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Geological Survey of Papua New Guinea

TECHNICAL REPORT WC/95/27
Overseas Geology Series

RAPID METHODS OF LANDSLIDE HAZARD MAPPING: PAPUA NEW GUINEA CASE STUDY

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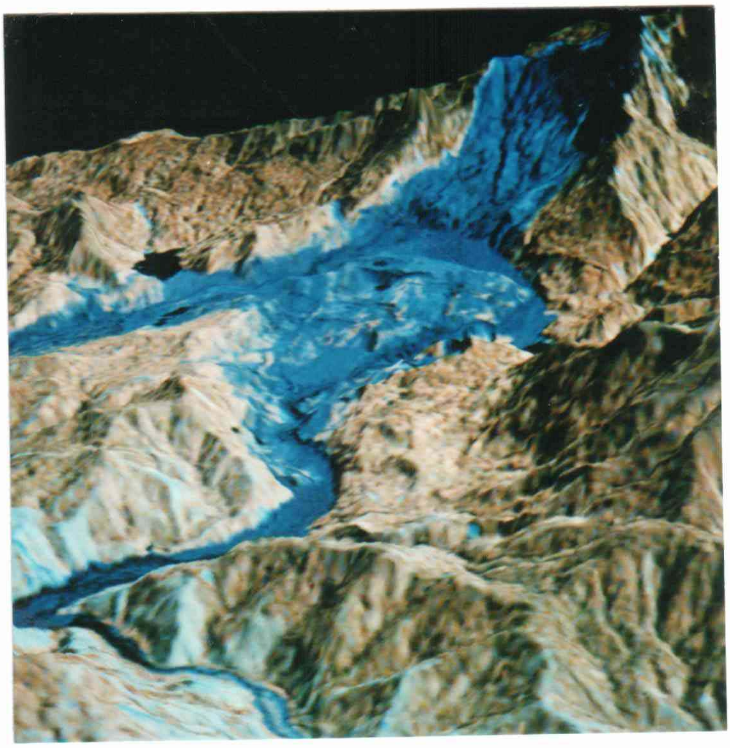

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Computer-generated simulation of the Kaiapit landslide produced from Landsat TM and a digital elevation model

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CONTENTS

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 United Nations 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 the highlands of Papua New Guinea (PNG) in collaboration with the Geological Survey Division. 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 cannot be achieved using conventional ground-based geotechnical methods.

In PNG, landslides are usually triggered by earthquakes or intense rain storms. Tectonic instability and the extreme ruggedness of the terrain make the highlands very susceptible to landsliding, but the extent to which regional factors influence the distribution and severity of landsliding is uncertain. The report discusses the remote sensing and GIS methodology, and describes the results of the pilot study over an area of approximately 4 500 km^2 in the Kaiapit/Saidor districts of the Finisterre mountain range. The landslide model uses geology, elevation, slope angle, lineaments and catchments as inputs. The resulting provisional landslide hazard zonation map, divided into 5 zones of landslide hazard probability, suggests that regional controls on landslide occurrence do exist and are significant. It is recommended that consideration be given in PNG 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 commonest 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 cumulative losses account for around 25 per cent of the annual death toll from 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 most important single 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 with zones indicating 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) avoid or minimise the risks associated with new developments, and (2) make contingency plans to prepare for, and mitigate against, the effects of landslide events on infrastructure, housing and people. 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. The reason is that, whereas the mechanisms of slope mass movement and controlling/triggering factors are in general well understood, the required geotechnical investigations have all too often not been undertaken. Analysis of landslide hazards involves the testing of materials' properties and extensive fieldwork. Such investigations are costly and time-consuming, and generally cannot be justified at the regional scale in many developing countries. Given the magnitude of the task worldwide, it is important that alternative approaches are developed that can provide provisional hazard information cheaply and quickly.

This report forms part of BGS project 92/7 (R 5554) 'Rapid assessment of landslide 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 was carried out jointly with the Geological Survey of Papua New Guinea (GSPNG) which provided support and funding for the collaborative 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 is a valid and useful interim solution. In any event, even limited information is often 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 of unnecessary, complicating detail, and be understandable by people from a non-geological background, including engineers, planners and decision makers. A GIS allows the production of simple thematic maps tailored to meet particular requirements. Second, the 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 has 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	~ 1:250 000- 1:1 000 000	National planning
Regional scale	~ 1:50 000-1:250 000	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: Papua New Guinea; Fiji 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.

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 with parts of the country 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. An area on the north side of the Markham Valley was selected for study (Figure 1.1). This is a mountainous area where landslides are common; in 1988, the Kaiapit landslide occurred during which some 1.8 km^3 of rock was displaced and 74 people died. This was one of the largest landsliding events ever recorded (see Chapters 2 and 7 for further details).

Fiji is a small south Pacific nation consisting of two main islands and many smaller ones. Though geologically young, the islands are tectonically more stable than PNG and the relief more subdued. The association of deep tropical weathering with high intensity rainfall, especially during tropical cyclones, results in generally small, though locally numerous and damaging, landslides. The requirement in Fiji is for medium to regional scale hazard maps covering at least the two main islands.

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 urban development, road construction 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 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.

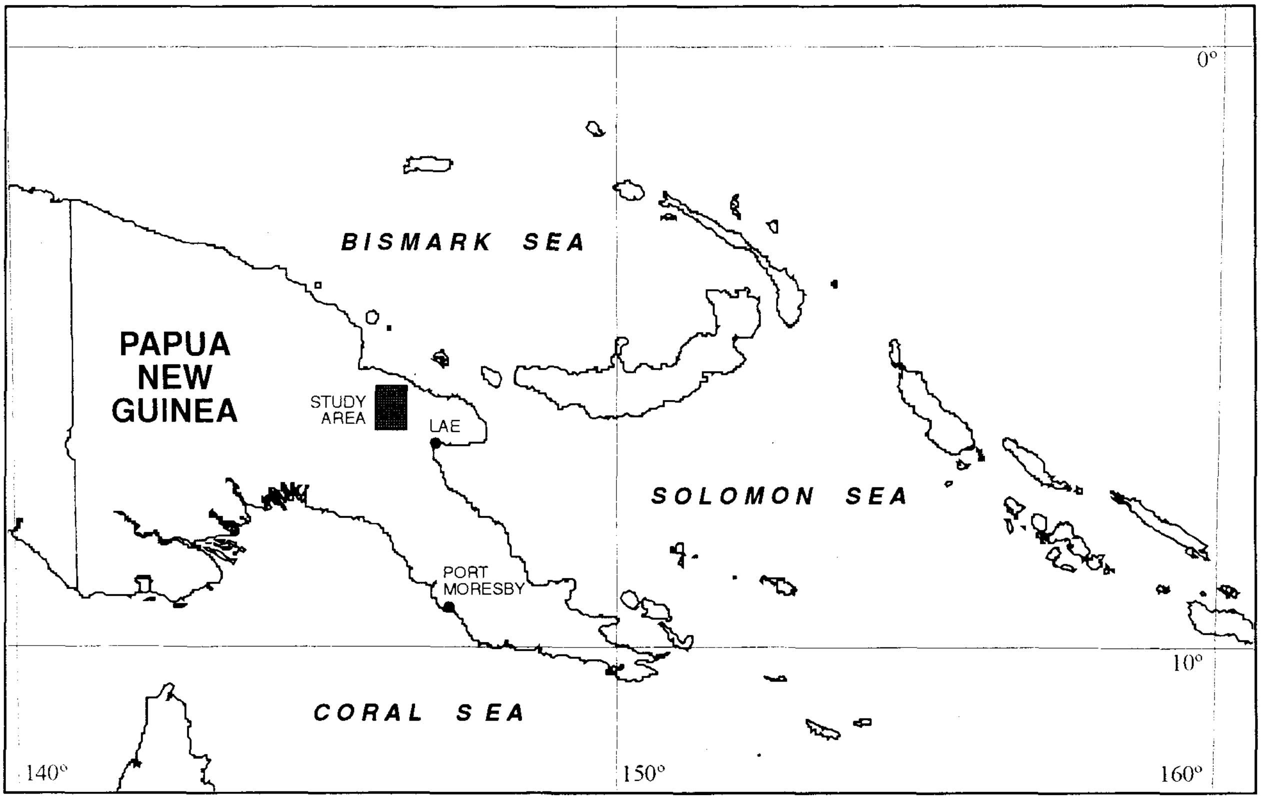


Figure 1.1 Study area location, Markham Valley, Papua New Guinea

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 Kaiapit region of PNG using satellite images acquired before and after the October 1993 earthquake 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 cultural base map for geographical reference.

A more informative map will include other categories of 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 can be inferred, but there is no attempt to analyse the data in any rigorous or quantifiable manner. A further stage involves the ranking of 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 a variety of ways depending on 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 will depend on the data types available and the scale of the study.

2. LANDSLIDE HAZARDS IN PAPUA NEW GUINEA

2.1 Introduction

Landslides are one of the most destructive natural hazards affecting Papua New Guinea. The words for *landslide* in Pidgin, the *Lingua Franca,* and in the local languages, are very much part of the common vocabulary, and landsliding affects the lives of many of the highland people. No official statistics are kept for landslide-related fatalities, but the Geological Survey of Papua New Guinea (GSPNG) which has investigated many of the events causing fatalities, estimate that about one hundred people each year are killed through landslides. In the study area alone, two major landslide events have occurred since 1988, the first killing 74, the second event killing 37 villagers.

Due to the very late exploration of the interior of Papua New Guinea by Europeans, many earlier landslide events have either not been recorded or documented with very few details, which have at times been taken from oral traditions. The following is typical of an early account of landsliding in the Torricelli Mountains following a magnitude 7.9 earthquake on 20 September 1935:

> 'The earthquake denuded whole mountain slopes of their cover, carrying away village houses, killing many of the inhabitants. Rivers were dammed with rubble, forming huge lakes. Some dams later burst, killing more people in the flood waters' (Stanley *et al.*, 1935).

Papua New Guinea's landslide-related fatalities, although accounting for an estimated ten percent of the world total, 674 worldwide fatalities in 1991 (IDNDR 1991), are not an accurate indicator of either the magnitude or frequency of landsliding in the country. This is because the population density averages only nine people per square kilometre and many of the larger landslides occur in mountainous and uninhabited areas. Furthermore, in the more remote areas, local people tend not to report fatalities unless the death toll is considerable and outside help is sought.

2.2 Geographical, climatic and tectonic setting

Papua New Guinea has a population of about 4 million. It is a relatively large country with a land area of 462 840 km^2, similar in size to France. The country lies close to the equator between the latitudes of 1°S and 12°S. The majority of the land area is located on the eastern part of the Island of New Guinea, the world's second largest island. Several sizeable islands, namely New Britain, New Ireland, Manus and Bougainville together with hundreds of smaller islands also form part of this nation (Figure 2.1). Commerce and industry can be found in provincial centres and large towns but the vast majority of the nation's population live within the subsistence sector of the economy relying on gardening to grow most of their food.

For the most part, Papua New Guinea is a land of high, rugged, rainforest-covered mountains, vast areas of swamp, and meandering rivers which, with the heavy rainfall

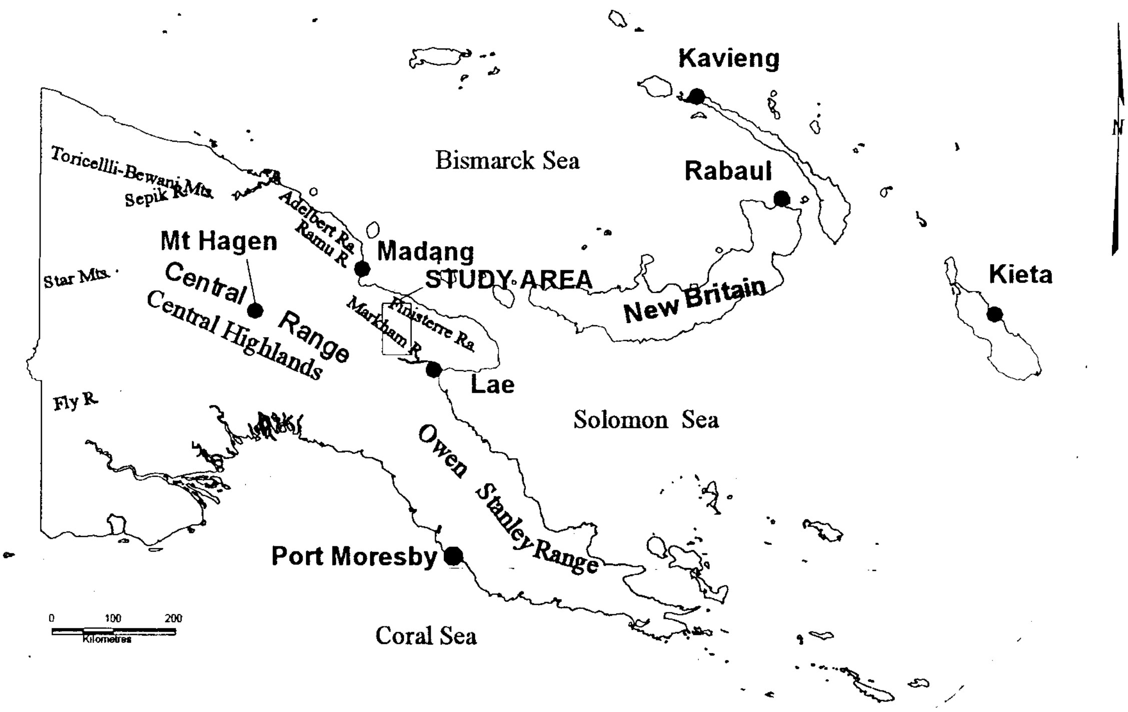


Figure 2.1 Main mountain ranges, Papua New Guinea

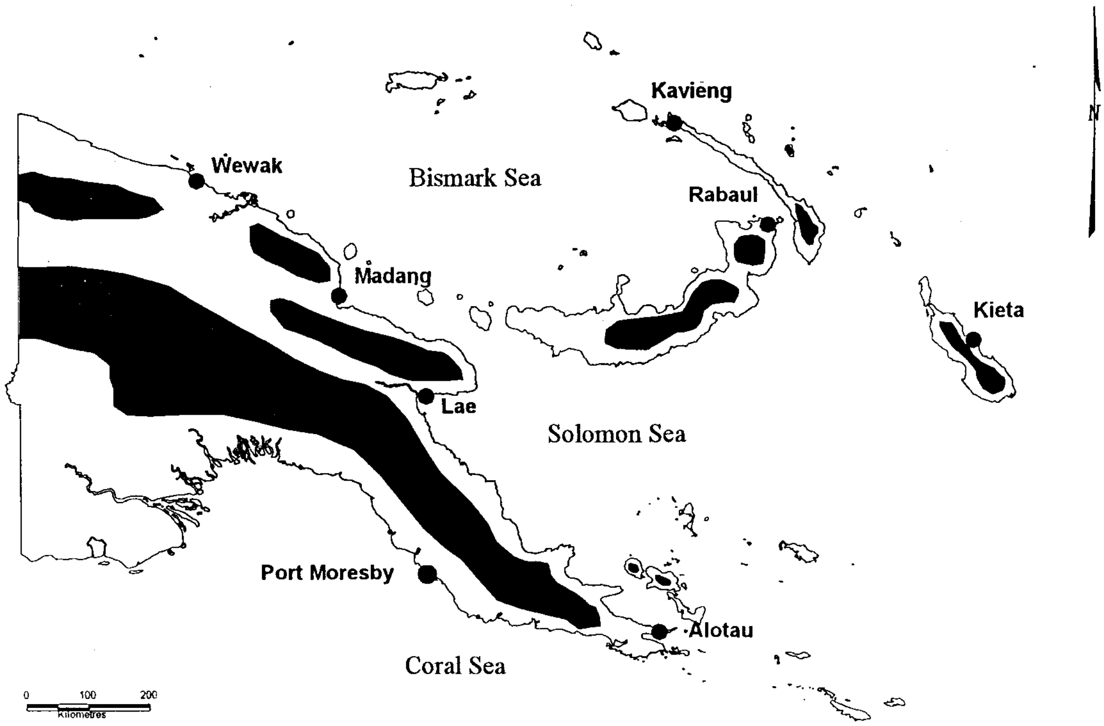


Figure 2.2 Main landslide prone areas, Papua New Guinea

and numerous offshore islands, create considerable communication difficulties and have resulted in the isolation of many tribal groups. It is estimated that over 700 local languages have developed because of this isolation. The difficulty of the terrain is also one of the reasons for the very late history of European exploration. Only in the nineteen-thirties were the central highland valleys, with a total population of about 1 million, discovered by Europeans. Significant areas of the Southern Highland and Enga Provinces remained uncontacted even as recently as the nineteen-sixties and early seventies.

These communication difficulties remain today. Only one road, the Highlands Highway, links the populated highland valleys with the coast. The capital city, Port Moresby, on the south coast has no road link to any of the eighteen other provincial towns or cities and there is no vehicular link between the south coast and the highlands. Unstable mountain sides and fast flowing rivers prone to flooding are some of the reasons why the extent of the road network is so limited. Even the important Highlands Highway is closed several times each year due to landsliding, or the destruction of bridges by floods.

The distribution of the main areas affected by significant landslides is shown in Figure 2.2. The total area affected by major landsliding is an estimated 170 000 km^2 or about a third of the total land area.

Papua New Guinea has a hot humid tropical climate, although temperatures can be moderated by altitude. Rainfall is generally high throughout the country with most areas receiving more than 2 000 mm year. Rainfall is perhaps the most common landslide triggering mechanism. In many parts of the country there are distinct wet and dry seasons. The wet season is usually November-June but in certain areas the wet-dry seasonal cycle can be the exact opposite. Figure 2.3 shows rainfall isohyets for Papua New Guinea indicating that the study area lies within a relatively dry part of the country.

The main island is divided by an east-west chain of mountains extending from Irian Jaya (Indonesia) in the west, through the full length of the Papua New Guinea mainland to the eastern tip of the Papuan peninsula (Figure 2.1). The cols or passes in the main divide are rarely lower than 2 000 m. Much of the range exceeds 3 000 m, and several peaks exceed 4 000 m, culminating with the highest mountain in the country, Mount Wilhelm at 4 529 m.

Despite the ruggedness of these mountains, the greatest population densities are concentrated in wide, high altitude valleys between the ranges of the central highlands. There are other significant ranges, namely the Torricelli, Adelbert, Finisterre and Sarawaget ranges on the mainland and other lesser ranges following the axes of the New Britain, New Ireland and Bougainville islands (Figure 2.1).

The study area is located in the Finisterre Range which is separated from the main island divide by the Markham and Ramu valleys (Figure 2.1). Within the study area the range rises to 4 015 m. The Finisterre and Sarawaget Ranges are located close to a plate boundary (Figure 2.4) and the mountain range is known to be subject to

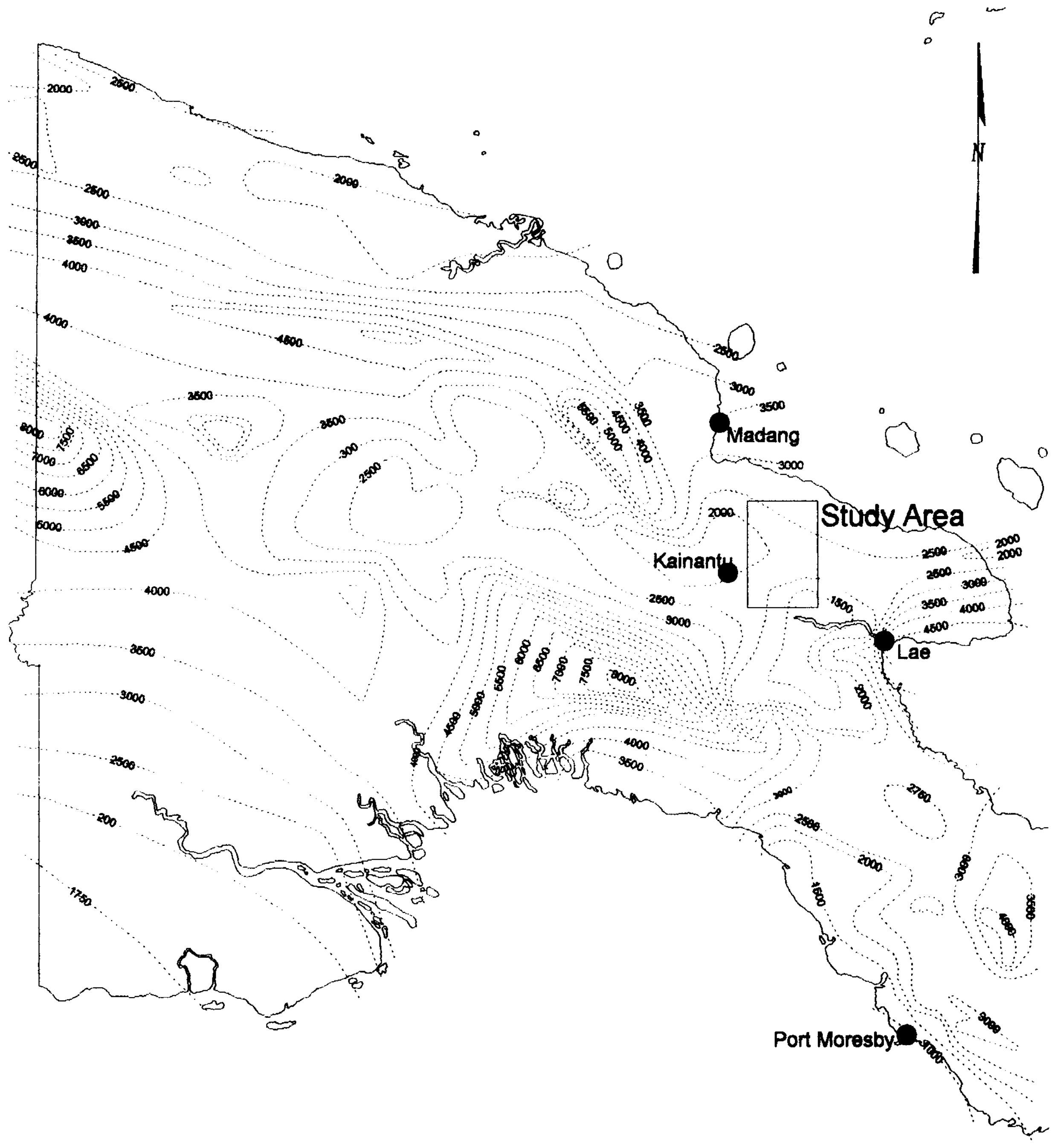


Figure 2.3 Rainfall isohyets for Papua New Guinea based on all stations and records to 1972

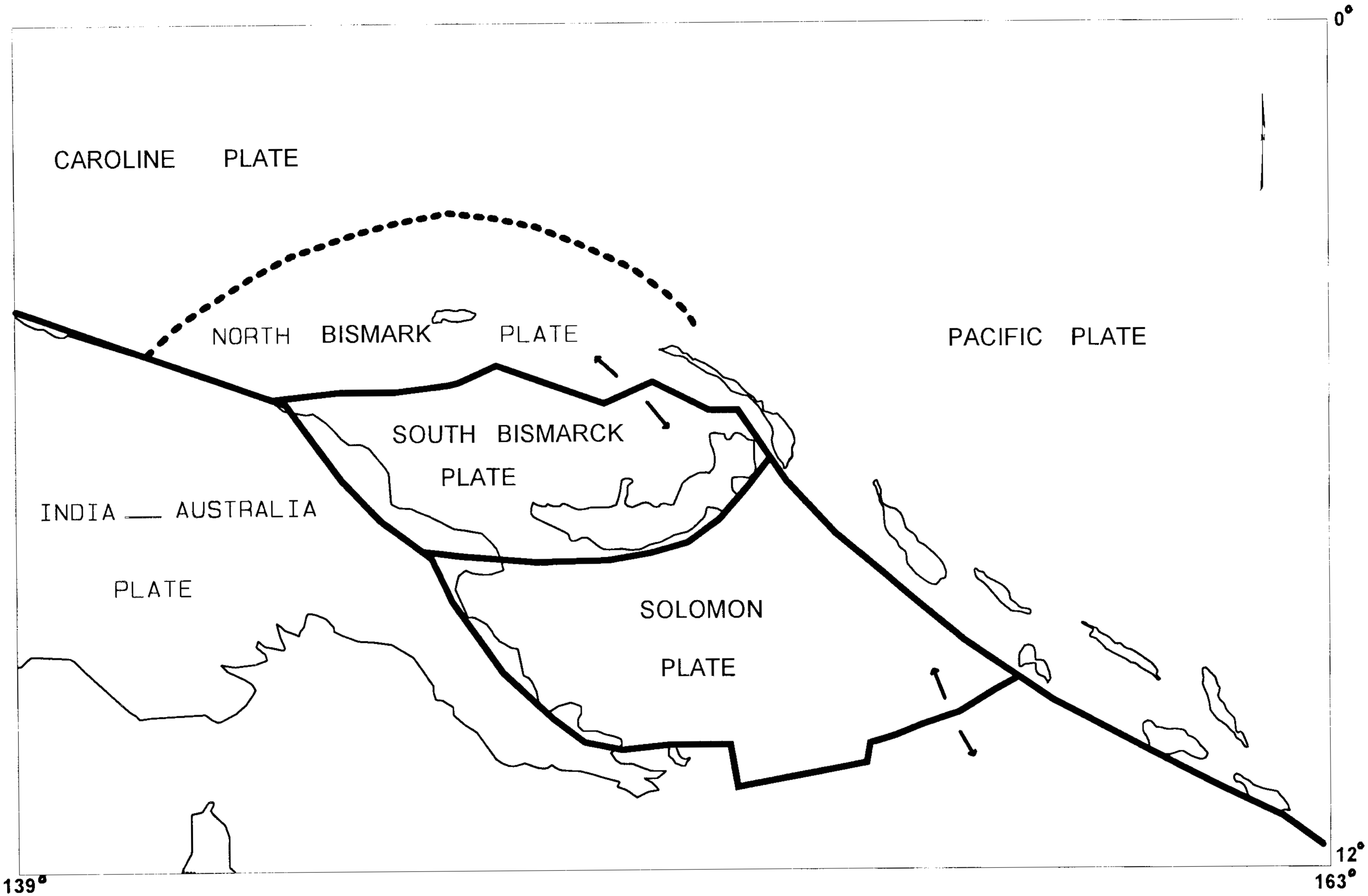


Figure 2.4 Simplified plate configuration of the Papua New Guinea region

exceptionally large uplift rates (4.3-6.8 mm yr^{-1}) (Crook, 1989). The result is that the Finisterre/Sarawaget mountains are extremely steep, rising from sea level at the coast to over 4 000 m over a distance of just 30 km. Within the mountains, some of the valley sides have gradients in excess of 45° for over 2 000 m.

The generalised tectonic setting is illustrated in Figure 2.4 (after Ripper and Letz, 1991). The country straddles several major plate boundaries and is part of the *Pacific Rim of Fire*. The Indian-Australian Plate has been modelled as moving NNE at a rate of 3.3 cm yr^{-1}, whilst the Pacific Plate is approaching the India-Australian Plate in a WSW direction at 10 cm yr^{-1}. Sandwiched between these two plates are the smaller Bismarck and Solomon Plates (Ripper and Letz, 1991, citing Le Pichon, 1968).

These relative plate motions have resulted in a significant subduction zone where the Solomon Sea Plate is subducted beneath the South Bismarck Plate. Associated with this subduction zone is an island arc to the north of New Britain that includes several active volcanoes, amongst them Tavurvur and Vulcan, which erupted in 1994 covering the town of Rabaul in volcanic ash. The Solomon Plate moves northwest with respect to the Australian Plate at a rate of 7 cm yr^{1} giving sinistral shear throughout southeastern Papua (Ripper and Letz, 1991). The Markham-Ramu fault system is widely thought to represent the plate boundary between the South Bismarck and India-Australia plates. However, due to the complexity of the plate configuration and distribution of earthquake epicentres and depths, it is not clear exactly where the plate boundary runs; neither is it clear whether the collision involves subduction, strike-slip or a component of both.

It is, however, evident that the complexity of movement of the plates has lead to exceptional uplift rates creating steep mountains prone to landslides. It has also lead to significant seismic activity, creating the potential for both shallow and large magnitude earthquakes that provide a triggering mechanism for landsliding. Figure 2.5 shows the distribution of earthquake epicentres throughout Papua New Guinea.

2.3 Classification of landslides in Papua New Guinea

It is difficult to be specific on the size, morphology, controlling or triggering mechanisms that characterise landsliding in Papua New Guinea. Nearly every type of landslide can be identified somewhere in the country. However, some generalisations can be made.

The size of landslides varies from roadside slumps of a few cubic metres to some of the largest landslides recorded anywhere on earth in modern times. The Kaiapit landslide that failed in 1988 mobilised 1.8 km^3 of debris (Peart, 1991) and only three years earlier a landslide in the highlands of New Britain mobilised 0.18 km^3 of debris (King *et al.*, 1989). Table 2.1 compares the size of the Kaiapit landslide with other famous large landslides worldwide.

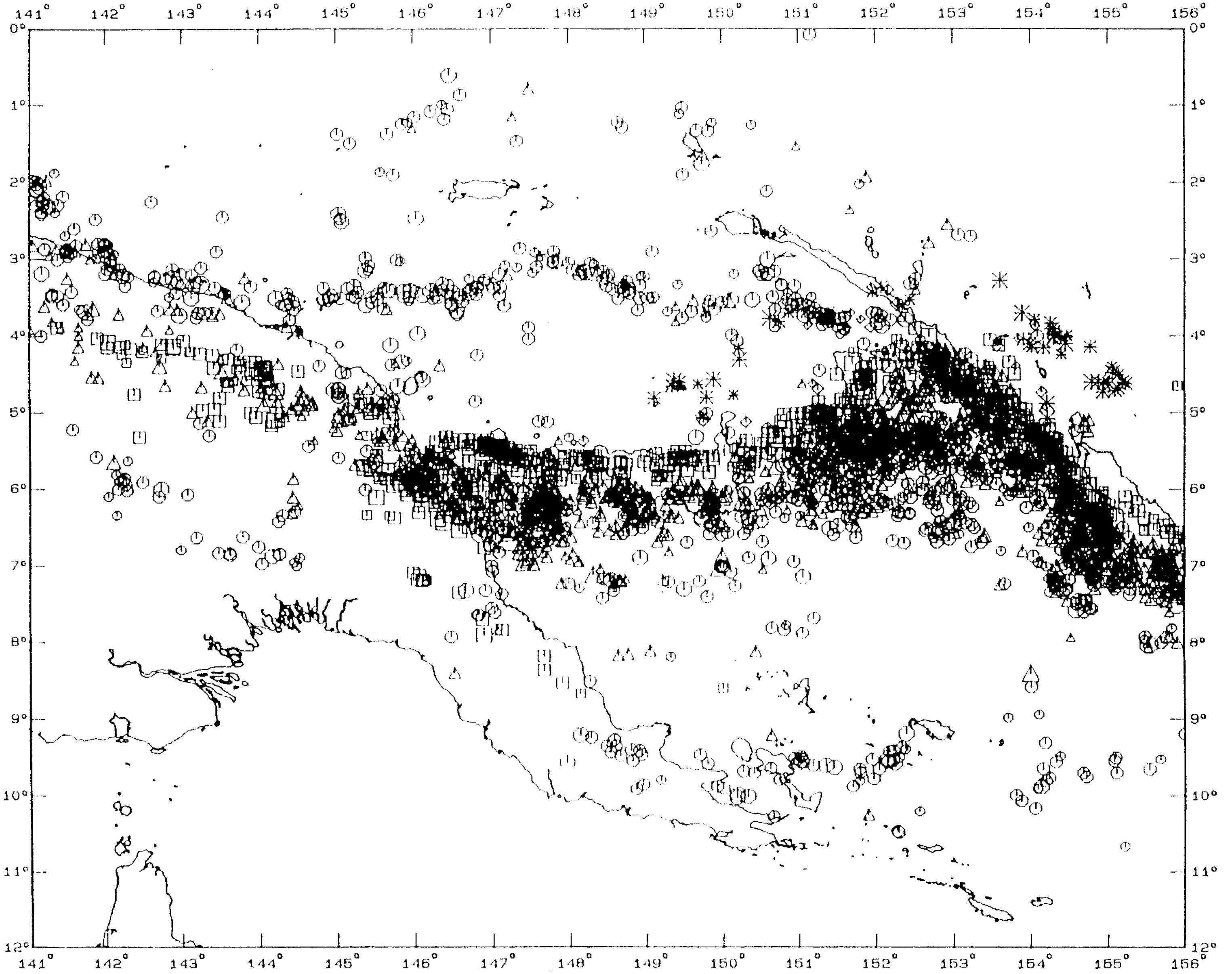


Figure 2.5 Earthquake epicentre map of Papua New Guinea for events recorded by 20 or more stations between 1964-1993

Table 2.1: Data on some of the world's large landslides

Locality of Event	**Volume ($x10^6$ m^3)**
Elm, Switzerland	10
Little Tahoma Peak, USA	11
Nevados Huascaran, Peru (1962)	13
Madison Canyon, USA	20
Frank, Canada	36.5
Lower Gros Ventre, USA	40
Nevados Huascaran, Peru (1970)	50-100
Bairamen River, PNG (1985)	180
Fernpuss, Austria	1000
Mayunmaca, Peru	1000
Kaiapit, PNG (1988)	1800

(Table modified from Peart, 1991)

Many landslides in Papua New Guinea are relatively shallow, mobilising only the deep tropical weathered profile, and not the underlying bedrock. Although the volume of debris mobilised may not be great, some of these landslides cover many square kilometres. Several new landslides with surface areas in excess of 1 km^2 occur every year. Many smaller landslides often occur together, particularly when triggered by a common mechanism (e.g. an earthquake or heavy rainfall), resulting in widespread landsliding over hundreds of square kilometres.

A recent example of this type of widespread landsliding straddles the study area. Earthquakes in 1993 caused landslides that completely denuded in excess of 52 km^2 of rainforest over an area of country of approximately 3 000 km^2. The actual extent of landsliding may be considerably greater, as this area was estimated from satellite imagery from the contrast between bare earth and rock (landslides) and areas of unaffected rainforest. It was not possible from the image to distinguish blocks of land that were displaced only a few centimetres or metres where the vegetation cover remained intact.

Table 2.2 lists some of the recent major landslide events that have occurred in Papua New Guinea in recent years.

Table 2.2: Examples of major slope failures in Papua New Guinea

Location	Date	Mechanism	Description
Yakatabari, Porgera, Enga Province	Nov. 1984 Dec. 1983	Mudslides	Mudslides of volume 1-4.34 10^6 m^3 occurring within an ancient landslide.
Anawa, Porgera, Enga Province	Dec. 1976	Mudslides	Surface slope 9°-10°
Ok Tedi, Western Province	Jan. 1984	Mudslide?	Major failure in slopes of Ok Ma valley after heavy rainfall.
Chuave, Highlands Highway, Chimbu Province	Oct. 1970	Mudslide	Mudslide within weathered Chim shale and fill. Occurred after heavy rainfall and earthquake.
Adelbert Range, Madang Province	Nov. 1970	Debris avalanches, earthflows, rockflows	Dense landsliding over an area of 240 km^2 occurred after a magnitude 7.0 earthquake. Estimated 27.6 x 10^6 m^3 debris moved into drainage channels.
Bairamen valley, Bialla, West New Britain	May 1985	Debris flows, debris slides,	Major debris flows and slides from the limestone valley slopes of the Bairamen River. Backscars of up to 200 m in height.
Kaiapit, Morobe Province	Sept. 1988	Rock avalanche	Major landslide mobilising 1.8 km^3 o debris, killing 74 people and destroying 3 villages. Occurred without rainfall or earthquake trigger
Finisterre Landslides Morobe and Madang Province	Oct. 1993- Jan. 1994	Mainly debris avalanches	Over 680 measured landslides with a surface area of 52 km^2 mobilising an estimated 1 km^3. Destroyed 3 villages, 2 airstrips and 2 bridges. Damaged 61 villages. Triggered by a series of large earthquakes (33 $>=$ magnitude 5 an 2 $>=$ magnitude 7).

(Table modified from Stead, 1990)

The type or form of landslides is primarily controlled by the type of material or materials that are mobilised. Varnes (1978) has categorised landslides into three primary classes, those involving *rock, earth* (predominately fine soils) and *debris* (predominately coarse soils).

Lithologies that are indurated and competent (engineering rocks); and soft, loose and uncemented (engineering soils) are represented in the landslide-prone areas of Papua New Guinea. Certain lithologies and landslide mechanisms, however, predominate. A Mesozoic mudstone, the Chim Formation which consists of grey and black micaceous siltstones and mudstones and is characterised by rapid slaking on excavation, is prevalent over much of the highlands. This formation is prone to widespread instability particularly affecting the highlands in Simbu (Chimbu) Province and the highways and structures at the Porgera Gold Mine in Enga Province. For the most part, the Chim Formation is affected only by creep, the slow but progressive downhill slumping of the near-surface weathered mantle, but strain-softening effects, compounded by high rainfall, commonly accelerate the downslope movement into mudslides. Throughout Papua New Guinea mudslides are widespread and are perhaps the most prolific of landslide mechanisms. The movement is often rapid once the mudslide has started.

Mudslides tend to be lobate in form and usually confined to shallow valleys between adjacent spurs. They are an extremely destructive landslide mechanism with a high potential to cause fatalities. They often propagate through cultivated areas, burying adjacent houses. Fatalities usually occur when the mudslide is at night and the houses are occupied. Nine people were killed by a single mudslide triggered by heavy rainfall falling on a cultivated area in Southern Highlands Province in late 1994. The ground was underlain by the Chim Mudstone Formation (Tutton, 1995).

The Chim Mudstone Formation is overlain in some parts of the country by competent limestone, and significant rock slumps resulting in the dislocation of large limestone blocks are not unusual. Relict slides of this nature can be seen in the Southern Highlands and in Simbu Province.

Many forms of landsliding in Papua New Guinea involve the rapid to extremely rapid displacement of material, these terms being used according to the scale of movement proposed by Varnes (1978). Diagrams illustrating soil creep, mudslides, rockslumps and debris/rock avalanches are illustrated in Figure 2.6.

Rock slides (rapid) and rock and debris avalanches (very rapid to extremely rapid) are relatively common (Figure 2.6). Rock slides are the result of a mass of rock sliding on a bedding plane, fault plane or other major discontinuities, and are commonly triggered by high pore water pressures, the result of heavy rainfall. Rock slides, due to their dependence on a single or perhaps a pair of discontinuities to form a release surface, tend to be a single and localised mechanism of limited geographical extent.

Rock and debris avalanches are, however, far more prolific and tend to occur together over a wider area, usually as a result of an earthquake. The 1993 earthquakes in Morobe Province resulted in both rock and debris avalanches. Only debris avalanches that were greater than 100 m x 200 m or 2 hectares (i.e. measuring 1 mm x 2 mm or larger on a 1:100 000 scale satellite image) were included in the landslide inventory. When the smaller, although still significant, landslides were excluded there remained some 680 landslides (debris avalanches)

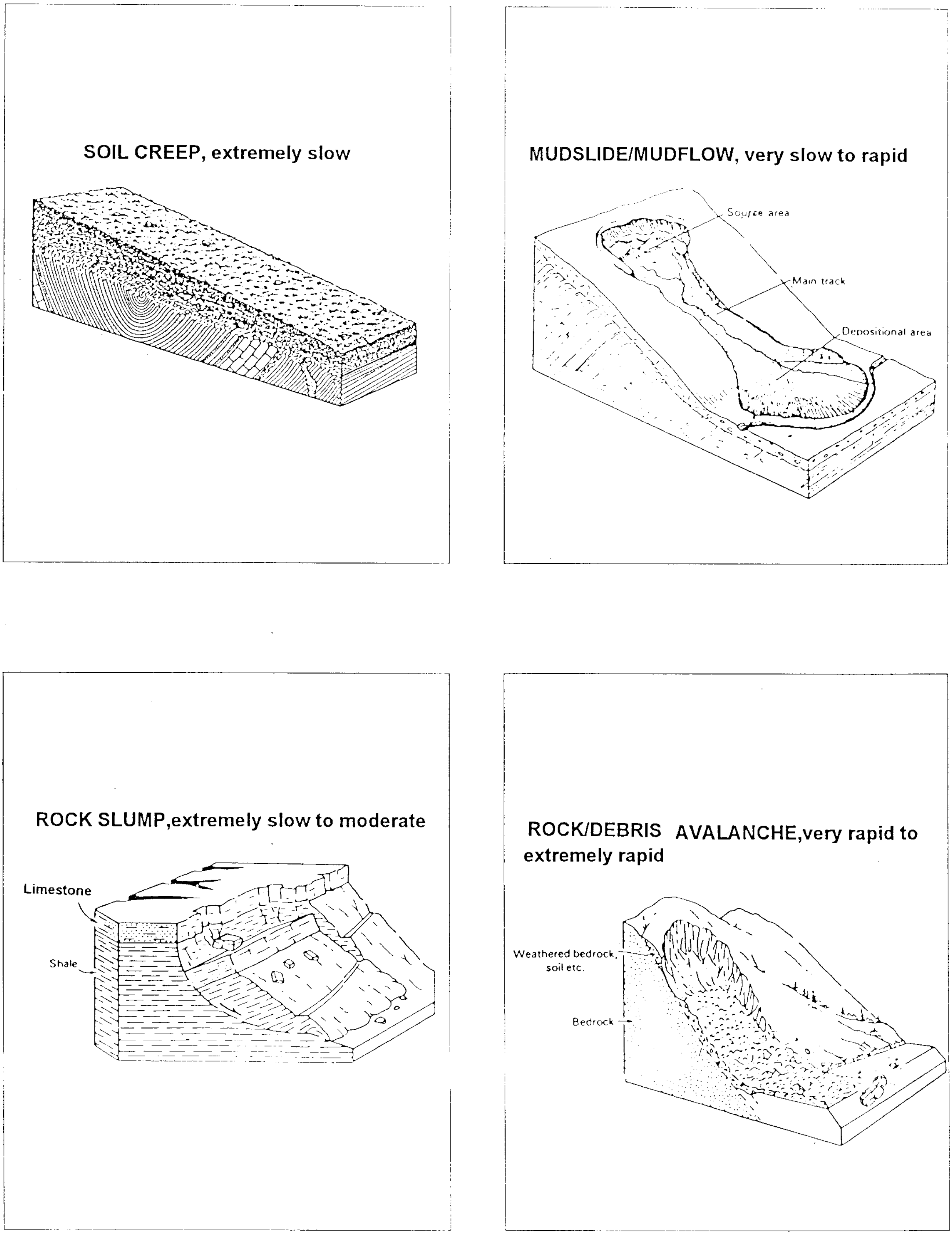


Figure 2.6 Landslide mechanisms common in Papua New Guinea (modified from Varnes (1978))

resulting from that series of earthquakes in the inventory. Some of the larger debris avalanches had areas in excess of 2 km^2.

In general, debris avalanches occur on very steep slopes, where tectonic uplift is perhaps so rapid that the only hillslope process that can match the uplift is landsliding. Debris avalanches happen rapidly giving very little warning for people living in their vicinity and as a consequence result in significant fatalities. Debris avalanches tend to be relatively shallow, removing the vegetation and regolith, but generally not affecting the underlying unweathered bedrock. They can have velocities greater than 3 m s^{-1}. On a very steep slope, this velocity may be sufficient for gravel and cobbles to escape from the landslide and fall freely, a phenomenon known as *fly rock*. Several deaths occurred during the 1993 earthquakes through fly rock and many more people received head injuries.

Occasionally if the *in situ* rock mass is highly fractured, and the joints and discontinuities are either uncemented or weakly cemented the avalanche may be deeper seated and can then mobilise a large volume of rock. If rock is the principal material that is mobilised, this form of landslide would be termed, a *rock avalanche*. The best example of a rock avalanche is the 1988 Kaiapit landslide, where 1.8 km^3 of rock was mobilised.

2.4 The need for hazard risk maps

Landslides and landslide prone terrain presents a very significant physical and financial hindrance to development in Papua New Guinea. This is particularly the case when considering *corridor infrastructure* such as highways, pipelines and electricity transmission lines which have to cross mountain ranges.

If the risks to the infrastructure through landsliding and related hazards are not properly addressed at feasibility stages, then much public money may be lost. This loss is not only related to high initial capital costs, but also due to excessive maintenance costs, together with the disruption to essential services and loss of trade when landslides sever highways or powerlines. In extreme cases a major landslide could result in the abandonment of a scheme, for example the Ok Tedi mine tailings dam (McMahon and Read, 1989) or the subsequent re-routing of highways etc.

It can be argued that if a road survives its design life the scheme has been successful. However, the design life strictly relates to the construction and fabric of the highway itself, but the corridor it follows must survive for far longer to allow successive maintenance, upgrading and widening to take place as the country develops. The careful choice of locating infrastructure in the first place is, therefore, of paramount importance for the long term development of the country.

Maps showing landslide hazards and associated risks can play an important role in ensuring that the information is available to the planners and engineers involved in the planning and design of major infrastructure schemes, to enable them to locate or route a scheme away from the greatest landslide risk area. Landslide Damage maps again also play an educational role in informing planners and engineers, who may be overseas consultants with little experience of conditions in Papua New Guinea, of the density, size and distribution of landsliding and related damage within an area.

The GSPNG often investigate the causes of landslides, particularly where they effect infrastructure such as mini hydro-electric schemes, road and electricity transmission lines. Very often schemes have been incorrectly sited, perhaps on a relict landslide, or the design of a scheme has failed to take account of the possibility of a landslide occurring. The geotechnical conditions in Papua New Guinea are challenging and some failures perhaps can never be avoided, but it appears that certainly for some schemes there has been a general ignorance to the presence of relict landslides and the possibility that landsliding might occur. At least by providing landslide hazard and risk maps, engineers can be informed of the possibility and risks of landsliding.

Several major schemes are in preparation and would benefit from landslide hazard maps. There is a proposal to build a highway between Port Moresby and Lae, across the Owen Stanley Range. A major pipeline scheme to carry natural gas from the Hides gas field in Southern Highlands over the rugged ranges of Enga Province and on to a port facility on the north coast has also been mooted.

A further role for landslide hazard maps is to bring to the attention of the authorities *landslide vulnerable* communities. For a nation of only 4 million people, an estimated landslide related death toll of 100 *per annum* is significant, and for many more, their livelihood is severely affected when food gardens and houses are buried beneath debris. Whilst little can be done before an event, disaster plans can be drawn up to mitigate the affects of major landsliding.

In the past, landslide risks have been assessed by carrying out local engineering geological mapping on the ground, assisted by aerial photograph interpretation. The technique is basically looking at the risks, within an area, once the location or route has been decided upon, and is not a sufficiently global technique to identify major zones of high, medium or low landslide hazard.

The need for a regional (say $<$1:100 000 scale) and rapid (say a mapping speed of 1 km^2/man hour) is therefore realised. Whilst a mapping rate of 1 km^2/man hour may seem to be extremely rapid, with an estimated 170 000 km^2 of land affected by significant landsliding, approximately 100 man years are needed before the mountainous landslide prone parts of the country will have been mapped. There are only three engineering geologists in the GSPNG, who also perform many duties other than landslide hazard mapping. Therefore, to complete the mapping of the landslide prone parts of the country within 20 years, with perhaps only 1 person dedicated to full time mapping, a rate of 5 km^2/man hour will be needed.

To achieve this, it is apparent that a remote sensing approach is needed. It is physically impossible to investigate and map at this rate using conventional geotechnical investigation techniques, particularly as much of the terrain is rugged and remote and can only be mapped by extensive use of helicopters and foot patrols. Whilst conventional hand drawn cartographic techniques can be used, a Geographical Information System (GIS) lends itself to *seamless* map making, and allows maps to be updated easily as information comes available. It also allows for importation and processing of spatial data directly from existing digital databases as well as the analysis and manipulation of the data to establish the probability of landsliding and assign a hazard risk rating. The use of GISs for rapid mapping of landslide hazard is discussed in Chapter 4.

2.5 Kaiapit study area

The 1:100 000 Kaiapit map sheet area was chosen as the study area for this project for the following reasons. It is a relatively easy area to get to as the Highlands Highway cuts the map sheet diagonally in half and it is only 2 hours drive from Lae, the country's second city. The furthest part of the study area can be reached in less than 45 minutes by helicopter from Lae. Within this area a very major landslide occurred in 1988, killing 74 people and subsequent surveys indicated a potential for significant future landsliding. The geology of the study area was also being re-mapped by the regional geology group of the GSPNG.

Other historical events including, landslides that killed 9 villagers in 1975 (Peters, 1975) and a major earthquake/landsliding in 1922 (Ripper and Letz, 1991) were sufficient to suggest that this area was landslide prone and suitable for this pilot study.

The study area was selected in March 1993, but in October 1993 a series of major earthquakes occurred beneath the Finisterre Range resulting in devastating landsliding across much of the study area and affecting the range beyond, both to the north and west. Following this pahse of landsliding, it was decided to enlarge the study area to incorporate much of the devastated area. The study area was enlarged to incorporate just over half of the map sheet to the north and is bounded by the parallels of 5°46'S, 6°30'S, 146°E and 146°30'E. Unfortunately the constraints of both time and budget prevented the incorporation of the whole of the 1993 earthquake affected area into the study area. A further reason for selecting the study area was to identify the impact of secondary related landslide damage that results in flooding either when landslide dams impounding river water breach, or when landslide debris choked river channels are unable to cope with an extreme rainfall event. The Kaiapit landslide mobilised 1.8 km^3, and the 1993 landslide 1 km^3 of debris. Much of this landslide debris, since 1988 has entered the river systems significantly changing their morphology and greatly increasing the likelihood of flooding. To give some impression of this volume of debris, for example in relation to volcanic hazards, the magmatic products of the 1980 Mt. St. Helens volcanic eruptions amounted to 0.2 km^3 whereas the expansion of the magma body triggered rockslide totalling 2.8 km^3 (Swanson, 1982).

3. REMOTE SENSING

3.1 Rationale of remote sensing approach

The combination of seismicity, high rainfall, tectonic uplift, and steep slopes with weakly indurated, low-strength rocks make parts of the PNG highlands some of the most unstable areas of the world in terms of earth/rock mass movements. Although thinly populated, many small communities are scattered throughout the interior of New Guinea island, and significant mining, agriculture and transport development is taking place. There is a clear need to provide regional scale hazard zonation and risk maps for much of the country, both for planning new developments, construction and infrastructure, and for establishing preparedness and mitigation procedures for vulnerable areas and populations.

An estimated land area of 170 000 km^2 is potentially affected by significant landsliding in PNG. Much of the region is extremely rugged and without roads, and access in such terrain is either on foot or by helicopter. Geotechnical investigations by the Geological Survey of Papua New Guinea (GSPNG) are in progress and are providing essential baseline information on the nature of the ground and on conditions that produce landsliding. Such field survey work is necessarily slow and expensive, and so cannot be regarded as an approach that, by itself, is capable of covering the large areas at risk in any realizable time frame. It is therefore important that a means is found to provide small-scale, regional maps quickly and at low-cost. Such provisional maps will serve to identify the areas most susceptible to landslide events and perhaps also show the main risks to life and property. The use of remote sensing, combined with other existing data, is a practical approach, potentially capable of satisfying these coverage requirements. The need, therefore, is to determine how such data may be used, and to develop an operational methodology.

Given the large area at risk and the potential consequences for infrastructure and population, the requirement is for regional hazard maps at a scale of around 1:250 000. This information can best be derived from either small-scale aerial photographs or satellite imagery. The first job is to determine what data are available. In the present study, comparisons were made of 1:48 000 photographs, Landsat Thematic Mapper (TM) imagery, and SPOT panchromatic (Pan) imagery. Although high-quality, geometrically-rectified airborne imaging radar (Intera SAR) exists for much of PNG, none was acquired over the test area. However, its use should be considered when extending the work to other parts of the country. The all-weather capability of SAR would overcome a major problem that affects all optical remote sensing techniques in the tropics - persistent cloud cover. However, radar does suffer serious problems of shadow in mountainous terrain caused by the low illumination angle, so that its overall use for this application remains uncertain.

3.2 Comparison of data types

Aerial photographs have the advantage of stereoscopic viewing which assists the interpretation of terrain features. Disadvantages at the regional scale include the large numbers 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. In this study, they were found to be useful mainly as a control for understanding the satellite interpretation.

A SPOT Pan image (path 365, row 362) was available for part of the area, although the scene contained significant cloud. A potential advantage of SPOT imagery is stereoscopic coverage; however, to obtain stereo coverage it is necessary for an area to be imaged from two different orbits on different dates. Given the difficulty in this environment of obtaining cloud-free data for even one date, the likelihood of stereo image acquisition is low. To obtain such imagery would probably involve placing an acquisition programme request with SPOT IMAGE in advance. This might be feasible if SPOT data were chosen as the data source for a major, long-term national hazard mapping programme. Other than stereo cover, an advantage of the SPOT system is the relatively high spatial resolution: 10 metres for Pan data and 20 metres for multispectral XS data. The Pan data can provide enlargements at scales of 1:20 000 or larger; however, this was not considered important in the PNG case where the adopted scale was 1:100 000.

Landsat TM is multispectral imagery with 3 spectral bands in the visible (V), 3 bands in the near/middle infrared (IR) and one band in the thermal infrared part of the electromagnetic spectrum. Stereo coverage is not available at the latitude of PNG. The six reflective VIR bands have a spatial resolution of 30 metres which allows colour-composite hard-copy images to be produced at scales up to 1:50 000. Compared with SPOT imagery, TM scenes cover much larger areas (9 times the ground area) and cost much less on an area-for-area basis. The problems of cloud cover remain but the use of three reflected IR spectral bands (rather than the visible bands) provides high-quality imagery in which atmospheric haze is significantly reduced.

PNG TM data is obtainable from the Australian Centre for Remote Sensing (ACRES) in Canberra, Australia. This national remote sensing agency offers an excellent customer service which in the present study included the loan of high-quality colour 'quick-look' images (on a microfiche arranged geographically across New Guinea island) from which the most appropriate data could be selected. ACRES also offers individual TM bands for sale on a *pro rata* basis; therefore, once a suitable 3-band combination is decided and standardised, the cost of data acquisition becomes far less. In the present study, three dates of imagery were used: 9 May 1991, 9 January 1994 and 20 July 1994. The use of multi-date imagery allowed the effects of different landslide events to be assessed (i.e. the 1988 events, the October 1993 earthquake and the subsequent seasonal rains) and a comparison of the interpretability of different seasons of imagery in relation to solar shadowing.

3.3 Satellite image processing

The initial scenes processed were the SPOT Pan image acquired 23 June 1991 and the Landsat TM image for 9 May 1991. Subsequently, following the October 1993 Finisterre earthquake and resulting landsliding, additional dates of TM imagery were purchased, processed and interpreted for comparison. Digital image processing was carried out at the British Geological Survey, Keyworth initially on an I²S System 600/Model 75 image analysis (IA) system and later on an Intergraph ImageStation workstation.

The first stage of digital image processing involved examining the raw data to assess appropriate band combinations (except in case of SPOT Pan which has only a single band). Past experience has shown that for geological studies across a range of climatic environments a combination of TM bands 4 (near IR), 5 and 7 (both shortwave IR) is satisfactory (referred to as a 457 false-colour composite, or FCC). This combination was selected for the PNG data.

The imagery was registered to the Australian UTM map grid, Zone 55, using ground control point information from the PNG 1:100 000 topographic survey series mapped by the Royal Australian Survey Corps and published by the PNG National Mapping Bureau. This process began by selecting a series of points chosen because they were readily identifiable on both the image and map. Once collected, the image processing software was used to establish least squares polynomial equations to relate the image and map co-ordinates of the control points. These equations were then used to transform the entire image to the map projection. The process primarily involved a rotation of the scene with respect to grid north, and an internal resampling to adjust for internal distortions within the scene. During this process, the image was resampled onto a new grid orthogonal to the map grid. The resampled pixel size used in this case was 25 m.

The main stages of image enhancement are 'edge enhancement' and 'contrast stretching'. *Edge enhancement* emphasizes high spatial frequency, local contrast differences whilst retaining the broad, low frequency brightness information. In other words, it enhances details within the image. This attempts to correct for image blurring caused by the electronic sampling by the sensor, which averages the intensity across each ground pixel, and by the optical systems. Edge enhancement is achieved by spatial filtering (or 'convolution') using a box filter designed, in this case, to increase the brightness difference between each pixel and its immediate neighbours. In this way 'edges' within the image (abrupt changes in brightness, such as lines or boundaries) are emphasized and the overall image appears sharper. Edge enhancement is especially important for structural (e.g. lineament) interpretation or where large-scale photographic enlargements are to be generated.

Contrast stretching involves redistributing the raw data brightness values for each band across the full dynamic range of the display system. For 8-bit (byte) image data, this corresponds to a range of 256 grey tones. In this way, images which originally occupy only a small portion of the possible brightness range, and therefore appear dark and lacking in contrast, are enhanced to exaggerate small differences inherent in the data. In the case of 3-band Landsat TM FCCs, it is often necessary to stretch each of the bands independently, balancing the colour tones visually to achieve the maximum discrimination between surface materials. The most useful contrast stretches are linear expansions of the data, but different portions of the data may be expanded by different amounts to obtain the optimum overall enhancement. The process, whilst a quantitative operation, relies very much on the qualitative judgement and experience of the operator who decides when an image has the right contrast and colour balance for the final hard copy output. In the case of landslides, it is important to try to develop a stretch that provides maximum discrimination of bare rock and soil areas, possibly at the expense of other surface categories.

For detailed interpretation of images it is essential to generate high-quality hard copy. The best medium for this is photographic, the image data having been transcribed digitally onto a large format negative using a laser film writer. Accurately scaled image maps for all or part of the area can then be made by photographic enlargement.

3.4 Interpretation of remote sensing data & data capture

3.4.1 Satellite imagery & aerial photographs

Satellite imagery and aerial photography can provide information on old and recent landslides, geological faults/fractures ('lineaments'), bedding and other lithological structures, recent erosional/depositional processes, habitation (including cultivation), infrastructure and roads. Each form of remote sensing data has its advantages and disadvantages; these were compared in the present study.

Comparison of the SPOT Pan and Landsat TM indicated that the latter images were more informative, mainly due to the spectral information content of Landsat (i.e. colour). Surprisingly, the higher spatial resolution of the SPOT Pan image did not appear to provide additional information; consequently, little use was made of this imagery. Initial processing and interpretation was carried out on the 9 May 1991 image. Subsequently, images dated 9 January 1994 and 20 July 1994 were obtained and processed. Winter images, such as the July 1994 image, tend to have very dense shadow which obscures certain details, although such images often better emphasise the major landscape features of the terrain. Both the January and May images showed moderate shadow and proved useful for general interpretative purposes.

In general, the interpretation of satellite imagery follows a standard route regardless of data type. Either of two basic approaches may be taken: the interpreted information can be annotated either onto a transparent overlay attached to the photographic print, or it can be directly digitised on the computer screen using the IA system or GIS. Advantages of the former are that the interpreter at all times sees the full image so that, for example, large-scale structures can be more easily recognized; it also allows the image to be viewed in all orientations. However, the interpreted linework must then be digitised as a separate stage of work. The alternative of interactive on-screen interpretation is possible only if a suitable IA system with vector graphics is available. The principal advantage of this is that the data are captured directly in digital form. In the present study, both methods were used at various times, as appropriate.

Aerial photographs are usually interpreted stereoscopically. Several types of stereoscope are available, but the most useful for systematic desk-based work is a mirror stereoscope. This allows the observer to view the complete 'stereo model' (the area of overlap between adjacent photographs) at low magnification, and provides an appropriate working arrangement for the manual plotting of interpreted features onto a translucent overlay attached to one of the photographs. Binocular attachments allow portions of the stereo image to be viewed at higher magnification, as required. Problems arise due to relief-related distortions and from the difficulty of accurately transferring interpreted information to a base-map.

In the PNG study, a dual-view stereoscope was used in the training of geologists from the GSPNG. This instrument allows two geologists to view the stereo model at the same time and discuss the terrain features being observed. In the case of training, it enables the instructor to demonstrate interactively how and why features are interpreted. More generally, it permits geologists working together on the same project to discuss approaches towards obtaining consistency in what is an essentially subjective process.

Usually, alternate photographs in a run are used for marking the interpretation (using the stereo overlap on either side of the central photograph). However, because relief distortions are greatest towards the photo margins, a more accurate method is to use only the central portion of *every* photograph. Even then, the subsequent transfer of interpreted information to a base map can prove difficult in areas where the relief is significant. In the PNG case, the interpretation was in part used as a reference to identify the same features on the Landsat image, which were then re-interpreted manually. Other approaches to photogeological transfer are possible, including the raster scanning of the interpretation followed by digital warping, but this is a time consuming operation and was not considered justified in the present case. Given the scale of operation in PNG and the large size of many slides, it was concluded that the use of satellite imagery at scales of between 1:50 000 and 1:100 000 is the more appropriate remote sensing technique for this region. The use of aerial photographs should be restricted to examination of particular slides or for validating/understanding the information provided by the low resolution imagery.

3.4.2 Recent landslides

Recent landslides, where of significant size, can be directly observed on 1:100 000 Landsat imagery. In the 457 FCC used, they appear as areas of dark blue (rock) and paler blue (mixed soil/rock/vegetation debris), and have forms and occur in locations characteristic of landslides. Where shadow is not too intense, recent landslides can be easily recognized and mapped over large areas. Some errors almost certainly result due to topographic shadowing, cloud and cloud shadow. There is also a problem of confusion between recent landslide scars and cultivation (gardens). These can sometimes be separated on the basis of form, general appearance and location, but there remains a possibility of mis-identification. Since the stripping of vegetation for gardens is itself a cause of landsliding, it is important to take account of areas containing gardens. Overall, it is likely that the recent landslide category includes some areas that are gardens and omits others as a result of cloud/shadow. Similarly, some slides may have been interpreted as gardens and therefore omitted. The alpine grasslands covering some of the mountain tops also look very similar and some slides in these locations may have also been omitted for this reason. However, the technique probably correctly identifies the great majority of slides.

An attempt was made to carry out an automatic classification of landslides using image processing techniques. Determining a signature for landslides is, however, difficult since the statistics are confused by shadowing. Because the classification techniques use only spectral information and do not take account of shape, texture or form, which the human interpreter can, they are not able to uniquely discriminate landslides in any reliable fashion. However, this is a subject that requires further work and is worth pursuing.

Recent landslides were interpreted/digitised separately for each of the three dates of TM imagery. Figure 3.1 is part of the Landsat image for May 1991 and shows the 1988 Kaiapit landslide together with a few other scars of recent origin. Figure 3.2 shows the same area as viewed in January 1994; landslide damage resulting from the October 1993 Finisterre earthquake can be seen, especially in the north west part of the area. Figure 3.3 shows a larger view in January 1994 from which the regional extent of landsliding can be seen.

3.4.3 Older landslides

Inspection of satellite images and aerial photographs of the Kaiapit area indicated that landforms produced as a result of landsliding are widespread. It is evident that landsliding has been an active process throughout the recent geological past; indeed, it is almost certainly the dominant mechanism of erosion in this highlands area. Terrain features formed by landsliding are typically sharp-ridged mountains, forming crescentic or bowl-shaped catchments, often several square kilometres in size. They represent the product of repeated landsliding events, both small and large, over a long period of time. Many of these older landscape features show evidence of repeated activity, and it is often apparent from fresh scars that scarps resulting from past events continue to be unstable and prone to further mass movements. Tectonic evidence suggests that the region is presently undergoing uplift at a rate of 4.3 to 6.8 mm yr^{-1}, perhaps associated with subduction of the Indo-Australian Plate beneath the South Bismarck Plate (Crook, 1989; Ripper and Letz, 1991). This, together with the low strength of many of the rocks, results in continued rock mass instability over very long periods and thus repeated landslides.

The size and frequency of landslide-landscape features in this area makes them especially suited to identification on TM imagery. The original TM interpretation was carried out using the May 1991 TM image. Towards the end of the project when the July 1994 image was acquired and processed, it became noted that terrain features were easier to map on this image, although the seemingly more dense shadow did obscure certain other features of interest including some smaller landslides.

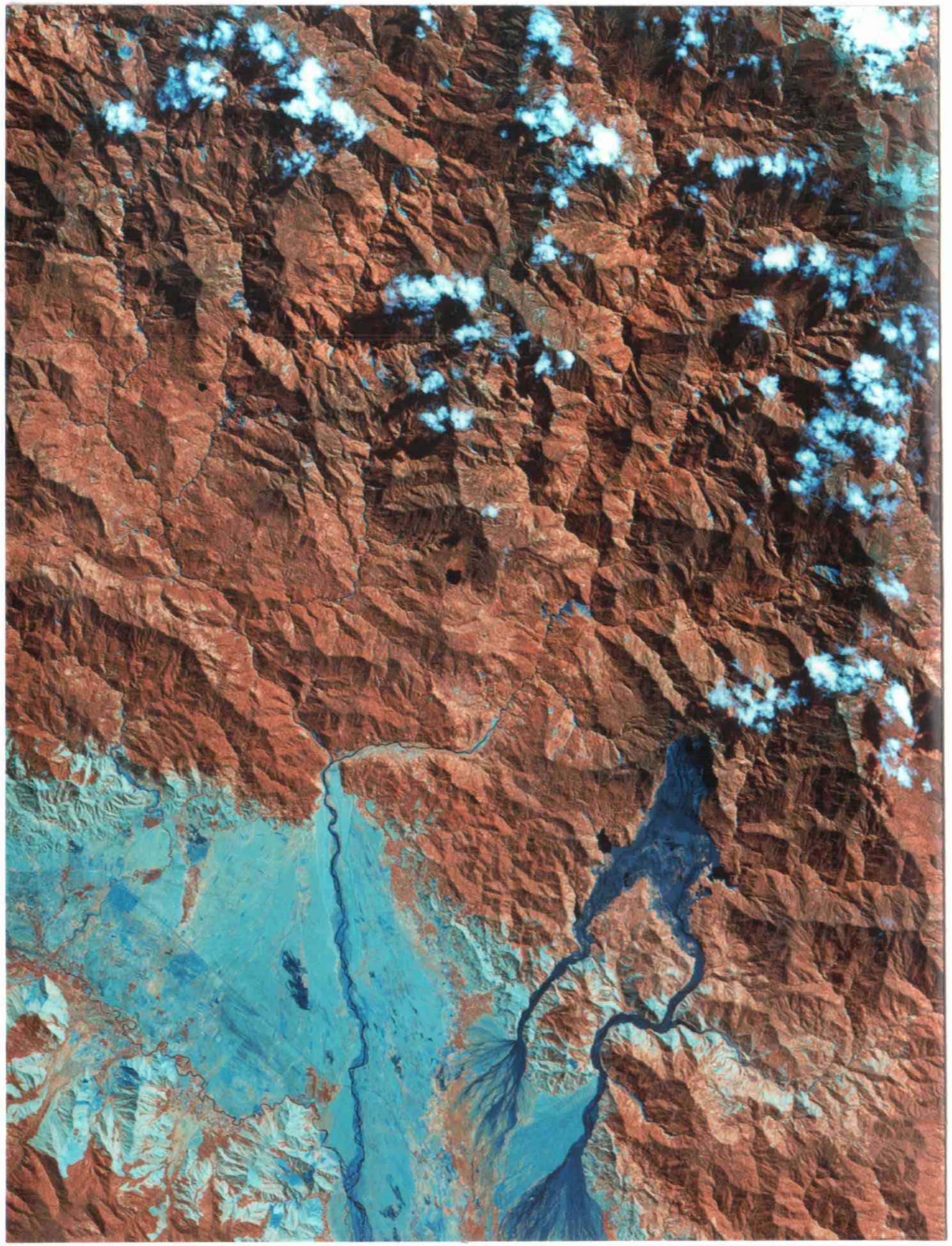


Figure 3.1 Landsat Thematic Mapper image of 9 May 1991; bands 457 false-colour composite.

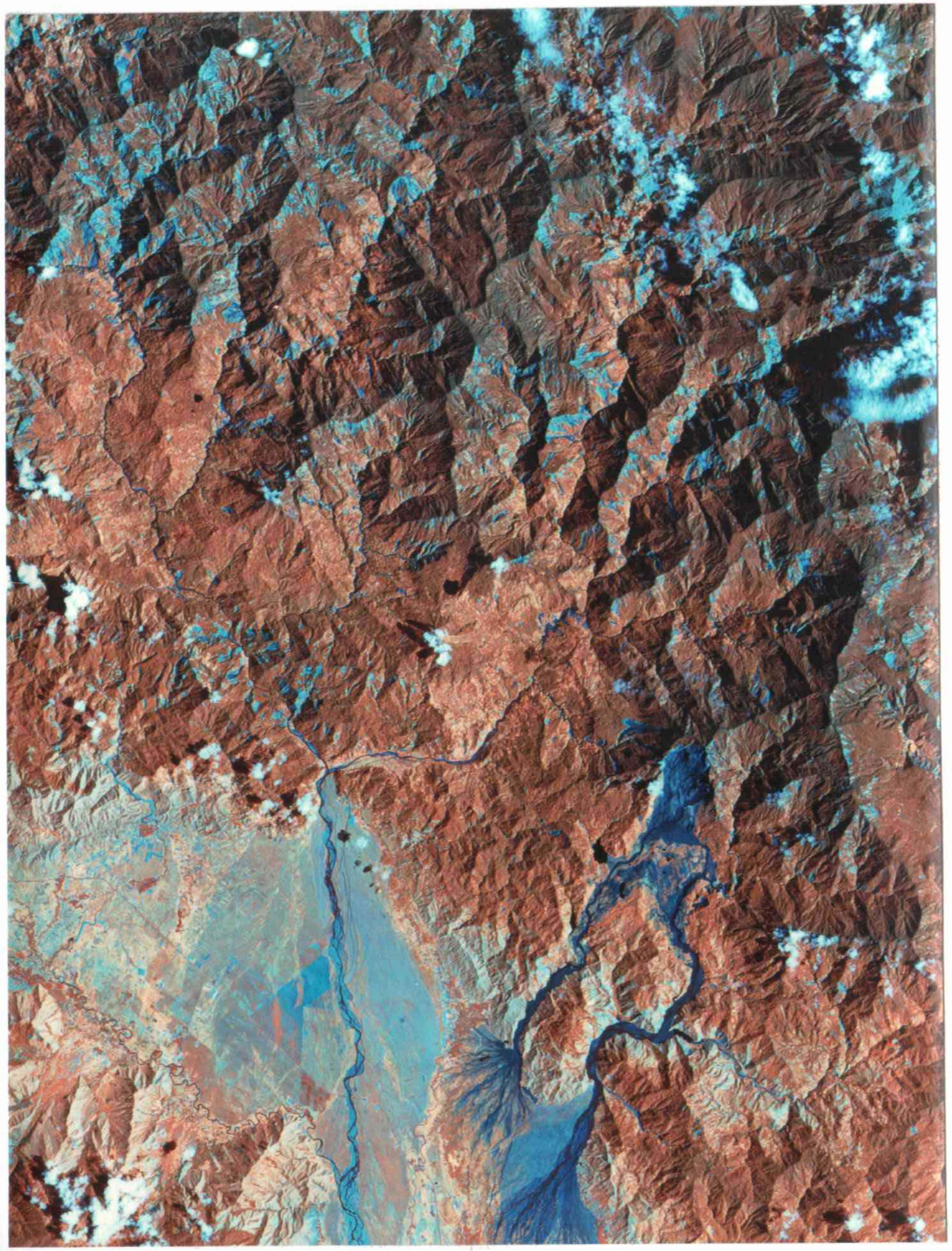


Figure 3.2 Landsat Thematic Mapper image of 9 January 1994; bands 457 false-colour composite.

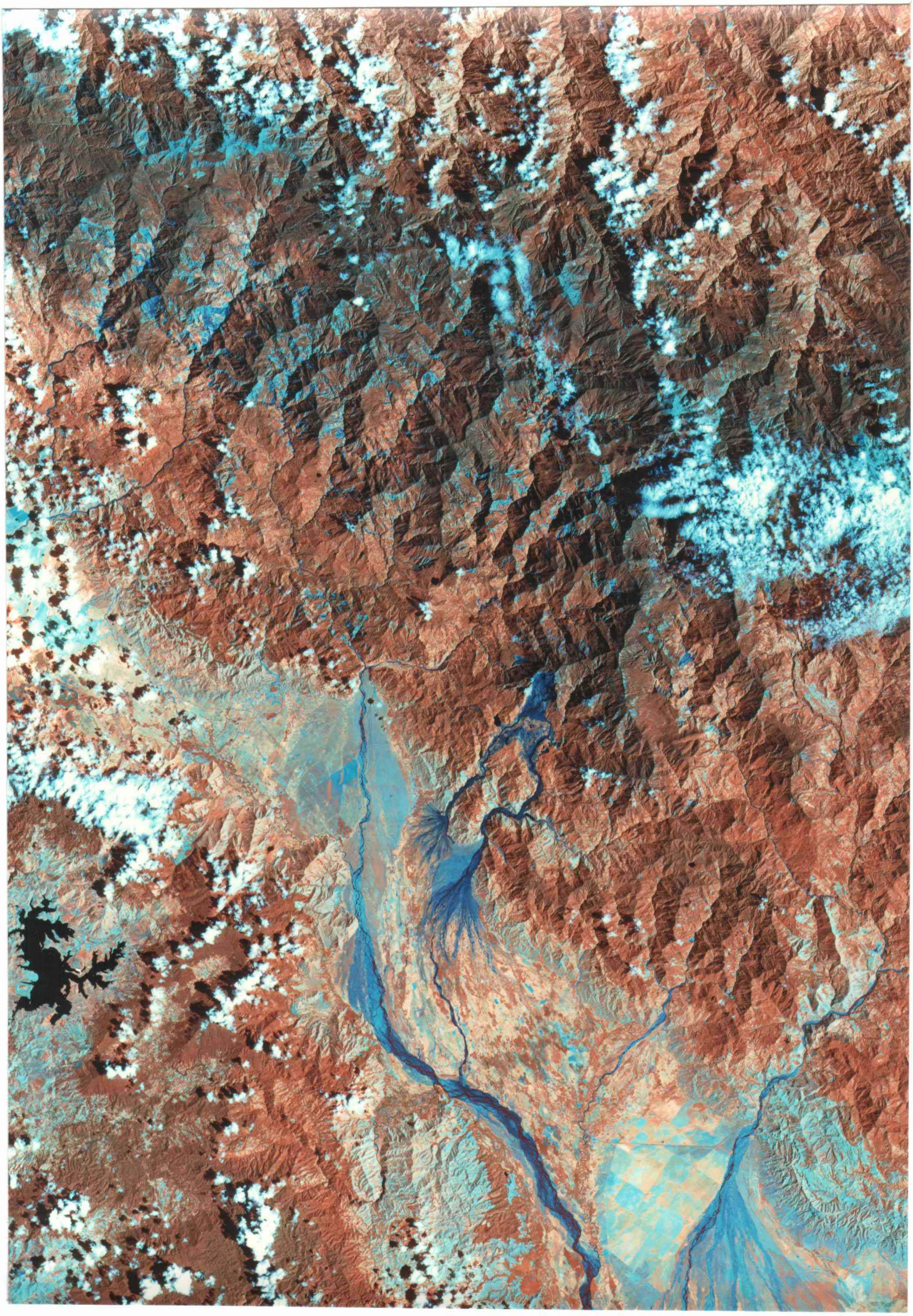


Figure 3.3 Landsat Thematic Mapper image of 9 January 1994; bands 457 false-colour composite.

Aerial photographs, viewed in stereo, are also well suited to interpreting terrain features. Unlike satellite images, the perception of relief is not dependent on shadowing and the landforms can often be interpreted with greater reliability. The drawbacks of using aerial photographs have been discussed above. Nevertheless, they are useful for establishing an initial understanding of what is contained in the TM imagery, and in this way they act as a form of 'verification' of the lower resolution satellite data.

3.4.4 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 (Hobbs, 1904; 1912; O'Leary *et al.*, 1976; Waters *et al.*, 1990). Lineaments are particularly well-expressed on satellite images due to the oblique constant illumination, the suppression of spatial detail and the synoptic coverage. They may correspond to various geological features such as fractures (faults and joints), bedding, dykes/veins and lithological boundaries, as well as to spurious, man-made features (roads, boundaries etc). The large lineaments seen on satellite imagery are often negative relief features (valleys) and are generally interpreted to be fractures or fracture zones. Fracture-related lineaments may be of significance in controlling the location or form of landslides. This is not proved but the indications from the Kaiapit landslide are that this was in part at least structurally controlled. The establishment of a relationship between landsliding and lineaments can be explored using the GIS; this is considered in Section 5.2.

Lineaments have been interpreted from both the aerial photography and the TM imagery. In relation to the scale of the study and extent of landsliding, TM is better suited for this. However, it should be appreciated that any individual satellite scene represents a 'biased' view of the ground. This is because sun azimuth (illumination direction) affects the appearance and prominence of lineaments of different orientations. Lineaments that trend normal to the illumination direction tend to be emphasized whereas those parallel to it are relatively suppressed. It was found in the present study that, although in general the same lineaments could be seen on the summer and winter images, differences in interpretation could easily result. It has also to be said that the interpretation of lineaments, as with any interpretation, is highly subjective and will vary from person to person. Therefore, less reliance should be placed on individual, unsubstantiated linear features than on lineament patterns and associations with landslides apparent across an area as a whole.

Figure 3.4A shows the May 1991 Landsat TM image for the full study area. Figure 3.4B is the same image overlain with the final digitised interpretation; this shows separately older landslides, two generations of young landslides and lineaments.

A

B

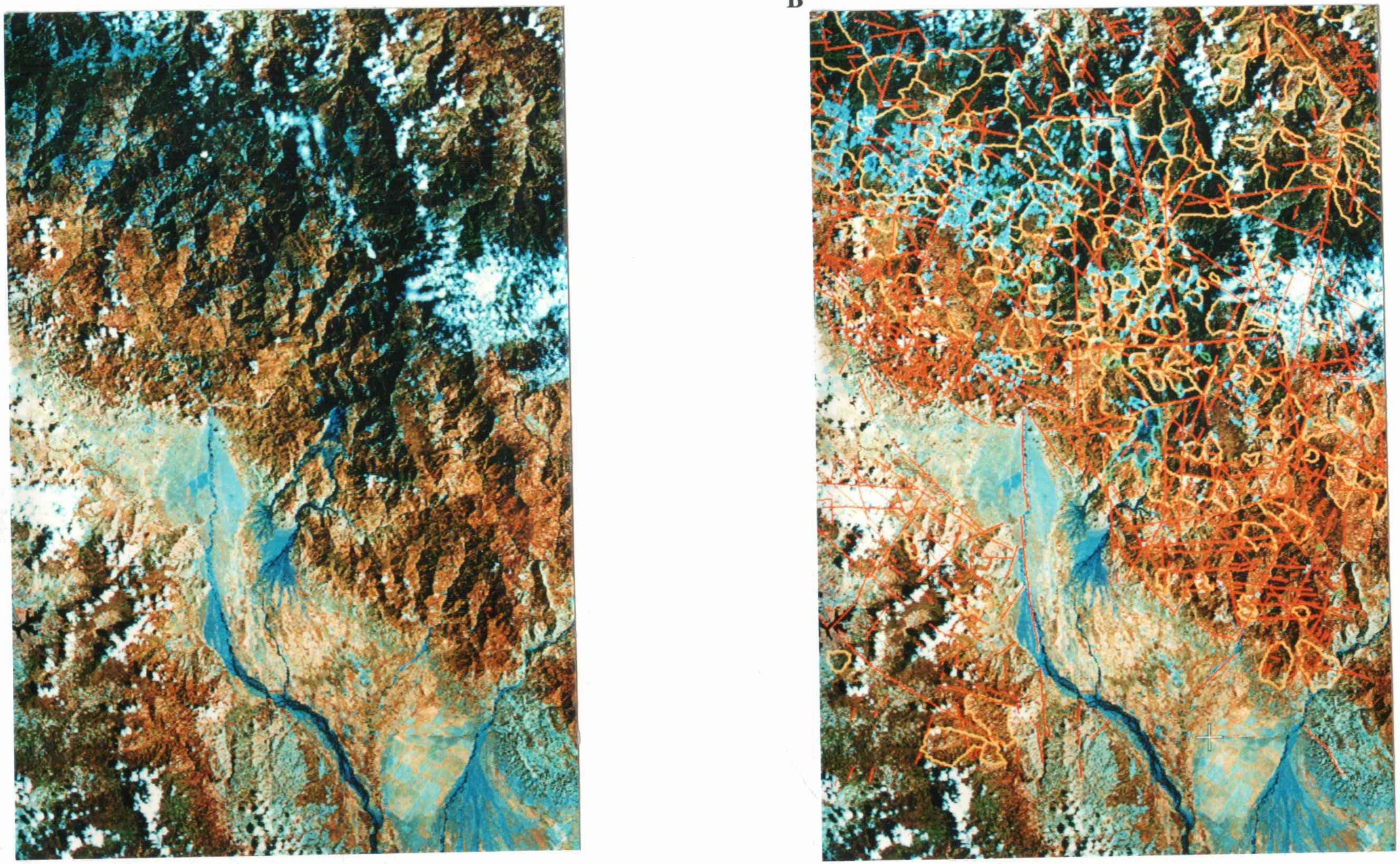


Figure 3.4 Landsat Thematic Mapper image of 9 May 1991:
A Bands 457 false-colour composite.
B With overlay of digitisied interpretation showing two generations of young landslides and lineaments.

4. GEOGRAPHICAL INFORMATION SYSTEMS PHILOSOPHY & DATABASES

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 co-ordinates and manage changes of projection, 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).

Conceptually, a GIS should be able to utilise spatial data in any form, whether raster, vector or tabular. 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 differences between GISs are discussed further in Section 4.2. The benefits of both architectures are being increasingly recognised and systems are now available in which analysis and display can take place 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, field structural and geotechnical data, laboratory test results, and so forth depending on what data exist or can be obtained. In many respects, the task 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 would suggest that more than 90 per cent of the GIS effort is concerned with digitising or other forms of data capture, and co-registering data sets from diverse sources, referenced using 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. The advantage of a GIS is that maps/plots can be created as required, designed to answer the particular user needs, using the latest available information held in the database. This is particularly important where the user is a non-geologist looking for 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 in relation to landsliding to be assessed. 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 to identify correspondences. The advantage of the GIS is that data sets may be more easily manipulated, and quantitative measures of correlation determined.

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 various environmental applications. The choice of GIS will depend on a number of factors, the main ones being: size/extent of problem; design requirements of the database; analysis needs; output formats; financial constraints; and, importantly, what computer systems/GISs 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 final 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 final choice of system may also be influenced by GISs already existing in the organisation, or a need to share the eventual system with other users having different requirements.

Another important consideration concerns 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 overly sophisticated for the task at hand. For example, to produce simple hazard maps, the output does not need to 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 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

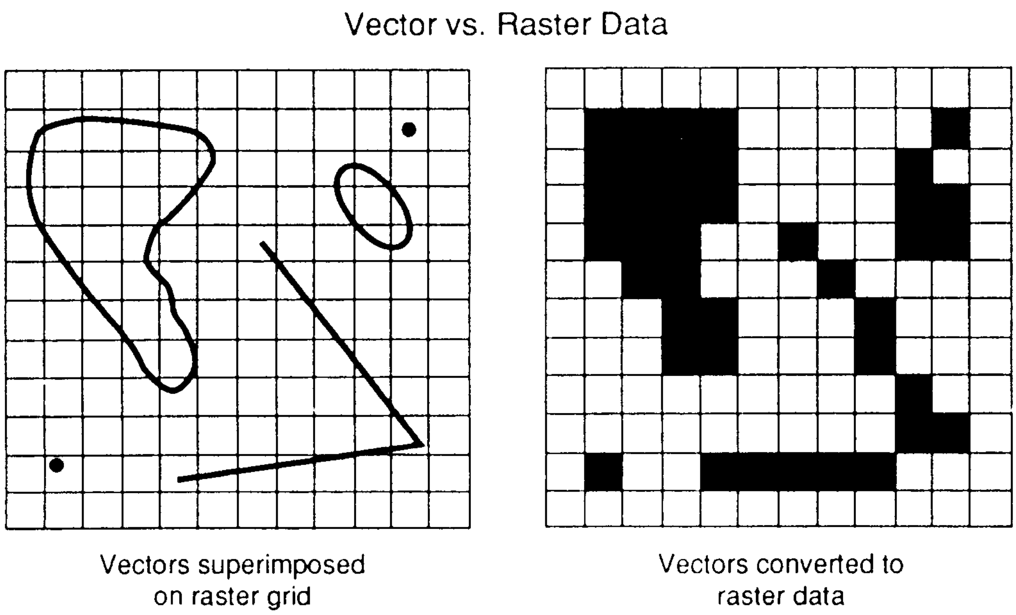


Figure 4.1 Concepts of vector and raster representations of points, lines and polygons.

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. With *raster* systems, the 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 vector since every pixel must have a value, even if it is a code to indicate the absence of information. They also produce less sophisticated map output. Their main advantage is they are better suited to analysing 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 commonly a compromise. In the present study various systems were used in developing a methodology. The choice was based on (1) immediate and long-term project requirements and (2) existing/potential hardware/software availability in the GSPNG and BGS. The following systems were employed:

- Intergraph Modular GIS Environment (BGS)
- ILWIS (BGS)
- IDRISI (BGS - potentially GSPNG subsequently)
- MapInfo (GSPNG)

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 digitised, the 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 creation of digital elevation models (DEMs).

The disadvantages of MGE are its complexity, cost and limited means of converting vector data to other proprietary vectors 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 the south west Pacific region.

ILWIS is capable of transferring data to and from many different systems, of digitising 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.

4.2.4 MapInfo

MapInfo (Version 3.0) is a relatively inexpensive PC based vector GIS. It runs under the Windows/DOS operating systems and requires a 386, or higher, processor.

Whilst not performing all the requirements needed from a GIS for digital geological mapping, MapInfo is the main GIS used by the GSPNG and has become the *de facto* standard for most of the Papua New Guinea government departments. This enables inter-departmental data sharing in MapInfo file format (MIF), although the software allows importation of other file formats.

Originally a pure vector-based system, MapInfo has now been updated to incorporate a raster backdrop facility and substantially extended software flexibility. The backdrop cannot be attributed but it does allow on-screen visual interpretation and digitising to be carried out. Similarly, imported data, such as a shaded relief map, can be used as a base map on which vector layers can be overlain (see landslide damage map appended to this report).

MapInfo has good presentation refinements but lacks the sophistications of other more expensive vector programs, particularly when it comes to creating multiple adjacent polygons and rotating geological symbols etc.

In summary, the vector program lacks the analytical capabilities of a raster or combined raster/vector GIS and the data capture facilities of some vector-based GIS software. However, the software is cheap, easy to learn, user-friendly, and has excellent presentation refinements.

4.3 Raster GIS analysis

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

Database query: This allows simple enquiries related to the stored information, such as ..*show all catchments larger than 5 km²*.. or combined queries such as .. *show all catchments greater than 5 km² underlain by 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* 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: This allows a *buffer zone* (or 'corridor') to be calculated around a point, line or polygon for techniques 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 that allow ideas about relationships to be formulated. Thus, by examining in turn the spatial occurrence of landslides within different lithologies, one can decide whether rock type is an important control on landslide occurrence. For example, the spatial association of landslide polygons with, say, volcanic breccia, may indicate that these rocks are prone to landslides, even though the reason is not known. This can be done between 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, in order for the landslide polygon distribution to be analysed it may be necessary to reduce this to landside density information. This could be done in a number of ways; one approach is to derive a value for the percentage of landslides in each catchment area. Catchments provide a convenient category of land area within which any landsliding tends to be contained.

4.4 PNG database

Mention has already been made of some of the information types assembled from the remote sensing data. These and other inputs are further described below.

Recent landslides: Recent landslides of at least two generations were interpreted from TM imagery. The May 1991 image provided a record of the 1988 Kaiapit slide and a few other slides that apparently occurred at around the same time. The regionally more important landslides occurred during the October 1993 Finisterre earthquake; these were interpreted manually from the January 1994 image and digitised. Figure 4.2 is a plot showing the two generations of landslide.

Older landslide-landscape features: These were separately interpreted from the aerial photographs and TM imagery. The photographs were initially interpreted for part of the area around the Kaiapit landslide. Subsequently, the TM data were used to carry out an interpretation for the whole of the project area using a combination of the May 1991, the January 1994 and the July 1994 imagery. Interpretation was carried out onto photographic hard copy for most of the area and subsequently digitised, although for parts of the area a digital interpretation was carried out directly on the BGS IA system. This data set derived from TM was the one finally used in the analysis. The older landslides are shown in Figure 4.3. The landslide map for the total landslide population (recent plus old) is shown in Figure 4.4. Initiation points for the total landslides are shown in Figure 4.5.

Lineaments: Three classes of lineaments, sub-divided according to length ($\geq$ 5 km; $<$ 5 $\geq$ 3 km; $<$ 3 km) were interpreted from the aerial photographs and digitised as separate layers. This information covered part of the study area only. A separate interpretation for the entire area was later made using a combination of the May 1991 and July 1994 TM imagery, and digitised as a further layer. A comparison of the aerial photograph and TM interpretations showed significant discrepancies. These may be due in part to inaccuracies inherent in transcribing photogeological interpretation to a corrected base map. They may also represent differences caused by the different scales of interpretation. Figure 4.6 is a plot of the TM-interpreted lineaments used in the raster GIS analysis. Figure 4.7 shows lineament buffers generated in 10 zones each of 100 m on either side of each lineament.

Geology: The geological boundaries were digitised from the 1:250 000 scale Markham and Madang published geological maps. These sheets are essentially reconnaissance maps and show considerable edge-match discrepancies. These differences were arbitrarily smoothed out prior to digitising. Although it is likely that lithological-structural differences affect/control landslides, the present maps probably do not contain sufficient lithostratigraphical information to allow a proper analysis. The digitised geology map is shown in Figure 4.8.

Topography: The published series of 1:100 000 scale maps of PNG provide contour information at 40 m intervals. This information was scanned from transparent separates, and converted to digital files from which a DEM was produced. The DEM was in turn used to generate slope class maps (in 5° ranges) and slope aspect maps

Figure 4.2 Recent landslides from Landsat TM interpretation; May 1991 (red), January 1994 (green), both dates (yellow).

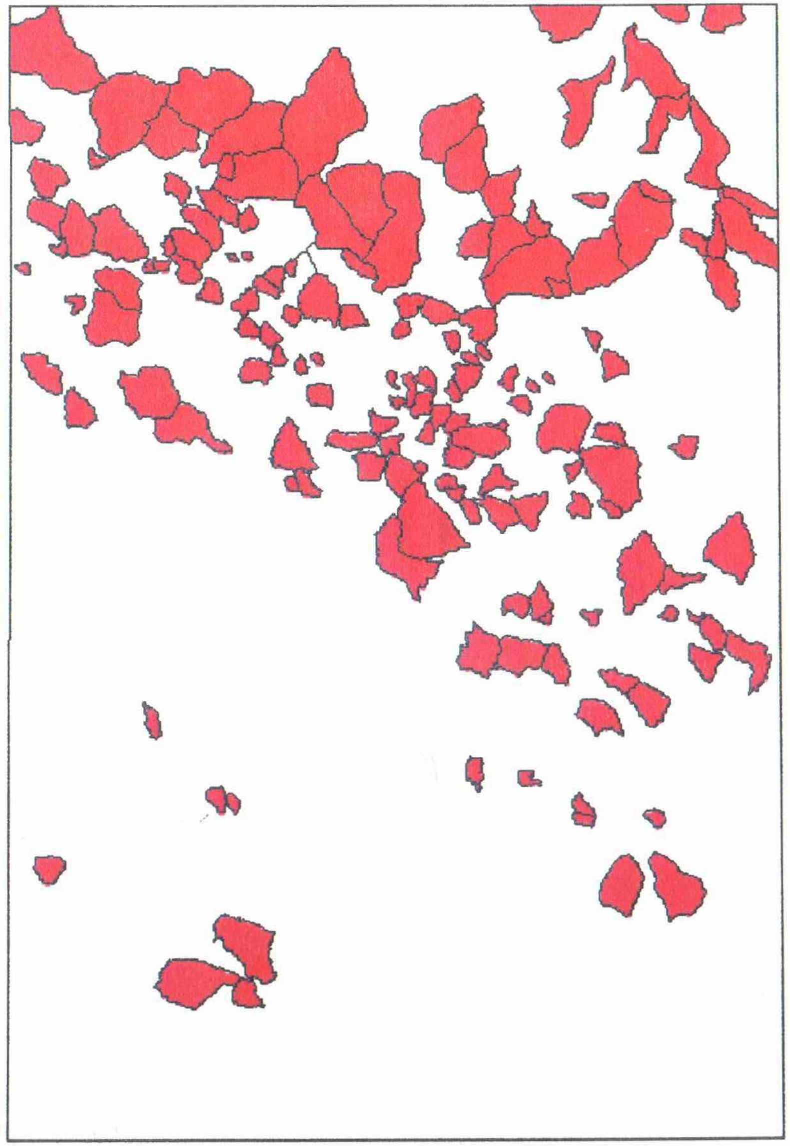


Figure 4.3 Older landslide-landscape features from Landsat TM interpretation.

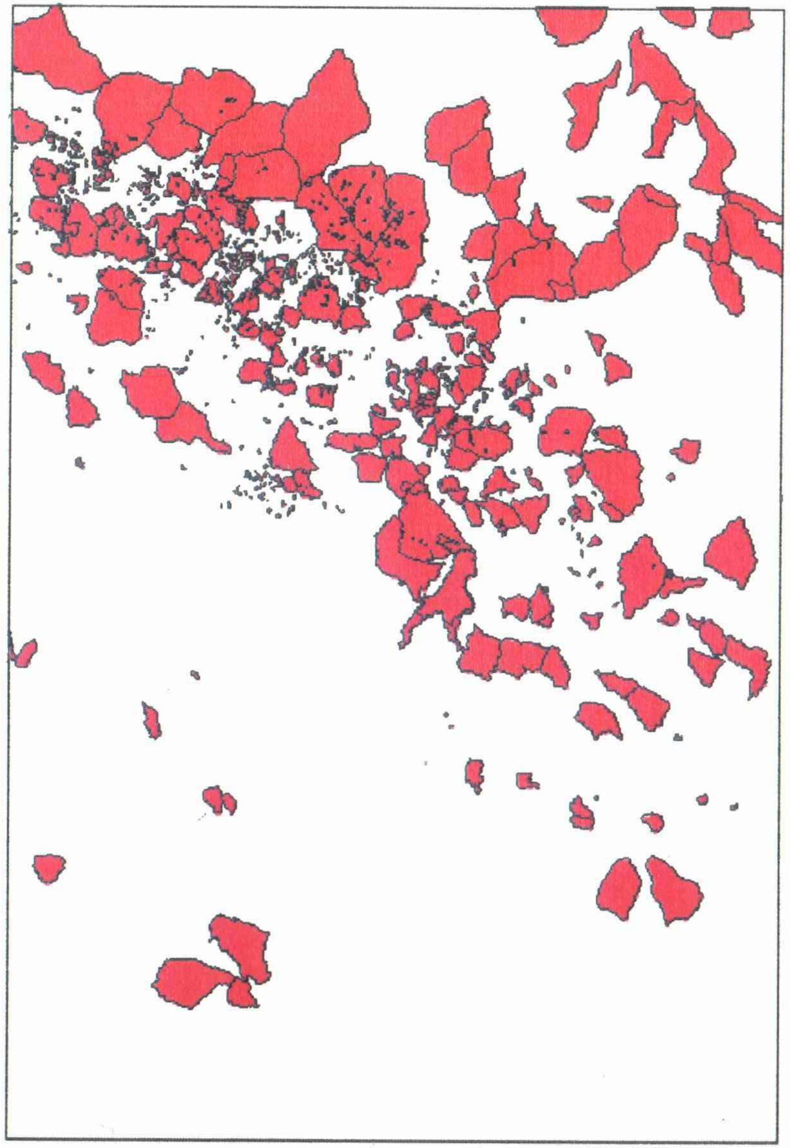


Figure 4.4 Total landslides from Landsat TM interpretation; (recent + older).

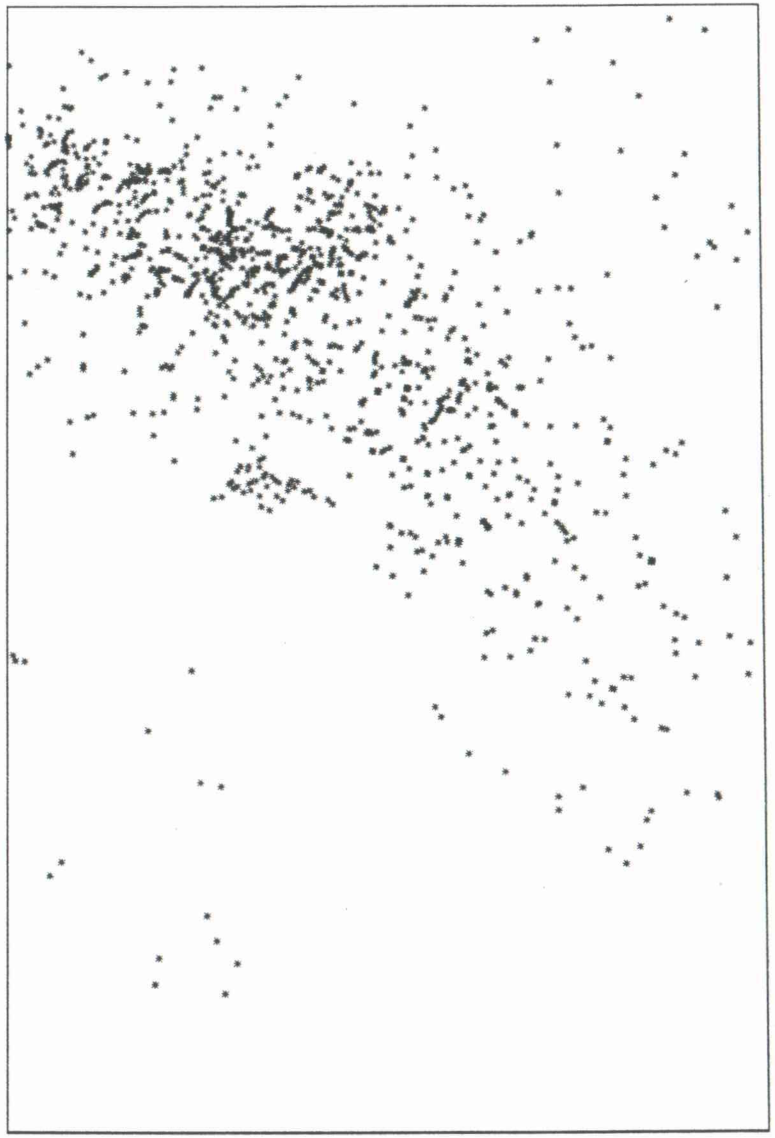


Figure 4.5 Total landslide initiation points.

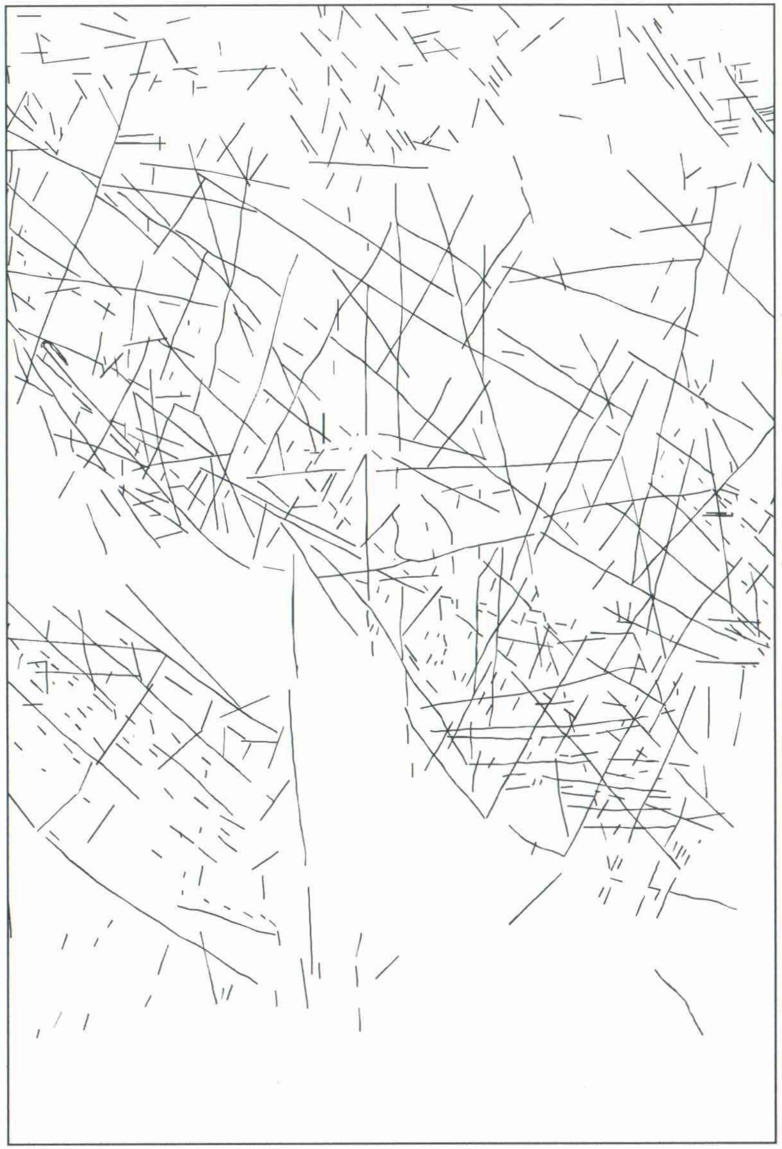


Figure 4.6 Lineaments interpreted from Landsat TM images

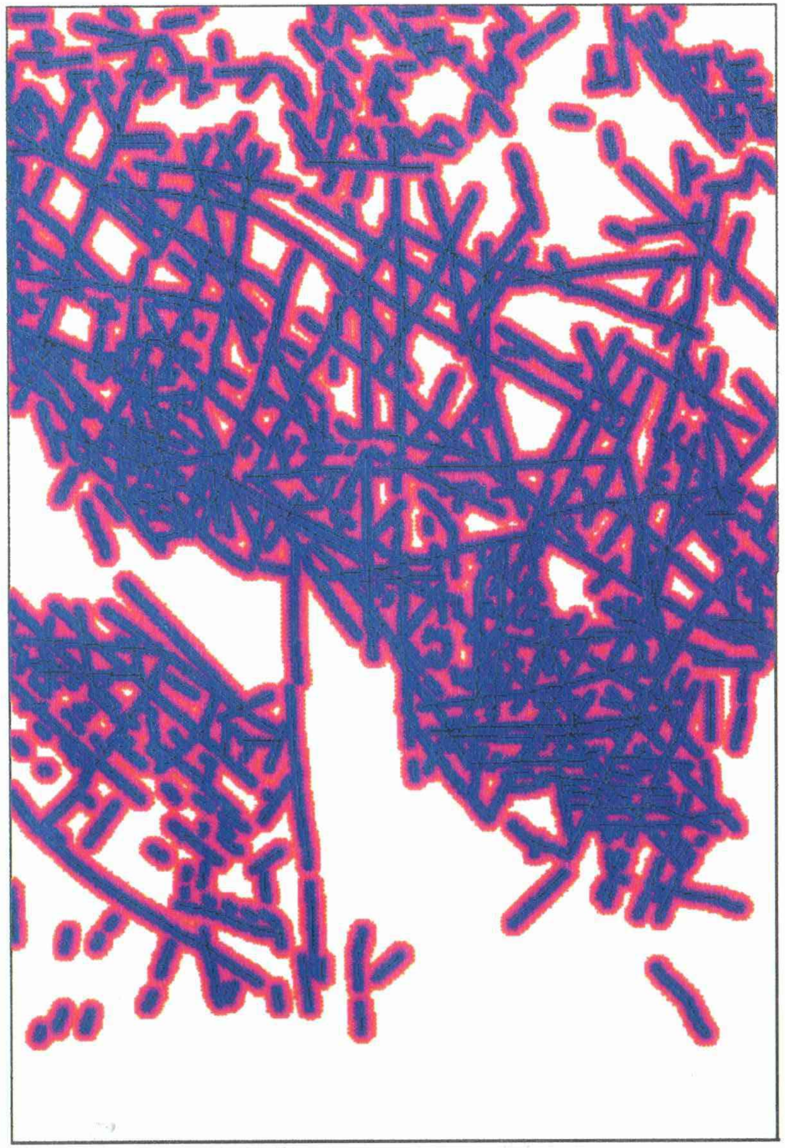


Figure 4.7 Buffer zones calculated to 1 km either side of lineaments.

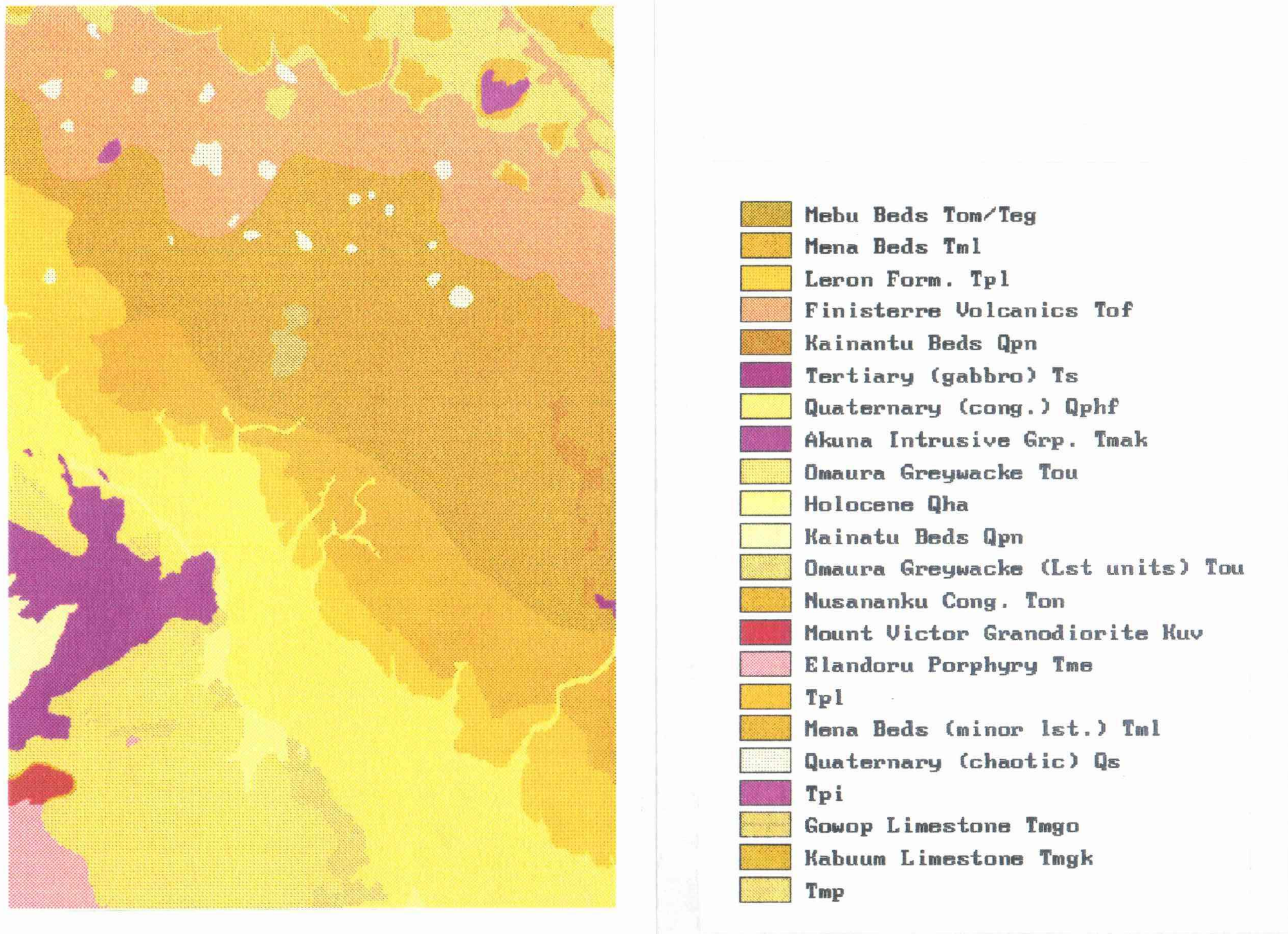


Figure 4.8 Geology of Markham Valley study area (compiled from published 1:250 000 scale maps).

(in 8 sectors). The details of this work are described separately in Section 4.5. Figure 4.9 is a colour coded plot of elevation; Figure 4.10 is a shaded-relief visualisation; Figure 4.11 is plot of slope angle in 5° classes; and Figure 4.12 is a slope aspect map.

Catchments: Catchments varying in size up to 734 km^2 (average 52 km^2) were defined manually on the 1:100 000 scale topographic maps and digitised. The choice of catchments was to some extent arbitrary; the rationale in this instance was to define catchments of a sufficient size, in relation to the regional nature of the study, to be of use in examining the distribution of landslides. Catchments were selected as a basis for such comparisons because many of the risks are downstream of the actual slide events. The catchment boundaries are shown in Figure 4.13.

Rivers: These are a purchased data set taken from the 1:1 000 000 map of the world. They were used only for geographical reference, and errors due to the scale of the source data are clearly apparent.

Roads: Again, these were digitised from the 1:100 000 topographic maps, and were used only for reference in relation to risks and contingency planning.

Villages: Population is widely scattered in the area studies. Villages indicate the locations of the known, main centres. In many instances, the village positions do not represent an actual village but rather several scattered hamlets.

4.5 Digital elevation model production

4.5.1 Description and use of digital elevation models

In simple terms, a digital elevation model is a representation of the land surface stored on computer. Digitised spot heights and contours do not comprise a DEM since they relate to individual points or lines and provide no information at locations 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 for each cell.

Clearly, topographic survey information, usually in the form of spot heights and contours, is fundamental to the creation of a DEM. One major difficulty is the transference of survey data from maps to the computer before the DEM can be calculated. This is discussed further in Section 4.5.2 below. Once digitised, 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 and the resulting DEM is likely not to have a value at each grid node. This is a particular problem in flat lying areas where the data points

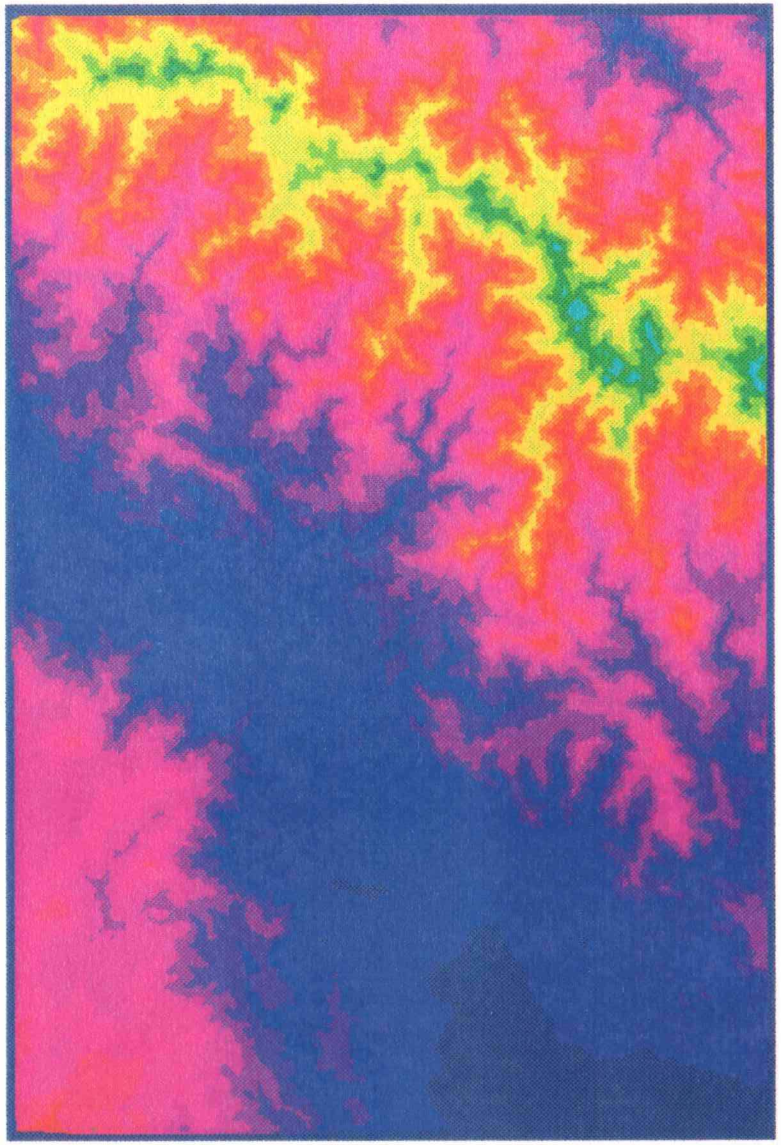


Figure 4.9 Digital elevation model (DEM) for Markham Valley; 17 classes of 250 m, range sea level to 4 015 m.

Figure 4.10 Shaded relief image of Markham Valley study area DEM illuminated from north west.

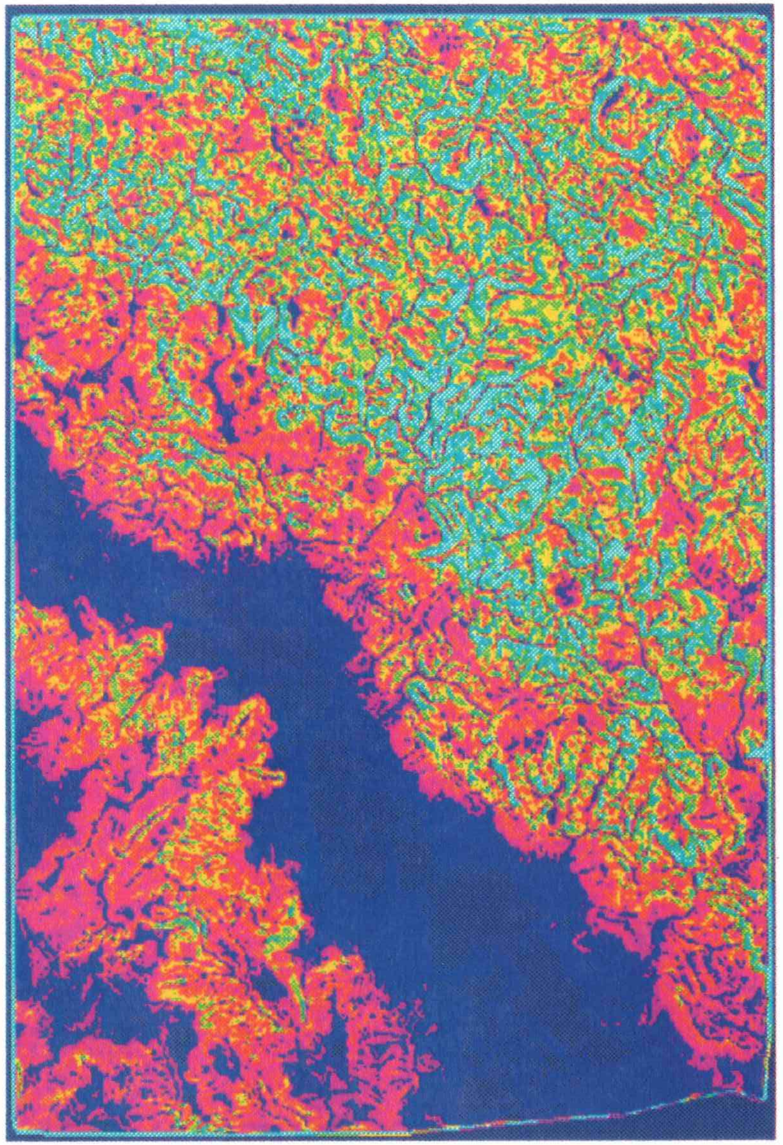


Figure 4.11 Slope angle map for Markham Valley study area; equal area plot based on 5° slope angle classes.

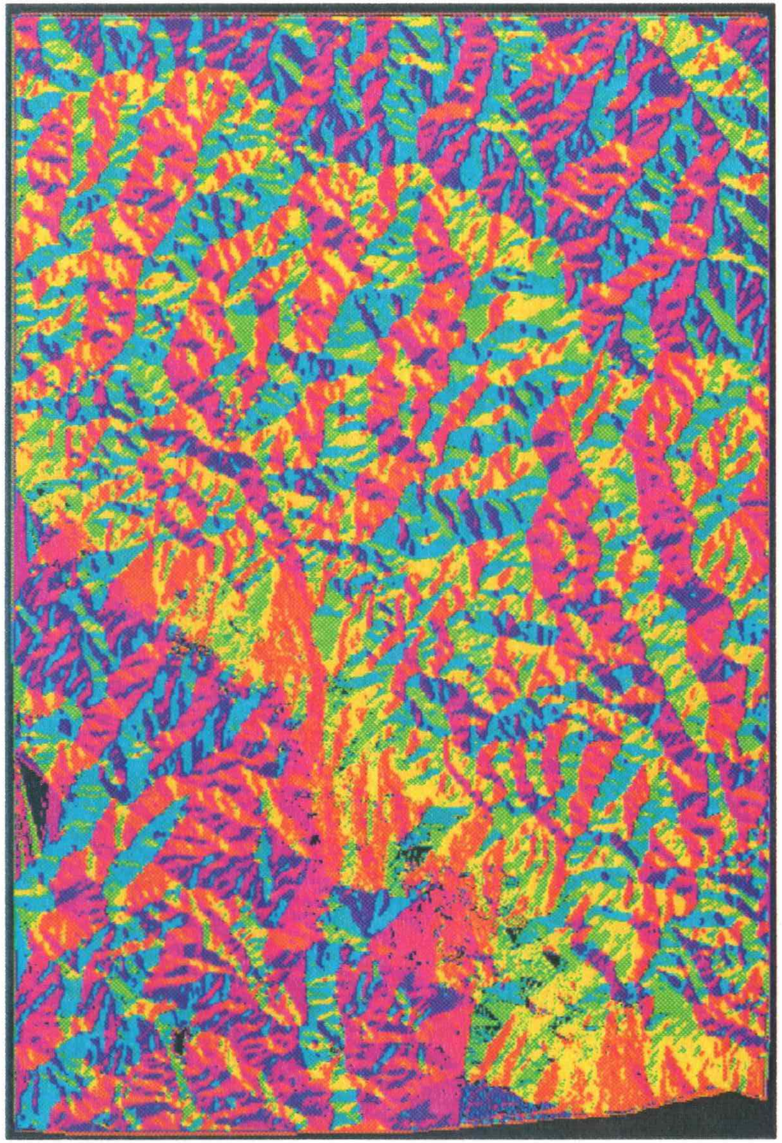


Figure 4.12 Slope aspect map for Markham Valley study area; 8 sectors.

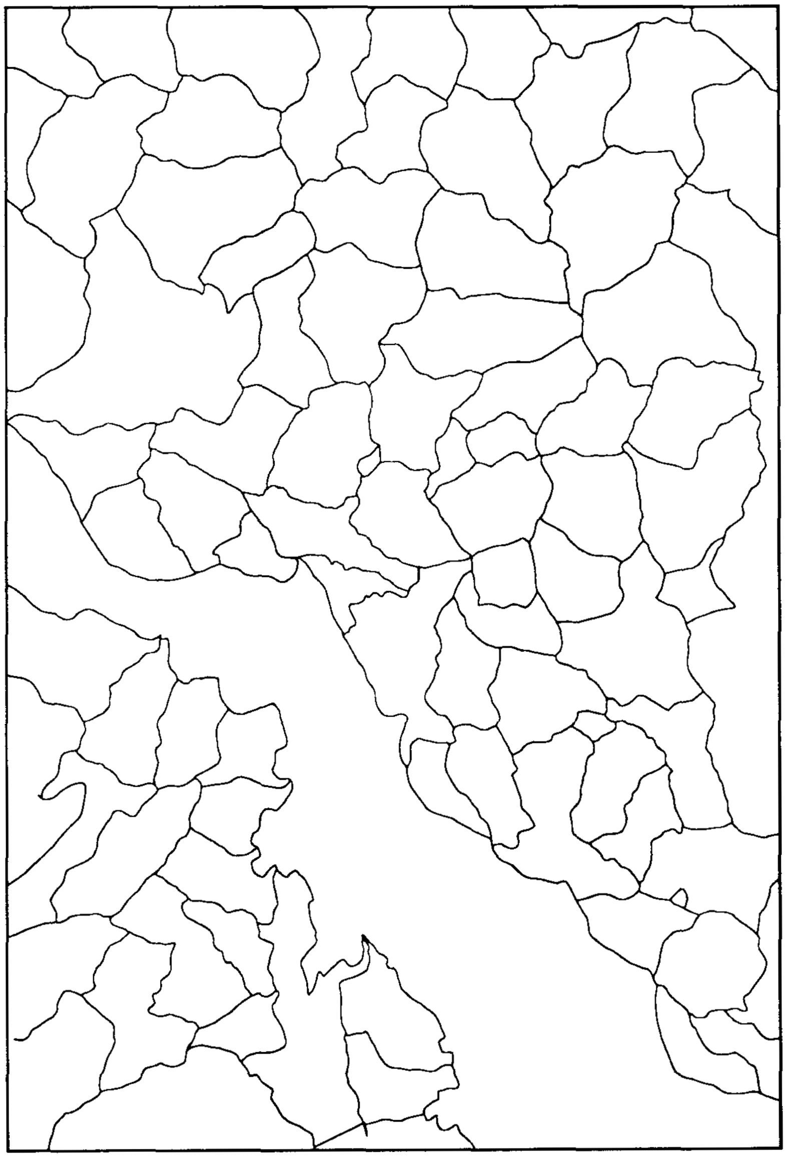


Figure 4.13 Boundaries of river catchments defined from 1:100 000 scale topographic map.

are widely spaced. 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 position 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 model 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 that of 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. In areas of sparse data, however, the calculated surface can contain artificial plateaux.

Irrespective of the method used to create a DEM, it must be recognised 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 at that point. The calculated surface depends on many factors: the chosen algorithm and parameters, the distribution of the observed data, and the required spacing between grid nodes are but examples. 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 directly from remote sensing is to make use of parallax differences in stereoscopic aerial photography or satellite imagery. Parallax is essentially a measure of apparent displacement of points on the ground, due to elevation, when viewed from two different positions. 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 information 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°.

4.5.2 Creation of DEM for PNG

The major difficulty to be overcome in creating a DEM is the digitising of the topographic survey map information. In the PNG study area, the terrain variation is extreme, with a range of about 4 000 m which, together with the 40 m contour interval, results in complex maps. To digitise the maps using normal, manual line-following methods would be extremely laborious, time consuming and prone to error. The alternative approach, and that followed within this project, was to scan transparent separates of the contours to form raster maps, and then convert these to vector format to enable the lines to be edited. Editing involved, for example, joining the line breaks occurring at the contour labels, and attributing them with the height values. Although the speed of initial data capture was improved, considerable manual intervention was still required.

The production of the PNG DEM was undertaken entirely on Intergraph workstations running MicroStation and other MGE applications. Even with the power of these computers, it was necessary to sub-divide the area into smaller sections since the terrain complexity resulted in data files too large to be manipulated on the systems. Having attached the height information to the digitised line work, grids were formed from the triangulation of the data. These sub-section grids were then merged to produce a complete coverage of the study area. Although measures were taken during the griding process to reduce edge effects, they were still present and gave an unacceptable surface.

Given these problems, the only means of creating a complete DEM was to grid the data for the entire area but reduce size of the data set by taking every fifth contour, that is 200 m intervals, and to use a grid spacing of 100 m. The digitised drainage network was used to refine the DEM by ensuring that valley bottoms were positioned to coincide with the stream locations.

The production of the DEM involved considerable effort both in terms of staff effort and computer resources, and took about 6 weeks to complete. It would not have been feasible to attempt this work on a PC-based system and maintain even this reduced level of detail. Given that the DEM and derived maps was essential to the landslide hazard zonation analysis, the expenditure of such effort was justifiable but its use in rapid hazard assessment using PCs must be questioned. A possible alternative would be to use semi-automated line following digitising and to simultaneously reduce the amount of data captured to match the resolution of the study. Software is available that enables a raster scanned contour map to be line followed quickly along selected contour values. Such an approach would considerably reduce the time requirement for this work.

4.5.3 Perspective views using Landsat TM and the DEM

The combination of a digital image and a DEM enables an x-y-z value to be calculated for every pixel in the image. Using IA modelling software, this allows the image to be viewed in 3-D perspective. In the present study, an experiment was carried out over a small part of the study area covering the Kaiapit landslide.

Figure 4.14 shows part of the May 1991 Landsat TM scene for the Kaiapit area with the digitised contours superimposed. The goodness of fit is noticeable despite the fact that the contours were originally derived from aerial photographs of a much earlier generation. Figures 4.15, 4.16 and 4.17 show three different perspective views and illustrate the power of modern workstation solutions to help visualise the landscape. Such visualisations may be of benefit in helping non-geologists appreciate the scale and significance of landslide hazards.

It is interesting that, despite the fact that the contours and derived DEM pre-date the major Kaiapit landslide, the landscape generated from the DEM appears in general to match the morphology of the post-Kaiapit satellite image. This suggests that the 1988 event was not the first major landslide to have occurred at this site but merely the most recent at a location where major events are a recurring phenomenon. This is perhaps a small piece of evidence to support the hypothesis that past landsliding is indicative of likely future events. This is further suggested by reports of villages in the Kaiapit area after previously being relocated due to landsliding (Peart, 1991). If uplift continues in the Kaiapit area, future landslides can be expected at this same site.

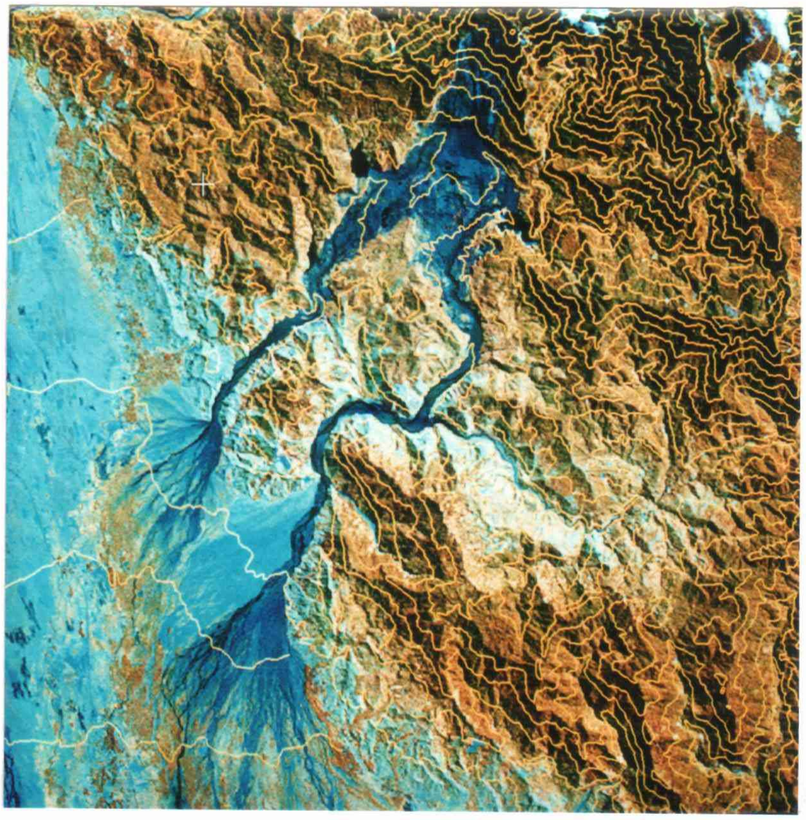


Figure 4.14 May 1991 Landsat TM 457 FCC of Kaiapit area with digitised contours superimposed.

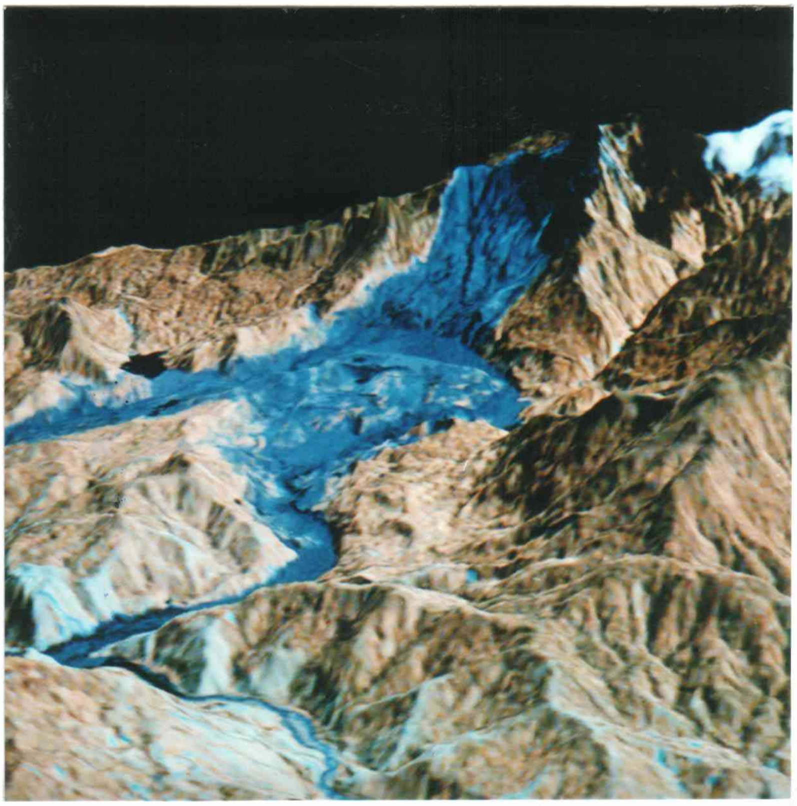


Figure 4.15 Perspective view from south south east of Kaiapit landslide formed by draping Landsat TM 457 FCC over DEM.

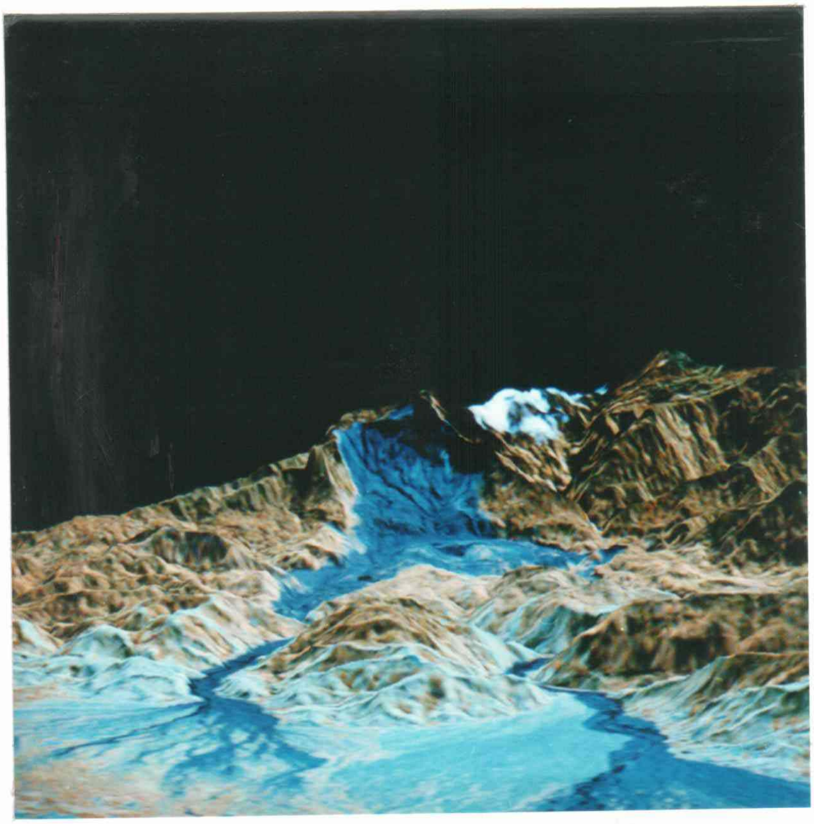


Figure 4.16 Perspective view from south west of Kaiapit landslide formed by draping Landsat TM 457 FCC over DEM.

Figure 4.17 Perspective view from crown of Kaiapit landslide looking south west formed by draping Landsat TM 457 FCC over DEM.

5. SPATIAL DATA INTEGRATION AND ANALYSIS USING RASTER GIS

5.1 Concepts

Hazard zonation using a geographic information system (GIS) requires the assembly of various spatially co-registered data, their analysis, and presentation in simple map form. The importance and relevance of each data set must be considered singly and in combination. The primary data will depend on what is considered relevant and what is available. A database might include such information as: a distribution map of past landslides; rock types and structures; site investigation and material test results; soil types; topography; drainages; 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 of a landslide occurring at a given location depends on a number of conditions which may be considered as (1) controlling factors and (2) triggering events. Controlling factors may be broadly divided into material properties (rock/soil type; *in situ* and post movement strength; etc) and terrain conditions (slope angle; fracturing; cultivation etc), while triggering events will include earthquakes, intense rainstorms and possibly new construction/development. If all the controlling factors in an area are understood and *full ground survey information available*, it should be possible to 'predict' where landslides are most likely to occur *given a particular triggering event.*

In the present regional study, the situation is rather different: here, 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. The approach is empirical and the results therefore only indicative; the approach is at best semi-quantitative. The potential benefits are that the method is relatively cheap and rapid compared to a full ground survey which may, in fact, be unachievable. Using a GIS, the geologist can test for spatial relationships between landslides and other potential influencing factors, can quantify their apparent importance, and can mathematically combine them to produce a hazard 'probability map'. The study represents a first attempt at modelling landslide occurrence based on a minimum of existing data. If encouraging results are obtained, it is hoped that additional, relevant data will be added to the database to improve and further develop the approach.

The fundamental indicator, obtainable from remote sensing, is a map showing the distribution of past landslides. The incidence of landslide events is used as a guide to where further landslides are likely to occur. Even on its own, the landslide inventory map may be regarded as a basic 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 each variable to landsliding is tested in turn. Thus, the occurrence of landslides may be compared with geology, slope angle, slope aspect etc. 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 the significant variables are established, the geologist must decide, and weight, the importance of each and add the weights to provide an overall probability estimate across the entire area. However, it should be remembered that the available inputs may not be sufficient to model the true situation completely.

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 PNG database were described in Section 4.4 but not all of these were used as layers in the raster analysis. Two layers formed the control for the analysis. The first was a Boolean mask formed by combining all the landslide polygon information irrespective of age or interpretation source. The second control layer was the distribution of notional landslide 'initiation points' taken as the landslide crown. It was against these control layers that the other variables were examined. The variables are listed in Table 5.1.

The GIS used for the analysis was IDRISI. This was chosen over ILWIS since it is likely that the latest version of this system which operates under Windows will become more widely used in the South 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.

$$\frac{\text{Number of landslide pixels in lithology Class 5*}}{\text{Total number of pixels comprising Class 5}} = \frac{619}{2\ 320} = 0.267$$

(* where Class 5 is equivalent to the Kainantu Beds).

Table 5.1: Variables used in the landslide analysis for PNG

Variable	Number of classes
Landslide polygons (total)	1
Notional landslide start points (total)	1
Elevation (250 m classes)	17
Slope (5° classes)	18
Aspect (45° sectors)	8
Geology	22
Catchments	91
Distance from lineaments	10

This provides information about the variables and classes which have an association with the presence of landslides. Thus, 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, 26.7% of the ground area mapped as the Kainantu Beds corresponds to landslides. The same analysis was carried out for all classes of all variables for the study area. The results of the cross tabulations are presented in Appendix 1 (Tables A1.1 to A1.5). They allow important deductions to be made regarding the role and possible significance of the variables, as discussed below:

1. **Lithology**: As might be expected, the different rock types give different responses (Table A1.1): the Mebu Beds/Gusap Argillite (Tom/Teg), Finisterre Volcanics (Tof), chaotic Quaternary (Qs) deposits and Gowop Limestone (Tmgo) all show a high incidence of landsliding. Other units have fewer landslides or none at all.

2. **Slope angle**: A positive correlation with slope angle might be expected, and is generally demonstrated, with a higher incidence between 30° and 50° Table A1.2). The anomalous high value for slopes greater than 85° is due to edge effects in the slope calculation from the DEM.

3. **Slope aspect**: There appears to be no significant association with aspect (as might have been the case if the triggering mechanism were related to the prevailing direction of high-intensity rainstorms). Consequently, this variable was excluded from the subsequent analysis.

4. **Elevation**: There is a general increase in landslide incidence from low altitudes to a maximum at about 2 750 - 3 000 m (Table A1.3). However, landslides are of common occurrence at all altitudes above 750 m.

5. **Catchments**: Catchments were used as a means of representing landslide density variations across the study area. Since the consequences of landsliding are, in the main, contained within catchments, such a map provides information that has direct relevance to planning (see Figure 4.13). Although density within catchments is not strictly a variable, it can be included in the analysis in order to make the high probability areas correspond more closely to the mapped distribution (Table A1.4). A true landslide density map was also calculated using a moving average technique (external to IDRISI). This type of plot can be regarded as a crude hazard map; however, in the present case, it was used as a visual check on the 'goodness of fit' of the final hazard model (Section 5.3 and Figure 6.1).

6. **Lineaments**: 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. However, it is difficult to analyse this association since lineaments have no areal extent. One method is to create a map of distance to the nearest lineament classified into a series of 100 m wide zones. The zonal map can then be cross tabulated against the landslide polygon distribution, and the percentage landslide area in each distance zone examined. When this was done, there was surprisingly an almost constant percentage of landslides in each zone.

   The reason for this is not known with certainty but may be that the important variable which is related to the lineaments is the distance of the landslide initiation point rather than the entire polygon. To examine this, a cross tabulation was carried out of the lineament distance map against landslide start points (Table A1.5). This was done by comparing the number of landslide initiation points falling within each distance zone with the 'expected' number for that size of area, calculated from the average incidence of start points over the study area as a whole. This showed an increased probability of landslides originating in the vicinity of a lineament, varying from 1.69 times the expected within 100 m of a lineament dropping to the regional average at 600-700 m. The rise in values beyond this distance out as far as 1 km was unexpected and may be due to the influence of more distant landslides.

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:

$$\frac{\Sigma \text{ landslide pixels}}{\Sigma \text{ pixels comprising study area}} = \frac{90\,905}{464\,800} = 19.56\%$$

Taking the earlier example of lithology Class 5, and dividing by the regional average, the chance of a landslide occurring is 26.7/19.56 = 1.41. This means that the incidence of landsliding in the Kainantu Beds is 1.41 times greater than for the region as a whole. Considered as a measure of prediction, one could say that landsliding is 1.41 times more likely to occur within this rock category than on average over the area.

This calculation was repeated for every class of every variable, and weightings derived. 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 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:

$$\frac{\Sigma \text{ landslide pixels in classes having a weighting } \geq 10}{\Sigma \text{ landslide pixels over the entire study area.}}$$

Another way to regard performance is in terms of '**reliability**', calculated as the percentage area of a variable corresponding to landslides. It is computed for each variable as:

$$\frac{\Sigma \text{ landslide pixels in classes having a weighting } \geq 10}{\Sigma \text{ landslide \& non-landslide pixels in the same classes}}$$

(*Notes*: (1) in both performance measures, only classes ≥ 10 (i.e. average and above average landslide incidence) are considered; (2) the values for lineaments are calculated on the basis of notional landslide initiation points, for which a reliability value cannot be calculated in a comparable way).

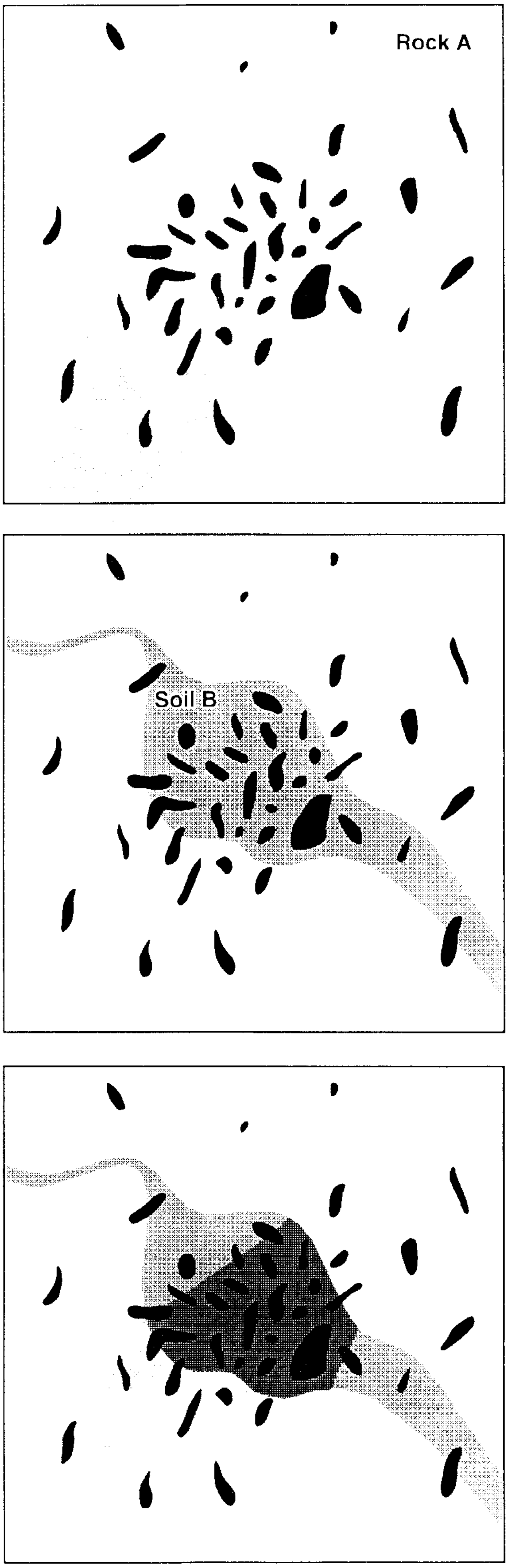
It can be seen that the two performance indicators do not provide the same information, nor is it possible to say which is the better indicator. For example, excluding catchments which is not strictly an independent variable (as discussed earlier), elevation is ranked highest on the basis of accountability (85.9%) but has the lowest reliability value (28.9%). However, geology scores quite highly on both.

Table 5.2: Measures of performance of variables in predicting occurrence of landslides in the Kaiapit/Saidor region (for explanation see text)

Variable	'<u>Reliability</u>' (% of variable corresponding to landslides) <u>Calculated as:-</u> Σ landslide pixels in all classes having weightings ≥10 divided by Σ pixels in same classes	'<u>Accountability</u>' % of landslides accounted for by variable <u>Calculated as:-</u> Σ landslide pixels in all classes having weightings ≥10 divided by Σ all landslide pixels	Ranking used in combinations
slope angle	29.41% (3)	78.70% (4)	2
geology	36.46% (2)	79.69% (3)	1
elevation	28.85% (4)	85.90% (2)	4
catchments	41.10% (1)	91.52% (1)	5
lineaments	NA	69.68% (5)	3

The reason why the two measures give different results can be best 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 landslide 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, each of these measures, in its own way, provides useful information.

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 multivariateinteractions. 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.



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.

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. Consequently, reliability is in many respects the more significant measure of performance of a model.

Based on the above logic, the next step was to combine variables to see if the predictability and/or reliability could be improved. Before this, 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 on the GIS and comparing their performance. In theory, the two variables individually showing the strongest relationship to landsliding should be combined first and lower ranked variables added sequentially. 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.

Two points need to be made about the PNG data. First, although 'catchments' shows the highest accountability and reliability values, it is arguable whether this factor should be included at all in the model since it is not a true variable and merely reflects the actual density of landslides according to catchments. Thus, for example, catchment data could not be used to extend the model to the adjacent areas (as could be done for the other variables, in theory at least) as the data is entirely area-specific. The overall effect of including the catchment density values is inevitably to improve the fit. In the present case since so few variables were available, it was decided to add it into the model at the final combination stage. However, to prevent the catchments data from dominating the model, the weightings were divided by two. Second, because the lineament data was based on landslide initiation points (rather than on landslide polygons), it was not possible to derive a reliability estimate in a comparable manner to the other variables. Given these considerations, the sequence finally decided on was: geology, slope angle, lineaments, elevation and catchments (final column in Table 5.2).

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. So 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 from a simple linear model (Table 5.3). It was concluded that higher-than-expected weightings were the result of the 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 for weights ≤ 9 - not shown in Table 5.3) suggested that interaction had, in certain cases, resulted in increased ground stability. The concept of logical and recalculated weights is illustrated in Figure 5.2.

Table 5.3: Comparison of logical and recalculated weightings for hazard models

Logical weightings of class	**Recalculated weightings within combinations**			
	2	**3**	**4**	**5**
10	9	11	11	12
11	2	16	13	14
12	11	17	16	14
13	16	16	18	17
14	15	17	19	20
15	16	18	19	25
16	18	22	19	33
17	25	20	22	35
18	21	19	20	45
19	24		15	47
20	19			51

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. As compared with each individual variable on its own, the first combination showed a lower value for reliability (33.0%) and a slightly higher value for accountability (88.8%) (Table 5.4; compare with values for geology and slope angle in Table 5.2). However, taken together, the values for the combination were probably overall an improvement.

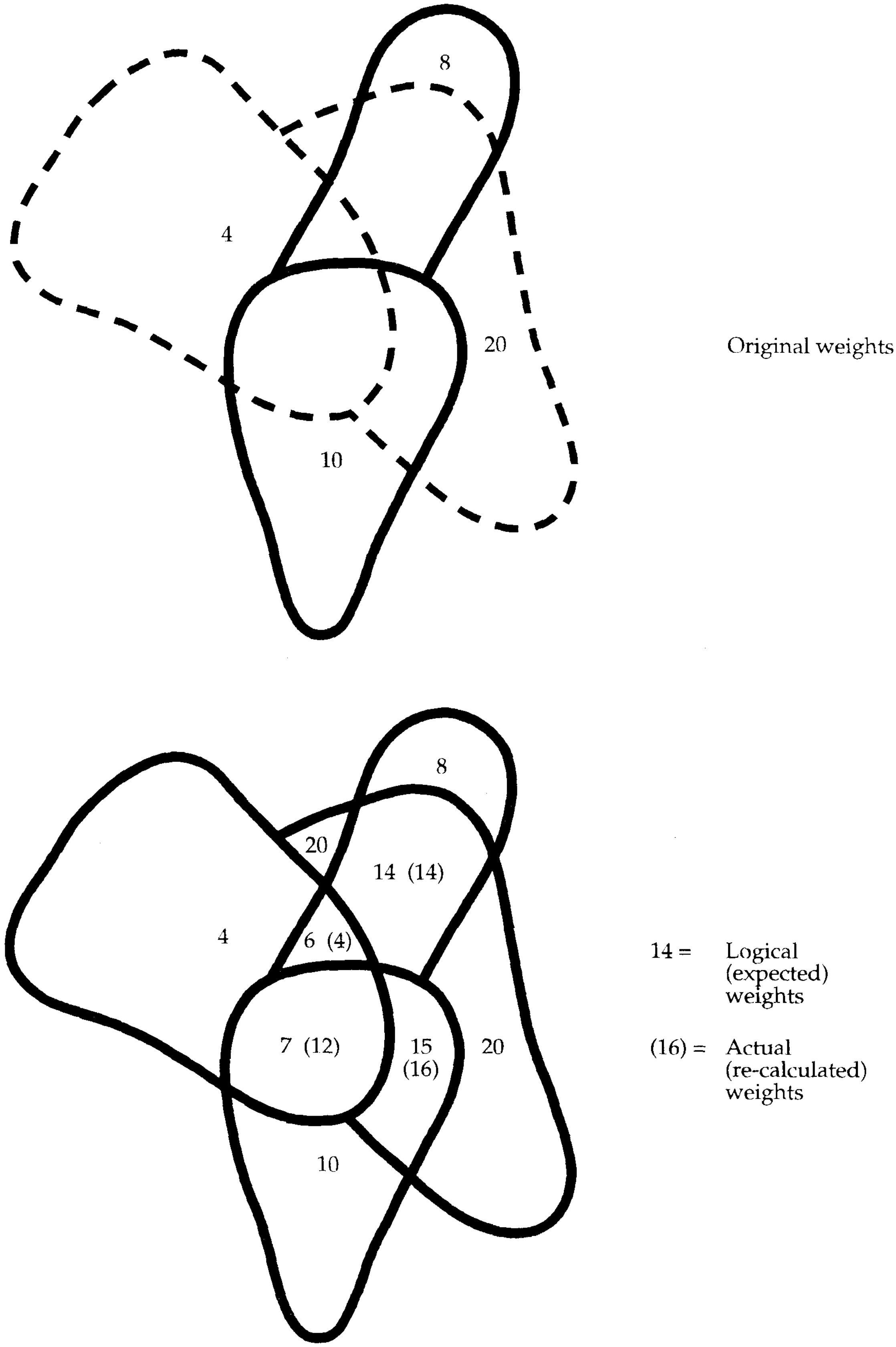


Figure 5.2 The upper diagrams show 2 variables each consisting of 2 weighted classes. In the lower diagram, summation of the 2 variables produces new 'logical weights' for the new polygon areas. However, the 're-calculated weights' (in brackets) do not necessarily match the logical weights.

Performance measures for the combinations are discussed in more detail in Section 5.3.

The analysis was continued by adding a third variable (lineaments) to the first two, summing the weights pixel by pixel and dividing by 3. Again, new weightings were calculated, compared with the expected (logical) weights, and reliability and accountability measures computed. This procedure was repeated in sequence for the fourth and fifth variables (elevation and catchments respectively). The results are provided in Appendix 1 (Tables A1.6 to A1.9).

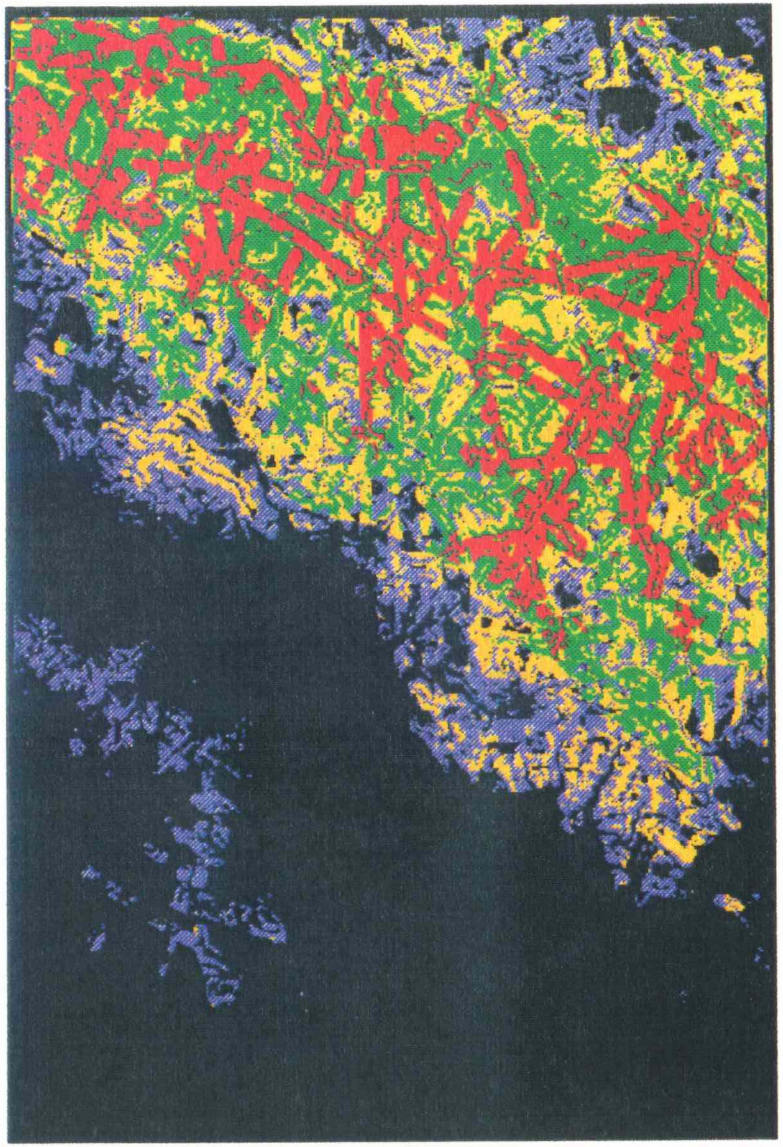
To present the combinations in simple map form, each model was sub-divided into a few probability levels. Five levels were used, four based on the quartiles of the cumulative frequency distribution of landslide pixels in classes with logical weights ≥ 10, plus a less-than-average (logical weights ≤ 9) level. The effect of using quartiles was to assign almost equal numbers of landslide pixels to each of the four main hazard classes. In order to improve the appearance of the final map (Model 5), all unnecessary, unrealistic and complicating detail was removed. This was done by 'smoothing' the map by replacing the central value of a moving 3 x 3 window by the mode within the window (i.e. 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 as performance measures of the successive models. As before, classes with logical weights of ≥ 10 were used for the comparisons. However, in this case performance measures were calculated for each quartile range of the cumulative frequency of landslide pixels to enable direct comparison with the plotted hazard maps.

The *totals* for reliability in Table 5.4 correspond to the single (average) reliability values used previously when discussing variables. These suggest that there is hardly a change from Model 2 to 4, and only a moderate increase in Model 5. Based on this information alone one might conclude that there is little improvement in successive models and might expect the resulting hazard plots to look very similar. That this is not the case can be seen from comparison of Figures 5.3A to 5.3D (Models 2 to 5). These plots are divided into 5 levels of hazard (equivalent to: below average, low, low-intermediate, high-intermediate and high). Visual comparisons with the landslide density map (Figure 5.4) shows that the models exhibit an increasingly good correspondence. This improved fit takes the form of a progressive segregation into areas of higher and lower hazard. Although this is obvious from visual inspection, the reliability totals fail to make this distinction.

C



D

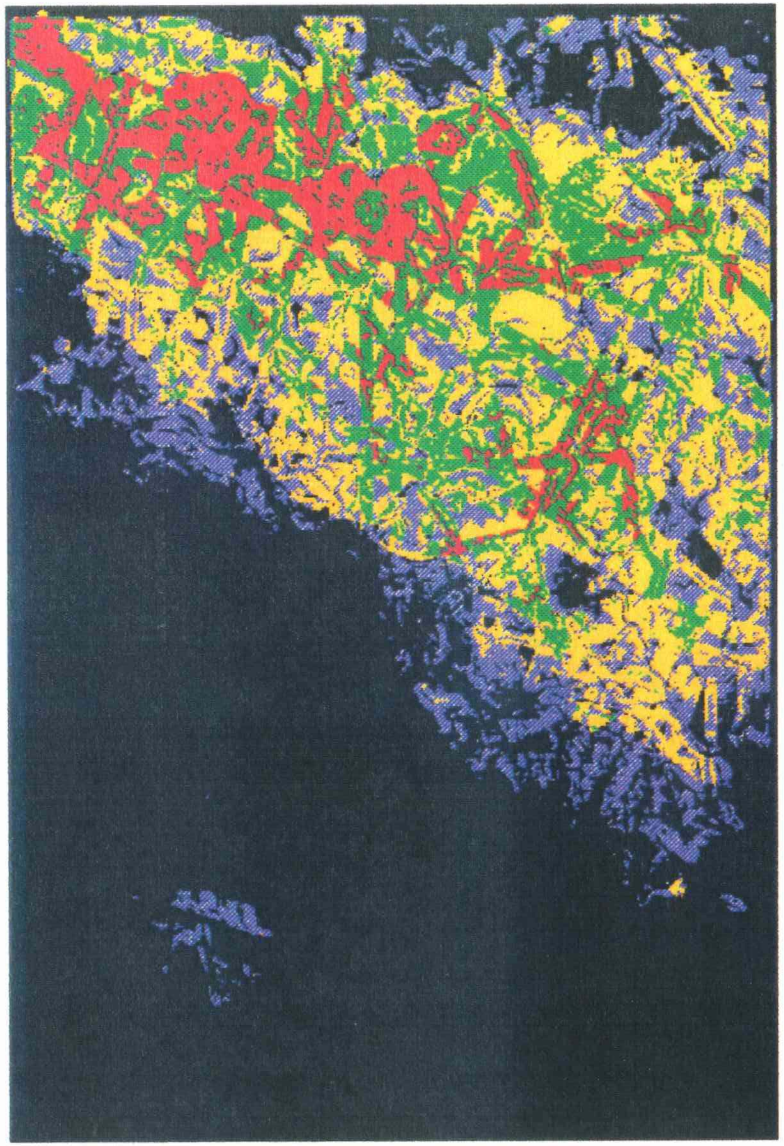


Figure 5.3 (contd.) Landslide hazard map of Markham Valley study area:
C Model 4 (geology + slope + lineaments + elevation).
D Model 5 (geology + slope + lineaments + elevation + catchments).

A

B

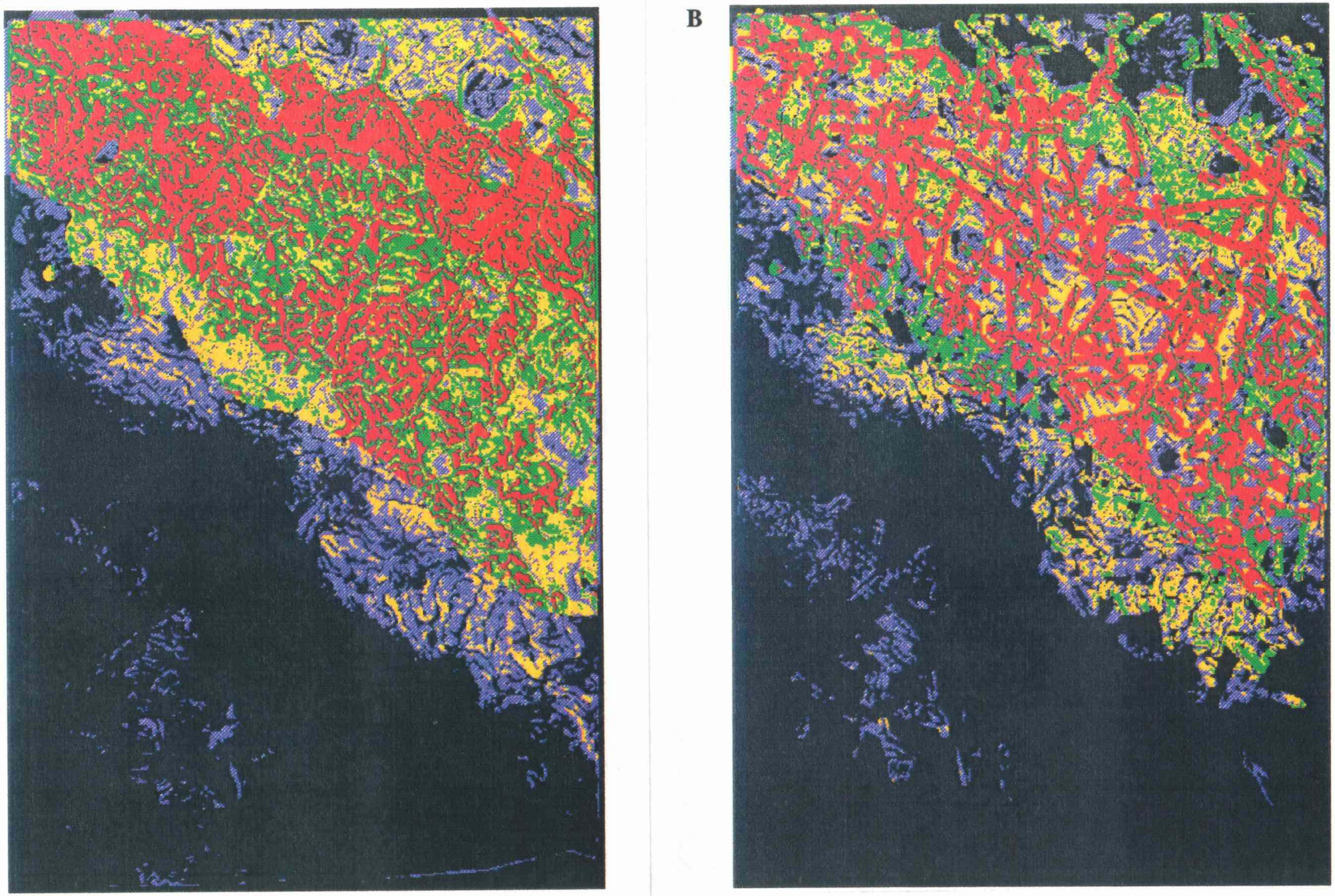


Figure 5.3 Landslide hazard map of Markham Valley study area:
A Model 2 (geology + slope).
B Model 3 (geology + slope + lineaments).

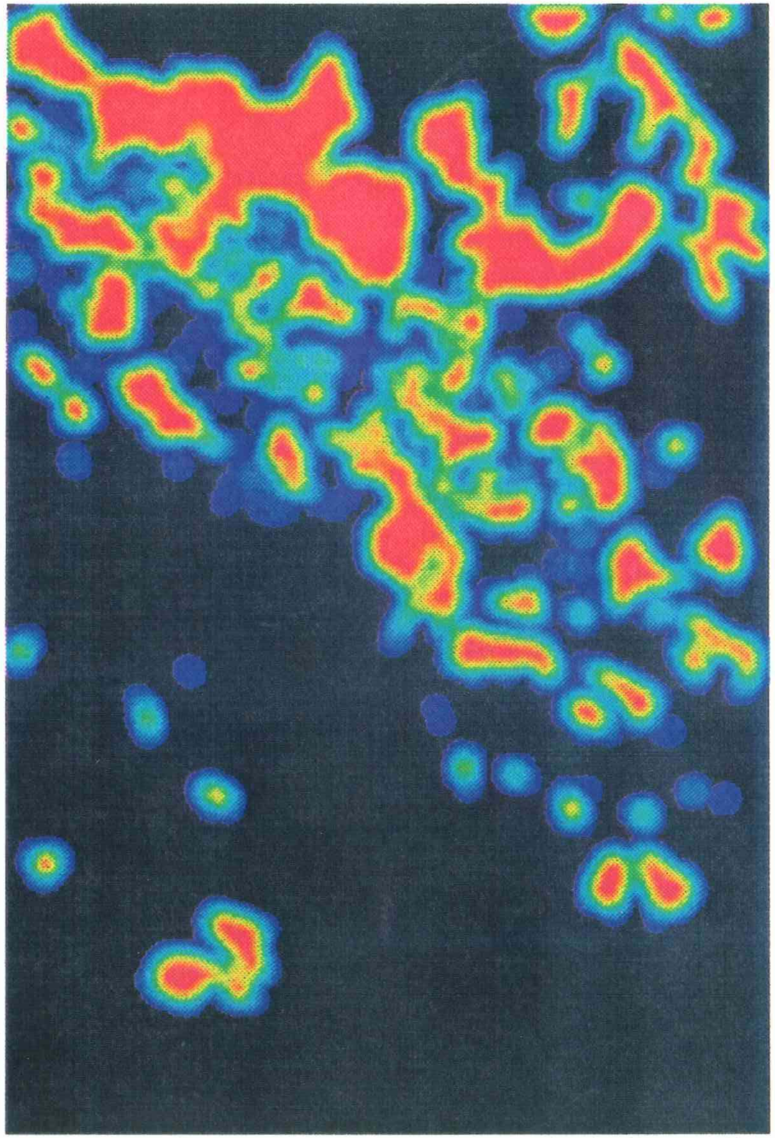


Figure 5.4 Landslide density map for Markham Valley study area.

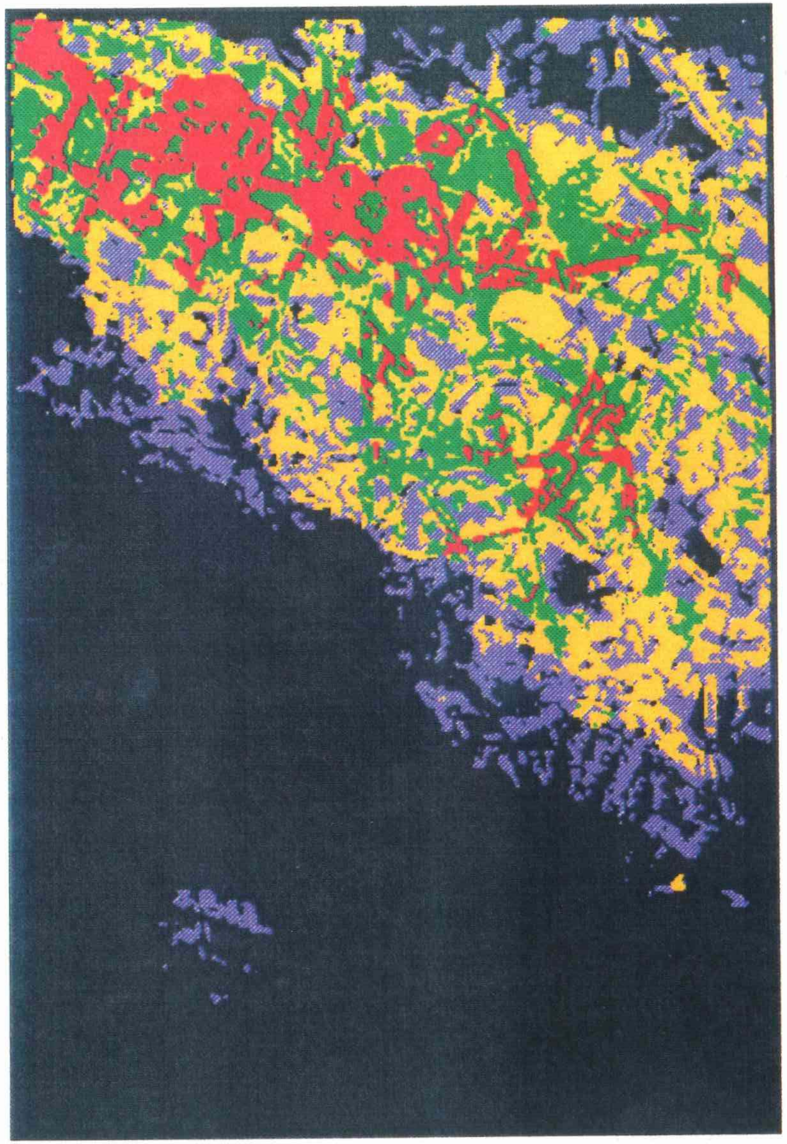


Figure 5.5 Final landslide hazard map (Model 5) smoothed to remove unwarranted detail.

Table 5.4: Reliability (R) and accountability (A) measures of PNG hazard models (values in per cent).

Model	2		3		4		5	
	R	A	R	A	R	A	R	A
1st quartile	*20.3*	12.9	*28.4*	20.0	*23.0*	14.1	*25.2*	16.6
2nd quartile	*30.1*	15.5	*32.6*	16.4	*32.5*	21.2	*30.4*	22.6
3rd quartile	*38.1*	25.2	*32.5*	15.2	*37.9*	28.5	*42.6*	23.0
4th quartile	*39.9*	35.2	*38.5*	30.7	*39.9*	22.3	*69.9*	21.5
Totals	***33.0***	88.8	***33.3***	82.3	***33.4***	86.1	***37.2***	83.8

[2 = geology+slope; 3 = geology+slope+lineaments; 4 = geology+slope+lineaments+elevation; 5 = geology+slope+lineaments+elevation+catchments]

For a more quantitative explanation it is necessary to consider how the reliability values vary for each model through the classes. To avoid undue importance attaching to classes which, for example, have high weights but represent very few landslide pixels, the comparisons were based on the quartiles of the cumulative frequency of landslide pixels for logical weights ≥ 10. (This sub-division could not be precisely achieved due to the integer nature of the class divisions; if it had been possible, the accountability figures in Table 5.4 would have been the same for each quartile of each of the models). When the reliability values are considered for each of the 4 quartile ranges, it can be seen that (1) there is a progressive increase in reliability from the 1st to the 4th quartile in each model and (2) the overall spread of reliability values generally increases from Model 2 to Model 5. This trend goes some way towards explaining the improvement seen in the models as more variables are added. However, the visually obvious improvement from Model 2 (geology + slope) to Model 3 (lineaments added), is still not adequately explained by the statistics. Nor is the improvement from Model 3 to Model 4. The statistics quantify the hazard probabilities but do not fully describe the regional distribution patterns evident in the plots. This aspect requires further work in order to make the decision-making process more objective. For the present, it is necessary to both consider the statistics and visually compare the 'goodness of fit' with the landslide density plot (Figure 5.4).

Figure 5.5 is Model 5 in its final form, smoothed to remove unnecessary detail. If compared with Figure 5.3D it can be seen that smoothing has the effect of removing spurious small groups of pixels and providing a map that is more understandable for the user.

Hhazard levels displayed on this map may be described as follows:

Black	*Very low*: below average incidence of landslides
Blue	*Low*: 25% average probability of landsliding
Yellow	*Low-intermediate*: 30% average probability of landsliding

Green	*High-intermediate*: 43% average probability of landsliding
Red	*High*: 70% average probability of landsliding

Model 5 represents a preliminary attempt to model landslide hazards over part of the PNG Highlands region. It is both preliminary, in the sense that further GIS analysis of the existing data is warranted, and provisional in that modified versions could easily be produced as more information becomes available. For example, more use made of the separate categories of old, transitional and new landslides. Time prevented this from being done.

The plots show interesting patterns that need some further explanation and/or validation. 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 may be that it is not the lithological classes themselves that are important but only certain physical properties of rocks (e.g. strength characteristics), which may cut across the mapped lithostratigraphic sub-divisions. 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.

The limiting factors of the present model are the few variables used in the analysis and the quality of some of the data (e.g. the reconnaissance geology map which is currently being remapped). Future work should also address the problem of quality control in the interpretation of the remote sensing data and should attempt to establish procedures to provide a fully consistent and quantifiable approach.

6. HAZARD MAP PREPARATION

6.1 Approach

The approach adopted for the preparation and production of the landslide hazard maps appended to this report was modified several times to adapt to the information, computer hardware, software, expertise and plotting facilities available at the time. In a developing country such as Papua New Guinea the degree of expertise and hardware available can decrease as well as increase during the currency of a project. An approach which has sufficient flexibility to cope with changing circumstances (for example, a computer expert leaving or a piece of equipment requiring expensive maintenance at a time when funds are not available) is therefore desirable.

Each of the final thematic maps appended to this report was prepared in Papua New Guinea using the facilities available at the Geological Survey of Papua New Guinea (GSPNG). It was originally hoped that by the time the final maps were to be produced, an A0 or A1 plotter would be available within the Department. The original concept of map production, in the absence of a raster GIS system, was to carry out a series of Structured Query Language (SQL) queries to compare and create combinations of vector layers and to plot a series of thematic maps side by side on an A0 sheet. The idea of having several maps plotted together was to allow visual comparison of the controlling and triggering mechanisms so that the user could see how the hazard map had been created. A similar concept is illustrated in Figure 6.1 (see A3 plot appended) showing the evolution of the final vector landslide hazard map produced from various combinations of raster data.

The provision of raster data using IDRISI enabled a more sophisticated approach to be adopted. Also, because only an A3 plotter was available, a series of three stand-alone thematic maps were produced instead. Whilst the amount of information relating to landslide hazard and damage was sufficient to justify map production at a scale of 1:100 000, a scale of 1:250 000 was actually adopted. This was due to the limitations of plotter size and because of the lack of cultural and locational detail that would be needed at the larger scale to locate oneself without having to refer to a grid or to map graticules. The 1:250 000 scale has proved to be appropriate as it is smaller than the scale of data capture (1:100 000) and corresponds with the scale of the main geological and topographical map series for Papua New Guinea.

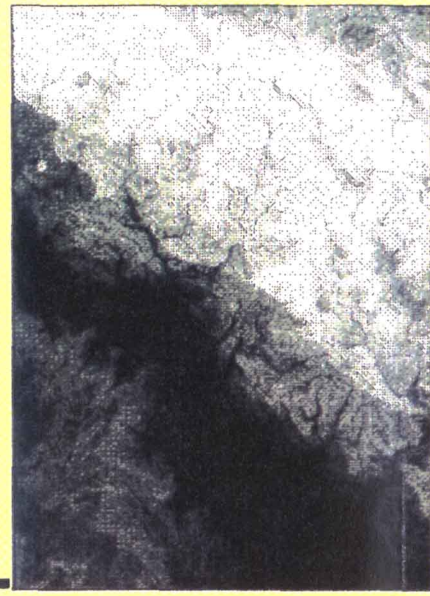
6.2 Landslide damage maps

In view of the amount of firm evidence for landsliding and landslide-related damage, it was decided that a wholly factual map showing landslide damage would be an useful published thematic map (see map: 'Landslide damage in the Markham').

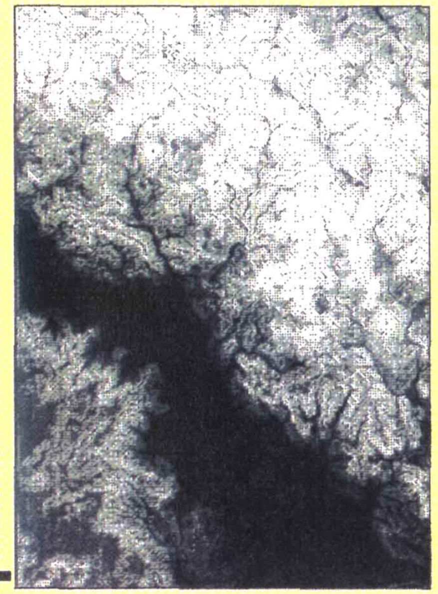
The damage map shows areas known in recent times (in this instance since 1975) to have been affected by landsliding. The map also shows related effects such as landslide-damaged villages, landslide fatalities, landslide dams, major earthquake epicentres that triggered landslides, and the location of landslide-induced flood

Combined elevation, slope steepness, rock type, buffered lineament and landslide density map

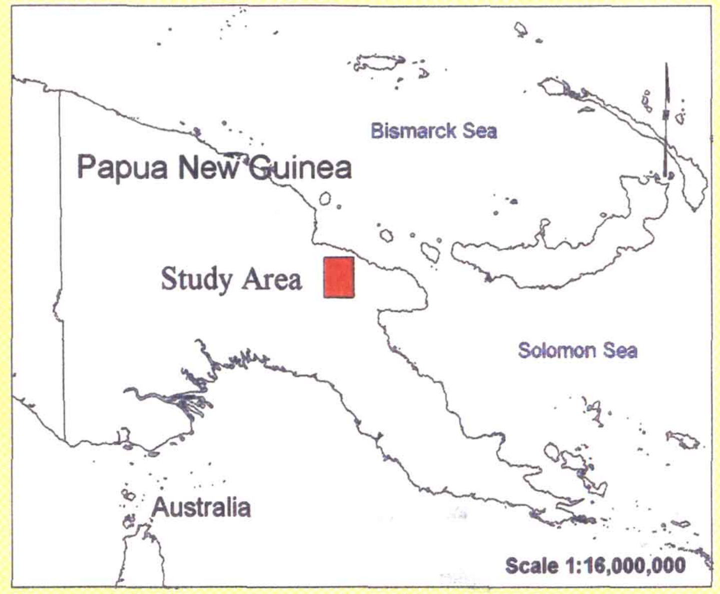
Combined elevation, slope steepness, rock type and buffered lineament map



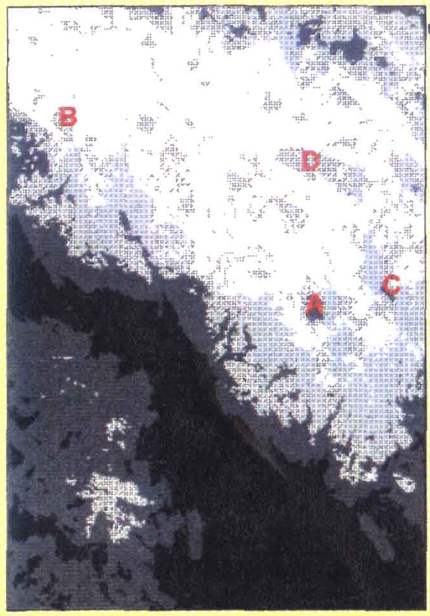
Combined elevation, slope steepness and rock type map



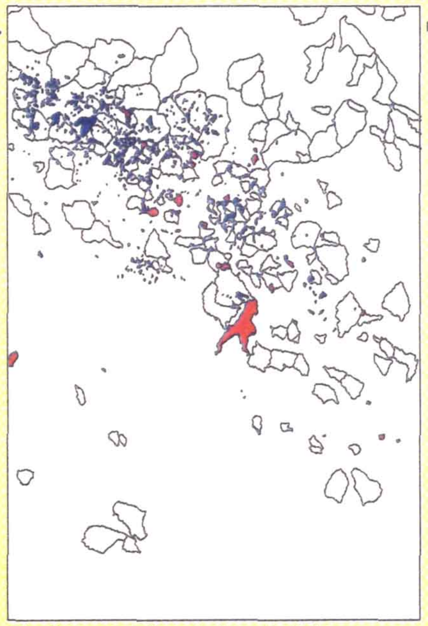
Combined elevation and slope steepness map



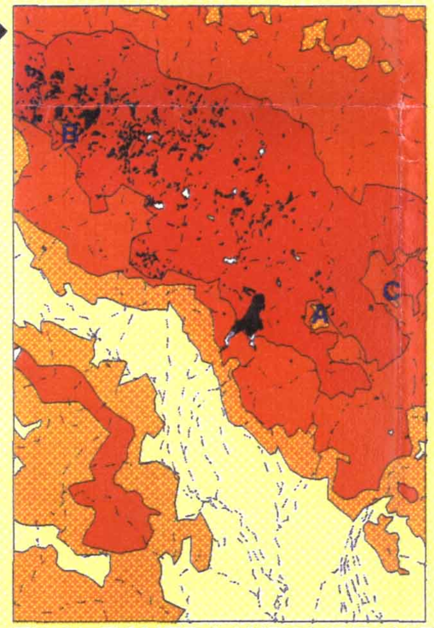
Location Plan



LANDSLIDE HAZARD MAP based on the last combination of attributes, smoothed and divided into equal classes of hazard



Relict and fresh landslides positions as seen on Landsat TM imagery for comparison purposes



FINAL ZONED LANDSLIDE HAZARD MAP (except for cultural data) based on the computer-generated Landslide Hazard Map with additional manual smoothing and interpretation

The maps shown are based on the following sources of information:

- Slope angle (steepness) and elevation. These data have been taken from a digital elevation model prepared by the Remote Sensing Group of the British Geological Survey (BGS) based on the Kaiapit and Saidor 1;100,000 topographical sheets.
- Lineaments. These were interpreted from Landsat TM imagery, Aerial Photography and other sources by the BGS and Geological Survey of Papua New Guinea (GSPNG) from Landsat TM imagery, Aerial Photography and other sources.
- Rock type. This is the distribution of Units shown on the Markham and Madang 1:250,000 Geological sheets, as digitised by the BGS.
- Relict Landslides. These were interpreted by both the BGS and GSPNG from a 1991 Lansat TM image.
- Fresh Landslides. These were interpreted by GSPNG from a 1991 Landsat TM image and from an image dated January 1994 showing landslides caused by earthquakes in 1993.
- The location of villages known to have been damaged or destroyed by past landslides and the location of landslide fatalities. Information held by GSPNG.
- Observations of officers of the GSPNG during foot patrols and helicopter reconnaissances that were part of the search and rescue operation following the 1993 earthquakes and associated landsliding.

Figure prepared in Papua New Guinea by M A Tutton of the Geological Survey of Papua New Guinea

m:\engineer\bgs\evolhaz1.wor

Scale of Thematic Maps 1;1,000,000

See section 6 of report for full explanation of maps

31 March 1995

The Evolution of a Zoned Primary Landslide Hazard Map of the Finisterre Range, Papua New Guinea

Landslide Hazard Mapping In Neotectonic Terrains Project

Geotechnical & Hydrogeological Surveys Branch
Geological Survey of Papua New Guinea
in technical association with the
Remote Sensing Group of the British Geological Survey

Figure 6.1

damage. The map makes no attempt to predict where future landsliding may occur although, clearly, users would naturally tend to make their own interpretations. Making planners and engineers aware of past landslide damage and how potentially landslides could affect their schemes, are among the reasons for producing hazard maps in the first place. The landslide damage map is, therefore, seen as a very useful product. The map also provides an indication of the degree of conjecture that has been involved in the preparation of the landslide hazard map.

The map shows only those landslides that can be seen as fresh on recent or archive remote sensing products rather than relict landsliding represented only by geomorphological features (and thus the subject of interpretation). A past history of landsliding does not necessarily indicate that future landsliding is likely to occur: indeed it could be argued that landsliding might lead to increased slope stability. However, landslides that are relatively recent, say less than 25 years old, will probably not have become fully re-vegetated and are unlikely to have become fully stabilised. It is also probable that, for some time following a landslide, rivers will continue to erode colluvium from the landslide toe, and river beds that were aggraded will not have returned to their former levels. It is for these types of reason that fresh landslides have also been shown as a theme on the landslide hazard maps; it is considered that the scars of recent landslides (say less than 25 years old) still have potential for re-activation and therefore represent an extreme hazard, albeit, a localised one.

It is recommended that landslide damage maps should be prepared as a complementary thematic map product whenever landslide hazard maps are produced.

The following is a list of the digital files used on the landslide damage map. The file names are listed under three groups; **thematic** - data files specific to the project or theme of the map; **cultural** - files of additional information, such as rivers and roads and generally data that should be available from other agencies, for instance the National Mapping Bureau; and **miscellaneous** - additional files needed to complete the map at production stage.

THEMATIC FILES

1.	VILLDEAD	A small database giving details and positions of all landslide fatalities since 1975. Information has been taken from GSPNG Archives.
2.	EARTHQ93	A database giving details of position, magnitude, depth and seismic moment of earthquakes in the Finisterre Range during 1993. Information provided by the GSPNG Geophysical Observatory.
3.	ranges by magnitude	This is a data subset based on an SQL query to show earthquake positions for $\geq$ Richter magnitude 5 events (based on the table EARTHQ93). The symbols are graduated according to the magnitude.

4.	DAMS	This data layer is not attributed and only shows the approximate maximum past areal extent of known landslide dams. Based on GSPNG field reconnaissance.
5.	FLOOD	This data layer shows the extent of selected floods. Based on data taken from GSPNG Archives and verbal/newspaper reports.
6.	VILLAGE	This file gives the location and name of the high risk villages consequent upon the 1993 earthquakes. The file is a subset taken from a larger database of high, medium and low risk villages. Data taken from GSPNG Archives.
7.	LS94_05	This file represents the areal extent of landslides seen as fresh on a January 1994 Landsat TM image. A true-to-scale 1:100 000 image was used and the interpretation and digitising carried out by GSPNG.
8.	TM_LS_FH	This file represents the areal extent of landslides seen as fresh on a May 1991 Landsat TM image. Digitised by GSPNG/BGS from a photographic true-to-scale enlargement of the image.
9.	CULTDAMA	Textural layer of map annotations specific to the damage map (prepared by GSPNG).

CULTURAL INFORMATION

10.	GAZETTEER/ Query1	SQL query to produce a subset of the gazetteer to show just the villages and not the other features listed in the gazetteer. The gazetteer database has been prepared by the National Mapping Bureau.
11.	VILLNAME	Labels layer taken from the gazetteer and is simply village name labels stored at a geographic location close to the village locality.
12.	RIV1MIL	This is a river database. It is a commercially available database prepared by MapInfo from the 1:1 000 000 scale *Digital chart of the world.*

NB: This layer strictly speaking is not accurate enough for use on a 1:250 000 scale map. It has been used, however, in the absence of other river data at a better scale being available and serves to indicate at least the approximate positions of the main rivers.

13.	MAINROAD	This layer shows the main roads digitised by GSPNG from the 1:100 000 topographical maps. Only national roads are shown.
14.	TRANKWL	This layer shows the electricity transmission line routes and principal tower locations. It has been digitised by GSPNG from a 1:100 000 map provided by the Papua New Guinea Electricity Commission.
15.	TENMIN	This is a map layer of graticule intersection crosses at ten minute intervals of both longitude and latitude.
16.	SHADED	This is a raster image of a shaded relief produced by BGS from a DEM digitised from contour information taken from the 1:100 000 topographical maps.

MISCELLANEOUS INFORMATION

17.	NORTH	North arrow.
18.	SCALEBAR	Scale bar created in Mapbasic.
19.	PNG_LOGO	A scanned image of the PNG logo registered in 'Non-earth' co-ordinates as a map layer.
20.	BGS_LOGO	A scanned image of the BGS logo registered in 'Non-earth' co-ordinates as a map layer.

6.3 Landslide hazard maps

The landslide hazard maps appended to this report were designed to portray both primary and secondary landslide hazards. The former is the hazard that is the direct result of landsliding and effects both the land where landsliding actually occurs, the land immediately above and that below, in the landslide debris path. The latter is an indirect hazard, for instance flooding that results following the overtopping of a landslide dam. The area affected by the secondary hazard may be remote from the area of landsliding. In both instances, a measure of the relative probability of the hazards occurring is provided by zoning the map.

The entire study area conveniently fits on an A3 sheet, in a portrait orientation with sufficient space for a simple legend and title block. Because additional space was needed for a legend describing the secondary landslide hazards, it was decided to produce a second map showing both the primary and secondary hazards but to limit its geographical area to cover just those areas where secondary hazards are present. It was found that all the secondary landslide hazards fitted conveniently within the boundaries of the 1:100 000 scale Kaiapit map sheet. A scale of 1:250 000 was chosen for both maps, in order to be consistent with the other thematic maps as well as the published geological and topographical map series.

6.3.1 Primary landslide hazard map

The primary landslide hazard map shows four main categories of hazard, together with a qualitative description of the anticipated risks to persons and property, and a description of the type and sizes of events to expect under certain triggering mechanisms.

A similar hazard map, in all probability could have been prepared, with a little intuition, almost entirely from the data shown on the landslide damage map. The hazard map appended to this report was however prepared largely from analyses carried out using IDRISI. The analyses involved the weighting and combining of data that relates to the controlling factors associated with landsliding. The fact that the results compared with the intuitive approach is encouraging. It provides a degree of confidence in the methods used for the production of a map which will be needed for areas where less obvious landslide damage may be present, and an intuitive approach may therefore not be possible. A further positive indicator of the *accuracy* of the map (if one can use this term about such a highly unpredictable event as landsliding), is the presence of three areas of lower relative landslide hazard that are clearly visible on the raster hazard map (Figure 6.1, bottom left) and which fall within the zone of the greatest landslide hazard. Each of these three zones corresponds to the three main areas within the range that were chosen by the villagers for new village sites following the 1993 earthquakes.

The final zoned landslide hazard map was prepared using MapInfo and represents a simplification of the raster landslide hazard map, with a few minor modifications to incorporate information collected during field reconnaissances. Figure 6.1 illustrates the process by which this final map was derived and the sources of information used. A degree of smoothing and simplification has taken place and small pockets and islands of excess or spurious information have been deleted. This smoothing process was not carried out blindly, but only after consideration was given at each location as to why a small parcel of higher landslide hazard might be present within a lower risk area of vice versa. For instance the area labelled D in Figure 6.1 (bottom left) has a lower hazard rating that the surrounding land because it is an area of flat land on top of the mountain. In reality this land could be effected by landslides occurring on the adjacent steep mountain slopes. In the smoothing process, this area was therefore incorporated into the higher landslide-hazard zone. Even greater consideration was given before removing pockets of higher hazard from within lower landslide hazard zones. Care was also taken when considering whether to preserve pockets of lower landslide hazard in areas of essentially higher landslide hazard. In many of these instances, an area of flat river terrace gravels, or a valley floor has resulted in a lower rating, and the question that the map-maker has then to ask, is, *if a landslide occurred on the mountain above this area where is the debris likely to go?*, and; *would it affect the lower risk area?*

Most of the major landsliding that has occurred in the recent past, falls within the moderate or high landslide risk zones. An additional fifth landslide hazard zone, labelled *extreme* is also shown on the map. The extreme risk zone is defined by the areal extent of the landslides and their immediate debris accumulation areas as seen on the 1991 and 1994 satellite images. In view of the fact that these landslides are very young and were not re-vegetated at the date of the image, these landslides can be considered locally to present an extreme risk to both persons and property and could be re-activated with minimum external trigger.

As well as a measure of the probability of landsliding occurring, the map legend provides a descriptive indication of the type of damage that may be expected for a given triggering event, and describes some of the risks to persons and property.

The following data files (tables) have been used in the making of the primary landslide hazard map:

THEMATIC INFORMATION

1	VECHAZ 1	Files defining the extent of zones of landslide hazard
2	VECHAZ 2	(Drawn by GSPNG)
3	VECHAZ 3	
4	LS94_05	See Section 6.2 for details
5	TM_LS_FH	See Section 6.2 for details
6	CULTHAZA	This is a textural layer of map annotations specific to the hazard map. (Prepared by GSPNG)

CULTURAL INFORMATION

7	GAZETTEER/ Query 1	See Section 6.2 for details
8	VILLNAME	See Section 6.2 for details
9	RIVIMIL	See Section 6.2 for details
10	MAINROAD	See Section 6.2 for details
11	TRANKWL	See Section 6.2 for details
12	TENMIN	See Section 6.2 for details

MISCELLANEOUS

13	NORTH	See Section 6.2 for details
14	SCALEBAR	See Section 6.2 for details
15	PNG_LOGO	See Section 6.2 for details
16	BGS_LOGO	See Section 6.2 for details

6.3.2 Secondary landslide hazard map

A combined primary and secondary landslide hazard map for the Kaiapit area is appended to this report.

The map portrays the same primary landslide hazard information as the primary landslide hazard map, but in addition also shows information relating to the secondary hazards that might be expected.

The secondary landslide hazard zones shown on the map relate to landslide induced flooding. Such flooding can be the result of a landslide forming a dam in the headwaters of a river, which is then subsequently overtopped and breached. Similarly, where landsliding has already occurred and rivers have aggraded, the likelihood of flooding is increased, and again a flood hazard is present. The first scenario is a possible future consequence of a possible event (landsliding). It could be argued that this is stretching a predictive process to the limits, and secondary hazards are too conjectural to be represented on a map. The fact remains that in this terrain, landslide dams and associated flooding are not unusual and secondary flood damage shown on the landslide damage map bears testimony to this. Secondary hazard information is also in some respects of more concern to planners and engineers, than the primary information. For example, the destruction of bridges by floods can close a road for weeks, be expensive to replace, and cost the economy millions of dollars through disrupted services.

As well as the localities where past landslide induced flooding has occurred, the process of determining where to locate the secondary hazard zones is based on an assimilation of a number of variables. These variables include the size of river channels, the size of catchments, the relative proportion of primary hazard zones within catchments, and whether the valley geometry in the headwaters is likely to result in a blockage occurring after major landsliding takes place.

In the case of rivers that have aggraded as a result of past landsliding, a measure of the relative likelihood of one river flooding rather than another was derived by calculating the area of *bare-earth landsliding (x)* as a percentage of each of the main *catchment areas (y)* using the SQL query, calculate area of variable x entirely within variable y.

As most of the Markham valley is a natural flood plain, and the villages that are built on the flood plain may be inundated relatively frequently, it was decided to limit the extent of the hazard zones to only those areas where major infrastructure is affected.

If Landsat TM images of different dates are available, the migration of a river or a change in the quantity of unvegetated sediment in the flood plain can be detected. Following the 1993 earthquakes, when a significant amount of landslide debris entered the river system (approximately 1 km^3) some significant changes in the morphology of the rivers leaving the mountain range can be seen by comparing the May 1991 and January 1994 images.

A pictorial insert of part of the May 1991 landsat TM image has been included on the secondary landslide hazard map to show a debris fan and debris in the Maniang river, introduced following the 1988 Kaiapit landslide. Anticipated landslide induced flood zones are shown for the same area for comparison.

The secondary hazard map lists some of the main infrastructure in the Markham valley considered to be at risk.

7. AN ACCOUNT OF THE FINISTERRE RANGE EARTHQUAKES OF 1993

7.1 Introduction

On 13 October 1993, a large shallow earthquake struck near Tauta in the Finisterre mountain range (Figure 7.1). The earthquake, and subsequent series of large and small aftershocks over a period of three months, caused widespread landsliding on an almost unprecedented geographical scale, affecting an area of over 3 000 km^2. Two airstrips were severely damaged and closed, three villages were completely destroyed, and a further 58 villages were sufficiently damaged to require the evacuation of their 8 000 inhabitants. Landslides caused significant blockages in all major rivers flowing southward from the mountain range. Lakes formed behind these dams and with the catastrophic breaching of the dams, two bridges on the important Lae-Madang Highway were washed away by debris laden floods.

7.2 The earthquakes

The first earthquake occurred at 12.06 hrs local time on 13 October 1993 at 5.9°S 146.0°E in the Finisterre Range close to the Ramu Sugar Project, one of PNG's main agriculture operations (Figures 7.1 and 7.2). The earthquake had a recorded depth of 24 km and magnitude of 7.1 on the Richter Scale. A total of five other earthquakes of Richter magnitude 5 and above were recorded, including magnitude 6.8 and 6.1 aftershocks. Over the next three months, a total of 33 large earthquakes greater than Richter magnitude 5 were recorded. Figure 7.3 shows the geographical distribution of the large earthquakes and the landslides caused by the earthquakes. The earthquakes occurred in two distinct phases. The second phase commenced on 25 October 1993 when five large earthquakes struck with similar epicentres to the first phase and included magnitude 6.1 and 7.1 earthquakes. This phase of earthquakes proved to be far more destructive than the first phase, possibly because the ground was significantly weakened by the first phase shocks.

Prior to the first main earthquake on 13 October, the digital seismograph maintained by the Geological Survey of Papua New Guinea (GSPNG) at the nearby Yonki Hydropower Station was recording on average 6 or 7 small earthquakes each day. On the first day of the Finisterre earthquake series, 174 aftershocks were recorded. On the second day 234 earthquakes were recorded before gradually reducing to 64 per day on 24 October. This level increased again to 194 on 25 October when the second phase of earthquakes struck (Figure 7.4). Since then, the number of earthquakes or aftershocks recorded daily diminished, but on day 85 (5 January 1994) this still remained approximately three times higher than the background count recorded prior to the first earthquake.

Many of the aftershocks were very small and in unbroken ground would have had a negligible effect on slope instability. However, in ground already cracked and broken as a result of the larger earthquakes, the smaller events kept the landslide debris unstable. The first earthquakes struck at the end of the dry season when the majority of the slides were dry. Landslide debris in the worst affected areas, resting in a state

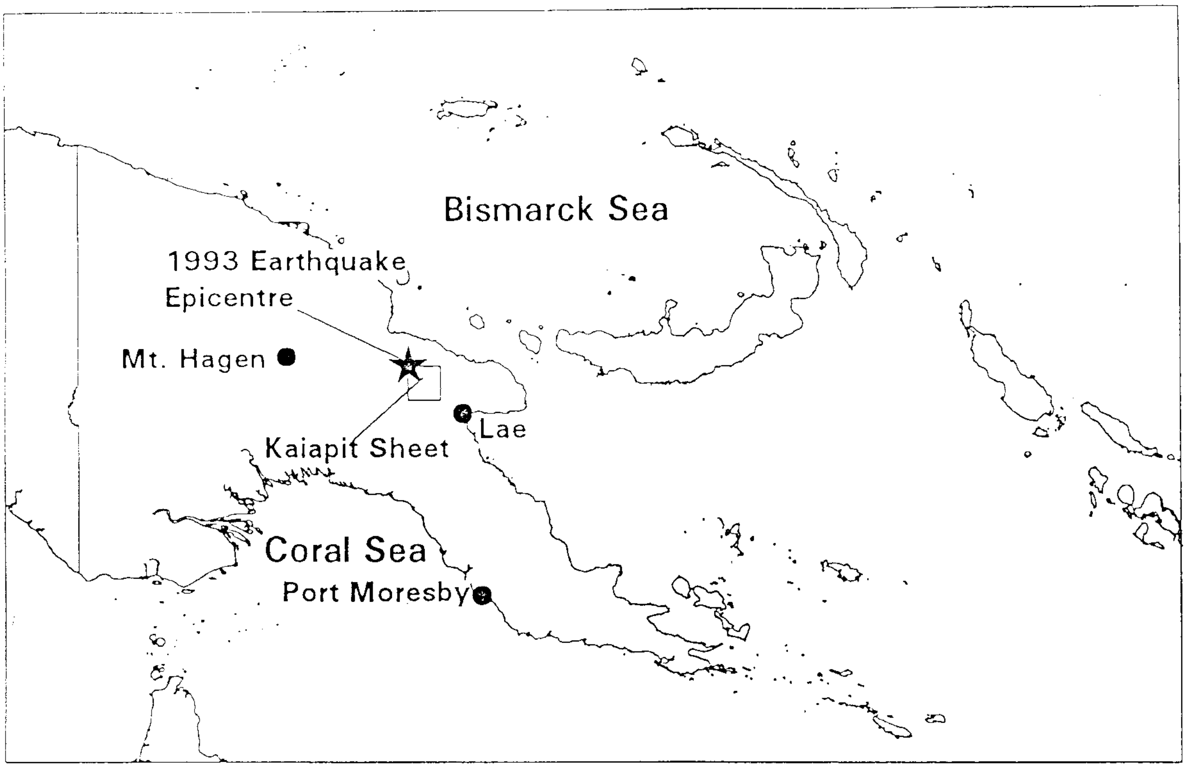


Figure 7.1 Epicentre of October 1993 earthquake.

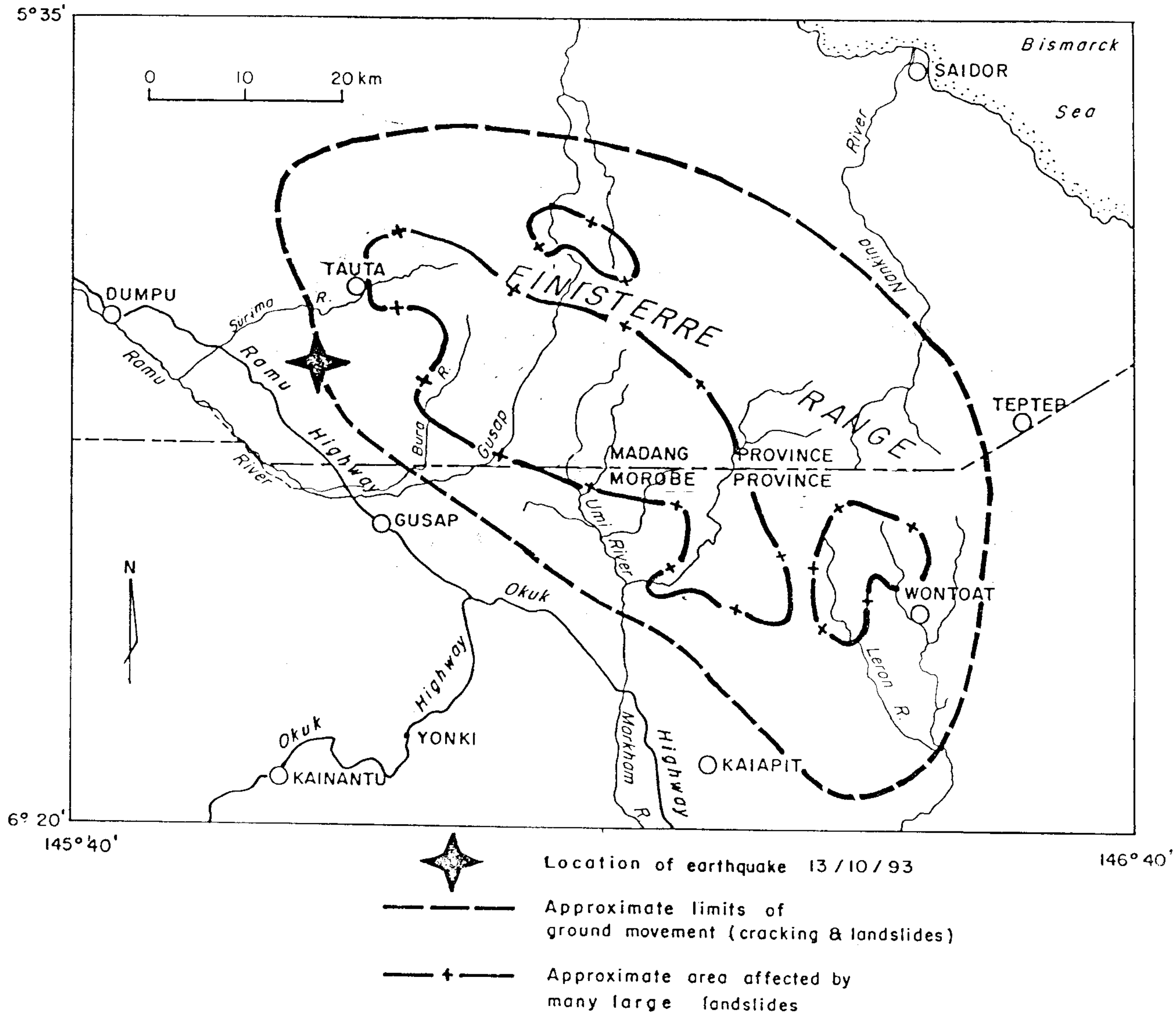


Figure 7.2 Location of earthqake affected area.

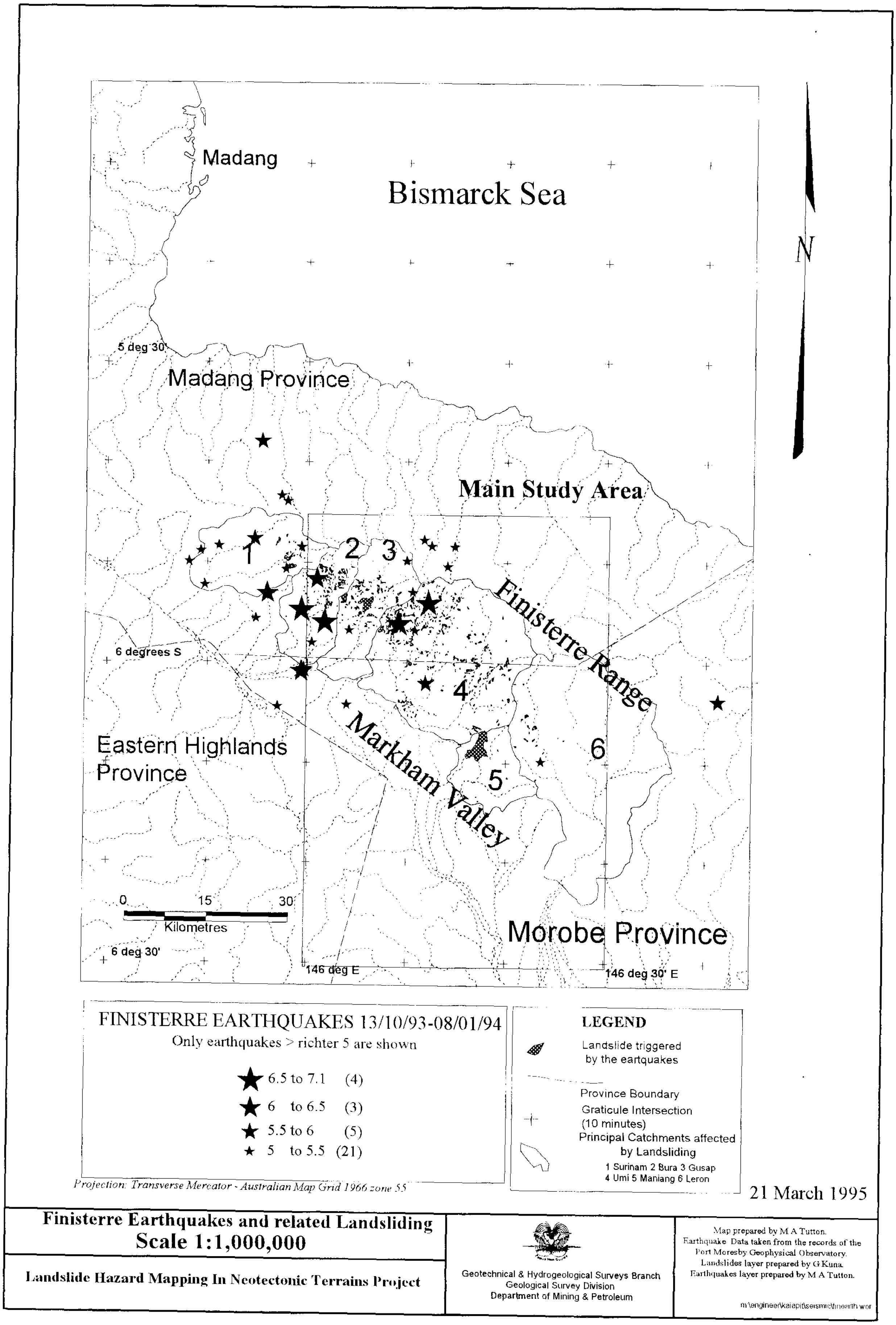


Figure 7.3 Finisterre earthquakes and related landsliding.

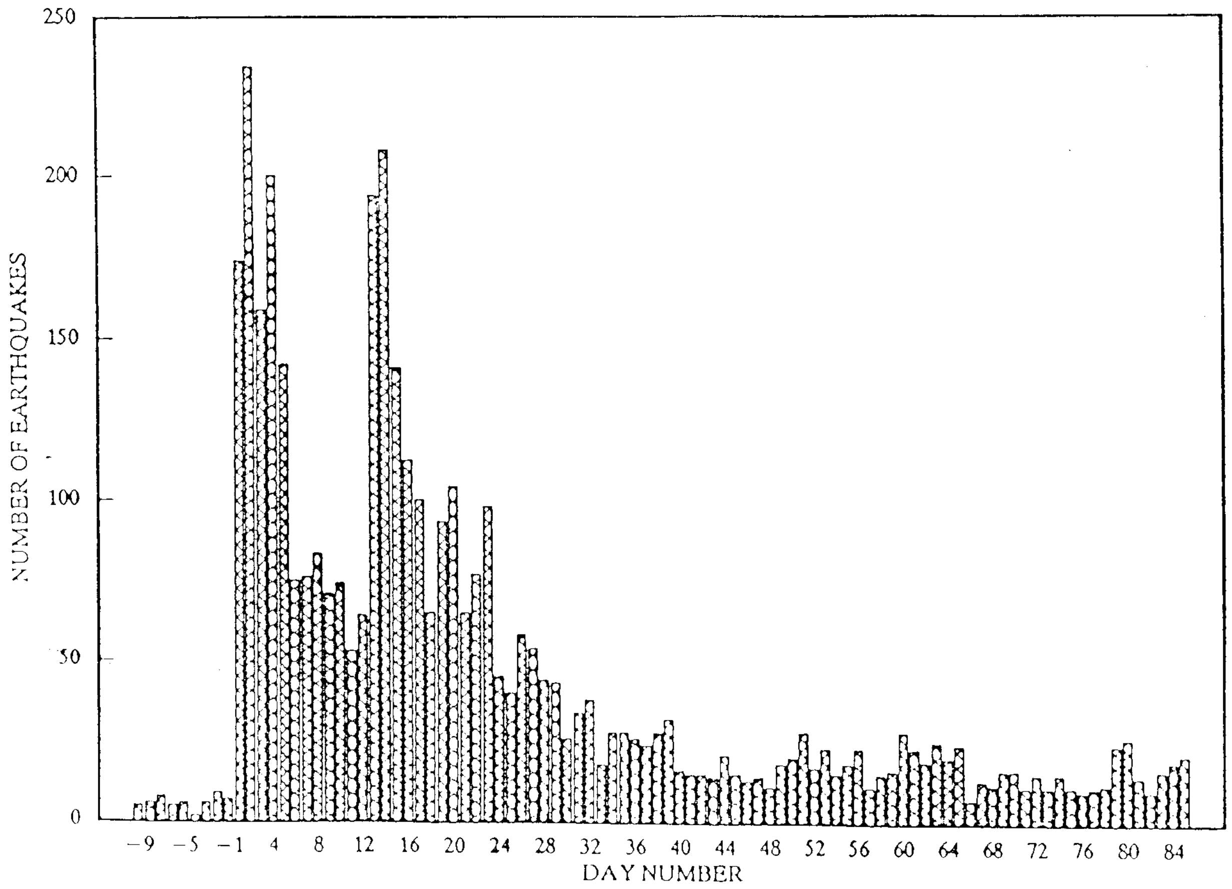


Figure 7.4 Number of seismic events per day recorded at Yonki seismograph station between October 1993 and January 1994.

of equilibrium, when subjected to further accelerations from aftershocks that on average occurred every 6 minutes at the peak of the seismicity, was remobilised and the finer material was released into the air producing dust clouds that could be seen 20 km away. The haze in Figure 7.5 is caused by dust.

7.3 Earthquake damage

Only minimal damage was caused to structures as a direct result of seismic loading induced by the earthquakes. The fail-safe mechanism of the nearby Yonki Hydropower Station shutdown operations automatically during each of the magnitude 7 earthquakes and no serious damage was reported by the Papua New Guinea Electricity Commission. The urban centres of Lae, Madang and Goroka were too far from the epicentre to experience any serious structural effects. Ramu Sugar, the largest development close to the epicentres, reported only minor structural damage, such as cracked rainwater tanks, dislodged asbestos-cement roofing sheets etc. Most major structures, including the bridges on the highway, are designed to withstand seismic loadings and no damage was reported to any of the bridges as a result of the earthquakes.

In the mountains close to the epicentre, small permanent structures, such as churches and schools built of roofing iron and sawn timber, suffered some distress. For instance, a wall in Numbugu Community School collapsed, but generally the damage was minor and limited to a handful of non-bush material buildings. Bush material houses and community buildings remained largely undamaged due to their inherent flexibility, although some would have collapsed as supporting poles gave way if it had not been for the piles of firewood stacked beneath them.

Although the direct effects of ground acceleration had negligible impact on structures, it had a tremendous impact on the stability of the land itself, causing landslides which under-cut villages and destroyed food gardens and bush tracks (Figures 7.5, 7.6, 7.7 and 7.8)

On the day the first earthquake struck, there were 37 fatalities (see appended map 'Landslide damage in the Markham'). A total of 680 landslides with a total surface area of 52 km^2 were mapped from a satellite image dated January 1994, following the earthquake. However, action taken either by villages or by the authorities responsible for the relief operation prevented any further direct fatalities. The relief operation involved hundred of hours of helicopter charter to carry out search and rescue. An alternative search and rescue strategy, formulated with the benefits of hind-sight and based on the findings this study, is given in Chapter 8.

When the first earthquake struck, a garden on a steep easterly facing hillside close to Getepa in the upper Leron River valley caused a landslide that buried 19 people who were working in the garden. The underlying geology is siltstone and an aerial inspection of the landslide scar three days later showed no evidence of water associated with the landslide. The landslide was a shallow translational slide approximately 10 m deep and mobilised only the residual soils and weathered rock mass. The debris dammed the Leron River to a depth of about 30 m causing a lake

Figure 7.5 Landslide denisty in the Finisterre Range seven days after the first earthquake.

Figure 7.6 The Gusap valley after the second magnitude 7.1 earthquake. Note the dust in the air and major blockages damming the river valley.

Figure 7.7 The Gusap valley, looking north, twelve hours after the major earthquake that devastated the valley

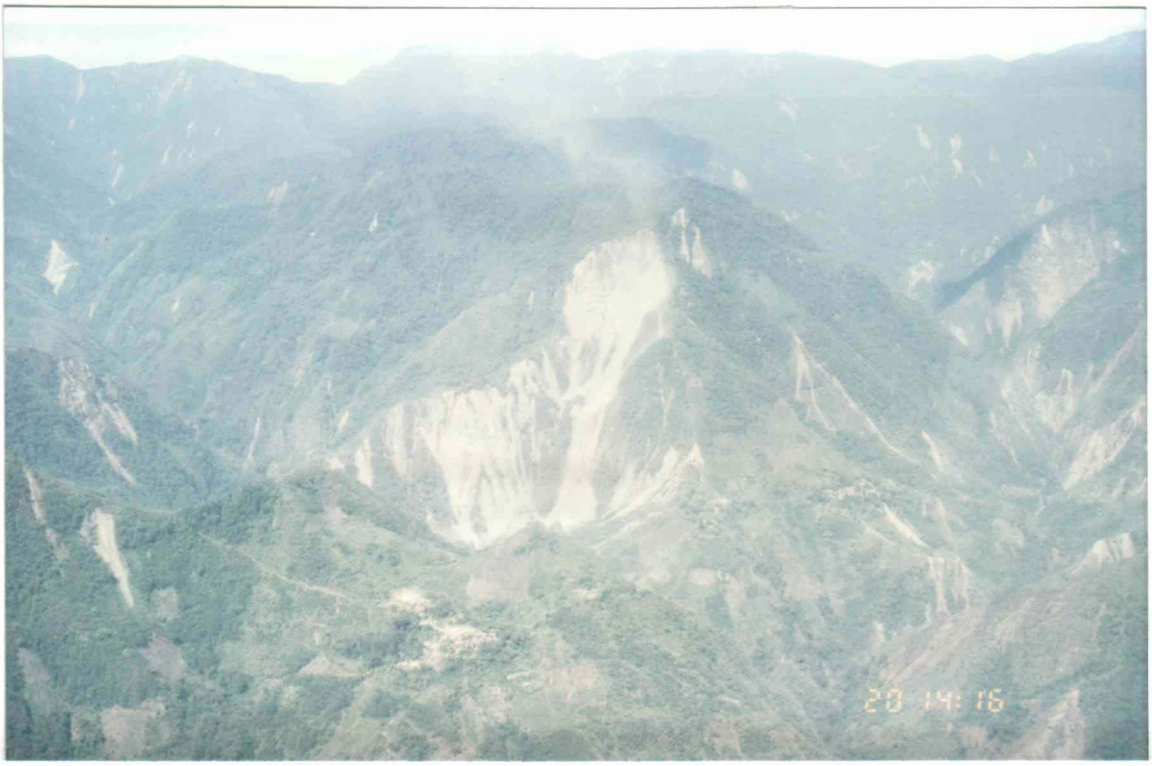


Figure 7.8 A major landslide at Sewe, close to the mountain divide affecting two villages to the right. Note the ridge top village of Moro in the foreground

to build up. The lake breached three weeks later and the flood passed without causing damage downstream. A feature very apparent at the Getepa landslide, but also typical of many of the slides that occurred in the Finisterre Range, is the effect of windblast. On the opposite side of the valley to the slide, trees have been defoliated and blown down for a distance of about 100 m from the debris toe. This can clearly be seen in Figure 7.9. The velocity of this landslide must have been considerable to have created this effect. Similar windblast damage was reported to have occurred due to the Kaiapit Landslide (Peart, 1991). The term *slide* is strictly speaking inappropriate for mass movement with such velocities and the term *debris avalanche* as defined by Varnes (1978) best describes many of the Finisterre landslides where velocities greater then 3 m s^{-1} can commonly be expected.

The second phase of earthquakes that began with a magnitude 6.1 earthquake at 20.07 local time and a magnitude 7.2 earthquake at 20.27 local time on 25 October resulted in an extension of the damaged area both northwards and westwards, affecting over 3 000 km^2 of land on both sides of mountain range. The second phase of earthquakes devastated the Bura and Gusap valleys, totally destroying the villages of Karapas and Bengumu (Figures 7.10 and 7.11) and blocking the Bura River at two locations and the Gusap River at four locations. The blockages were in two instances approximately 200 m thick, a kilometre from upstream dam toe to downstream dam toe and 300 m wide along the crest of the dam.

The first rains marking the end of the dry season arrived on 10 November 1993, and within a month of the damming of the Gusap and Bura valleys, large lakes had built up (Figure 7.12). The lowermost Bura lake and the uppermost Gusap lake each had volumes of about 60 Mm^3, the other lakes were slightly smaller.

On 26 November 1993, heavy rains resulted in overtopping on the third Gusap dam, holding a volume of about 40 Mm^3, which started to overflow. The water spilling over breached the dam resulting in the filling and subsequent breaching of the two downstream Gusap dams which had until that time impounded very little water. Villagers in the Gusap Care Centre close to the Gusap River heard the dams breaching, about an hour before the flood arrived at the bridge. The Care Centre manager then drove to the Gusap bridge and recorded the arrival of the flood at 2205 hrs. Within 5 minutes, the bridge was overtopped and torn from its abutments, shearing the holding-down bolts (Figure 7.13). The flood stayed at bankfull level for about 2 hours before gradually subsiding over the next 6 hours. A simple hydrograph drawn from these eye witness reports gives a peak water flow of about 2 800 m^3 s^{-1}.

The channel of the Gusap River was originally 19 m wide and 11 m deep. The flood changed the channel form considerably, widening it to about 28 m but also causing the river bed to rise, reducing under-bridge clearance to approximately 6 m. Since then, further debris has reduced the clearance to approximately 2 m.

On 5 December 1993, the Bura dam was partially breached. The resulting flood only overtopped the Bura bridge, although it was similar in size to that which destroyed the Gusap bridge. It was not until 12 December 1993 that the dam failed catastrophically washing away the bridge, deck and severely aggrading the river channel. Like the Gusap bridge, the clearance beneath the original bridge

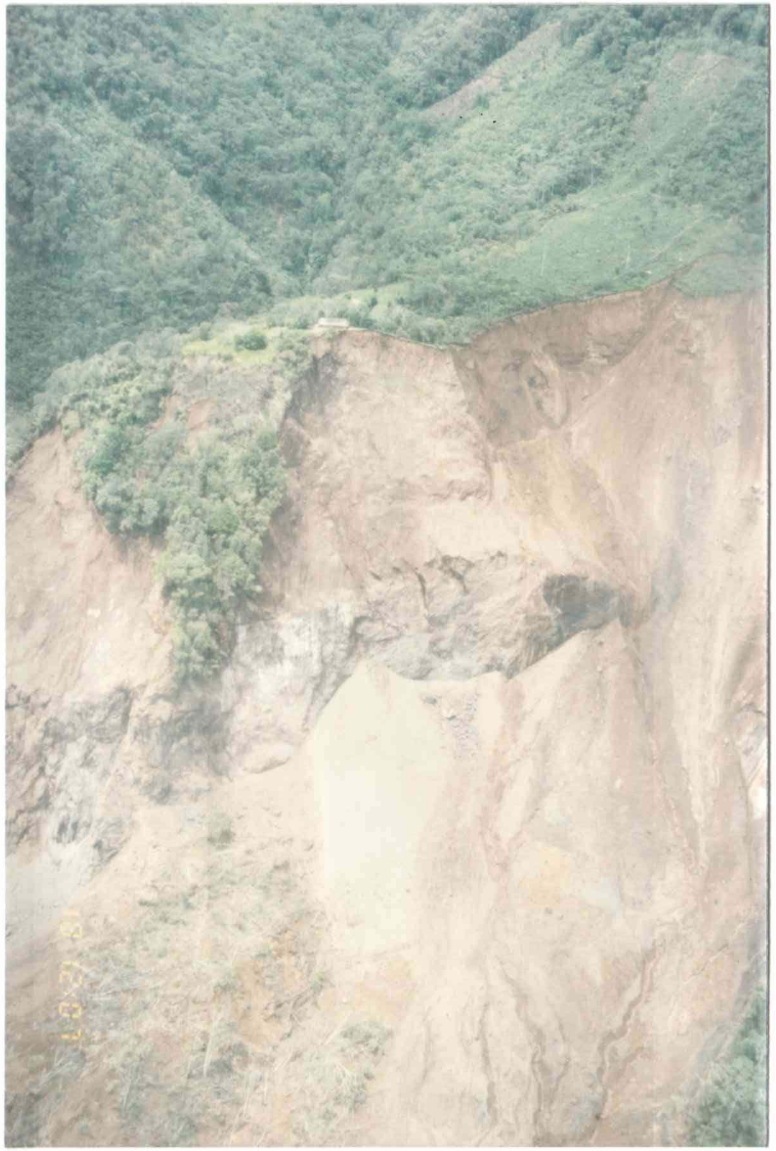


Figure 7.10 Site of village of Benguma (187 people) destroyed by landslide.

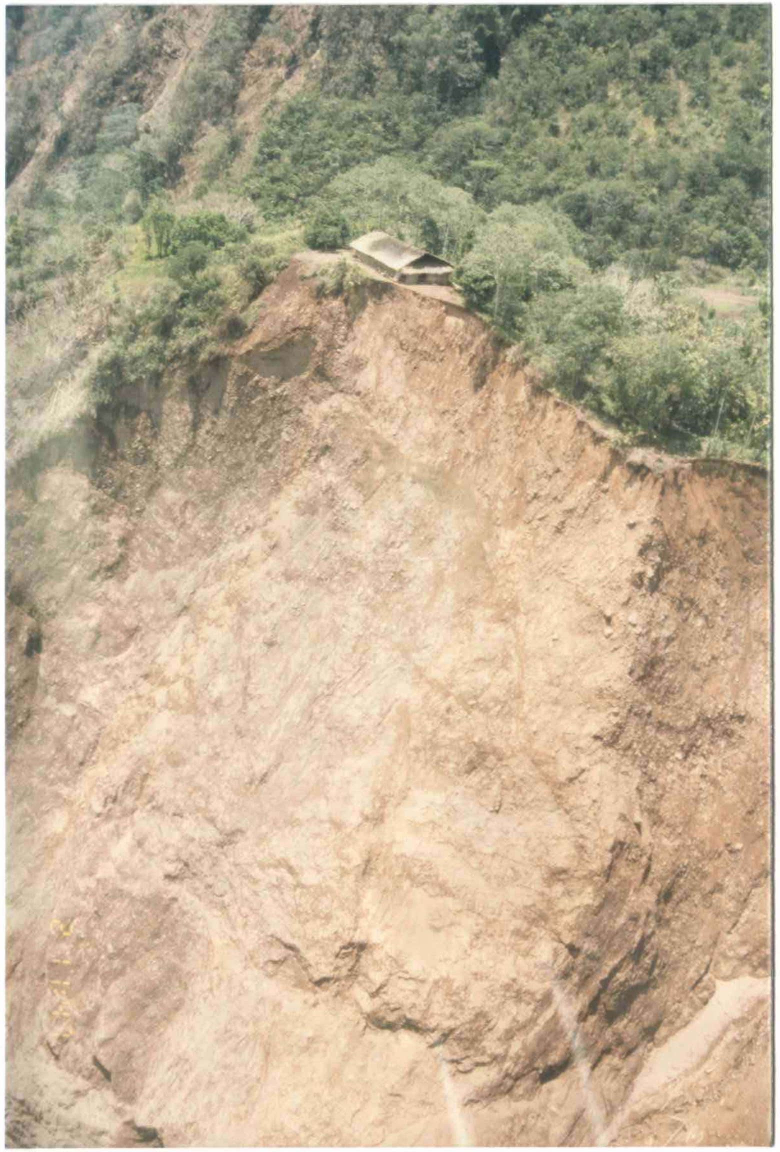


Figure 7.11 The church in Benguma, the only remaining building (also visible in landslide photograph (Figure 7.10) for scale.

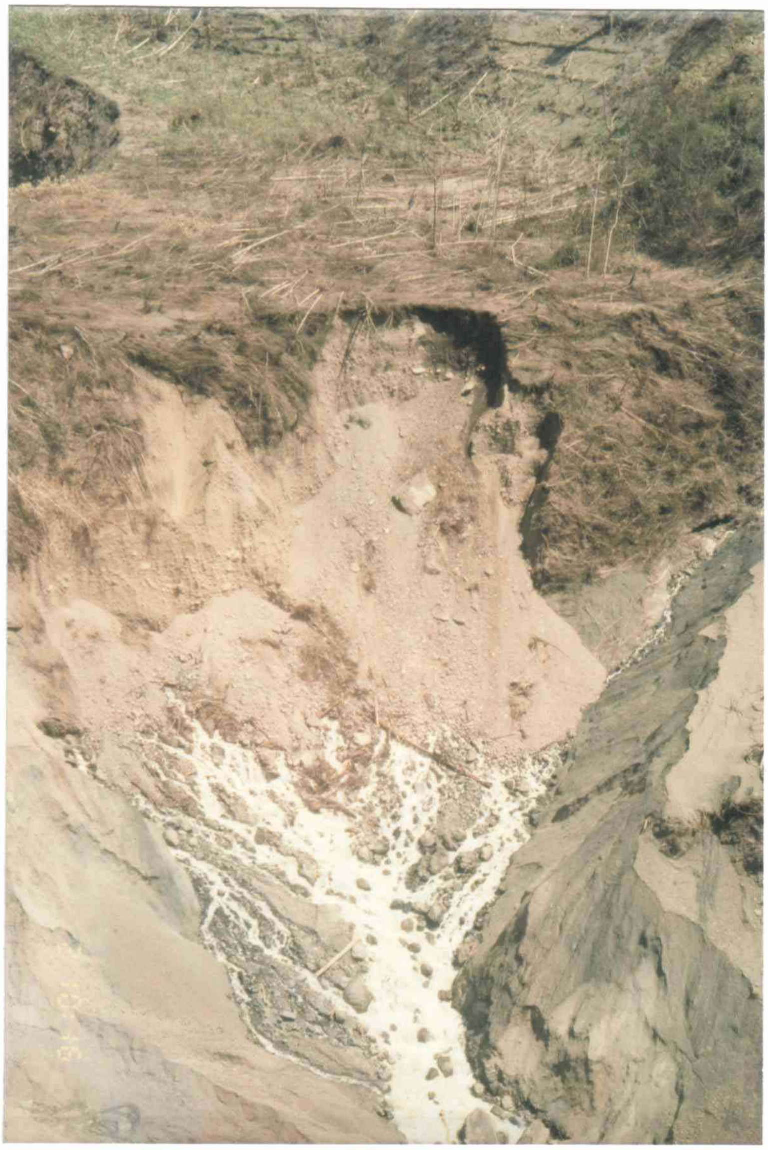


Figure 7.9 Wind blast damage to gardens opposite the Getepa Landslide. The seepage is the result of water impounded by landslide debris blocking the river.

Figure 7.12 The Gusap valley, looking south, showing the water impounded behind landslide dams three weeks after the earthquake

Figure 7.13 Landslide induced flooding overtops and washes away the Bura bridge.

was 11 m. The river has, however, since aggraded by 11 m, but as the replacement Bailey bridge was raised above the level of the original bridge, about 1 m of clearance remains beneath the new bridge.

In January 1994, the largest dams in the Bura and Gusap valleys had not completely breached and were providing a significant sediment load to the river. Added to this, smaller landsliding events continued to occur during rainfall events bringing further debris into the valley. Clearance beneath the replacement Bura bridge was such that a relatively small rainfall event could create a flood sufficient to wash away the bridge and it was regularly being overtopped. Further aggradation of the two river channels was expected. It is likely that the Bura channel may fill up completely, close to the bridge site, allowing the river to meander over the flat Ramu flood plain, creating a braided channel. This eventually will not only present difficulties for bridging, but could also inundate sugar cane fields belonging to Ramu Sugar located along both sides of both river channels.

7.4 The repatriation of evacuated villages

As a result of the earthquakes and landslides 8 000 people from 61 villages were displaced. At an early stage the government concluded that, even it was possible to micro-zone the mountain range with respect to landslide risks, all parts of the range were at some risk, and the decision to return the people to villages and traditional land must therefore rest firmly with the villagers themselves.

The displaced people, however, expected an answer from the government as to where, when and how they should return to their traditional land. To assist in this, the GSPNG devised an education programme concerned with 'Living with Landslides'. Workshops were held, and simple cartoons with pidgin captions used to illustrate the sort of things to look for when either assessing the safety of their village for re-habitation or potential landslide risks at alternative sites. Figure 7.14 is an example of one of the cartoons. Some cartoons illustrated the relationship between cultivation practices, involving the clearance of trees, and landsliding.

Within a month of completing the education programme, all villagers had returned to traditional lands. Of the 61 villages evacuated, 37 villages were re-established on their original sites; the remainder were relocated to land perceived to be at lower risk. Of particular interest is the fact that two sites were chosen as suitable land for new larger villages amalgamating the populations of several smaller villages. The sites chosen by the villagers are labelled A and B on Figure 6.1 and coincide with areas clearly identified as lower relative risk on the computer generated landslide hazard map.

7.5 Historical precedent for landsliding in the Finisterre Range

There is a historical precedent for both landsliding and earthquakes, of similar magnitude to that described, both in the Finisterre/Sarawaget Range and elsewhere in PNG.

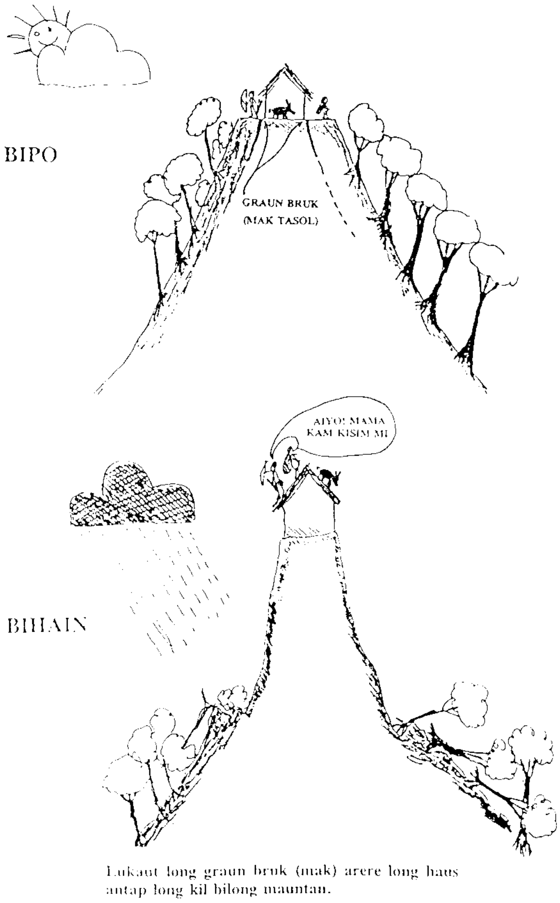


Figure 7.14 Example of cartoon used in landslide awareness education programme

Magnitude 7 earthquakes occurred in both 1987 and 1992 in the Umboi Islands and Huon Peninsula region, whilst in 1922 a shallow earthquake of the same magnitude as the 13 October 1993 earthquake occurred at almost the same location in the Markham Valley (Ripper and Letz, 1991). Landslide scars that are probably associated with the 1922 earthquake can still be seen. Villagers from Mataya have reported tension cracks along ridges that formed during the 1922 earthquake and that were not reactivated until the 1993 earthquakes, at which time the whole valley side slipped leaving the former tension crack at the landslide crown.

Similar precedents for landslides can also be found. Villagers from Barim near Tauta, reported a major landslide reactivating every wet season. In 1975, a landslide in the Ufim valley killed nine people and prompted the relocation of the village (Pieters, 1975). In 1988, an exceptionally large landslide occurred near Kaiapit, mobilising 1.8 km^3 of rock and killing 74 people (Peart, 1991). Neither the Numbugu nor the Kaiapit landslides were apparently triggered by seismic events. Unconfirmed reports from throughout the affected area give accounts of landslides and landslide dams both big and small of which no published reports are available. Events causing fatalities or significant damage since 1975 are shown on the landslide damage map appended to this report.

7.6 The long term effects of the Finisterre earthquakes and lessons to be learnt

Devastating events similar to the Finisterre earthquake are by no means unique, as described in Section 7.5. For some regions of the country, the return period of such earthquakes is short enough to justify the formulation of emergency procedure plans to be followed after future earthquake and landslide disasters. Even with the benefits of hind-sight and a landslide hazard map, there is little that can be done before an event to protect landslide vulnerable communities, other than to relocate them. The 'post event' response can, however, be planned beforehand: a proposed strategy for a rapid response to appraise the extent of a potential disaster is discussed in Chapter 8.

It is clear that not only should essential items, such as food, tents and clothing, be stocked for care centres as a preparation for future disasters, but items such as Bailey bridges should also be held in stock to cater for the secondary disasters which, despite several weeks of warning, still resulted in road closures for over 3 weeks.

It is probable that the real effects of the Finisterre Earthquakes are still to be felt. So far the infrastructure that was destroyed, includes: 2 permanent bridges and an electricity transmission tower. The loss of the tower sent Lae, the country's second city into a blackout for a week. Landsliding since 1988 has, however, resulted in at least 3 km^3 of debris entering the headwaters of the Markham and Ramu river systems, and the tributary channels will continue to aggrade reducing clearance beneath bridges and resulting in the overtopping of river banks for the foreseeable future. Undoubtedly, further bridges will be washed away by floods passing along the choked river channels that are no longer capable of carrying the same flood that would have passed safely beneath the bridge 10 years ago.

Landslide-induced flood devastation is likely to reoccur repeatedly in the next few years. The secondary landslide hazard zonation map of the Markham (appended) illustrates the extent of potential landslide-induced floods that would affect the Highlands Highway, the electricity transmission lines and villages in the Markham valley. Indeed, on 25th April 1995 a magnitude 6 earthquake 180 km to the east of the study area caused a dam to breach. The resulting flood washed away the Bura valley bridge which itself was a replacement following the 1993 earthquake sequence.

The lesson to be learnt from the Finisterre disaster is that landslide damage in the remote areas of a mountain range can result in flood damage many kilometres away in a lowland valley. Landslides cause a significant threat at many major river crossings particularly on the Highlands Highway, which could be severed for months through landslide induced floods, resulting in loss of trade and disrupted services worth millions of dollars.

8. RAPID RESPONSE TO MAJOR LANDSLIDE EVENTS: AN ALTERNATIVE STRATEGY

8.1 Introduction

This chapter discusses a possible alternative strategy that could be adopted by the Geological Survey of Papua New Guinea (GSPNG) to advise the disaster and emergency services on the extent of the damage, hazards and risks to life and property, following a major landslide event.

The first requirement is to provide early, albeit speculative, advice to the authorities on what damage to expect, say following a large earthquake. This advice would be modified as information becomes available. A statement detailing of what has happened is important, but a degree of interpretation is also needed in order to advise on subsequent events caused by continuing aftershocks, rainfall etc.

It is beyond the scope of this report to describe the response of the disaster authorities to the information provided by the GSPNG. That described here is, therefore, a simple strategy that could be adopted to appraise the extent and implications of a major landslide event both quickly and cost effectively.

8.2 Background

In recent years major landsliding on a scale similar to the 1993 Finisterre event has occurred in PNG about every four years. Clearly, smaller events occur more frequently, but it is the large events that will benefit from the strategy proposed below. As such, it can be expected that this strategy may be put into effect two or three times a decade.

8.3 Why is a special strategy needed?

A special strategy to assess and appraise major landslide disasters is needed to ensure that the emergency authorities are aware of the location, size and implications of a disaster as soon as possible after it has occurred. This will enable them to carry out operations that will mitigate against further loss of life or damage to property, and will give them the necessary information as to which communities may require material assistance. Following previous disasters, the GSPNG has provided the emergency authorities with similar information, but this has often involved the extensive use of helicopters when the affected areas are remote, as is usually the case. Clearly, with a charter rate of approximately US$ 1000/hr, helicopters are a costly and sometimes a time-consuming means of appraising a landslide disaster.

The Finisterre earthquake and landslide disaster is a good illustration of why an alternative response to the traditional helicopter reconnaissance is needed. Following this disaster, approximately one hundred helicopter flying hours were needed to assess the situation fully. To appreciate why so many hours were required it is necessary to understand something of the geography of the disaster area. When the disaster first struck, there was no information on the extent of the damage. The first reports of extensive landsliding came from villages close to the Markham valley, on the fringes of the affected area. The villages in the mountain range area are not served by any roads and have no telephones. Of the 193 villages affected, less than a handful had a working HF radio transmitter. The onus was, therefore, on the authorities to determine the extent of the damage. Locating the main areas of damage was relatively easy, but identifying the communities at risk was more difficult since only about half of the villages in the range are marked on the 1973 topographical map. The search operations were necessarily conducted without knowing either the extent of damage or location of the villages. Indeed, some villages were so remote that the neighbouring villages were not even aware of their existence!

The operation was further hindered by low cloud and by having to operate below the helicopter operational ceiling of 3 000 m. This restriction meant that in a range that rises to 4 000 m, a lot of traversing in and out of valleys was necessary as the dividing ridges were too high to fly over. Clearly this operation was both expensive and time consuming, taking a full four weeks before the situation had been fully assessed.

What was needed was an accurate map of where the villages were, and a means of getting high enough up on a cloud-free day to get an overview of the whole situation. During the search and rescue operation some of the larger landslides were in fact positioned and reported by *Air Niugini* pilots crossing the range at over 6 000 m on scheduled services.

8.4 A framework for a rapid assessment strategy

A strategy that avoids some of the problems described above would ideally involve the following:

1. <u>Landslide Hazard Maps</u>

These maps should already be available and could be used immediately after a large earthquake has been recorded, or a disaster reported, to advise the authorities on what to expect, thus allowing them to mobilise resources earlier than would otherwise be the case.

2. <u>Post-event satellite imagery</u>

By obtaining a satellite image of the region soon after a landslide disaster it would be possible to obtain a rapid overview of the situation and provide a map showing the extent of the damage. There is a need for a reliable map of an affected area at the earliest occasion. This information would enable the disaster services to be mobilised and support sought from relief agencies. It would also allow the media to report accurately and not speculate in the absence of information.

3. Village database and GIS

A spatial database accurately giving the name, position and population of villages is needed if vulnerable communities are to be identified quickly. Fortunately, since the 1993 earthquake, a digital gazetteer that can be used with GIS software has been issued. So far, the names and positions of most villages in the country have been recorded, and gradually population and other census data is being added to the database.

8.5 The proposed strategy

It is proposed that when reports of major landsliding are received, or when a large earthquake within or close to a landslide prone area is recorded by the Geophysical Observatory, the Geotechnical and Hydrogeological Surveys Branch of the GSPNG is immediately notified. If the earthquake seems to be of a magnitude, depth or at a location that may have triggered major landsliding, the nearest district office could be contacted for reports of any landslide damage.

If indications suggest that a major landslide event has occurred, then a special request should be placed for an enhanced satellite image to be provided urgently from data obtained during the next available pass of the satellite following the disaster. At present, this may require processing to be done by the supplying agency (e.g. the Australian Centre for Remote Sensing) but in future this could be done in PNG. The present study has identified the potential of Landsat TM to map landslides; based on these results, it is recommended that the standard image product should be a false-colour composite of bands 4, 5 and 7. This should be contrast stretched, edge enhanced and geometrically corrected to the PNG map projection. Photographic prints of the enhanced image at a scale of 1:100 000 are recommended. The extent of the satellite coverage should be sufficient to cover the largest perceived area of damage. Even when processing is done externally, it is recommended that the image is also obtained in a digital format to enable future use in PNG in a GIS.

Funds must be reserved and kept on account to purchase the satellite imagery so that no delays occur as a result of seeking finances.

Unfortunately, Landsat TM has a repeat orbit period of 16 days, and thus even allowing for urgent enhancement and courier delivery a minimum of three to four weeks could elapse before an image is available for use. For the larger disasters, however, to be able to get an accurate overview even within this time frame would be of great assistance and could significantly reduce the requirement for helicopter reconnaissance. Cloud cover is unfortunately is a major problem in PNG, but even on a cloudy image the information obtained through gaps in the cloud may be enough to indicate the extent and degree of damage until a better image becomes available.

An alternative for the future may be the use of satellite synthetic aperture radar (SAR) imagery. Radar has an all-weather, day and night capability and will penetrate cloud. It could thus play a significant role in identifying fresh landsliding particularly after a disaster when it might not be possible to obtain a cloud-free Landsat or SPOT image for months. Images from existing satellite SAR systems, such as ERS-1 and ERS-2, contain significant distortion and intense shadowing in mountainous regions. However, RADARSAT, due for launch in August 1995, may provide a better geometry for this type of terrain. Although such imagery would still contain terrain distortion, and for detailed mapping would be less satisfactory than Landsat, it could provide the important early indication of overall damage extent that is needed. Radar imagery has not been used as part of this study, and more work is needed to determine its usefulness. A cursory assessment of aircraft SAR images showing part of the Papua fold belt area of the southern highlands, however, did not reveal any obvious landslide related features. A detailed study is needed to assess fully whether radar imagery can be used as tool in landslide disaster response and mapping.

It is further recommended that following a major disaster a computer, scanner and printer is set up locally in the disaster co-ordination centre. The use of these facilities, particularly once a satellite image has been obtained, would allow the geologists to produce up-to-date maps showing the occurrence of landslides, onto which could be superimposed the positions and names of villages taken from the gazetteer. This would allow the vulnerable communities to be readily identified and a list of location names, together with map co-ordinates printed out to enable helicopter rescue teams to locate and if necessary evacuate the inhabitants. Daily situation maps could be produced using the GIS software MapInfo and landslide hazard zones could be drawn up regularly to convey to the disaster authorities a possibly changing situation, in terms of risk.

In conclusion, it is recommended that following a major landslide disaster, a procedure along the lines outlined above is followed. In addition to field reconnaissance, the engineering geologists should should spend a proportion of their time at the local field disaster centre preparing maps showing damage and vulnerability, anticipated short, medium and long term risks etc., in order to advise more effectively the disaster authorities. The same GIS software and computer hardware could also be used by the relief organisations to plan the distribution of food, equipment and personnel, and the databases could be interrogated to provide the accurate and instant statistics needed to inform politicians and to procure aid from donors and relief agencies.

9. CONCLUSIONS AND RECOMMENDATIONS

The PNG study represents a test of the combined 'remote sensing-plus-GIS' approach to rapid landslide hazard mapping in an active neotectonic terrain. The basis of the method is the assumption that the distribution of past landslides, interpreted from remote sensing, can indicate the probability of future landsliding events. The rationale involves establishing relationships with several independent variables, such as geology, topography, etc., which are then used to model combined probability weightings. The GIS has been demonstrated to be a convenient tool for (1) storing and displaying data, (2) analysing relationships between landslides and variables, and (3) generating thematic hazard (and risk) maps. The techniques are directed towards an operational methodology for producing provisional regional hazard maps quickly and cost-effectively.

Some specific conclusions are:

1. Given the requirement for landslide hazard maps at the regional to national scale, interpretations of enhanced Landsat TM imagery enlarged to 1:100 000, provide a practical means of mapping major landslide-landscape terrain features, recent landslide events and regional fractures (lineaments). The use of the reflected infrared bands TM 4, 5, and 7, combined as a red-green-blue false-colour composite, provide a relatively haze-free image with good discrimination of ground materials. Once geometrically registered to the national map projection, relevant geological, infrastructural and cultural, information can be readily extracted from the imagery and entered into the GIS. The availability of suitable satellite imagery is, however, somewhat limited due to persistent cloud.

2. Before any analytical work can be done on the GIS, 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 availability and quality of existing data and on what new information can be obtained. The work of capturing existing data involves digitising analogue (usually map) data, as well as converting existing digital data to an appropriate format. This is a time-consuming, labour-intensive operation involving a large amount of effort. *The size of the task should not be under-estimated.* Databasing should be regarded as an ongoing activity.

3. Once a database is established, the GIS can be used to produce customised map outputs quickly and at minimal cost. As further data become available, more reliable thematic interpretations can be produced, tailored to meet the specific requirements of users.

4. The ideal GIS for landslide hazard map production, suitable for all situations, probably does not yet exist. Vector-based GISs are efficient for storing data and providing high quality map output (see appended maps), but raster-based GIS systems are needed for analysing spatial inter-relationships between

variables. 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. For PNG, MapInfo is becoming widely used and appears to be a highly functional and user-friendly vector system. In terms of a raster system, IDRISI is a simple, low-cost system that is likely to find increasing acceptance in the south west Pacific region (especially the newly released Windows version). (ILWIS is another, slightly more powerful PC-based system than the present version of 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 stages of the work. Although in the present study, all the final modelling and output was achieved on simple PC-based GIS systems, more powerful workstations were needed to derive some of the input layers. The creation of a digital elevation model, in particular, required a major effort and the use of a powerful workstation and sophisticated software.

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 falling within each class of each variable (e.g. every lithology on the geological map), and comparing these values with the regional average. This indicates whether the landslide frequency in a class is higher or lower than might be expected over the area as a whole. 'Weights' are calculated for each class of each variable according to the strengths of the correlations established. For the Finisterre study area, landsliding was separately compared against rock type, slope steepness, slope aspect, elevation, and proximity to lineaments. According to this approach, it is not necessary to enquire why a relationship exists, nor to understand what it means, but only to demonstrate that it *does*. Once the relative weights are established, combinations of variables ('models') can be produced by summing the weights class by class over the area. The effect of combining factors which individually influence ,or at least relate to, landsliding to different degrees is to improve progressively the reliability of the model. The statistics allow the combined variable map to be quantified in terms of relative hazard probability.

6. The value and reliability of the model developed depend on the input data. Relatively few data layers were used in the pilot study and some of these were very generalised. An improved result might be expected if, for example, a detailed lithological map and a soils map were available.

7. Finally, although the approach is less than rigorous, it would appear to provide the basis for a workable solution capable of providing provisional regional hazard maps in PNG at reasonable cost and in a realistic time frame. The remote sensing/GIS approach can provide (1) landslide inventory maps and (2) provisional hazard zonation and risk maps. However, it must be

stressed that the approach is an empirical one. Clearly, many factors combine to cause a landslide and the maps produced by such rapid methods have their limitations. However, used properly, they can provide valuable information for planning and disaster preparedness.

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 PNG. The following **recommendations** are made in the context of such a possible implementation.

1. A review is needed to define priorities for landslide hazard mapping in PNG and to devise a long term strategic programme and timetable. Consideration should be given to identifying those areas potentially most at risk in terms of infrastructure, new developments and population. Flexibility should be included to allow responses to new requirements and events.

2. A project needs to be defined, lead by the Geological Survey of Papua New Guinea (GSPNG) but involving other Government departments concerned with planning and disaster preparedness, to implement a programme of regional hazard mapping on a realistic time scale.

3. The project 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 will be among the capabilities needed:

    (i) A team dedicated to landslide hazard mapping possibly comprising: project leader (engineering geologist), data manager and assistant (both GIS/image analysis specialists), project geologist(s), support technicians (2 or more), and field assistants.

    (ii) Vector- and raster-based GIS systems (MapInfo and IDRISI are recommended initially, but both systems will need to be reviewed in the light of new developments).

    (iii) Computing hardware (high-level PC or workstation, scanner, digitiser, etc.) and software to carry out in-house data capture and conversion, including the creation of digital elevation models. A separate review should be carried out to establish operational requirements; this should take into account systems already being used, or supported, elsewhere in PNG. To begin with, the creation of the digital elevation models may have to be contracted to outside agencies.

    (iv) Access to an image analysis system to carry out standard processing of Landsat TM imagery. Combined vector GIS functionality, enabling on-screen digitising of interpreted features, would be an advantage. If an in-house system is installed, specialist training will be required. (N.B. Such a system, if installed in the GSPNG could have considerable benefits for other sections).

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

4. The results reported here, though very encouraging, are preliminary. The entire methodology used in the pilot study should be critically reviewed, both in scientific terms and in relation to the work programme and time scale. The review should also consider which data are available to improve the final hazard map output. Further work, including geotechnical field investigations and laboratory testing, is required to fully validate the hazard maps by conventional engineering geology techniques. The results of such evaluations should be used, if necessary, to modify and improve the methodology. To achieve consistent results over a period of time, quality assurance procedures need to be established. This is particularly important in regard to the interpretation of satellite imagery: by its nature, this is a subjective process and checks are required to ensure, as far as possible, that different workers adopt the same interpretative procedures. Liaison with other GIS workers in the country should be established to agree on data catalogues, exchange procedures and formats.

5. Consideration should be given to the use of Intera SAR imagery (high-resolution airborne radar) for areas of the country where this is available. Because this type of imagery is unaffected by cloud, it could provide a very important and useful remote sensing data set. The use of satellite radar (such as the Canadian RADARSAT due for launch in August 1995) may provide a reliable means of obtaining regional information on the extent of major new earthquake/landslide events rapidly as part of a national disaster response strategy.

In conclusion, the study has decribed the past occurrence and significant future potential for destructive landsliding in Papaua New Guinea. It has identified the need for regional and national landslide hazard maps to identify vulnerable communities, and to provide information to planners and others involved in the design of major infrastructure. By locating infrastructure away from the areas of greatest landslide risk, significant economic savings can be made.

The approach described has been largely empirical, but the results have been extremely encouraging; it believed that landslide hazard maps of this type are an essential prerequisite to improved communications and infrastructure development within Papua New Guinea. It is strongly recommended that serious consideration be given to implementing a landslide mapping programme based on this general approach as a national priority.

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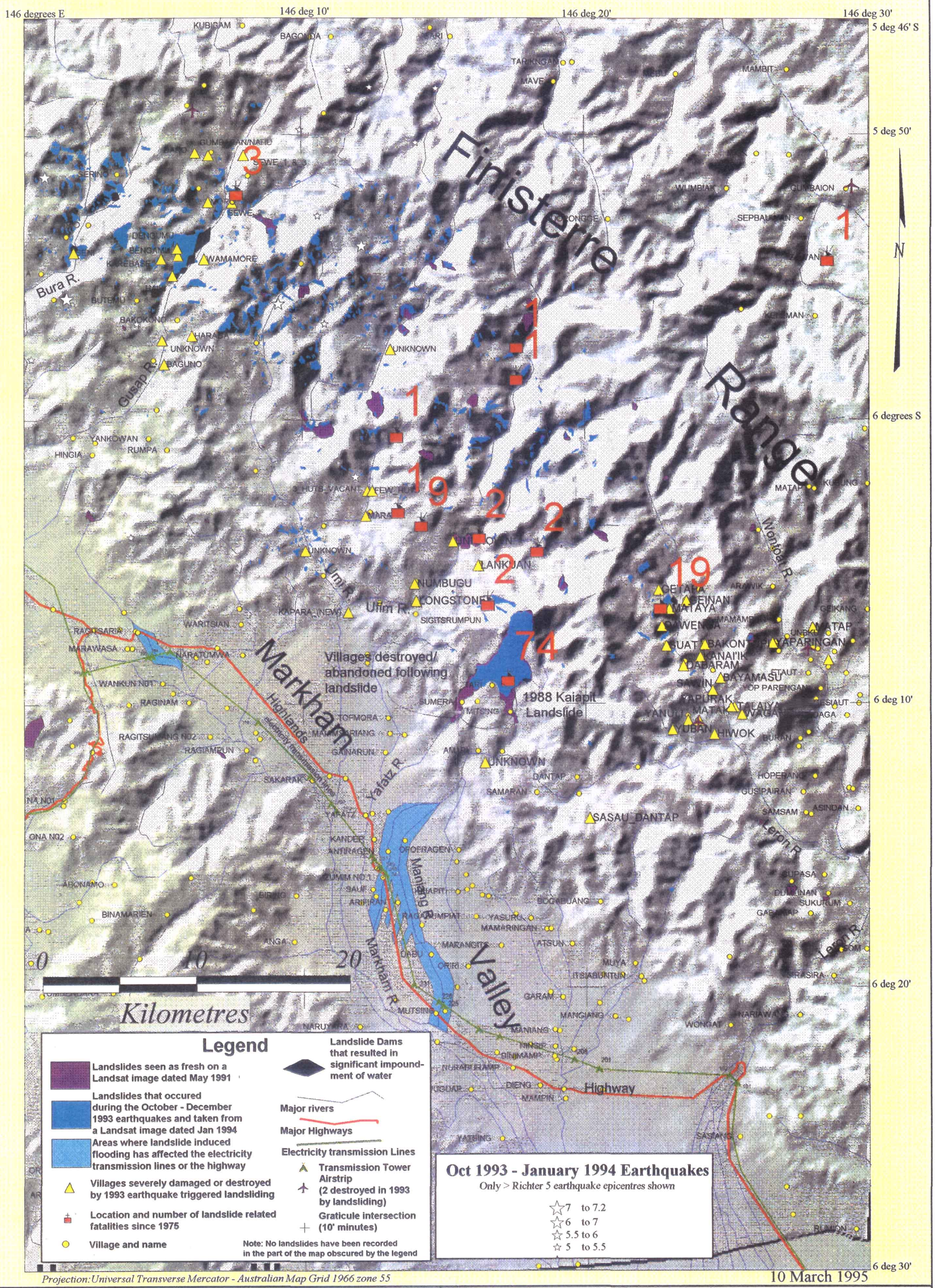
The Geological Survey of Papua New Guinea is pleased to have worked jointly with the British Geological Survey on this project and to co-author this report.



LANDSLIDE DAMAGE IN THE MARKHAM
Scale 1:250,000

The map shows landslides, landslide related flooding, landslide related fatalities, selected earthquake epicentres and villages damaged or destroyed by landslides since 1975

Landslide Hazard Mapping In Neotectonic Terrains Project

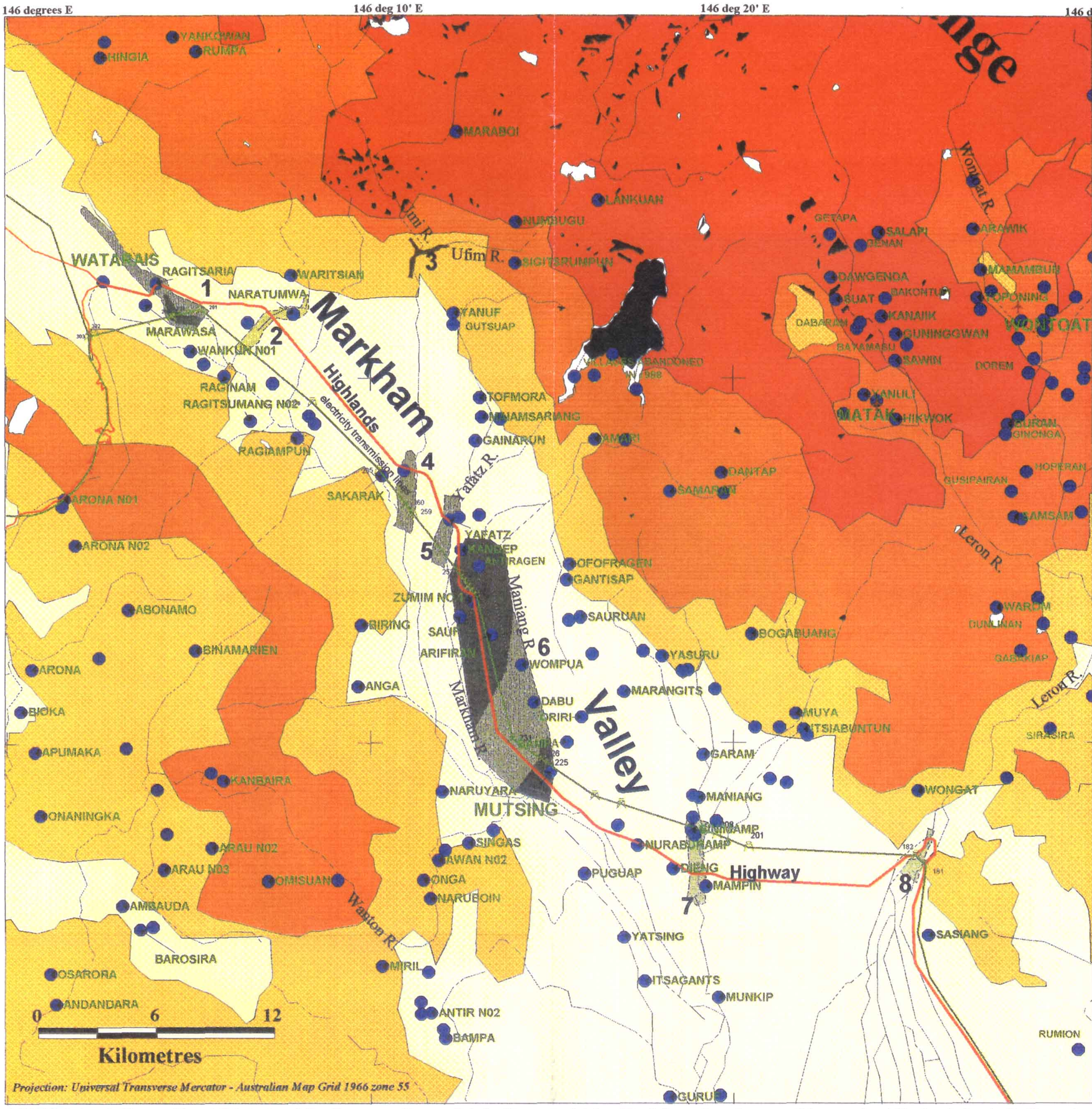
Papua New Guinea

BGS 1835

Geotechnical & Hydrogeological Surveys Branch
Geological Survey of Papua New Guinea
in technical association with the
Remote Sensing Group of the British Geological Survey

Map prepared by M A Tutton. Digital data layers prepared by T J Browne, J Buleka, G Kuna, and M A Tutton of the Geological Survey of Papua New Guinea.

Shaded relief backdrop has been prepared by the Remote Sensing Group of the British Geological Survey from a digital elevation model made from the Kaiapit and Saidor 1:100,000 topographical Map sheets.



CAUTION: Landslides and Landslide induced flooding cannot be predicted with any certainty. The information shown on this map should be treated as indicative only.

Scale 1:250,000

LEGEND

Primary Landslide Hazard Zones

Anticipated Qualitative Risks to Persons and Property directly arising from landslides

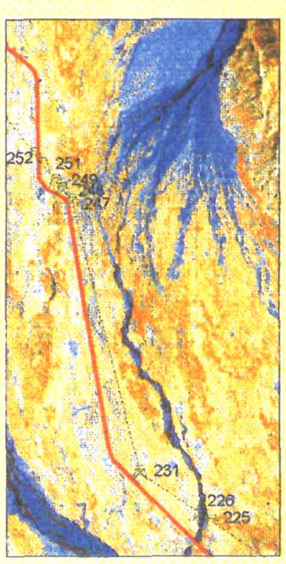
Negligible	*Landsliding on any scale rare even following extreme earthquakes or rainfall (secondary landslide induced flood risks may however prevail)*
Slight	*Small landslides likely to occur after intense earthquakes or rainfall*
Moderate	*Small scale landsliding possible at any time, significant landsliding possible after intense earthquakes or rainfall*
High	*Significant landsliding possible at any time, landsliding may be catastrophic and widespread following intense earthquakes or rainfall. All major infrastructure should avoid this zone*
Extreme	*Landslides active in 1994 and 1991 and likely to re-activate without warning giving rise to extreme vulnerability for persons, gardens, villages and roads located on or below these areas*
Village	
Electricity Lines and Towers	
Graticule Intersection (10 minutes)	

Secondary Landslide Hazard Zones

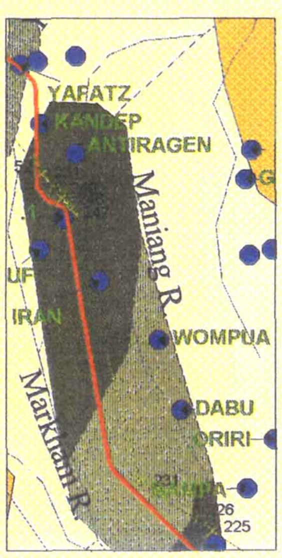
Anticipated Qualitative Risks to Major infrastructure through flooding as a secondary or induced effect of landsliding.

NB.: Only potential landslide induced flood paths affecting significant infrastructure are indicated. Much of the Markham valley is a natural flood plain.

Low	*Generally less than 2% of the upper catchment affected by landsliding and river channels not currently choked by debris but a flood risk is perceived possible especially following future landsliding*
Moderate	*Upper catchments currently affected by landsliding and river channels aggrading reducing the rivers capacities to cope with high periods of discharge*
High	*Upper catchments currently affected by landsliding, river channels aggrading and river geometries such that during periods of high discharge serious flooding could occur with serious implications to engineering structures*



Scale 1:200,000



Scale 1:200,000

The lefthand inset is taken from a May 1991 image. It shows an alluvial fan fuelled by the debris from the 1988 Kaiapit Landslide. Comparison with a similar image taken 3 years later shows that the river channel has migrated westwards towards the main road and electricity transmission line corridor. The righthand inset is included to show the two zones of anticipated flood risk.

Selected Infrastructure at risk

1. *Beboi creek crossing and transmission towers. (Tower was undercut due to flooding in February 1995)*
2. *Highway and transmission line crossings at Binta Creek*
3. *Provincial road to Sigitsrumpun. (Road effected by flooding in 1993)*
4. *Leron Bridge and transmission line crossings. Significant landslide debris is available in the upper catchment to aggrade the river.*
5. *Yafatz crossings*
6. *Highway between Kandep and Mutsing, Mutsing bridge and the electricity transmission towers between Kandep and Mutsing. (Serious flooding in 1988, minor flooding in 1993)*
7. *Gorambampan Creek crossing*
8. *Leron Bridge (Although the clearance beneath the bridge is generous, the upper Leron catchment has much potential for large landslide dams to occur that could lead to catastrophic flooding on breaching. Such flooding could damage the central pier of the bridge)*

Geotechnical & Hydrogeological Surveys Branch
Geological Survey Of Papua New Guinea
in technical association with the
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PRIMARY AND SECONDARY LANDSLIDE HAZARD ZONES
The Markham Valley, Papua New Guinea — Kaiapit sheet 8185

Landslide Hazard Mapping In Neotectonic Terrains Project

Map is based on digital Landslide, topographical, geological, structural, seismic and cultural data. Digital data layers have been compiled by T J Browne, J Buleka and M A Tutton of the Geological Survey of Papua New Guinea, the Remote Sensing Group of the British Geological Survey and the Papua New Guinea National Mapping Bureau.
Map drawn by M A Tutton 10 April 1995 using MapInfo version 3.0
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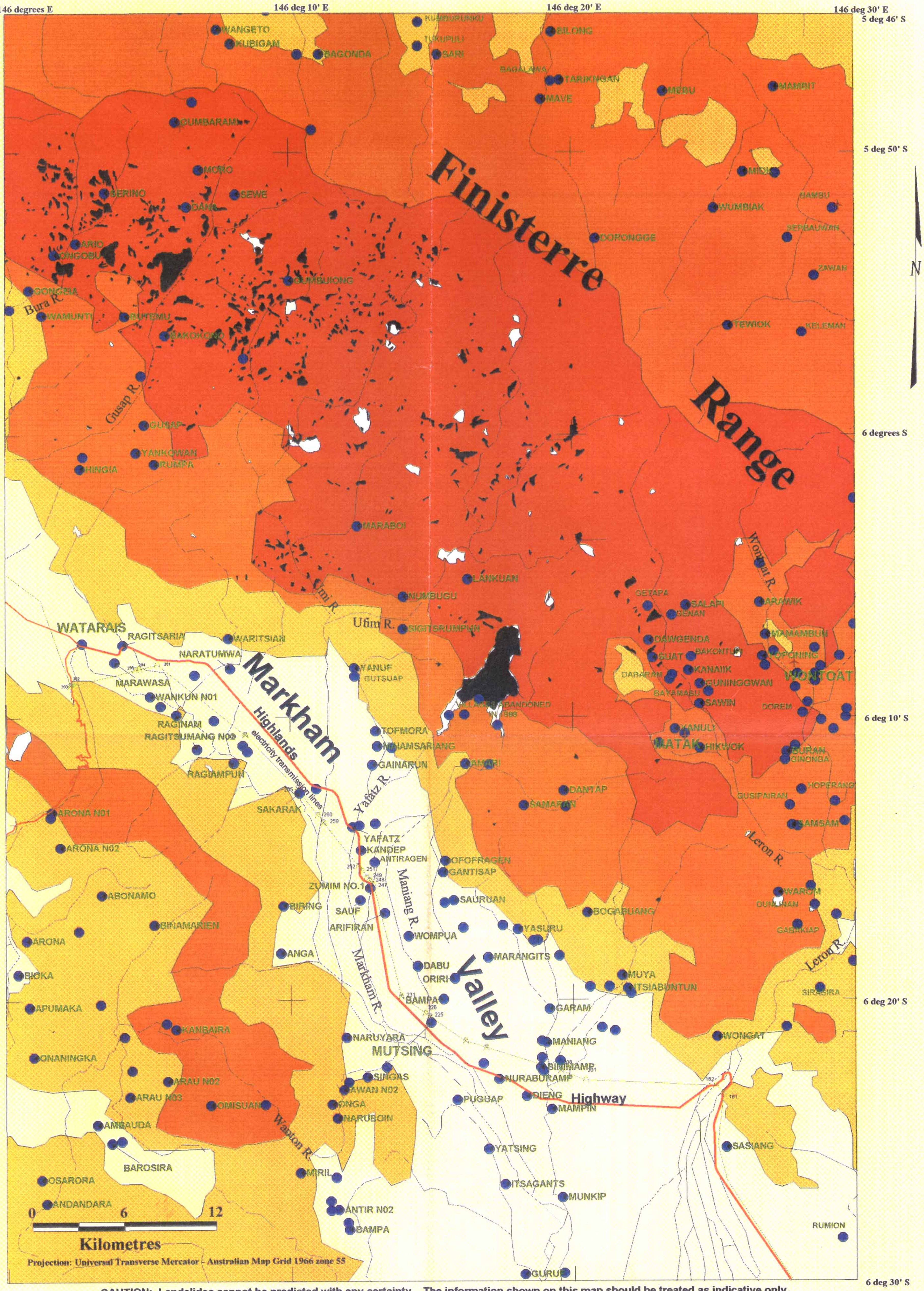

CAUTION: Landslides cannot be predicted with any certainty. The information shown on this map should be treated as indicative only.

LEGEND

Primary Landslide Hazard Zones

Anticipated Qualitative Risks to Persons and Property

Negligible	Landsliding on any scale rare even following extreme earthquakes or rainfall (secondary landslide induced flood risks may however prevail)
Slight	Small landslides likely to occur after intense earthquakes or rainfall
Moderate	Small scale landsliding possible at any time, significant landsliding possible after intense earthquakes or rainfall
High	Significant landsliding possible at any time, landsliding may be catastrophic and widespread following intense earthquakes or rainfall. All major infrastructure should avoid this zone
Extreme	Landslides active in 1994 and 1991 and likely to re-activate without warning giving rise to extreme vulnerability for persons, gardens, villages and roads located on or below these areas

Village

Electricity Lines and Towers

Graticule Intersection (10 minutes)

Geotechnical & Hydrogeological Surveys Branch
Geological Survey Of Papua New Guinea
in technical association with the
Remote Sensing Group of the British Geological Survey

PRIMARY LANDSLIDE HAZARD ZONES IN THE MARKHAM

Scale 1:250,000

Landslide Hazard Mapping In Neotectonic Terrains Project

Map is based on digital Landslide, topographical, geological, structural, seismic and cultural data. Digital data layers have been compiled by T J Browne, J Buleka and M A Tutton of the Geological Survey of Papua New Guinea, the Remote Sensing Group of the British Geological Survey and the Papua New Guinea National Mapping Bureau.

Map drawn by M A Tutton 4 April 1995 using MapInfo version 3.0

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

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
0	100	7209	0	0
1	37485	108959	34.4	18
2	7548	41746	18.1	9
3	3587	37596	9.5	5
4	27264	64708	42.1	22
5	619	2320	26.7	14
6	0	172	0	0
7	397	71496	0.6	0
8	620	20378	3.0	2
9	3370	48648	6.9	4
10	0	4868	0	0
11	0	3056	0	0
12	0	6425	0	0
13	0	280	0	0
14	0	1506	0	0
15	0	5589	0	0
16	0	108	0	0
17	0	75	0	0
18	1457	3471	42.0	21
19	173	1394	12.4	6
20	602	1535	39.2	20
21	2671	15558	17.2	9
22	5012	17703	28.3	14
TOTAL	90905	464800		

1.	Tom/Teg	Mebu Beds (greywacke)/Gusap Argillite
2.	Tml	Mena Beds (micaceous sandstones, greywacke)
3.	Tpl	Leron Formation (bedded sandstone)
4.	Tof	Finisterre Volcanics (basalt andesite breccia)
5.	Qpg	Kainantu Beds (sand, gravel)
6.	Ts	Tertiary (gabbro)
7.	Qphf	Quaternary (conglomerate)
8.	Tmak	Akuna Intrusive Complex
9.	Tou	Omaura Greywacke (tuffaceous shale & siltstone)
10.	Qha	Holocene (gravel, sand, silt etc)
11.	Qpn	Kainatu Beds (conglomerate etc)
12.	Tou	Omaura Greywacke (limestone units)
13.	Ton	Nasananka Conglomerate
14.	Kuv	Mount Victor Granodiorite
15.	Tme	Elandoru Porphyry
16.	Tpl	Leron Formation
17.	Tml	Mena Beds (minor limestone lenses)
18.	Qs	Quaternary (chaotic)
19.	Tpi	
20.	Tmgo	Gowop Limestone
21.	Tmgk	Kabwum Limestone Member
22.	Tmp	Tipsit Limestone

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

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
1	2976	108661	2.7	1
2	5426	50431	10.8	6
3	10614	57722	18.4	9
4	14910	62141	24.0	12
5	16520	60548	27.3	14
6	15801	52991	29.8	15
7	13390	38324	34.9	18
8	7793	20471	38.1	19
9	2487	6618	37.5	19
10	481	1408	34.2	17
11	72	426	16.9	9
12	21	122	17.2	9
13	7	107	6.5	3
14	0	87	0	0
15	0	597	0	0
16	54	836	6.5	3
17	191	2586	7.4	4
18	162	724	22.4	11
TOTAL	90905	464800		

Class 1 0 - 5°
Class 2 6 - 10° etc

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

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting
1	1239	33437	3.7	2
2	371	66230	0.6	0
3	2475	46751	5.3	3
4	8731	47724	18.3	9
5	9344	41725	22.4	11
6	9660	47653	20.3	10
7	8563	42518	20.1	10
8	8647	29269	29.5	15
9	9237	24560	37.6	19
10	8816	22504	39.2	20
11	7814	20116	38.8	20
12	6894	16514	41.7	21
13	4764	12078	39.4	20
14	2875	8346	34.4	18
15	1305	4590	28.4	15
16	170	779	21.8	11
17	0	6	0	0
TOTAL	90905	464800		

Class 1 0 - 250 m asl
Class 2 251 - 500 m asl etc

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

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting*
0	156	3138	5.0	2
1	0	5564	0	0
2	0	11358	0	0
3	1	5114	0	0
4	0	4270	0	0
5	2	8634	0	0
6	240	1943	12.4	3
7	0	5	0	0
8	0	2919	0	0
9	0	73665	0	0
10	0	4042	0	0
11	1472	5061	29.1	8
12	1273	2154	59.1	15
13	0	3251	0	0
14	6	4969	0.1	0
15	299	2458	12.2	3
16	321	4310	7.5	2
17	0	2599	0	0
18	11	3084	0.4	0
19	0	1	0	0
20	0	5313	0	0
21	197	4109	4.8	1
22	187	5583	3.4	1
23	0	2454	0	0
24	0	1854	0	0
25	9	4381	0	0

Class	Landslide pixels	Total pixels	Landslide Total (%)	Weighting*
26	0	1737	0	0
27	648	5145	12.6	3
28	886	2874	30.8	8
29	517	6042	8.6	2
30	112	112	100.0	26
31	205	3288	6.2	2
32	152	2403	6.3	2
33	391	3381	11.6	3
34	625	4221	14.8	4
35	1094	4120	26.6	7
36	394	438	90.0	23
37	0	1895	0	0
38	1045	6385	16.4	4
39	1101	3220	34.2	9
40	4840	18225	26.6	7
41	1792	6636	27.0	7
42	10	1618	0.6	0
43	581	3863	15.0	4
44	2966	4109	72.2	19
45	55	1853	3.0	1
46	912	2433	37.5	10
47	105	3230	3.3	1
48	1687	4319	39.1	10
49	2079	4547	45.5	12
50	209	6590	3.2	1
51	480	1538	31.2	8
52	45	3753	1.2	1
53	0	3465	0	0

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting*
54	10	3971	0.3	0
55	0	1560	0	0
56	1094	4552	24.0	6
57	1807	5061	35.7	9
58	149	213	70.0	18
59	2119	4398	48.2	13
60	633	1037	61.0	16
61	1488	3463	43.0	11
62	232	4738	4.9	2
63	605	5364	11.3	3
64	5641	15336	36.8	10
65	1629	3991	40.8	11
66	609	3743	16.3	4
67	655	1349	48.6	13
68	289	7804	3.7	1
69	4349	7768	56.0	15
70	507	2098	24.2	6
71	2397	2792	85.9	22
72	5163	8183	63.1	16
73	515	2809	18.3	5
74	2631	6116	43.0	11
75	1762	6199	28.4	8
76	3331	6157	54.1	14
77	4778	5271	90.7	23
78	3291	6509	50.6	13
79	109	3733	2.9	1
80	4685	4956	94.5	24
81	3480	5325	65.4	17

Class	Landslide pixels	Total pixels	Landslide / Total (%)	Weighting*
82	106	5927	1.8	1
83	165	3491	4.7	1
84	1	4049	0	0
85	4	3552	0.1	0
86	3521	7614	46.2	12
87	1119	5632	19.9	5
88	1898	6434	29.5	8
89	1346	5529	24.3	6
90	1202	2255	53.3	14
91	480	2121	22.6	6
TOTAL	90905	464800		

* Weighting divided by 2 (for explanation see Chapter 5)

Table A1.5: Cross-tabulation of lineament buffers against landslide initiation points

Class	Initiation points	Total for buffer	Expected	Actual / Expected (%)	Weighting
1	88	21199	52	1.69	17
2	219	58416	144	1.52	15
3	194	52783	130	1.49	15
4	108	33592	83	1.30	13
5	83	29229	72	1.15	12
6	103	34780	86	1.20	12
7	50	20330	50	1.00	10
8	65	20240	50	1.30	13
9	55	17085	42	1.31	13
10	48	13324	33	1.45	15
TOTAL	1013	300978	742		

Based on:

Total initiation points in study area = 1141
Total pixels in study area = 464800
Expected initiation points = 1141/464800 = 1 per 407 pixels

Class 1 Buffer zone 0 - 100 m
Class 2 Buffer zone 101 - 200 m etc

Table A1.6: Cross-tabulation of geology + slope against total landslides (Model 2)

Logical weighting	Landslide pixels	Total pixels	Landslide Total (%)	Recalculated weighting
0	119	82139	0.1	0
2	322	12091	2.7	1
3	328	15704	2.1	1
4	200	8882	2.3	1
5	1264	16560	7.6	4
6	1685	27991	6.0	3
7	1071	14077	7.6	4
8	3005	27518	10.9	6
9	2209	14819	14.9	8
10	4157	23573	17.6	9
11	33	813	4.1	2
12	6357	29612	21.5	11
13	1199	3828	31.3	16
14	8997	30022	30.0	15
15	5063	16659	30.4	16
16	18339	50763	36.1	18
17	4522	9368	48.3	25
18	24539	60270	40.7	21
19	153	330	46.4	24
20	7343	19781	37.1	19
TOTAL	90905	464800		

Table A1.7: Cross-tabulation of geology + slope + lineaments against total landslides (Model 3)

Logical weighting	Landslide pixels	Total pixels	Landslide Total (%)	Recalculated weighting
0	87	74245	0.1	0
1	71	2240	3.2	2
2	227	19121	1.2	1
3	1016	18018	5.6	3
4	983	23668	4.2	2
5	1361	21812	6.2	3
6	2077	19769	10.5	5
7	1199	11480	10.4	5
8	3179	20973	15.2	8
9	5858	28499	20.6	11
10	7040	28888	24.4	12
11	11186	35345	31.6	16
12	14911	45761	32.6	17
13	6962	22238	31.3	16
14	6833	20171	33.9	17
15	10450	29870	35.0	18
16	11717	27777	42.2	22
17	3828	9823	39.0	20
18	1920	5102	37.6	19
TOTAL	90905	464800		

Table A1.8: Cross-tabulation of geology + slope + lineaments + elevation against total landslides (Model 4)

Logical weighting	Landslide pixels	Total pixels	Landslide / Total (%)	Recalculated weighting
0	2	43230	0	0
1	81	28895	0.3	0
2	126	11886	1.1	1
3	654	14255	4.6	2
4	825	28885	2.9	1
5	796	19272	4.1	2
6	1917	26502	7.2	4
7	1839	15522	11.8	6
8	3458	26217	13.2	7
9	2967	15959	18.6	10
10	7827	35608	22.0	11
11	5031	20350	24.7	13
12	10680	34773	30.7	16
13	8590	24548	35.0	18
14	17177	45171	38.0	19
15	8692	23027	37.7	19
16	8867	23481	37.8	19
17	7338	16700	43.9	22
18	3995	10369	38.5	20
19	43	150	28.7	15
TOTAL	90905	464800		

Table A1.9: Cross-tabulation of geology + slope + soil + lineaments + elevation + catchments against total landslides (Model 5)

Logical weighting	Landslide pixels	Total pixels	Landslide Total (%)	Recalculated weighting
0	0	42916	0	0
1	28	32891	0.1	0
2	110	12226	0.9	0
3	210	29628	0.7	0
4	555	24919	2.2	1
5	981	23962	4.1	2
6	1565	20626	7.6	4
7	3077	21532	14.3	7
8	3305	24693	13.4	7
9	4914	26804	18.3	9
10	7023	29824	23.5	12
11	8085	30042	26.9	14
12	9373	34728	27.0	14
13	11205	32975	34.0	17
14	10877	28181	38.6	20
15	10044	20889	48.1	25
16	9895	15225	65.0	33
17	5615	8184	68.6	35
18	2831	3225	87.8	45
19	1186	1304	91.0	47
20	26	26	100.0	51
TOTAL	90905	464800		