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 km^2. 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.

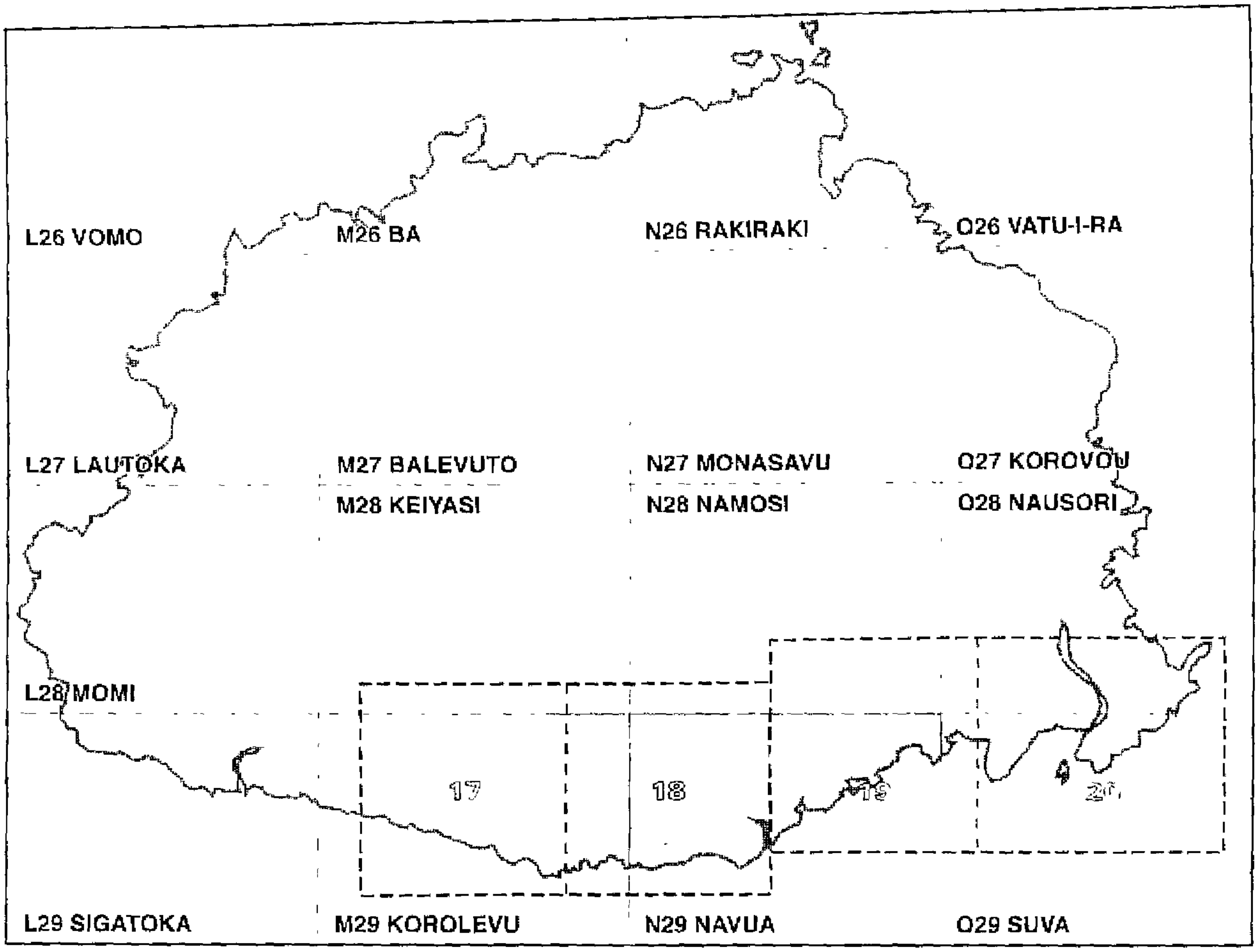

Figure 1.1 Map of Viti Levu showing the old 1:50,000 topographic series (dashed) and the new 1:50,000 series (faint). The location of the project area is indicated.

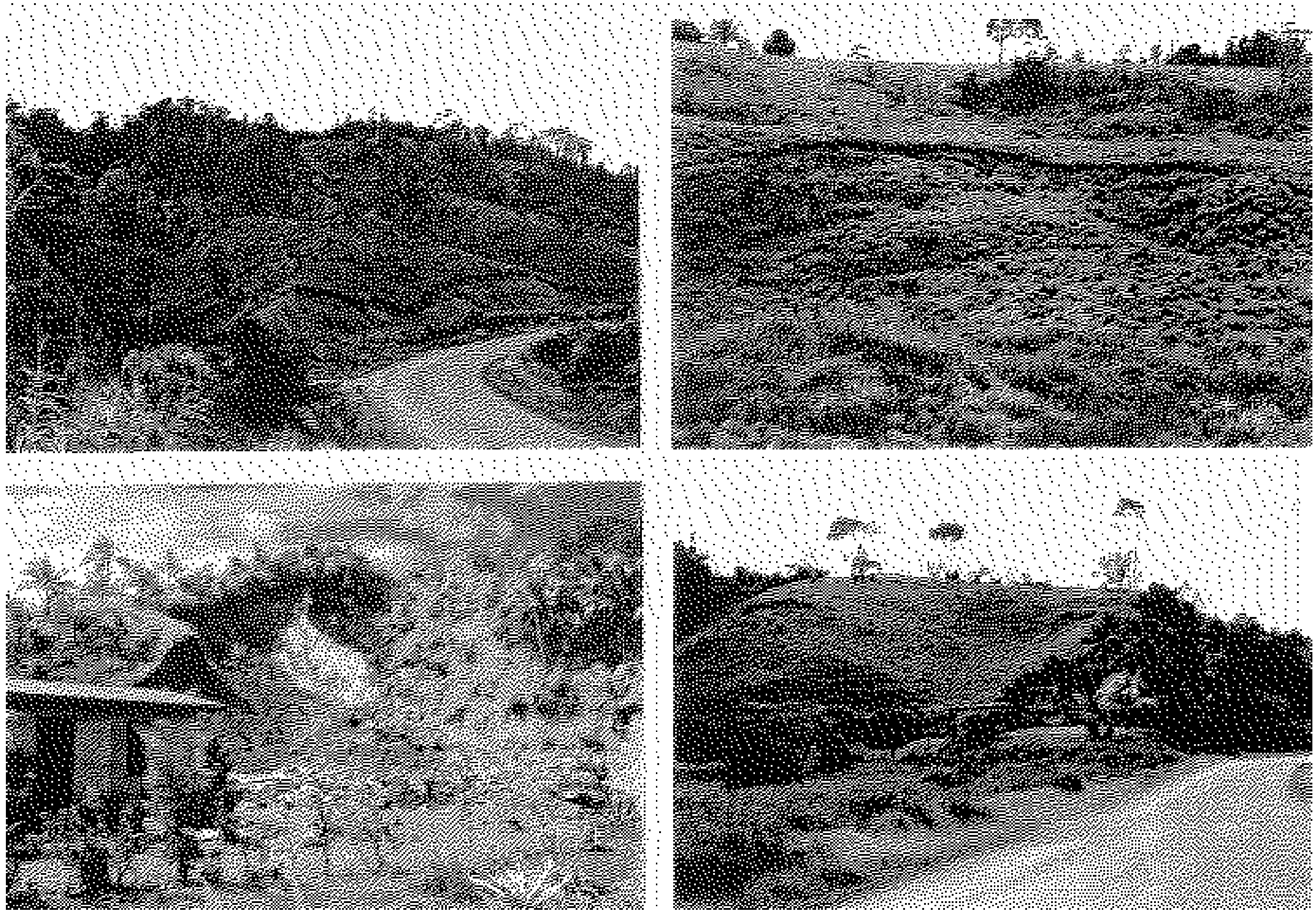

Figure 1.2 A: Recent landslides, Galoa-Korovisilou area; B: slump in natural ground, 1 km west of Korovisilou; C: landslide at Taunovo, near PWD depot; D: house built on slide debris, Korovisilou (note the 'amphitheatre' like form of old landslide).

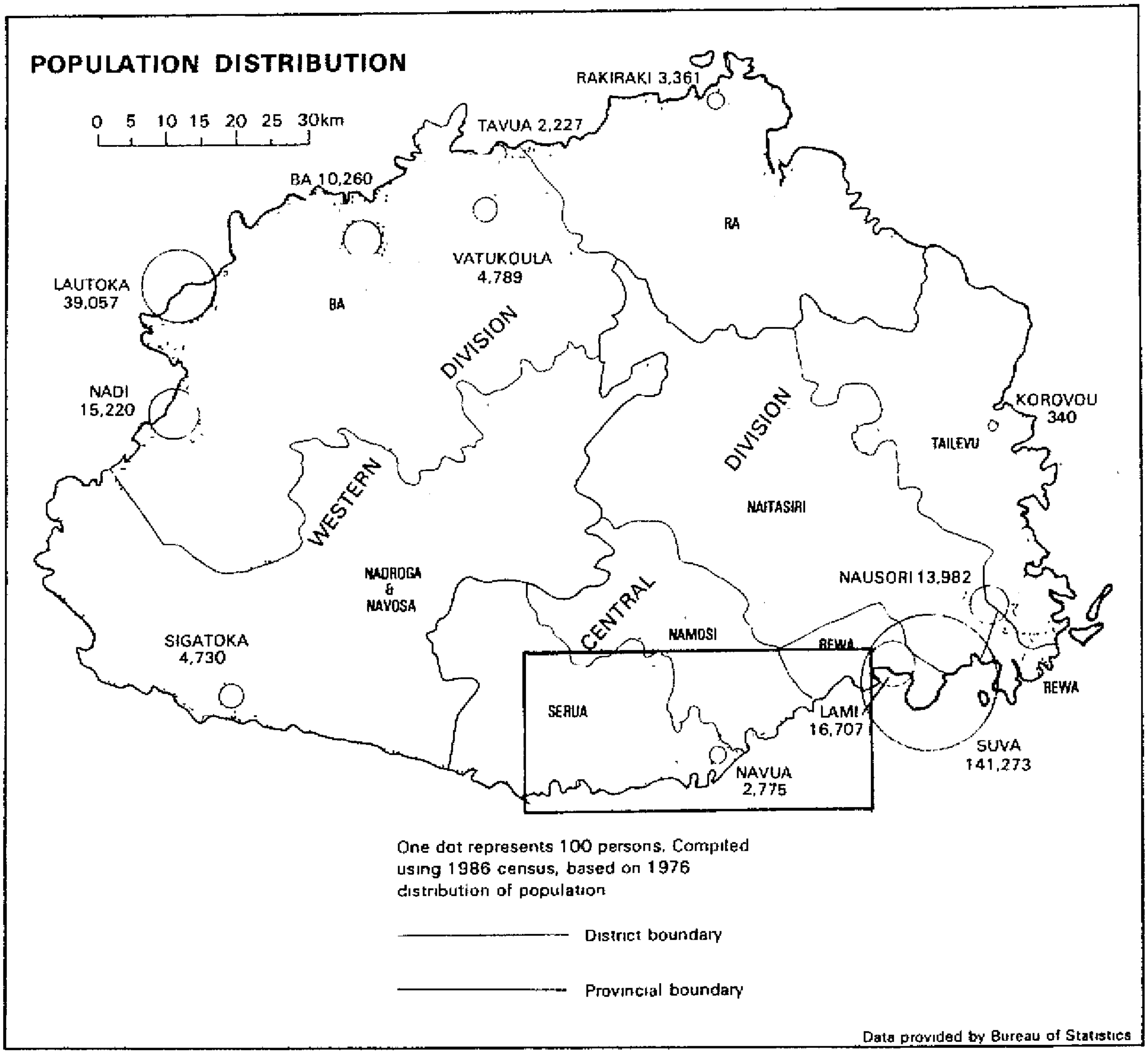

Figure 1.3 Population distribution in Viti Levu (reproduced from Gale and Booth, 1991). Study area outlined.

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.

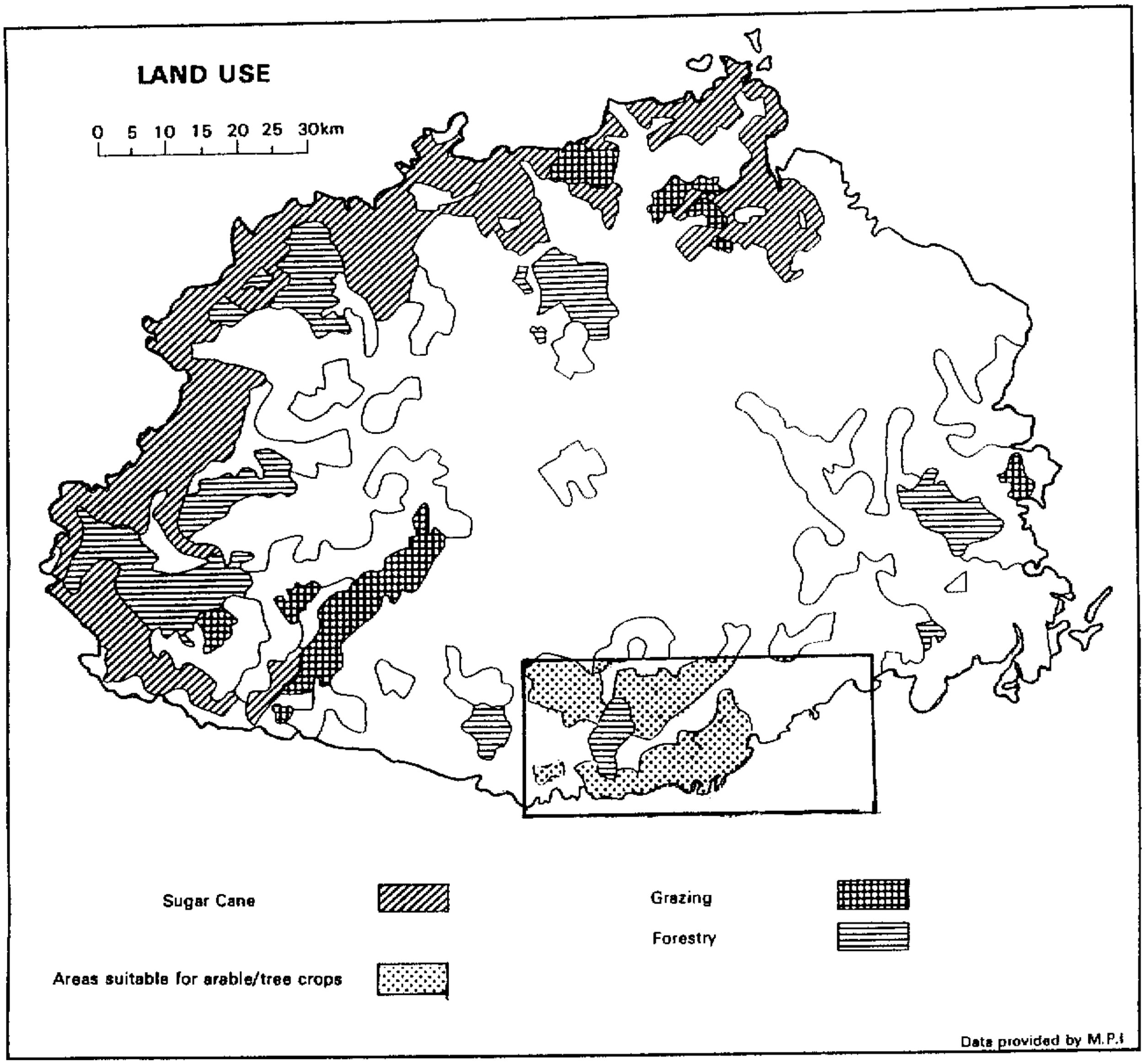

Figure 1.4 Land use map of Viti Levu showing areas designated for arable/tree crops (reproduced from Gale and Booth, 1991). Study area outlined.