012.42 N	1964752.89 E	3862012.34 N
20	SW	18° 14' 48"	178° 25' 00"	18.24666667	178.4166667	1964753.42 E	3862012.42 N	1964752.89 E	3862012.34 N
	NW	17° 59' 48"	178° 25' 00"	17.99666667	178.4166667	1964703.36 E	3889679.09 N	1964702.82 E	3889679.01 N
	NE	17° 59' 48"	178° 43' 00"	17.99666667	178.7166667	1996469.54 E	3889710.50 N	1996470.30 E	3889710.42 N
	SE	18° 14' 48"	178° 43' 00"	18.24666667	178.7166667	1996474.55 E	3862044.21 N	1996475.30 E	3862044.12 2N

In order to overcome these problems, it was assumed that the old maps were incorrect. The digitised map data were transformed by a least squares adjustment to the FMG using Intergraph Projection Manager software. Even after this transformation, it was discovered that the raster GIS files supplied by the FGIP needed a shift in origin to achieve full registration. This was achieved on the GIS.

Landslides: The classification of photointerpreted landslides was described in Section 3.3.2. The 'old', 'transitional' and 'fresh' landslide categories were separately digitised. The old and transitional types were digitised as filled polygons. However, many of the fresh landslides are narrow and often sinuous gulley run-outs, which were difficult to digitise directly as polygons. During interpretation, all were marked with a point representing the nominal 'initiation point' near to the top of the backscarp. The fresh landslides were finally digitised in several ways: as a point (where very small), as a point plus a line to the toe (where narrow/sinuous), or as a point plus polygon (where sufficiently large). During GIS processing, polygons were created of all the 'points' and 'points-plus-lines' sub-categories by generating a narrow 1-pixel wide buffer around them. Finally, all fresh landslides were merged into a single category in which every slide was represented by both a polygon and an initiation point. Figures 4.2 to 4.5 show the distribution of old, transitional, young and total landslide polygons, respectively.

Lineaments: Lineaments related to drainage and topography were interpreted by some investigators only. As this was not a consistent nor complete data set across the study area, and due to lack of time, it was not digitised.

Geology: The geological boundaries were digitised from the published 1:50 000 scale geological maps. These sheets are essentially large-scale reconnaissance maps and show some edge-match discrepancies. These differences were arbitrarily reconciled prior to digitising. Although it is likely that lithological-structural differences affect/control landslides, the present maps may not contain enough underlying lithostratigraphical information to allow significant conclusions to be drawn. A plot of the digitised geology map is shown in Figure 4.6.

Topography: A digital elevation model was provided by the FGIP based on the digitised old series 1:50 000 topographic sheets. It is understood that this information was scanned and converted to digital files from which a digital elevation model (DEM) was produced. The DEM was in turn used in the study to generate slope angle maps (in 5° classes) and slope aspect maps (in 8 sectors). The details of this work are described separately in Section 4.4. The elevation, slope angle and slope aspect maps are shown in Figures 4.7, 4.8 and 4.9 respectively.

Soils: The pedological soil scheme used in this study is a modified version of the classification developed by the Ministry of Primary Industries (MPI) which represents an adaptation of the original Twyford and Wright (1965) classification (section 2.3.1). The soil types in the MPI scheme, based largely on parental lithological associations and geographic domains, were simplified into five groupings for description purposes. However, in order to test the wider variability of pedological soils against other data sets, 43 classes were digitised for GIS analysis. The soils distribution map is shown in Figure 4.10.

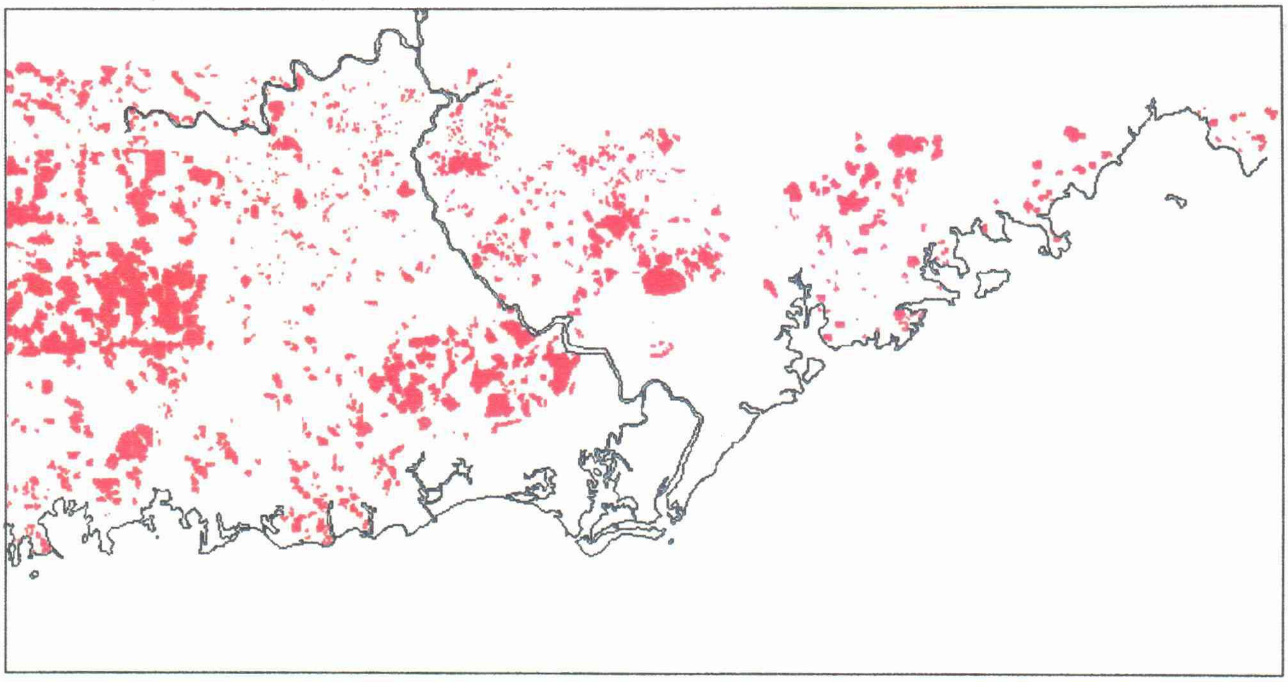


Figure 4.2 'Old' landslides interpreted from aerial photographs.

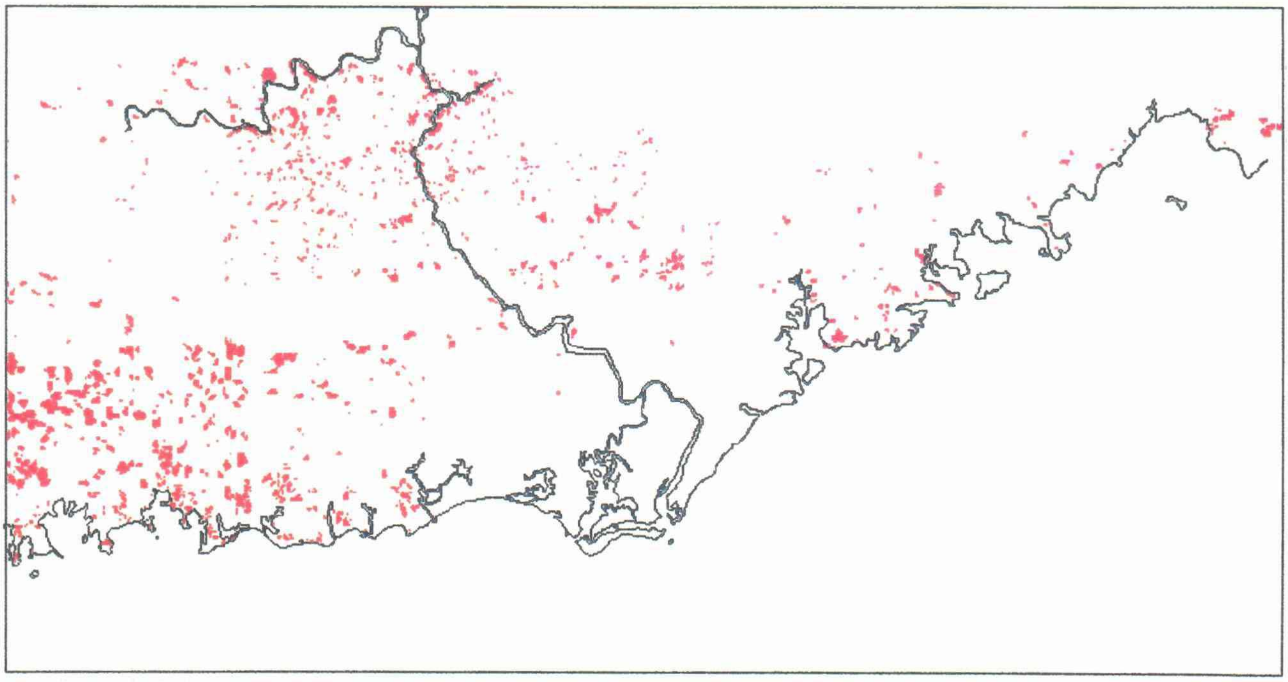


Figure 4.3 'Transitional' landslides interpreted from aerial photographs.

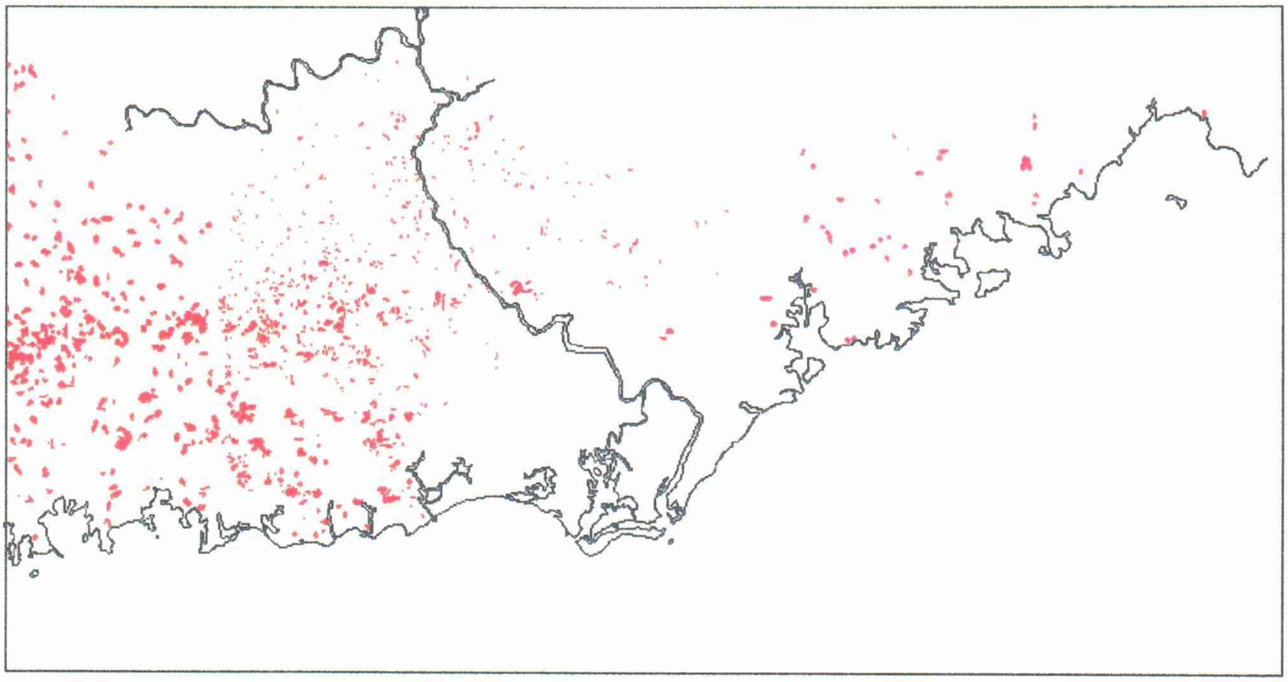


Figure 4.4 'Young' landslides interpreted from aerial photographs.

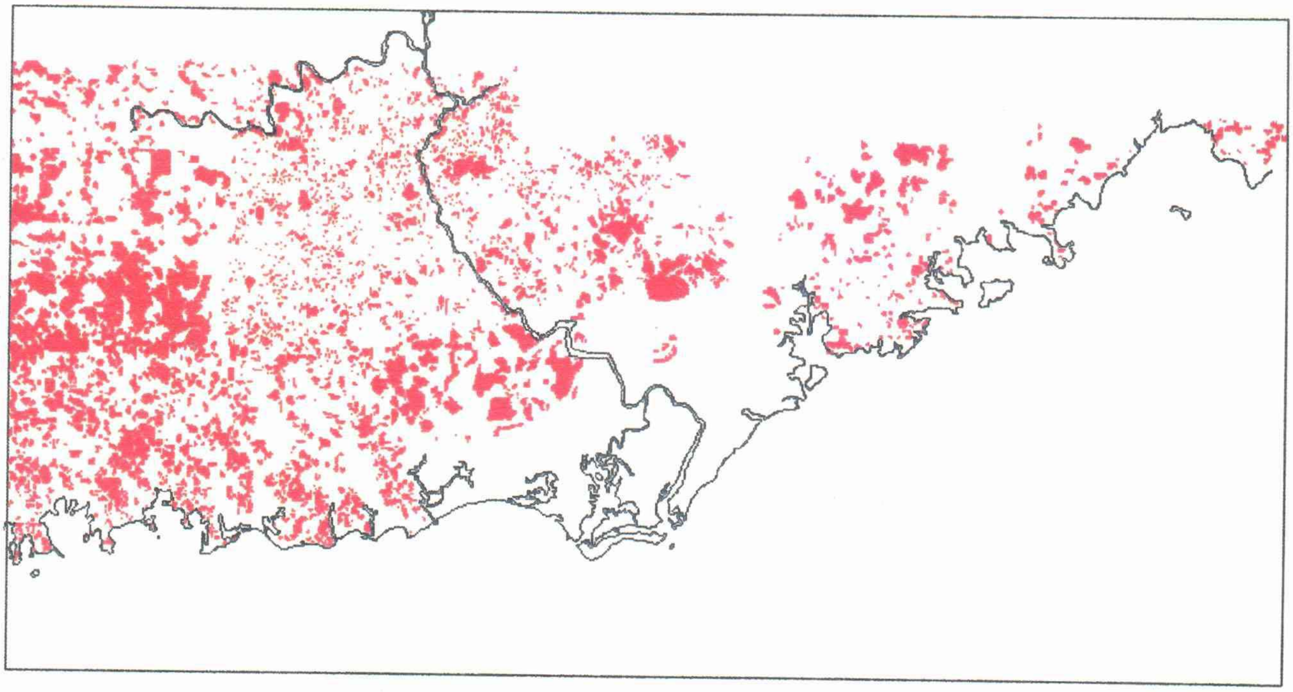


Figure 4.5 Total landslides ('old' + 'transitional' + 'young').

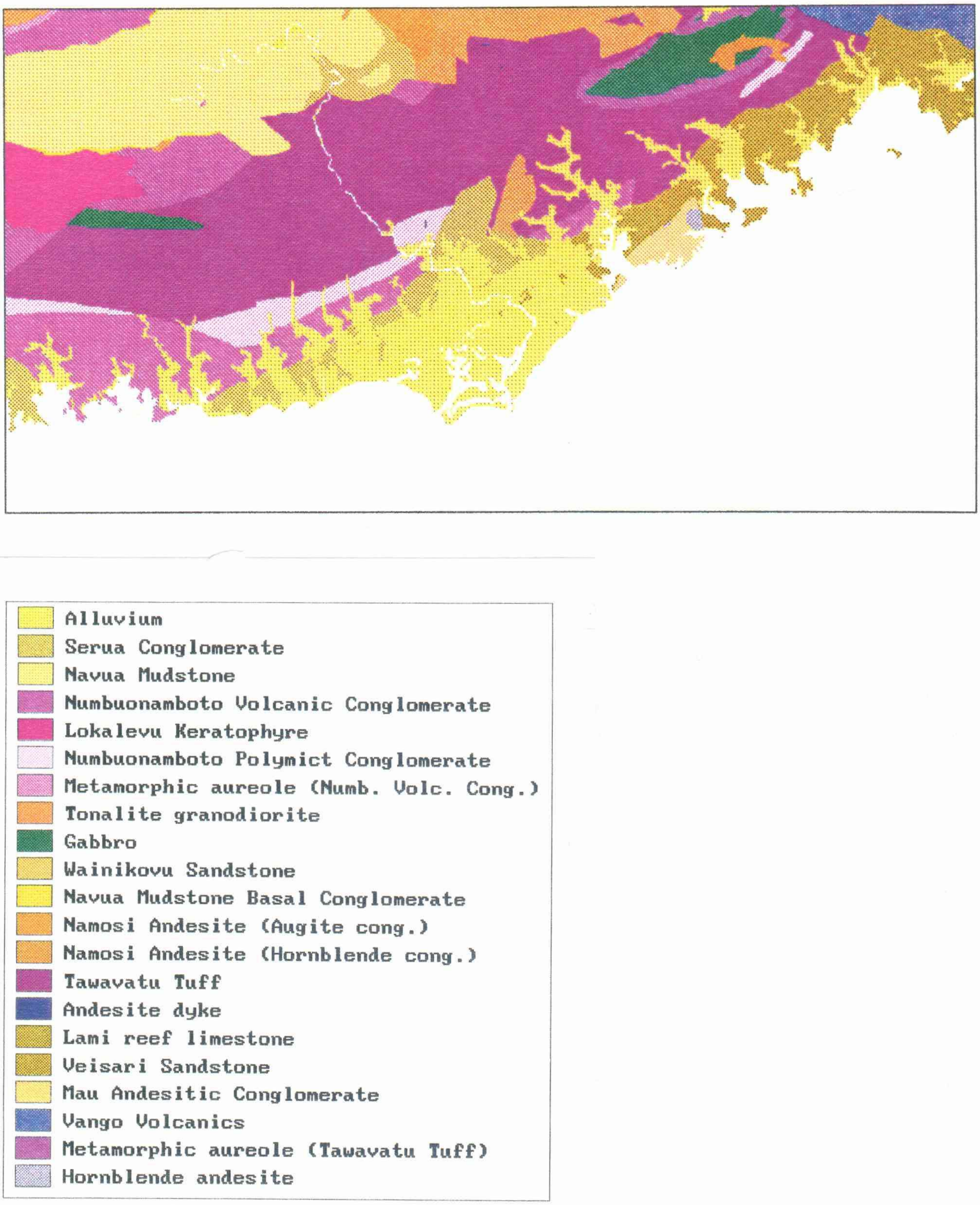


Figure 4.6 Geology of south east Viti Levu (compiled from published 1:50,000 scale maps).

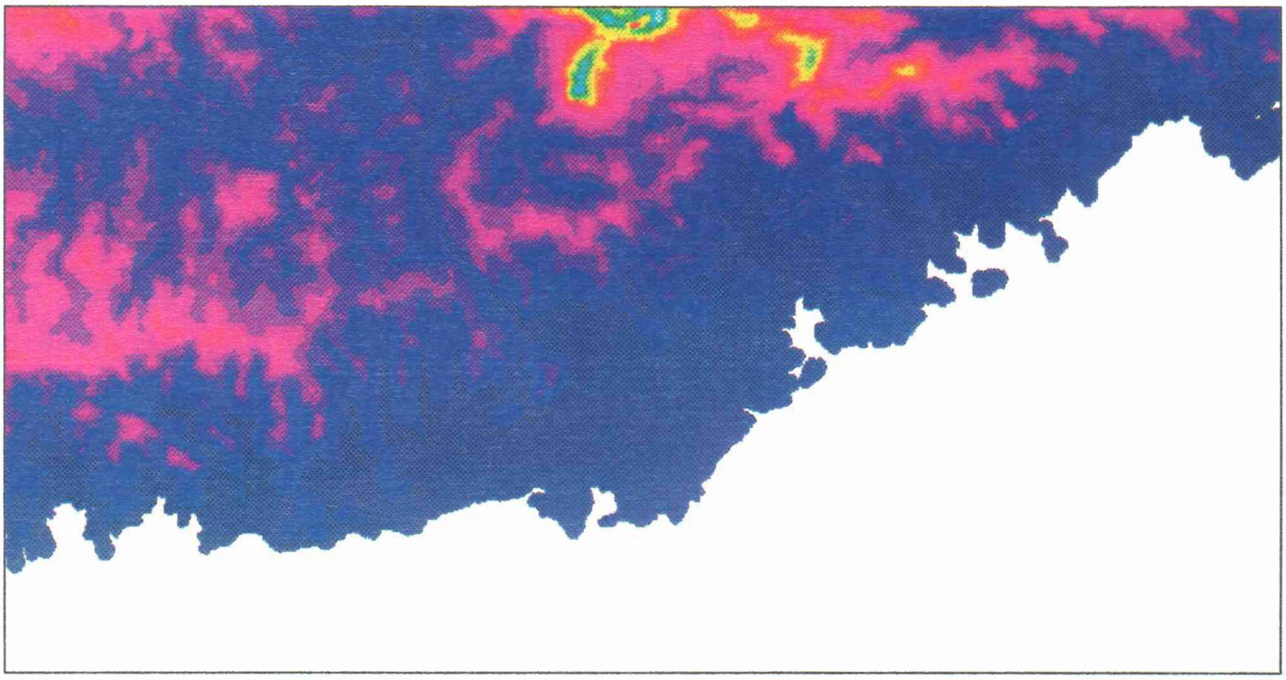


Figure 4.7 Digital elevation model (DEM) for south east Viti Levu (17 classes of 50 m, range sea level to 850 m).

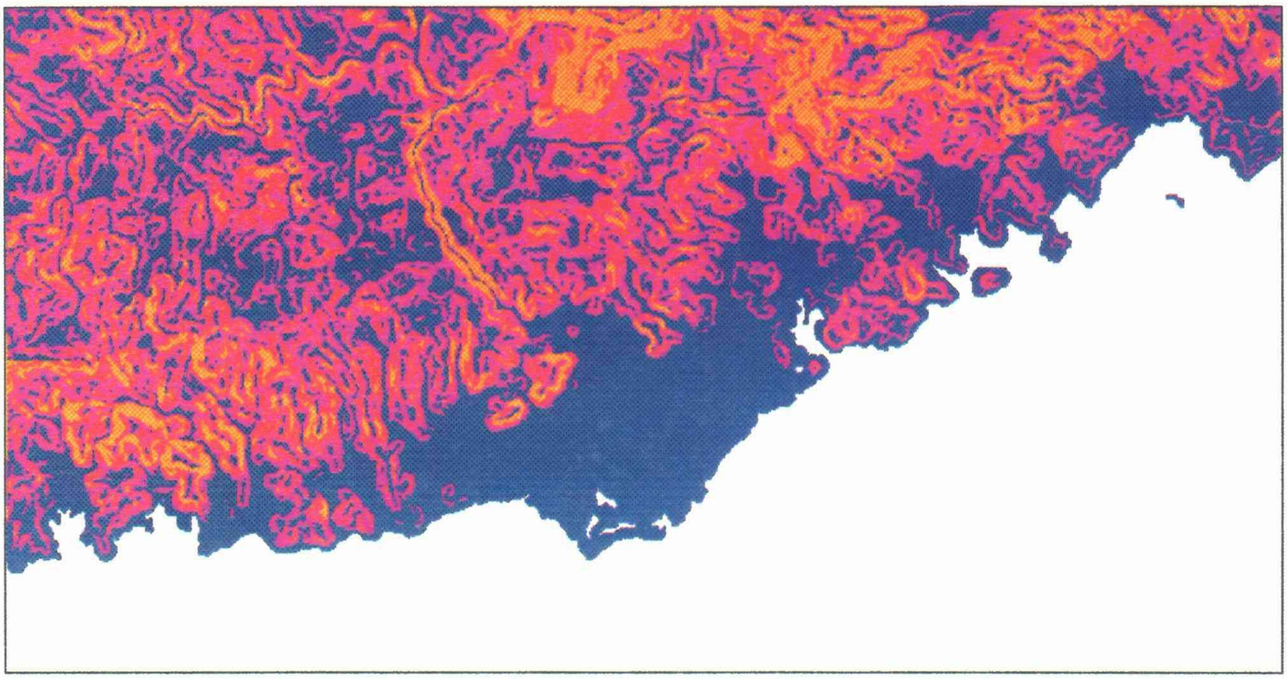


Figure 4.8 Slope angle map for south east Viti Levu (equal area plot based on 5° slope angle classes).

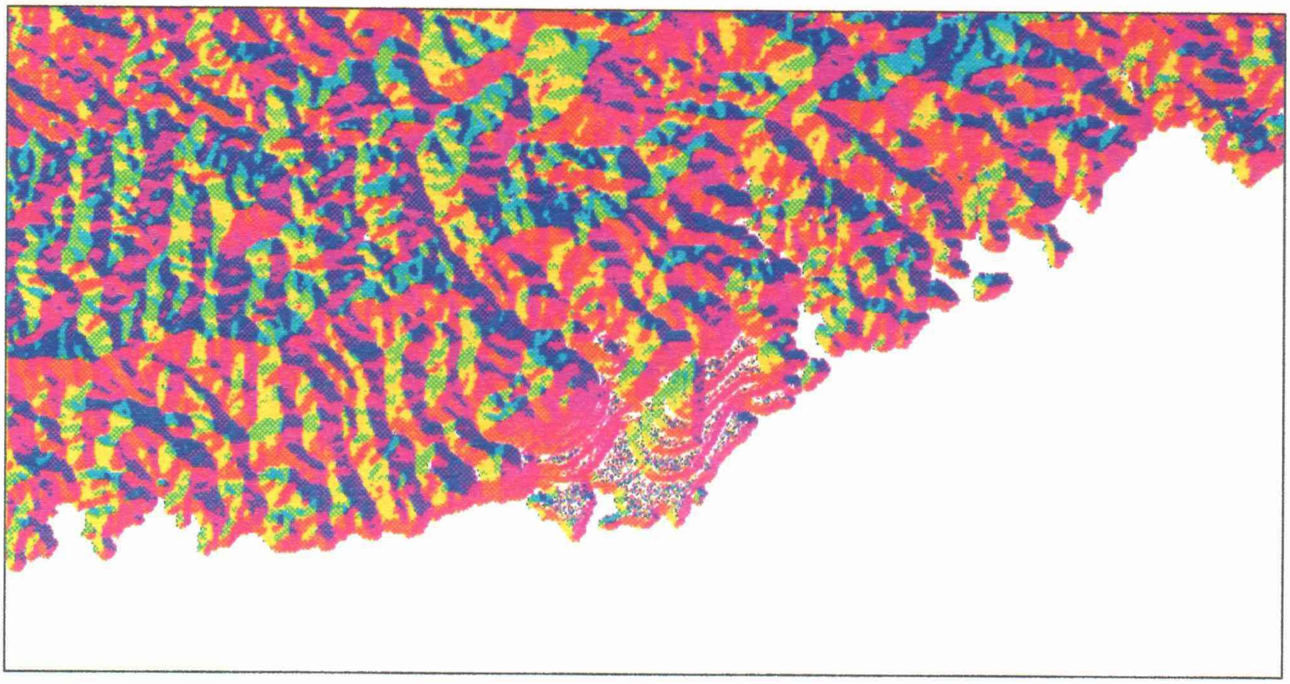


Figure 4.9 Slope aspect map for south east Viti Levu (8 sectors).

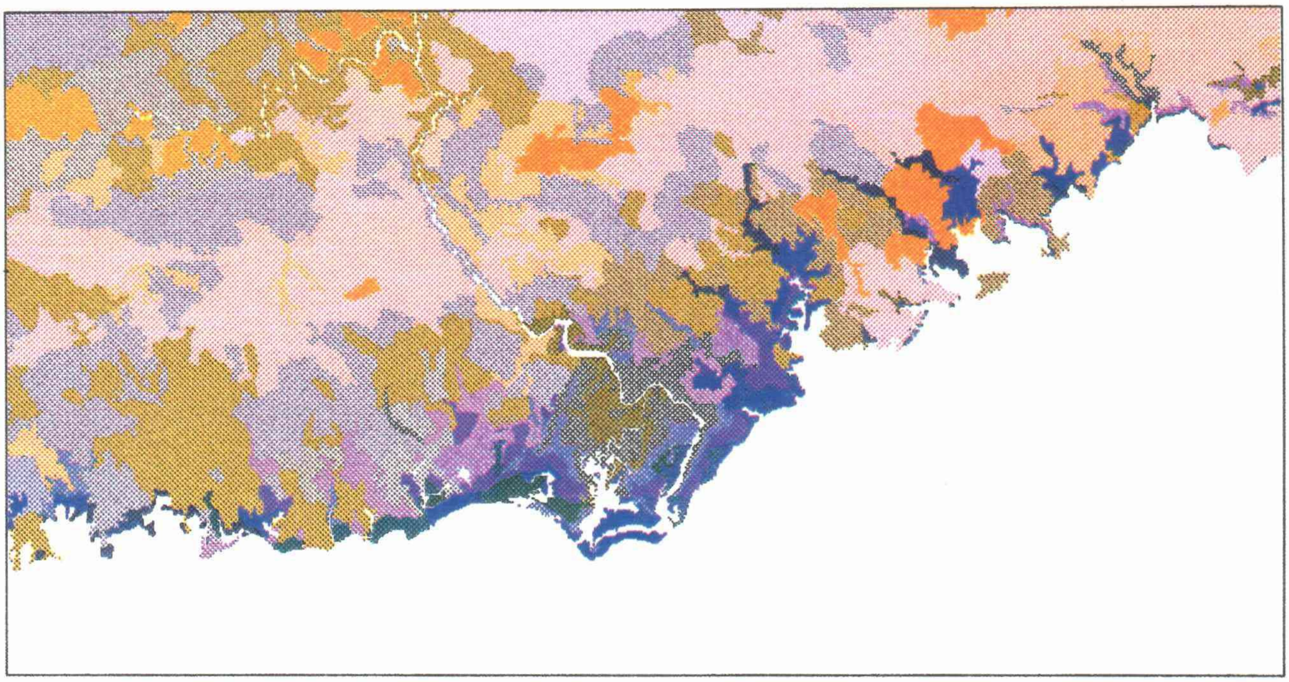


Figure 4.10 Soil classification map for south east Viti Levu (43 classes based on Ministry of Primary Industries survey).

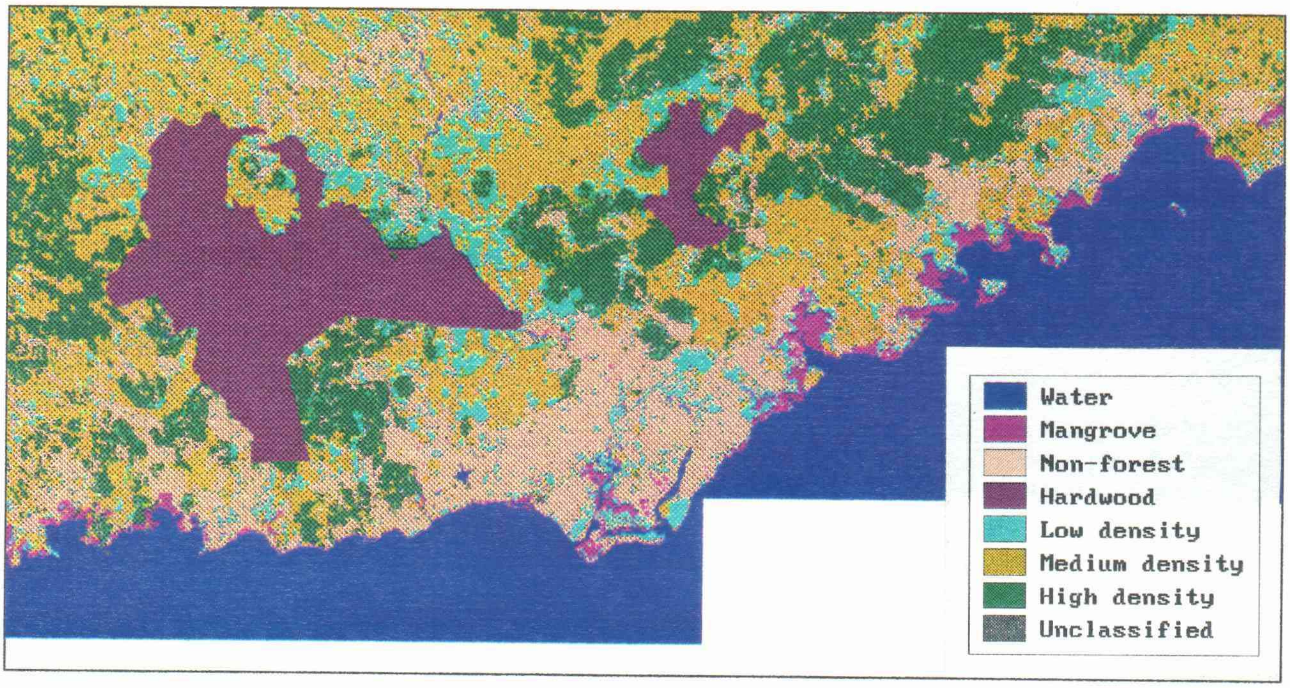


Figure 4.11 Forestry land classification map for south east Viti Levu (provided by Fiji-German Inventory Project).

Forest: A forestry/land-use digital data set divided into 8 classes was provided by the FGIP. This is shown in Figure 4.11.

Rivers: These were digitised from the 1:50 000 topographic maps. They were used only for geographical reference.

Roads: Again, these were digitised from the 1:50 000 topographic maps, and used for reference in relation to risks and contingency planning.

Coastline: This was also digitised from the 1:50 000 topographic sheets.

4.5 Description, derivation and use of a digital elevation model (DEM)

Although in the present study, the DEM was supplied to the project by the FGIP, some general information on DEM production is nevertheless appropriate. It is important to note that creating a DEM is a major, time-consuming task requiring specific computer hardware and sophisticated software. It may not be possible to achieve using a standard PC.

A DEM is a representation of the land surface stored on computer. Digitized spot heights and contours do not in themselves form a DEM since these relate to individual points or lines and provide no information about locations in between, whereas a DEM is continuous over an area. For this reason, DEMs are often held in a grid or raster format with a height value assigned to each cell.

Clearly, topographic survey information, usually in the form of spot heights and contours, is fundamental to the creation of a DEM. The major work involves the transference of survey data from maps to the digital form before the DEM can be calculated. This usually involves raster scanning a map of the contours and the use of line-following software to convert them to attributed vectors (i.e x-y-z strings). Once digitized, the height information can be interpolated onto a regular grid using a variety of computer algorithms.

The simplest procedure calculates the average of all the height points within a circle of specified radius centred on each of the grid nodes. Since the moving average technique is easy to calculate, it is often the interpolation algorithm implemented in PC-based GISs. Its advantage is that the calculated height values are restricted to the range of the observed data. Choosing the correct search radius, however, can be difficult. Too small a radius will result in the DEM not having a value at each grid node. This is a particular problem in flat lying areas where the data points are widely spaced. Conversely, too large a radius will result in an overly smooth surface which does not accurately represent the terrain.

Other, more sophisticated, interpolation procedures are available but usually in software packages external to the GIS. The least squares algorithm best fits a plane to the observed data within a specified distance of the grid node accounting for local surface trends, by reducing the significance of the more distant points. Projection algorithms use surface gradients and trends calculated at each observed point and then determines the height values at the grid node positions by projection and averaging. This procedure yields smooth surfaces and satisfactorily interpolates into areas of sparse data but can give unrealistic highs or lows for some data sets. The minimum curvature method can be compared to the flexing of a thin metal plate to the surface. This procedure produces the smoothest possible surface whilst attempting accurately to fit the observed data.

An alternative technique for creating a surface model is 'triangulation', in which a set of facets spanning the area are created by fitting a plane between each group of three data points which form the vertices of a triangle. The regular grid of height values is then determined by projection to the facets. The advantage of this procedure is that the surface is closely tied to the observed data and can never exceed the limits of the data. However, in areas of sparse data, the calculated surface can contain artificial plateaux.

Irrespective of the method used to create a DEM, it must be recognized that the result is a mathematical model; there is no guarantee that the height at a grid node is close to the actual elevation that would be measured on the ground. The calculated surface depends on many factors, some examples of which are: the chosen algorithm and parameters; the distribution of the observed data; and the required spacing between grid nodes. With contour data the distance between observed points is generally much smaller along the contour lines than between them, and this may lead to artifacts being produced parallel to the contours.

An alternative method of deriving a DEM is directly from remote sensing data using the parallax differences present in stereoscopic aerial photography or satellite imagery. Parallax is essentially a measure of apparent displacement of ground points, due to their relative elevation, when viewed from two different positions (e.g. successive aerial photographs along a flight line). Since parallax shift is proportional to height and can be calculated, such measurements can be used to derive a DEM. Modern computer systems such as the Intergraph ImageStation use sophisticated pattern matching software to correlate pixel groups across a pair of images (or scanned photograph pair), and use this to determine parallax on a regular grid.

Once the DEM has been calculated it is a relatively simple procedure to create secondary (derived) data sets such as slope and aspect using readily available GIS functions. The local slope and aspect at each grid node is determined from the results of simple filtering operations in the x and y directions. The slope can be given either as a percentage gradient or as an angle between 0° and 90°. Aspect, the direction of maximum slope, is given as an angle from 0° through 360°.

5. SPATIAL DATA INTEGRATION AND ANALYSIS USING A RASTER GIS

5.1 Concepts

Hazard zonation mapping using remote sensing and a geographical information system (GIS) involves the assembly of various spatially co-registered data sets and their comparison with landslide distribution. The composition of the database will depend on what data is available and what is considered likely to be useful. Primary data sets might include: a distribution map of old and recent landslides; geology; structure; site investigation and material test results; soils; topography; drainage; roads; centres of population; etc.

Combining data sets is a common activity in many areas of geoscience. The purpose is generally to represent meaningful relationships between the inputs. The resulting map is merely one possible interpretation of the data, which may need to be modified as more information becomes available. Printed maps are usually for general purpose use; consequently, they may include too much information for the non-specialist but still not provide what is actually important to a user. This can be a problem for those who do not have a geological background, such as planners and regional authorities, whose needs are for simple thematic products. In the case of landslide hazard, such users require a map that clearly indicates zones of potential risk. Recent advances in computer technology and GIS now allow more flexibility in map outputs.

The probability that a landslide will occur at a particular location depends on a number of conditions which may be regarded as (1) controlling factors and (2) triggering events. Controlling factors may be broadly divided into material properties (rock/soil type; *in situ* and bulk strength; etc) and terrain conditions (slope angle; fracturing; cultivation etc), whereas triggering events might include earthquakes, intense rainstorms and possibly new construction/development. If the controlling factors were completely understood and *full ground survey information available* it should be possible to 'predict' where landslides are likely to occur *given a particular triggering event.*

In the case of Fiji the problem is rather different; although much is known about the general causes of landsliding (Chapter 2), little mapping of landslides on a regional basis has been done. In terms of the present study, we are trying to determine whether correlations between past landsliding and other data sets exist that can provide a crude measure of regional hazard probability. It is evident in Fiji that intense rain storms are the main triggering event responsible for major mass movement events such as the Serua Hills landslides of 1980. What is uncertain is the extent to which regional variations in ground and geological conditions influence the location and/or severity of landsliding (given that such rainfall events could occur anywhere).

The approach taken here is empirical and the results therefore only indicative; the method is at best semi-quantitative and at this stage provisional. The potential benefits are that the method is relatively cheap and rapid as compared to a full ground survey (which may, in fact, be unachievable over large areas). Using a GIS, the geologist can test for spatial relationships between landslides and other potential influencing factors, can quantify their importance, and can mathematically combine them to produce a hazard 'probability map'. The objective of the pilot study is to develop an approach to modelling landslide occurrences based on a minimum of existing data. If encouraging results are obtained, additional, relevant data can be added to the database to improve and further develop the technique.

The fundamental indicator, obtainable from remote sensing, is a map showing the distribution of both old and recent landslides. This is then used as a basis for deciding where further landslides are likely to occur. Even on its own, the landslide inventory map may be regarded as a crude hazard map, but in order to try to understand what factors influence landsliding, and thus to be able to rank the degree of hazard, the relationship of different variables to landsliding is tested in turn. Significant variables can be thought of as 'controlling factors' for the purposes of the analysis *even though the manner of their relationship to landsliding may not be known*. Once these empirical relationships are established, the geologist must decide, and weight, the importance of each variable, and combine the weights to provide an overall probability estimate across the entire area. However, it should be remembered that the available database layers may not be sufficient to completely model the true situation. It is also possible that the apparent 'controls' modelled using this approach may be relatively insignificant compared to the overriding importance of triggering events (i.e. intense rainfall).

The resulting hazard map produced in this way will be similar, but by no means identical, to the landslide distribution map used to develop the model. In the hazard map, the zones will not be restricted to the precise areas where landslides are recorded but will extend beyond these limits based on the correlations found in the data. The use of a raster GIS enables these operations to be carried out quickly, and provides flexibility that allows inputs to be easily varied.

5.2 Analysis

The variables comprising the Fiji database were described in Section 4.4. Two layers form the basis of the analysis. The first is a Boolean mask formed by combining all the landslide polygon information irrespective of age and interpretation criteria. The second is the distribution of landslide 'initiation points' for recent landslides. It is against these control layers that the other variables are examined. The variables are summarized in Table 5.1.

Table 5.1. Variables used in the landslide analysis for Fiji

Variable	Number of classes
Landslide polygons (total)	1
Landslide start points (total)	1
Elevation (250 m classes)	17
Slope (5° classes)	16
Aspect (45° sectors)	8
Geology	22
Forestry	8
Soils	43

The GIS used for the analysis was IDRISI. This was chosen in preference to ILWIS since it seems likely that this system, in its soon-to-be-released Windows version, will become more widely used in the south west Pacific region.

GIS analysis relies on examining the spatial relationships between interpreted landslides and variables, individually and in combination. To begin with, each class within each variable (e.g. each lithology of the geology layer) was cross tabulated with the map of landslide polygons to determine the number of landslide pixels and non-landslide pixels comprising that class: e.g.

$$\frac{\text{Number of landslide pixels in lithology Class 12*}}{\text{Total number of pixels comprising Class 12}} = \frac{171}{602} = 0.284$$

(* where Class 12 is equivalent to the Basal Conglomerate of Navua Mudstone)

This provides information about the variables and classes which have an association with the presence of landslides. For example, different rock types may have a higher or lower tendency to slip due to cohesive strength related to composition, grain size, degree of fracturing etc. In the above example, 28.4% of the ground area mapped as Basal Conglomerate corresponds to landslides. The same analysis was carried out for all classes of all variables for the south east Viti Levu test area. The results of the cross tabulations are presented in Appendix 1 (Tables A1.1 to A1.6). They allow important deductions to be made regarding the role and possible significance of the variables, as described below:

1. **Geology**: As might be expected, different rock types provided different responses (Appendix 1: Table A1.1). Formations showing the highest incidence of landslides are: Lokalevu Keratophyre, Basal Conglomerate (Navua Mudstone), Nubuonaboto Volcanic Conglomerate, Serua Conglomerate, Navutulevu Polymict Conglomerate, and the Tawavatu Tuff.

2. **Slope angle**: The relationship between landsliding and slope is complicated (Appendix 1: Table A1.2). Because most slopes in this region area are gentle, the majority of landslides occur on slopes of 25° or less. In these areas, the highest risk of landslides (21.1%) would appear to be on slopes of 10-20°. Although there are relatively few very steep slopes, there is an increased incidence associated with angles greater than 45°.

3. **Slope aspect**: There appears to be only a slight relationship with slope aspect, with a tendency for landsliding to occur on northerly or northeast facing slopes (Appendix 1: Table A1.3).

4. **Soils**: There is an apparent relationship with a number of soil categories (Appendix 1: Table A1.4). However, it is difficult to interpret the significance of these results in the context of the MPI classification. Further examination of these results is warranted to see if any correspondence exists between the observed weightings and the fivefold division suggested in section 2.3.1.

5. **Elevation**: The majority of landslides occur at elevations of between 50 m and 350 m (Appendix 1: Table A1.5). The highest risk of landsliding (23.5%) would appear to correspond to the elevation range 250-300 m.

6. **Forestry**: The strongest correlation is between landsliding and hardwood, followed by coconut plantation and non-forest (Appendix 1: Table A1.6).

7. **Lineaments**: Although there is a suggestion in some areas that regional fractures exert a controlling influence on the location of landslides, lack of time prevented this data set from being compiled and digitised. It is recommended that in any follow-up study such information be added, and included in the model. Intuitively, one would expect there to be an association between lineaments and landslides since lineaments mainly represent faults or lines of weakness along which movement could occur, or simply zones of more broken ground. One way of testing the significance of lineaments is to compare the relationship of lineaments to landslide initiation points. To do this requires a cross tabulation to be carried out of the lineament buffer map against landslide start points. This is done by comparing the number of landslide initiation points that fall within each distance zone against the 'expected' number, taken as the average incidence of start points over the land area as a whole.

8. **Catchments & landslide density**: The density of landslides within catchments can be included as a variable in the model to improve the correspondence between observed distributions and the model predictions. In the present study, time limitations prevented the catchment data being digitised. However, landslide density is in any case not strictly a 'variable' in the sense that cannot be used to extend the model beyond the area of landslide photointerpretation. In the present case, landslide density was calculated as a moving average using image processing software external to the GIS. Rather than incorporate it in the actual analysis, the map was used as a means of visual comparison for the goodness of fit of the final model.

Having considered the relative significance of each class of each variable, the analysis was continued by calculating whether a class contained more or fewer landslides than was typical for the area as a whole. To do this, the earlier calculated class percentage values were normalised by dividing by the *regional average* incidence of landslides, calculated as:

$$\frac{\Sigma \text{ landslide pixels}}{\Sigma \text{ pixels comprising study area}} = \frac{42498}{285362} = 14.89\%$$

Taking the earlier example of lithology Class 12 and dividing by the regional average, the result is 28.40/14.89 = 1.91. This means that the incidence of landsliding in the Navua Mudstone Basal Conglomerate is 1.91 times greater than for south east of Viti Levu as a whole. Considered as a measure of prediction, one could say that landsliding is almost twice as likely to occur within this rock type than on average over the area.

The same calculation was repeated for every class of every variable, and weightings derived (Appendix 1: Tables A1.1 to A1.6). To avoid the use of decimals, weights were multiplied by 10 and rounded. A value of 9 or less indicated that the class had a lower that average incidence of landslides, a value of 10 an average incidence, and values of 11 and above a higher than average incidence. The *overall* (or average) importance of a variable was judged by how far the class weights diverged from 10. If all classes were close to 10, then the effect of the variable was neutral, whereas if some classes had a much higher value than 10, then the variable was likely to be significant. The larger the weight, the greater was the chance of landsliding within the class.

Quantifying the significance of a variable as a predictor of landsliding is not straightforward since this can be considered in different ways. Two possible measures of performance are provided in Table 5.2. The first of these - here termed **'accountability'** - calculates the percentage of the total landslide population accounted for by each variable. It is computed for each variable as:

$$\frac{\Sigma \text{ landslide pixels in classes having a weighting } \geq 11}{\Sigma \text{ landslide pixels over the entire study area.}}$$

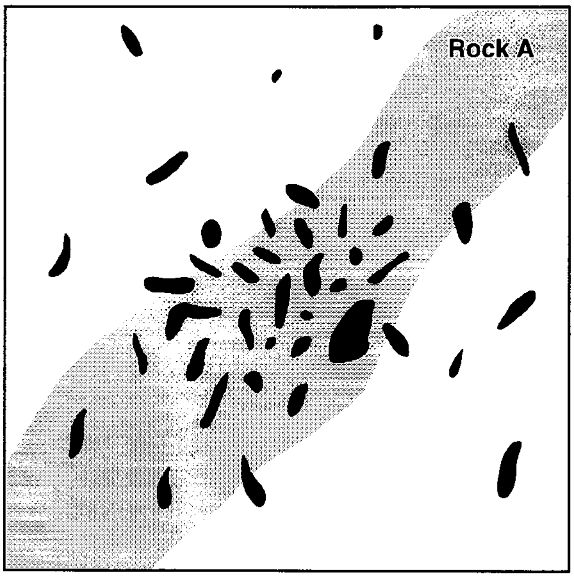
Another way to regard performance is in terms of **'reliability'** (i.e the chance, or probability, that a pixel in a class will be a landslide), calculated as the percentage area of a variable corresponding to landslides. It is computed for each variable as:

$$\frac{\Sigma \text{ landslide pixels in classes having a weighting } \geq 11}{\Sigma \text{ landslide \& non-landslide pixels in the same classes}}$$

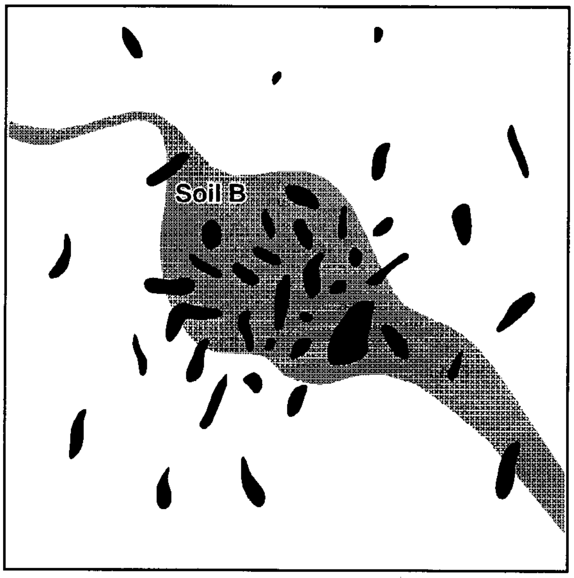
(Note: in both performance measures, only classes ≥ 11 (i.e. showing above average landslide incidence) are considered).

It can be seen from Table 5.2 that the two indicators do not provide the same information, nor is it obvious which is the better measure. For example, whereas the soils variable is the most reliable indicator in that 23.3% of the variable corresponds to landslides (1st ranked), it accounts for only 64.5% of all landslides in the area (4th ranked). On the other hand, slope angle accounts for more of the total landslide population (77.3%) than any other variable, although less of this variable corresponds to landslides (19.0% - 4th ranked).

The reason why the two performance indicators give different results can be explained by a simple illustration involving 2 variables each comprising one class. In Figure 5.1A, Rock A accounts for 80% of all landslides but only 20% of the unit corresponds to landslides. In Figure 5.1B, Soil B accounts for 60% of total landslides, but here 25% of the variable is landslide. So, whereas Rock A accounts for more of the total landslides population, Soil B more reliably indicates the likelihood of a landslide. The reason is that within each category the landslides are not evenly distributed but form clusters. Nevertheless, in their own way,



5.1A Rock A accounts for 80% of the landslides in the region but only 20% of Rock A corresponds to landslides



5.1B Soil B accounts for 60% of the landslides in the region but only 25% of Soil B corresponds to landslides

5.1C The combined category of 'Rock A + Soil B' now accounts for 55% of the region's landslides and 45% of this category corresponds to landslides

Figure 5.1 Hypothetical situation where landsliding is controlled by 2 independent variables, Rock A and Soil B.

each of these measures provides a good predictor of landslides, although the reliability factor may be overall the more important.

Table 5.2. Measures of performance of variables in predicting occurrence of landslides in SE Viti Levu (for explanation see text)

Variable	**'Reliability'** **% of variable corresponding to landslides**	**'Accountability'** **% of landslides accounted for by variable**	**Overall ranking**
	Calculated as:- **Σ landslide pixels in all classes having weightings ≥11 divided by Σ pixels in same classes**	**Calculated as:-** **Σ landslide pixels in all classes having weightings ≥11 divided by Σ all landslide pixels**	
slope angle	19.0% (4)	77.3% (1)	2
geology	21.8% (2)	76.7% (2)	1
elevation	19.6% (3)	71.0% (3)	4
soils	23.3% (1)	64.5% (4)	3
aspect	16.7% (6)	46.2% (5)	6
forest cover	17.6% (5)	41.0% (6)	5

Having assessed the variables separately, it is necessary to consider their combined relationships to landsliding. Logically, if two variables *individually* relate (in some undefined way) to landsliding, then the two *taken together* should provide a still better indicator. Such combinations may, for example, help explain, and model, particular spatial patterns evident in landslide distributions resulting from multivariate interactions. This is further illustrated in Figure 5.1C. Here, the combination of Rock A-plus-Soil B (occupying the shaded ground) accounts for 55% of the landslides, but the reliability factor of the combined variable is now 45%. Thus, the use of two variables improves some aspects of prediction at the expense of others: fewer landslides are accounted for than by Rock A on its own, but the higher risk areas are predicted much more reliably than for either Rock A or Soil B alone. It might be concluded in this example that, whereas areas where Rock A and Soil B occur together are particularly prone to landsliding, such high risk conditions do not apply over most of the region. Thus, it appears that a more *reliable* model can also be one that *accounts* for less of the total landslide population.

Based on the above logic, the next step was to combine variables to see if the reliability and/or accountability could be improved. Before this could be done, however, it was necessary to test whether the variables were truly independent. Correlated variables contain redundant information and should not be included together in the analysis without risking duplication and biased weighting. This was achieved by pairwise cross tabulation between each of the variables. In most cases, only limited correlation was found, and the variables were accepted as being independent.

Multivariate analysis involved calculating successive combinations of the variables and comparing their performance, both visually and statistically. In theory, the two variables individually showing the strongest relationship to landsliding should be combined first and lower ranked variables sequentially added. However, as noted above, there is no single measure of performance on which to base this sequence. Consequently, the rankings were decided somewhat subjectively by taking account of both the reliability and accountability values. The final column in Table 5.2 above shows the ranking assigned to the 6 variables.

The combinations of variables ('models') were produced on the GIS by first recasting each class of each variable in terms of the weightings previously calculated, and then adding these weights pixel by pixel across the area. (N.B. all classes were included in the analysis regardless of their individual weights). This resulted in a new combined (or *logical*) weight for every pixel. In order that different models could be more easily compared, these new weights were divided by the number of variables used in the combination (i.e by 2 in the case of the 2-variable combination).

To test whether the first combination (geology + slope angle) provided a better or worse model of landslide distribution, the logical weights were considered as 'classes' of the *new variable* 'geology-plus-slope' and tested in the same way as the single variables; that is, the number of landslide pixels in each new 'class' was divided by the total pixels making up that class, and divided by the regional average. For most classes it was observed that the recalculated weights were higher than the logical weights, suggesting that more of the variability was being accounted for in that class than might be expected by a simple linear addition (Table 5.3). It was concluded that higher-than-expected weightings were the result of variables combining in a multiplicative manner due to interaction (synergy) between them (i.e. certain conditions in each variable supported each other). Lower-than-expected values in some classes (particularly classes ≤ 10 - not included in Table 5.3) suggested that interactions in certain cases had the effect of increasing ground stability. This concept of logical and recalculated weights is illustrated in Figure 5.2.

The overall significance of the first model as a predictor of landsliding was assessed in terms of each of the two measures of performance discussed earlier. Compared with the individual variables, the combination of geology plus slope angle showed a higher value for reliability (23.7%) at the expense of reduced accountability (66.7%) (Model 2 in Table 5.4: compare with the separate values for geology and slope angle in Table 5.2). Performance measures for the combinations are discussed in more detail in section 5.3 below.

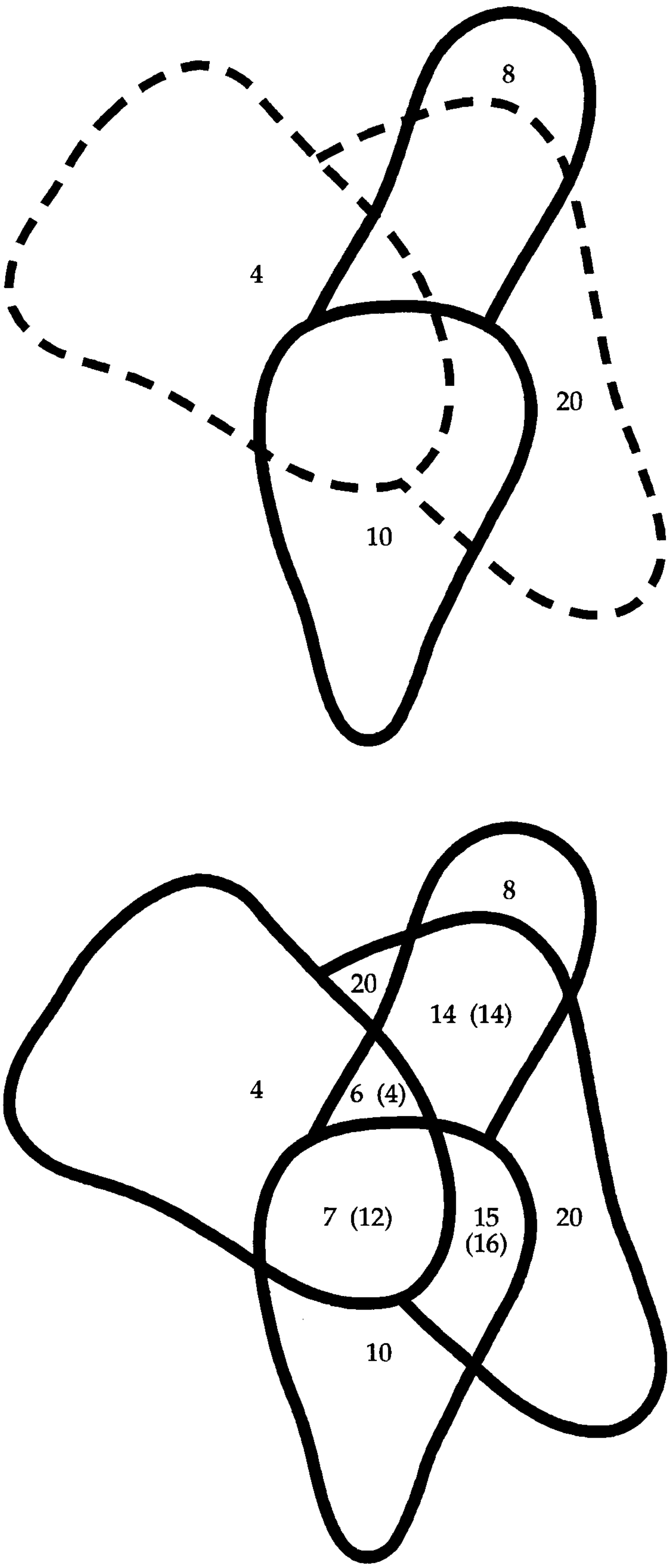


Figure 5.2 The upper diagrams show 2 variables each consisting of 2 weighted classes. In the lower diagram, summation of the 2 variables produces new 'logical weights' for the new polygon areas. However, the 're-calculated weights' (in brackets) do not necessarily match the logical weights.

Table 5.3 Comparison of logical and recalculated weightings for the Fiji hazard models

Logical weightings of class	**Recalculated weightings within combinations (models)**				
	2	**3**	**4**	**5**	**6**
11	10	11	10	11	12
12	13	15	14	14	16
13	15	14	15	19	22
14	17	19	21	22	21
15	24	20	23	22	33
16	20	22	22	33	39
17		25	32	34	
18	24	35	36		
19		26			
20	18	36			

The analysis was continued by adding a third variable (soils) to the first two, summing the weights pixel by pixel and dividing by 3. Again, new weightings were calculated, these weights compared with the expected (logical) weights, and reliability and accountability computed. This procedure was repeated for each further combination of variables with elevation, forest cover and aspect respectively being added in turn. The results are given in Appendix 1 (Tables A1.7 to A1.11).

In order to present the results in simple map form, each model was sub-divided into a few levels (representing high, medium and low hazard) and smoothed. The sub-division was based on the final *recalculated* weightings: high was taken as all classes ≥ 21, medium 11-20, and low ≤ 10. In order to improve the appearance of the final map, all unnecessary, unrealistic and complicating detail was removed by 'smoothing' the map. This was achieved by replacing the central value of a moving 3 x 3 window by the mode of the window (the most commonly occurring pixel value within the window), the procedure being applied repeatedly until broad, consistent classes resulted.

5.3 Discussion and evaluation

Table 5.4 compares reliability and accountability values for the successive combinations of variables.

Table 5.4. Reliability (R) and accountability (A) measures for the Fiji hazard models (values in per cent).

Model	2		3		4		5		6	
Re-calculated weights	**R**	**A**	**R**	**A**	**R**	**A**	**R**	**A**	**R**	**A**
$\Sigma \leq 10$	*8.5*	33.2	*6.7*	23.5	*7.4*	31.6	*6.0*	22.5	*6.3*	24.4
Σ 11-20	*22.9*	60.6	*22.4*	61.9	*20.8*	33.0	*21.6*	56.6	*21.4*	46.5
$\Sigma \geq 21$	*36.4*	6.1	*35.3*	14.7	*32.8*	35.4	*33.5*	20.8	*32.4*	29.0
Totals for $\geq$ 11	***23.7***	66.7	***24.1***	76.6	***25.7***	65.4	***23.9***	77.4	***24.6***	75.5

[Where: $\Sigma \leq 10$ is the sum of pixels in classes with a recalculated weighting less than or equal to 10. 2 = geology+slope; 3 = geology+slope+soil; 4 = geology+slope+soil+elevation; 5 = geology+slope+soil+elevation+aspect; 6 = geology+slope+soil+elevation+aspect+forest cover]

The *totals* for reliability in Table 5.4 are comparable to the single (average) reliability values used previously in discussing the individual variables (Table 5.2). These values show little variation and seem to imply that Models 2 to 6 are very similar. Based on this information alone, one might conclude that successive models show no improvement. That this is not the case can be seen by comparing 5.3A to 5.3E (Models 2 to 6). As described earlier, these plots are divided into 3 simple levels of hazard (low, medium and high). The plots show discrete zones of higher and lower hazard over the study area. From Model 2 to Model 6, the shape of these zones exhibits a decreasing dependency on the boundaries of the individual input layers (compare with Figures 4.6 to 4.11). For example, the influence of geology (Figure 4.6) in defining the zones is much less evident in the higher combination models than in the lower ones. Although this improvement is apparent from visual inspection, the reliability **totals** by themselves fail to make this distinction.

For a more quantitative assessment, it is necessary to consider how the reliability and accountability values vary from model to model. The statistical results in Table 5.4 relate to the same threefold sub-division of levels used to plot the models. By thus grouping classes, any undue importance attaching to individual classes is avoided (for example, classes with high weights but composed of very few landslide pixels). In the following paragraph, the changes evident in the plots are described on the basis of the statistics in Table 5.4.

Model 2 (Figure 5.3A) shows only a small region (A = 6.1%) of high hazard probability (R = 36.4%), and the total of landslides accounted for in the medium-plus-high zones is 66.7%. In Model 3 (Figure 5.3B), the size of the high reliability (R = 35.3%) area has increased (A = 14.7%), as has the total accountability for the medium-plus-high zones (A = 76.6%). In Model 4 (Figure 5.3C), there is a large increase in the size of the high reliability zone (A = 35.4%). Model 5 (Figure 5.3D) shows a reduction in the size of the high hazard zone (A = 20.8%), but a significant increase in the medium hazard zone

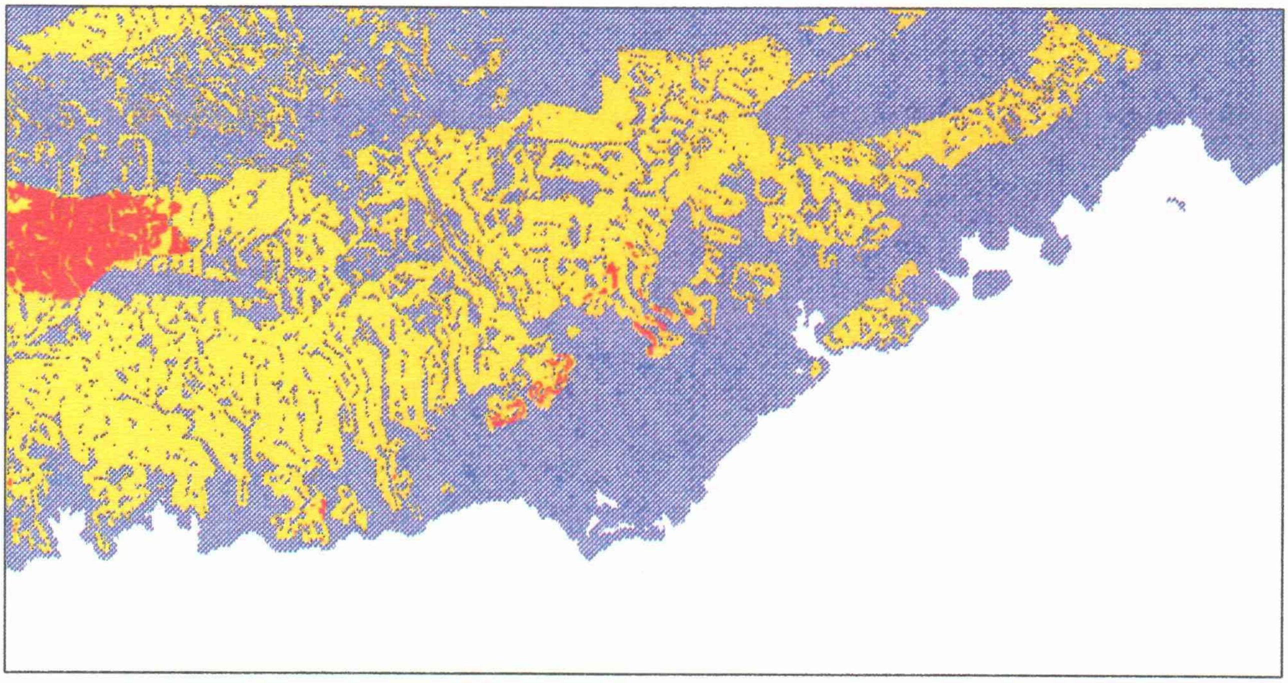


Figure 5.3A Landslide hazard map based on 'geology + slope' (Model 2).

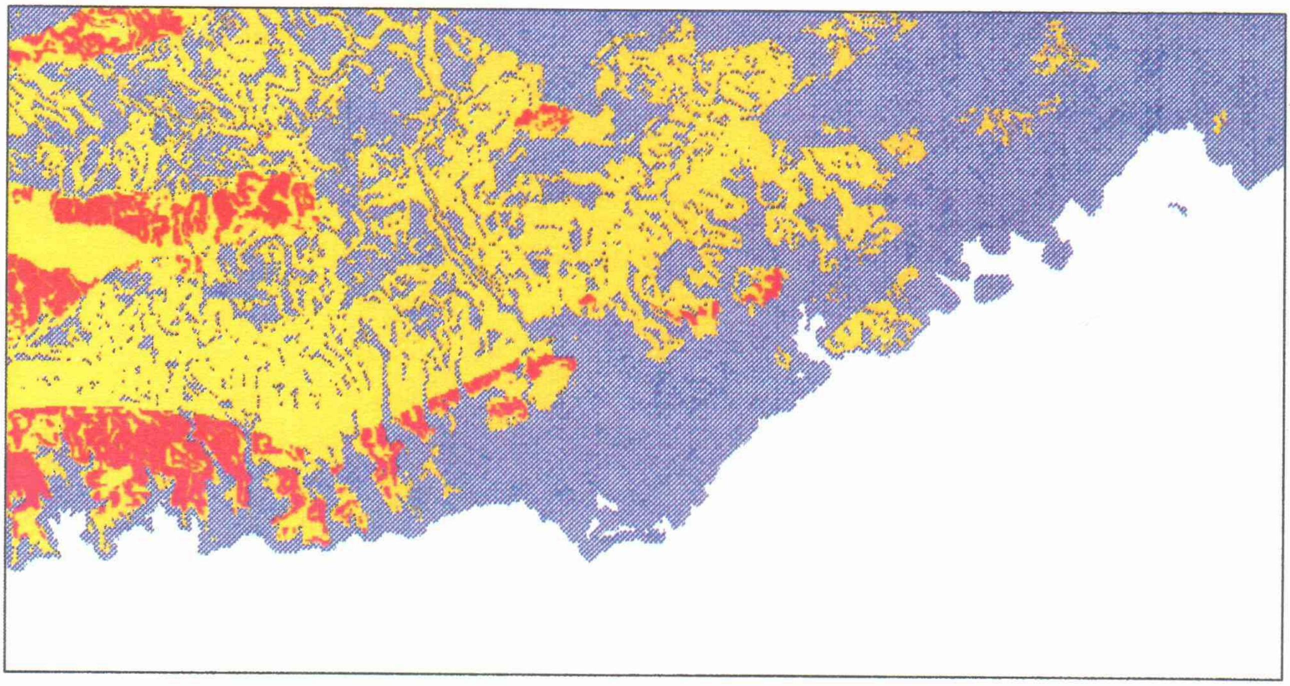


Figure 5.3B Landslide hazard map based on 'geology + slope + soils' (Model 3).

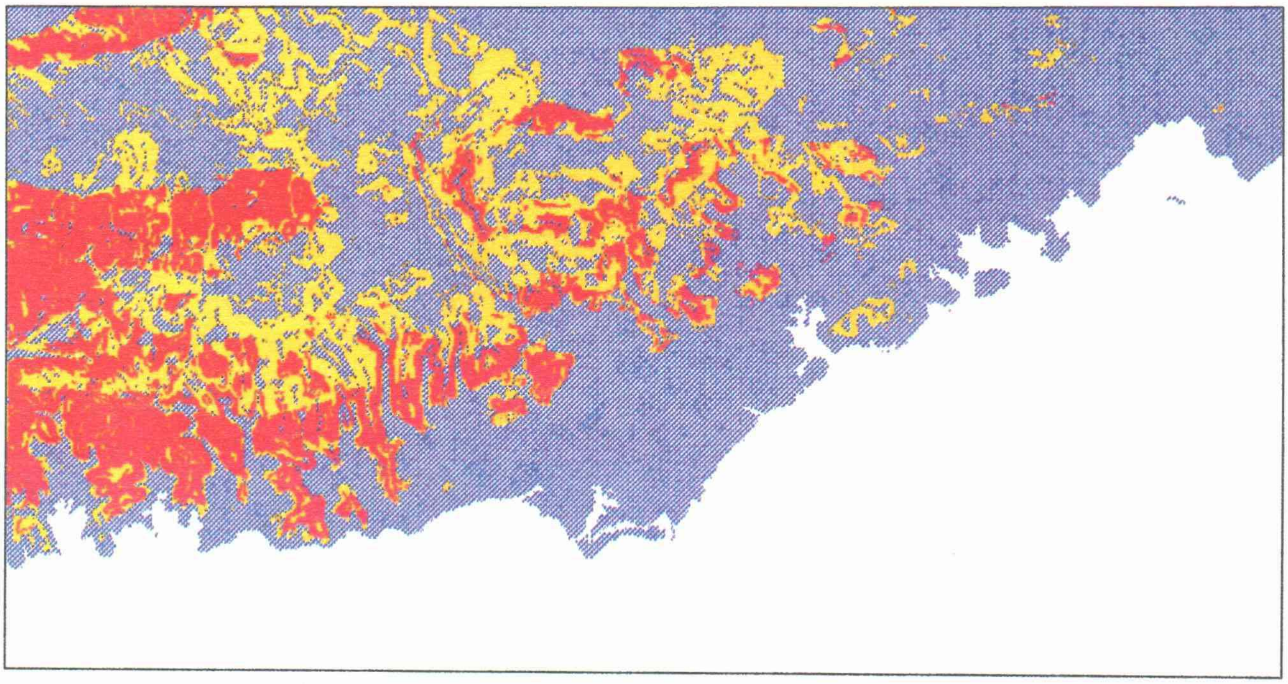


Figure 5.3C Landslide hazard map based on 'geology + slope + soils + elevation' (Model 4).

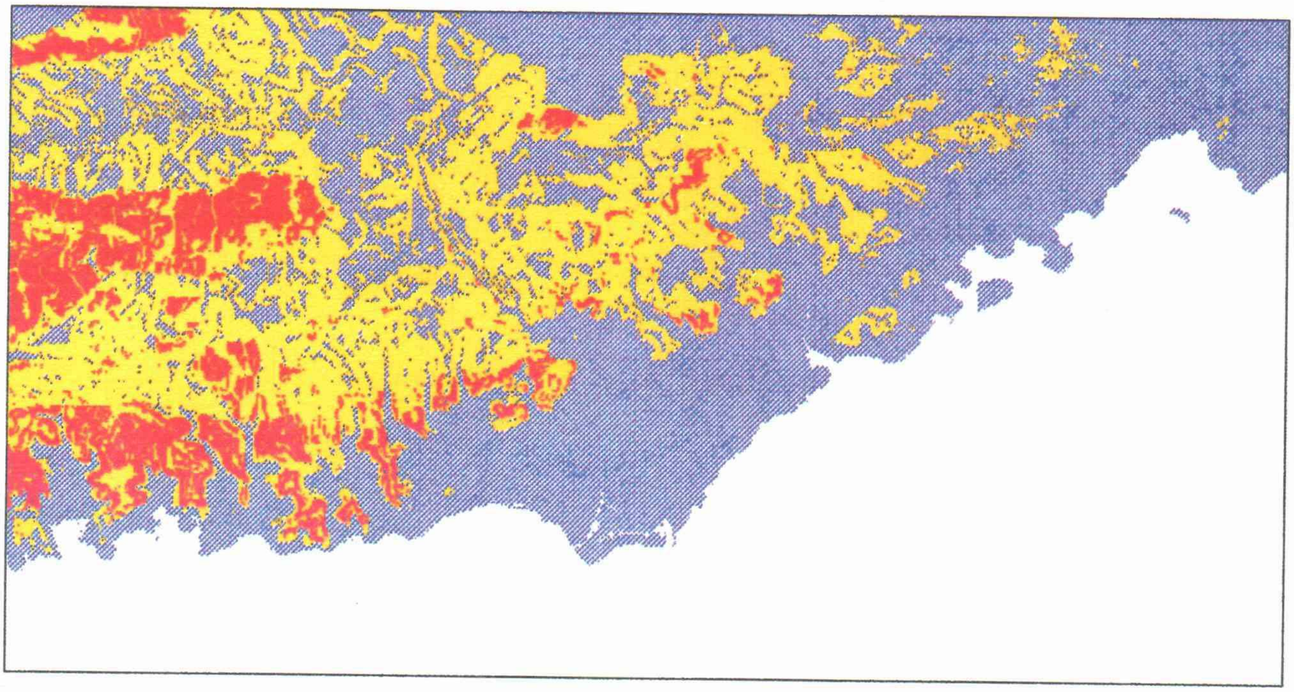


Figure 5.3D Landslide hazard map based on 'geology + slope + soils + elevation + forest' (Model 5).

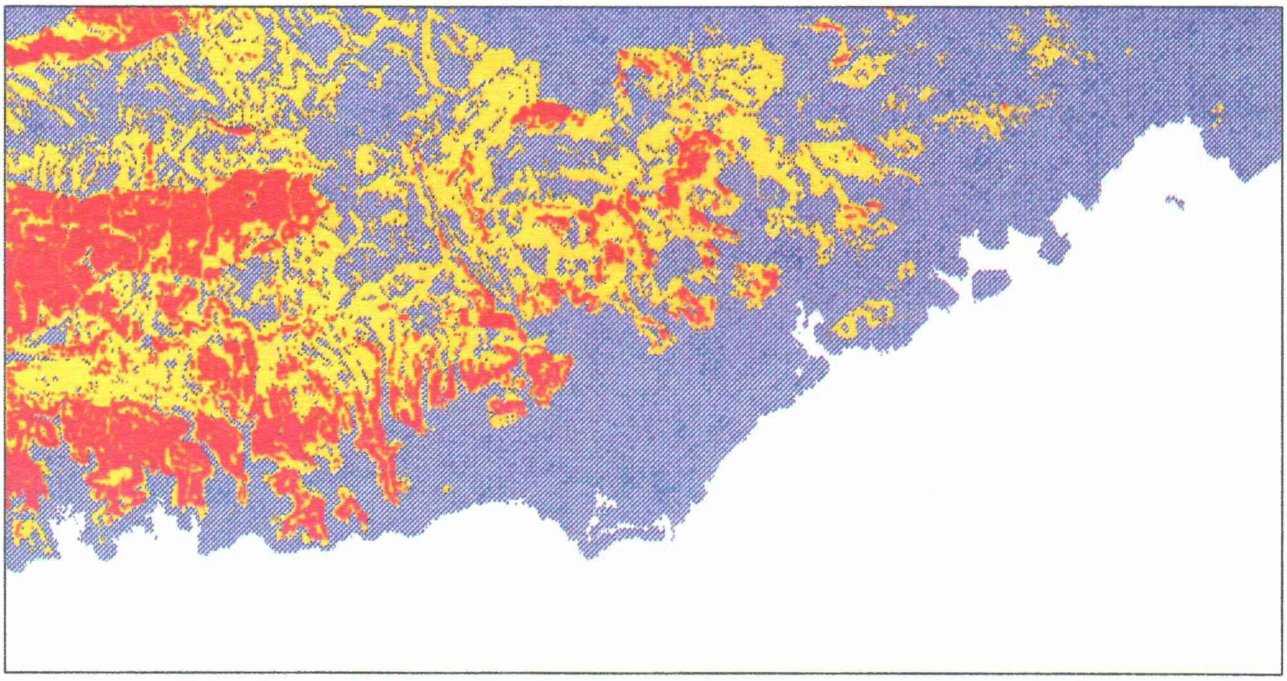


Figure 5.3E Landslide hazard map based on 'geology + slope + soils + elevation + forest + slope aspect' (Model 6).

(A = 56.6%). In Model 6 (Figure 5.3E), the size of the high hazard zone has increased again (A = 29.0%) and the reliability factor is nearly unchanged (R = 32.4%).

Whereas the statistics can be used to describe and characterise the plots, they do not provide a simple quantitative basis on which to measure the improvement, or otherwise, of the successive models. This aspect still requires further work so that models can be more objectively assessed. For the present, it is necessary to consider both the statistics of the models and to visually compare the hazard plots with the total landslide distribution map or, still better, a landslide density plot derived from it (Figure 5.4). Not surprisingly, the models show each varying degrees of similarity with the density plot but the comparison is strongest for Models 4 and 6. Interestingly however, neither of these models show a particularly high correlation with the main high density area seen in the western part of Figure 5.4. This difference is apparently real and demonstrates that the hazard maps are not the simple equivalents of the density plot.

Figure 5.5 is Model 6 in its final form, smoothed to remove unnecessary detail. If compared with Figure 5.3E it can be seen that smoothing has the effect of eliminating spurious small groups of pixels and providing a thematic plot comprising more uniform broad groups.

Based on the statistics in Table 5.4, the hazard levels displayed on this map may be interpreted as follows:

Blue	*Low*:	below average incidence of landslides
Yellow	*Medium*:	21% average probability of landsliding
Red	*High*:	32% average probability of landsliding

Figure 5.5 represents an attempt to model landslide hazards in south east Viti Levu. It is both preliminary, in the sense that further GIS analysis of the existing data is warranted, and provisional in that modified versions could be produced as more information becomes available. For example, lineaments should be added to the GIS and more use made of the separate categories of old, transitional and new landslides, and landslide initiation points. Time prevented this from being done.

The plots show interesting patterns that need explanation and/or validation. For example, the high hazard zone in the southern coastal area does not appear to be wholly a reflection of the Serua Hills landslides. The interactions between the variables are clearly complex, possibly because the variables used do not relate in a direct and simple manner to landsliding. For example, it is possible that the mapped lithostratigraphic sub-divisions do not equate in a simple manner to geotechnical rock properties (e.g. weathering characteristics). It is clear from comparing the recalculated weights with the logical weights in each combination that the effects are non linear but the true nature of what is happening is still far from clear.

Perhaps the greatest limiting factor of the present data set is the variability in the landslide data caused by several workers contributing to the aerial photograph interpretation. This is fundamental since all correlations are based on this information. Future work must address

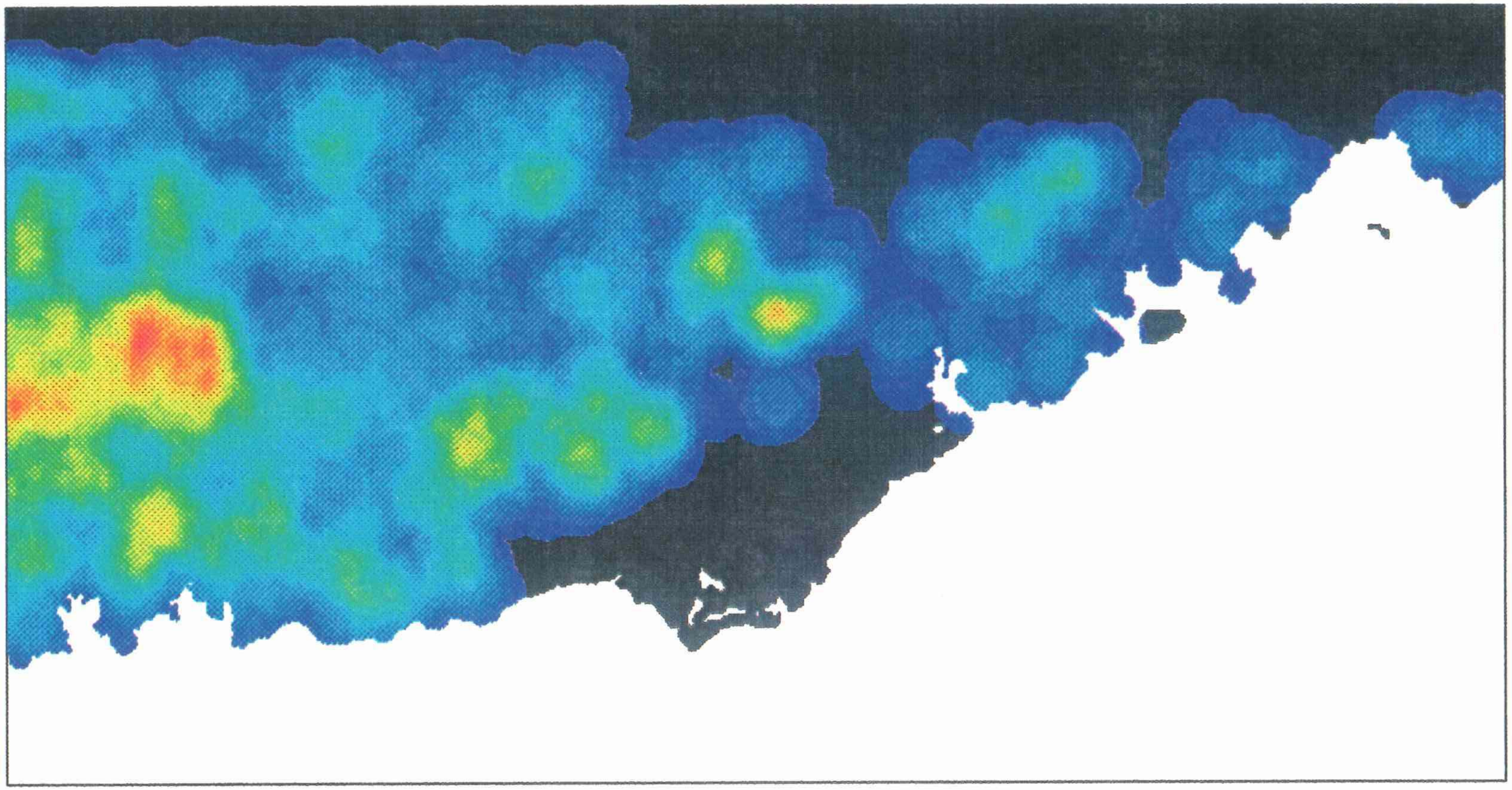


Figure 5.4 Landslide density map for south east Viti Levu.

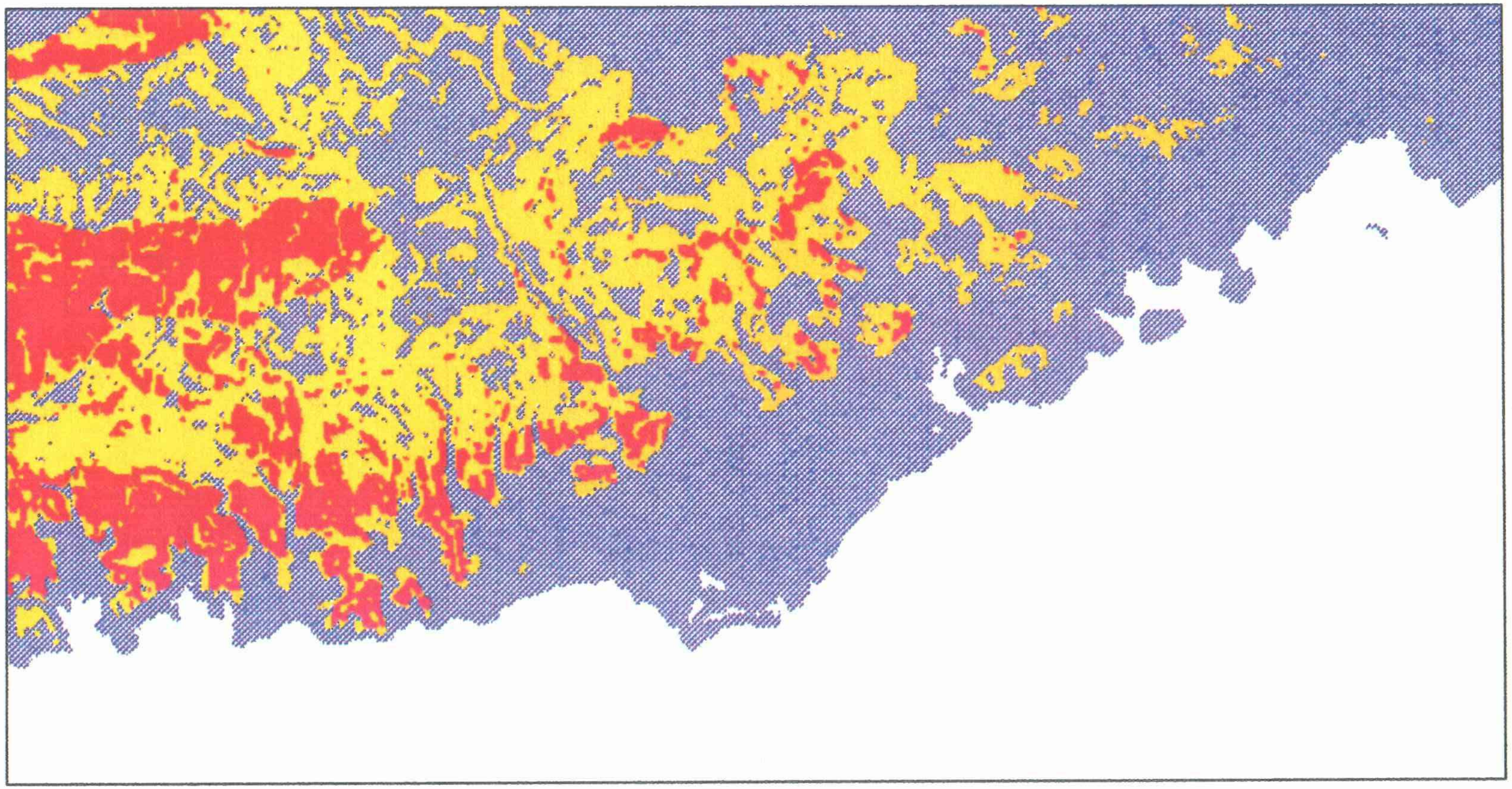


Figure 5.5 Final landslide hazard map (Model 6) smoothered to remove unwarranted detail.

this problem and ensure that adequate quality control procedures are in place to provide a fully consistent and reliable approach.

Finally, Figure 5.6 is Model 6 presented in a cartographically more acceptable manner using a vector GIS (in this case Intergraph MGE). The map shows the raster-based hazard zones combined with digital locational information.

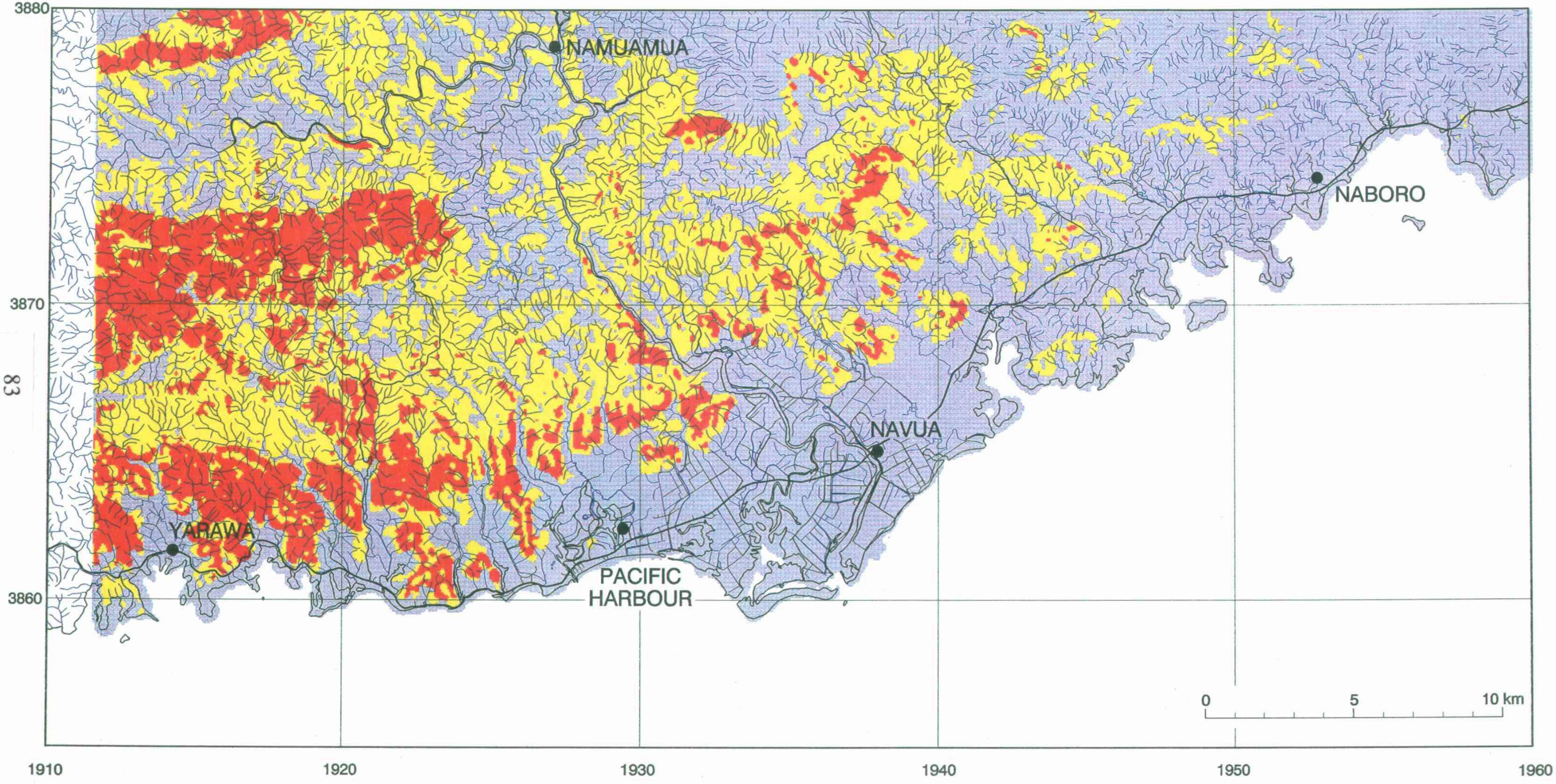


Figure 5.6 Landslide hazard map for south east Viti Levu modelled from geology, elevation, slope angle and aspect, soil type and forestry plotted using the cartographic capabilities of a vector GIS. The relative hazard zones are: blue = low; yellow = intermediate; red = high probability.

6. CONCLUSIONS AND RECOMMENDATIONS

The Fiji pilot study represents a test of the combined remote sensing plus GIS approach to rapid landslide hazard mapping in an active area of landsliding. The basis of the method is that the distribution of past landslides, here determined from aerial photograph interpretation, can provide an indication of the likely extent and severity of future events given a high intensity of rainfall associated with a cyclone. The rationale involves establishing relationships with independent variables, such as geology and topography, which are then used to model landslide probability. The GIS is a convenient tool for (1) storing and displaying data, (2) analyzing relationships between variables, and (3) generating thematic hazard (and potentially risk) maps. The techniques are directed towards developing an operational methodology for producing provisional regional hazard maps quickly and cost-effectively.

Some specific conclusions are as follows.

1. Given the extent of landsliding in Fiji and the scale at which regional hazard maps are required, conventional aerial photography provides the most appropriate source of remote sensing data. Satellite imagery is probably less useful although cloud-free stereo SPOT coverage, if available, could provide an alternative. Aerial photographs enable older landslide-landscape terrain features as well as transitional and recent landslide events to be documented. They are also a source of information on regional fractures (lineaments), although this information was not utilised in the present study.

2. Prior to GIS analysis, it is necessary to build a database of spatially co-registered information. The extent of this database, and thus the reliability of the final hazard map, will depend on the type and quality of data available. There is already much GIS work going on in Fiji and various data sets are available. But where digital information does not exist, it must be digitised from existing analogue (usually map) sources. This is a time consuming, labour-intensive operation involving a large amount of effort. *The size of the task should not be under-estimated.*

3. Once a basic database is established, the GIS can be used to produce customised map outputs quickly and at low cost. As more data become available, new thematic interpretations can be produced, tailored to meet the specific user requirements.

4. The ideal GIS for landslide hazard map production, suitable for all situations, probably does not exist. Vector-based GISs are more efficient for storing data and providing high quality map output, but raster-based GIS systems are needed for analyzing spatial inter-relationships between variables (e.g. the significance of rock type to landslides). Developments are slowly moving towards combining both functionalities. The choice of GIS should take into account local support and systems already in use. However, there are penalties in choosing a system that is more complex than the task requires. In terms of a raster system, IDRISI is a simple, low-cost system that is likely to find increasing acceptance in the southwest Pacific region, especially when the new Windows version is released. (ILWIS is another, slightly more powerful PC-based system than IDRISI, but is more expensive and presently

less widely used in the region). For the present, both raster and vector systems are needed for different aspects of the work.

5. The analytical capabilities of the raster-based GIS provide a means of 'modelling' the distribution of landslides in terms of independent variables (e.g. geology, slope, etc). An important result of the present study was the development of a systematic statistical approach to achieve this. It begins by calculating the proportion of landslide to non-landslide pixels within each class of each variable (e.g. every lithology of the geology map), and comparing these values with the average for the area as a whole. This indicates whether landslide frequency in a class is higher or lower than expected. 'Weights' are calculated for each class of each variable according to the strengths of the correlations established. In the Fiji study, landsliding was separately correlated against geology, slope angle, slope aspect, elevation, soil type and forestry cover. In this approach, it is not necessary to enquire why a relationship exists, nor to understand what it means, only to demonstrate that it does. Once the relative weights are established, combinations of variables ('models') can be calculated across the entire area by adding the weights class by class. The effect of combining factors which individually influence (or at least relate to) landsliding to different degrees is to rank high risk areas. The statistics allow the combined variable map to be quantified in terms of relative hazard probability.

6. The validity of the model developed depends fundamentally on the extent, detail and reliability of the input data. Relatively few data layers were used in the pilot area; some of these were rather generalised whereas others contained detail that may be irrelevant to landsliding.

7. Time did not allow a complete evaluation of the observed statistical relationships resulting from the GIS analysis. There also remains some uncertainty regarding the best way to compare the hazard models, since different criteria can be used to measure performance. In the present study two different indicators were used: 'reliability' provides an overall measure of how likely a landslide is to occur, and 'accountability' provides an indication of the proportion of total landslides likely to be accounted for. Moreover, statistical measures may not tell the full story, and visual comparisons may be required. Nor did time allow all the available digital data to be evaluated. In particular, further work is needed on the separate categories of old, transitional and young landslides, landslide initiation points of the young slides, and other data supplied by the FGIP (e.g. erosion risk). However, these data exist on the GIS database and it is a relatively simple task to evaluate these factors. Further advancement of the ideas will critically depend on such assessments in order to achieve a fuller understanding of the data.

8. The remote sensing/GIS approach can provide (1) landslide inventory maps and (2) provisional hazard zonation maps. It must be stressed, however, that the approach is an empirical one. The hazard map produced is both preliminary, in the sense that further GIS analysis of the existing data is required, and provisional in that improved versions could be produced as more information becomes available. The assumption that past landsliding provides an indication of where future events are most likely, still requires validation. Indeed, the opposite could be true in some cases; certain

amphitheatre-like terrain features could in fact have attained relative stability and thus be *less* prone to slide. Another viewpoint is that remote sensing provides only a limited and subjective picture, and that in such rugged terrain, a landslide could occur almost anywhere given the right triggering event. Nevertheless, it is clear that, although the approach is less than rigorous, it provides the basis for providing provisional regional hazard maps in Fiji at reasonable cost and in a realistic time frame. Maps produced by such rapid methods have their limitations and should only be used to provide general information. They cannot be expected to provide reliable information at the detailed scale for which ground-based engineering geological/geotechnical surveys will be required.

This pilot study represents a preliminary test of the methodology. Despite certain practical difficulties usual in feasibility studies of this type, it is considered that the results justify the techniques being introduced operationally in Fiji. The following **recommendations** are made in the context of such possible implementation.

1. A review should be undertaken to define priorities for landslide hazard mapping in Fiji and to devise a long term strategic programme and timetable. Consideration should be given to areas are most at risk in terms of infrastructure, new construction and population. Cooperation and support from developers should be considered. Flexibility should be included to allow responses to changing requirements.

2. A project needs to be defined, lead by the Mineral Resources Department but involving other Government departments concerned with planning, disaster preparedness and GIS, to implement hazard mapping on a realistic time scale. This is likely to involve the commitment of staff and resources dedicated to this work.

3. The project team will require resources and expertise to carry out a number of functions in-house or, failing that, to buy in the services as required. The following capabilities will probably be required:

   (i) A team dedicated to landslide hazard mapping possibly comprising: project leader (engineering geologist), data manager (GIS specialist), project geologist(s), support technician, and field assistant(s).

   (ii) Vector- and raster-based GIS systems (MapInfo possibly and IDRISI are recommended at this stage, but this will need to be reviewed in light of new developments and support e.g. that provided by SOPAC).

   (iii) Additional computing hardware (high-level PC or workstation, scanner, digitiser, etc) and software to carry out in-house data capture and conversion may be required. A separate review may be needed to establish operational requirements; this should take into account systems already in use, or supported, in Fiji.

   (iv) Recurrent funding for data purchase, computer maintenance and upgrades, and services as required in order to carry out the defined programme.

4. The methodology used in the pilot study needs to be critically reviewed, both in scientific terms and in relation to the work programme and time scale. This review should also consider which data are, or could be made, available that would improve the final hazard map. In order to achieve consistent results over a period of time, quality assurance procedures need to be established. This is particularly important in regard to the photointerpretation of landslides which, by its nature, is a subjective process; checks/procedures must be introduced to ensure that, as far as possible, different workers over periods of time adopt the same interpretative procedures. Cooperation with other GIS workers in the country should be strengthened and agreement reached nationally on data exchange procedures and formats.

5. Further work, including geotechnical field investigations and laboratory testing, is required to decide whether the hazard maps produced are meaningful and can be validated by more conventional techniques. The results of such work should be used, if necessary, to modify and improve the methodology.

In conclusion, the pilot study has demonstrated that rapid landslide hazard mapping using remote sensing and GIS is a practical possibility in Fiji. The results of the pilot study are encouraging and support the view that consideration be given to implementing the methodology more widely. However, the map produced is very much a first attempt and should not be regarded as a final product. It demonstrates only what can be done.

ACKNOWLEDGEMENTS

Many people contributed directly or indirectly to the study, and their interest and help are gratefully acknowledged. We should also like to thank all those in Fiji who provided data and information. Particular thanks are due to the Director of Mineral Development, Fiji, for his support and for the involvement of his staff.

REFERENCES

ANON. 1990. Geological Society Engineering Group Working Party Report: Tropical Residual Soils. *Quarterly Journal of Engineering Geology*, Vol. 23, No. 1.

BAND, R.B. 1964. Geology of Navua River area, Viti Levu Sheet 18, Scale 1: 50,000. Geological Survey of Fiji, Suva.

BAND, R.B. 1965. Geology of Mau area, Viti Levu Sheet 19, Scale 1: 50,000. Geological Survey of Fiji, Suva.

BRAND, E W. 1982. Analysis and design in residual soils. Proceedings of the Specialty *Conference on Engineering and Construction in Tropical and Residual Soils, Honolulu*, American Society of Civil Engineers, 89-146.

GALE, I. N. and BOOTH S. K. 1991. Hydrogeology of Fiji. Technical Report WD/91/36. Hydrogeology Series. British Geological Survey, Keyworth.

HANSEN, A. 1984. Landslide hazard analysis. *in* Slope instability. Brunsde, D and Prior, D.B (eds). Wiley & Sons: New York. 523-602

HATHWAY, B. 1993. The Nadi Basin: strike-slip faulting and sedimentation in a fragmented arc, western Viti Levu, Fiji. *Journal of the Geological Society, London*, Vol. 150, Part 3, 563-581.

HOWORTH, R, BALEIVANUALALA, V, and PRASAD, S. 1993. Initial reconnaissance of the effects of cyclone Kina in central and eastern Viti Levu. *South Pacific Applied Geoscience Commission (SOPAC)*, SOPAC Miscellaneous Report 149, 27p.

HOWORTH, R, and PRASAD, S. 1981. Morphology of typical landslides which occurred Good Friday 1980 in the Serua Hills, Viti Levu, Fiji. *Fiji Mineral Resources Department*, Report 28, 29p.

HOWORTH, R, CROZIER, M, and GRANT, I. 1980. Slope stability study, Viti Levu, Fiji. *Victoria University of Wellington, New Zealand*, 24p.

HUTCHINSON, J N. 1988. General report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. 3-35 in *Landslides*, Vol. 1, Proceedings of the Fifth Symposium on Landslides, Lausanne, July 1988. BONNARD, C (ed). (Rotterdam: A A Balkema).

IRFAN, T F. 1994. Mechanism of creep in a volcanic saprolite. *The Quarterly Journal of Engineering Geology*, Vol. 27, Part 3, 211-230.

KEEFE, O C. 1980. Report on Landslides in the Suva Area, Fiji. *Fiji Mineral Resources Department*. MRD Report (un-numbered), 10p.

LARSEN, M C, and TORRES SANCHEZ, A J. 1992. Landslides triggered by hurricane Hugo in eastern Puerto Rico, September 1989. *Carribean Journal of Science*, Vol. 28, No. 3-4, 113-125.

LAWSON, T. 1993. South east Viti Levu landslide project - preliminary study. *Fiji Mineral Resources Department,* MRD Note BP59/2, 76p.

LOUAT, R. and PELLETIER, B. 1989. Seismotectonics and present-day relative motions in the New Hebrides-North Fiji Basin region. *Tectonophysics*, 167, 41-55.

LOVEGROVE, G W, and FOOKES, P G. 1972. The planning and implementation of a site investigation for a highway in tropical conditions in Fiji. *The Quarterly Journal of Engineering Geology*, Vol. 5, No. 1&2, 43-68.

READING, A J. 1991. Stability of tropical residual soils from Dominica, West Indies. *Engineering Geology*, Vol. 31, 27-44.

RODDA, P. 1994. Geology of Fiji. *in*: Stevenson, A.J., Herzer, R.H. and Ballance, P.F. (eds) Geology and Submarine Resources of the Tonga-Lau-Fiji Region. SOPAC Technical Bulletin **8**, 131-151.

ROUSE, W C, READING, A J, and WALSH, R P D. 1986. Volcanic soil properties in Dominica, West Indies. *Engineering Geology*, Vol. 23, 1-28.

ROUSE, W C. 1990. The mechanics of small tropical flowslides in Dominica, West Indies. *Engineerining Geology*, Vol. 29, 227-239.

SHORTEN, G. 1982. Deuba reservoir site inspection. MRD Note BP 32/2. Ministry of Energy and Mineral Resources, Mineral Resources Department. Suva.

SKEMPTON, A W, and DE LORY, F A. 1957. Stability of natural slopes in London Clay. 378-381 in *Proceedings of the 4th International Conference on Soil Mechanics*, Vol. 2, London.

SOETERS, R and VAN WESTEN, C.J. 1994. Slope instability: the role of remote sensing and GIS in recognition, analysis and zonation. *in* Wadge, G. (ed): Natural hazard and remote sensing, Proceedings of a conference held on 8/9 March 1994 at the Royal Society, London. 44-50.

TWYFORD, I.T. and WRIGHT, A.C.S. 1965. The Soil Resources of the Fiji Islands, Department of Agriculture, Suva, Fiji.

VAN WESTEN, C.J. 1993. Training package for geographical information systems in slope instability zonation. Volume 1: Theory, ITC, 245 pp.

VARNES J. 1978. Slope movement types and processes. 11-33 in *Landslides; analysis & control.* Special Report 176, Transportation Research Board, 1978. SCHUSTER, R L &

KRIZEK, R J (editors). (National Acadamy of Sciences: Washington D.C.)

VAUGHAN, P R. 1985. Pore pressures due to infiltration into partly saturated slopes. *Proceedings of the 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brazil,* Vol. 2, 61-71.

WESLEY, L D. 1977. Shear strength properties of halloysite and allophane clays in Java, Indonesia. *Geotechnique*, Vol 27, 125-136.

Table A1.1 : Cross-tabulation of geology against total landslides

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
0	127	201610	0	0
1	1080	44398	2.4	2
2	2504	9900	25.3	17
3	5262	38472	13.7	9
4	8751	31598	27.7	19
5	2939	8412	34.9	23
6	1745	7782	22.4	15
7	0	371	0	0
8	25	606	4.1	3
9	1078	8951	12.0	8
10	0	88	0	0
11	393	3381	11.6	8
12	171	602	28.4	19
13	0	3190	0	0
14	742	10738	6.9	5
15	16061	88750	18.1	12
16	0	55	0	0
17	0	10	0	0
18	1145	17325	6.6	4
19	428	2473	17.3	12
20	0	3774	0	0
21	20	4171	0.5	0
22	27	315	8.7	6
TOTAL	42498	486972		

1. Alluvium
2. Serua Conglomerate
3. Navua Mudstone
4. Nubuonaboto Volcanic Conglomerate
5. Lokalevu Keratophyre
6. Navutulevu polymict conglomerate
7. Nubuonaboto volcanic conglomerate (metamorphic aureole)
8. Tonalite-granodiorite
9. Gabbro
10. Veisari Sandstone
11. Wainikovu sandstone (Navua Mudstone)
12. Basal conglomerate (Navua Mudstone)
13. Namosi Andesite (augite andesite conglomerate)
14. Namosi Andesite (hornblende andesite conglomerate)
15. Tawavatu Tuff
16. Andesite dyke
17. Lami limestone (Suva Marl)
18. Veisari Sandstone
19. Mau andesitic conglomerate
20. Vango Volcanics
21. Tawavatu Tuff (metamorphic aureole)
22. Hornblene andesite

Table A1.2 : Cross-tabulation of slope angle against total landslides

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
1	8297	300787	2.8	2
2	16440	92999	17.7	12
3	12221	57823	21.1	14
4	4185	21701	19.3	13
5	975	8029	12.1	8
6	198	3234	6.1	4
7	59	1404	4.2	3
8	24	467	5.1	3
9	5	130	3.9	3
10	9	129	7.0	5
11	4	42	9.5	6
12	3	29	10.3	7
13	12	36	33.3	22
14	13	81	16.1	11
15	53	75	70.7	47
16	0	6	0	0
TOTAL	42498	486972		

1. Class 0: 0 - 5°
2. Class 1: 6 - 10° etc

Table A1.3 : Cross-tabulation of slope aspect against total landslides

Class	Landslide Pixels	Total Pixels	Landslide Total (%)	Weighting
0	66	197863	0.03	0
1	4792	29742	16.1	11
2	6563	37380	17.6	12
3	6702	43664	15.3	10
4	5184	42890	12.1	8
5	5478	46819	11.7	8
6	5417	38153	14.2	10
7	4896	29480	16.6	11
8	3400	20981	16.2	11
TOTAL	42498	486972		

1. N - NE
2. NE - E
3. E - SE
4. SE - S
5. S - SW
6. SW - W
7. W - NW
8. NW - N

Table A1.4 : Cross-tabulation of soils against total landslides

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
0	89	202388	0	0
1	206	3608	5.7	4
2	12	1488	0.8	1
3	16	606	2.6	2
4	58	2590	2.2	1
5	48	1708	2.8	2
6	15	146	10.3	7
7	19	1739	1.1	1
8	0	1242	0	0
9	79	1604	4.9	3
10	0	158	0	0
11	0	144	0	0
12	70	1846	3.8	3
13	106	3063	3.5	2
14	0	79	0	0
15	1	84	1.2	1
16	75	3374	2.2	1
17	0	151	0	0
18	137	6984	2.0	1
19	0	228	0	0
20	171	4107	4.2	3
21	478	5532	8.6	6
22	19	2431	0.8	1
23	0	592	0	0
24	14	367	3.8	3

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
25	11840	46013	25.7	17
26	1832	12690	14.4	10
27	1743	12253	14.2	10
28	629	2476	25.4	17
29	11381	51852	21.9	15
30	478	1154	41.4	28
31	0	658	0	0
32	862	10915	7.9	5
33	56	158	35.4	24
34	245	5442	4.5	3
35	41	9586	0.4	0
36	824	7752	10.6	7
37	7695	55215	13.9	9
38	0	6291	0	0
39	33	134	24.6	17
40	666	4207	15.8	11
41	0	431	0	0
42	2334	11433	20.4	14
43	226	2053	11.0	7
TOTAL	42498	486972		

Classes based on Ministry of Primary Industries soils classification

Table A1.5 : Cross-tabulation of elevation against total landslides

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
0	36	194859	0	0
1	4985	77070	6.5	4
2	7358	37328	19.7	13
3	6714	46587	14.4	10
4	8794	49865	17.6	12
5	6776	34238	19.8	13
6	4785	20376	23.5	16
7	2459	11807	20.8	14
8	591	5934	10.0	7
9	0	2772	0	0
10	0	1933	0	0
11	0	1141	0	0
12	0	1005	0	0
13	0	679	0	0
14	0	537	0	0
15	0	481	0	0
16	0	318	0	0
17	0	42	0	0
TOTAL	42498	486972		

1. 0 - 50 m asl
2. 51 - 100 m asl etc

Table A1.6 : Cross-tabulation of forestry cover against total landslides

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
0	0	72692	0	0
1	63	119371	0.1	0
2	129	6817	1.9	1
3	9198	74003	12.4	8
4	7480	37202	20.1	14
9	3642	32094	11.4	8
10	12042	82137	14.7	10
11	9940	61590	16.1	11
99	4	66	6.1	4
TOTAL	42498	486972		

0. background
1. water
2. mangrove
3. non-forest
4. hardwood
9. low density
10. medium density
11. high density
99. unclassified

Table A1.7 : Cross-tabulation of geology + slope against total landslides (Model 2)

Logical weighting	Landslide pixels	Total pixels	Landslide / Total (%)	Recalculated weighting
0	77	202476	0	0
2	597	41297	1.4	1
3	525	7341	7.2	5
4	72	3562	2.0	1
5	282	1879	15.0	10
6	1365	20863	6.5	4
7	3227	28643	11.3	8
8	1253	14003	8.9	6
9	209	4796	4.4	3
10	5849	37642	15.5	10
11	718	4970	14.4	10
12	9907	52678	18.8	13
13	5340	23296	22.9	15
14	2842	11067	25.7	17
15	220	619	35.5	24
16	7649	25345	30.2	20
18	2363	6484	36.4	24
20	3	11	27.3	18
TOTAL	42498	486972		

Table A1.8 : Cross-tabulation of geology + slope + soils against total landslides (Model 3)

Logical weighting	Landslide pixels	Total pixels	Landslide Total (%)	Recalculated weighting
1	52	204814	0	0
2	208	27881	0.7	0
3	210	9545	2.2	1
4	145	6754	2.1	1
5	370	10644	3.5	2
6	708	12175	5.8	4
7	1114	17581	6.3	4
8	2019	19132	10.6	7
9	1447	16261	8.9	6
10	3663	26962	13.6	9
11	4839	29521	16.4	11
12	4219	18894	22.3	15
13	6276	30997	20.2	14
14	6580	23017	28.6	19
15	4386	15037	29.2	20
16	3925	11851	33.1	22
17	1672	4551	36.7	25
18	327	631	51.8	35
19	122	319	38.2	26
20	216	405	53.3	36
TOTAL	42498	486972		

Table A1.9 : Cross-tabulation of geology + slope + soils + elevation against total landslides (Model 4)

Logical weighting	Landslide pixels	Total pixels	Landslide / Total (%)	Recalculated weighting
0	9	193405	0	0
1	0	984	0	0
2	122	30946	0.4	0
3	175	10553	1.7	0
4	275	9710	2.8	2
5	359	6493	5.5	4
6	619	14557	4.3	3
7	553	11806	4.7	3
8	1678	23452	7.2	5
9	1771	16411	10.8	7
10	4197	32444	12.9	9
11	3676	23954	15.3	10
12	7690	38040	20.2	14
13	6331	28318	22.4	15
14	8169	25908	31.5	21
15	3784	11206	33.8	23
16	2417	7462	32.4	22
17	326	676	48.2	32
18	347	647	53.6	36
TOTAL	42498	486972		

Table A1.10 : Cross-tabulation of geology + slope + soil + elevation + forest against total landslides (Model 5)

Logical weighting	Landslide pixels	Total pixels	Landslide / Total (%)	Recalculated weighting
0	0	190660	0	0
1	9	5835	0	0
2	17	2356	0.7	0
3	59	19895	0.3	0
4	294	20014	1.5	1
5	299	6735	4.4	3
6	579	10960	5.3	4
7	696	14970	4.6	3
8	1175	20776	5.7	4
9	2226	24240	9.2	6
10	4237	32775	12.9	9
11	5720	34744	16.5	11
12	9431	44906	21.0	14
13	8906	31650	28.1	19
14	6240	19052	32.8	22
15	2005	6165	32.5	22
16	565	1161	48.7	33
17	40	78	51.3	34
TOTAL	42498	486972		

Table A1.11 : Cross-tabulation of geology + slope + soil + elevation + forest + aspect against total landslides (Model 6)

Logical weighting	Landslide pixels	Total pixels	Landslide / Total (%)	Recalculated weighting
0	3	191199	0	0
1	0	623	0	0
2	4	4447	0	0
3	18	6385	0.3	0
4	104	20133	0.5	0
5	252	15761	1.6	1
6	537	12105	4.4	3
7	637	12539	5.1	3
8	1300	26084	5.0	3
9	1808	21487	8.4	6
10	5733	45934	12.5	8
11	6240	35183	17.7	12
12	13530	57008	23.7	16
13	7485	23322	32.1	22
14	4146	13344	31.1	21
15	627	1290	48.6	33
16	74	128	57.8	39
TOTAL	42498	486972		