An implementation strategy for landslide hazard preparedness

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EXECUTIVE SUMMARY

This document is the principal report resulting from successive research projects undertaken by the British Geological Survey under support from the Department for International Development (DFID) on landslide hazard mapping. The aim of the studies has been to develop a generic approach to landslide hazard modelling that can be applied and adapted in developing (as well as developed) countries worldwide. The purpose of this report is to outline a strategy for landslide hazard preparedness based on this generic approach. The ultimate aim of the work is to prevent or minimise loss of life and damage to property.

Conventional landslide hazard mapping involves detailed and costly ground geotechnical surveys. These result in accurate, reliable maps that are essential in site planning in difficult terrain. However, such surveys are time-consuming and expensive, and are therefore impractical and usually unjustified for larger regions. The approach described here provides an alternative, rapid and cost-effective solution to the problem of providing regional hazard information. It is based on the concept that the past is the key to the future; that is, landslides are most likely to happen in areas where the ground conditions that caused them in the past still persist today. By identifying the distribution of past landslide events, understanding why they occurred and mapping the relevant ground conditions over wider areas, it is possible to predict where landslides are most likely to occur in the future. The resulting regional hazard susceptibility maps are not as reliable as those produced by conventional ground surveys but they do provide a preliminary indication of hazard over an entire region. They can be used for general development planning purposes, as a guide to where more detailed ground surveys are required, or in disaster mitigation contingency planning.

This report is intended to be read by both technical and non-technical people in countries where landsliding is a problem. For the technically minded, it is intended to provide an outline of the methodology, skills and resources needed to plan and cost a work programme. For others, including decision makers, it should provide an understandable guide to landslides, why they occur, and how regional landslide hazard maps can possibly help. The report is written in general terms that stress the need to assess the problem and to consider requirements and constraints in terms of local and national circumstances. Implementation of the methods will require an investment in resources and probably staff training but it should be achievable in many cases within a reasonable time scale and, given the falling price of information technology, at reasonable cost.
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1. INTRODUCTION

This report is the final output from successive research projects on landslide hazard modelling undertaken by the British Geological Survey with support from the Department for International Development (DFID). The original work (Project R5554: Greenbaum, 1995, Greenbaum and others, 1995 a and b) was carried out in Papua New Guinea and Fiji and focused on geologically very young and active terrains. The current project (R6839) was aimed at extending the methodology to other regions in order to develop a generic approach that could be adapted and applied more generally to developing countries worldwide. The purpose of this report is to present a strategy for landslide hazard preparedness based on this generic approach. It draws on six years of cumulative experience and extracts the common themes that are likely to apply whatever the region under study.

Landslides are a common natural hazard throughout much of the developing and developed world. They occur when extreme events, such as heavy rainfall or seismic activity, trigger mass movements of ground that is only marginally stable. Because on a human scale the interval between landsliding events may seem large and erratic, they tend to be regarded as unusual occurrences. However, from a geological viewpoint landslides are nothing exceptional. Indeed, over longer (geological) periods, landsliding is probably the main erosional process operating in many regions. Thus, prevention may be only possible to a limited degree (although an understanding of the causes may prevent human actions that increase ground instability, such as road cutting or land clearance in inappropriate terrain). Nevertheless, the fact that landslides are a geologically common event makes it possible to examine their distribution in space and time, and to ‘predict’ (statistically) the likelihood of such events occurring in the future. This is the rationale behind landslide hazard modelling.

Conventional approaches to landslide hazard mapping operate at the local level and involve detailed ground surveys, including subsurface investigation, to determine the nature of the slip surface and the groundwater pressures acting upon it, rock and soil strength tests, etc. Such methods result in detailed, reliable maps that can be used for site-specific planning. However, such surveys are time-consuming and therefore expensive. They are justifiable, and even essential, where major new infrastructure or other development is planned in an area having a history of previous landsliding. But because of the expense and slowness of coverage they are impractical for larger regions.

The approach described here provides an alternative, cost-effective solution to this problem for large, rural areas. The technique is rapid and low-cost. It uses information which is either already available or which can be easily obtained, to classify broad regions in terms of their probable susceptibility to landsliding. It is based on the concept that the past is the key to the future; that is, landslides are most likely to happen in areas where the ground conditions that caused them in the past persist today. By mapping the existing landslides, understanding why they occurred and mapping the relevant ground conditions over wider areas, it is possible to predict where landslides are most likely to occur in the future. The resulting maps may not be as reliable as those produced by conventional ground surveys for small areas, but they at least provide a preliminary indication of hazard over a whole region. This can be used for general planning purposes and as a guide to where more detailed studies are required.
This report is intended for both technical and non-technical people in developing countries where there is a landslide problem. For the non-specialist it should provide an understandable guide to landslides, why they occur, and how regional landslide hazard maps can help. For the technically minded, it is intended to provide sufficient information on the methodology, skills and resources needed to plan and cost a work programme. Because the nature of the landslide problem varies so much, the report is written in general terms that emphasise the need to assess the problem, requirements and constraints in terms of local and national requirements. The method requires an investment in technology and probably staff training but it should be achievable in many cases within a reasonable time and, given the falling price of information technology, at reasonable cost.
2. BACKGROUND

2.1 Landslide hazards – a global view

Landslide hazard is the potential for harm caused by existing and future landslides. It is dynamic, because landslides and other mass movements vary in extent, magnitude and frequency over time due to environmental change. Its interaction with human activities continues to increase due to population growth and economic development. The diversity of causes and types of landslides is matched by their great range in size and scope, from innumerable, insignificant minor failures to occasional very destructive high-magnitude events that can have disastrous impacts on society.

Perceptions of landslide hazards vary considerably. To the general population, the causes of landsliding are obscure and often attributed to some overwhelming force or an “Act of God”. Consequently, a fatalistic attitude still prevails in many areas, particularly in parts of the developing world. This reduces the perceived need for investigations to assess the potential for landslide hazards. In other instances, ignorance as to the nature and causes of landsliding results in the underestimation of the role of human activity in exacerbating slope instability. This may be coupled with an over-confidence in ‘engineering solutions’, often involving massive machinery and reinforced concrete, which have resulted in excessive earthworks being constructed with limited stabilisation measures. Inadequate or inappropriate engineering frequently leads to further failures. There are many examples of the generation of new, or the reactivation of existing, landslides by building construction and road developments.

Landslides are often considered as significant hazards only when catastrophic failures have involved large loss of life. However, as tragic as these events may be they are, fortunately, of relatively low frequency (Table 1). The vast majority of landslides are rarely disastrous and infrequent catastrophic events tend to divert attention away from the huge numbers of relatively small- to medium-sized slope movements. Yet, cumulatively, the latter impose at least as great (or greater) cost to society. The costs of these smaller failures are much more widely distributed, and both their occurrence and frequency are exacerbated by human activity, so that total losses attributable to landslides are growing rapidly. The true global costs of landslide hazards in monetary terms are extremely difficult to estimate although some published estimates of landslide costs give an idea of the scale of the problem. For example, landslide costs in the USA, Japan, the Alpine nations (Austria, France, Italy and Switzerland) and India have been assessed as being similar in magnitude at between USD1-1.5 billion per year (Arnould & Frey, 1977; Schuster, 1978; Aleotti & Chowdhury, 1999). Estimates for developing countries are rare or grossly inaccurate. This is, in part, due to an under appreciation of the significance of landslide impacts because they are often the secondary consequence of triggering events such as earthquakes, volcanic eruptions, hurricanes, floods or intense rainstorms. Therefore, the cost of landsliding tends to be subsumed within the effects of these more dramatic and conspicuous hazard events.

Assessment of landslide hazards is especially needed in the developing world because the frequency and magnitude of their impacts is almost certain to increase, as illustrated by data in Table 2. Of greatest priority are those regions where progressive infrastructure development and/or population concentration is occurring in areas where the potential for landslides is
The principal 'type areas' of landslide prone terrain and associated types and extent of slope failure which require priority consideration are summarised in Table 3.

### Table 3.

<table>
<thead>
<tr>
<th>Place</th>
<th>Date</th>
<th>Type of landslide</th>
<th>Estimated volume (million m³)</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frank, Alberta, Canada</td>
<td>1903</td>
<td>Rock fall-debris flow</td>
<td>37</td>
<td>c. 70 killed</td>
</tr>
<tr>
<td>Java</td>
<td>1919</td>
<td>Debris flow</td>
<td>-</td>
<td>5100 killed, 140 villages destroyed</td>
</tr>
<tr>
<td>Kansu, China</td>
<td>16 Dec 1920</td>
<td>Loess flows</td>
<td>-</td>
<td>~100,000 killed</td>
</tr>
<tr>
<td>California, USA</td>
<td>31 Dec 1934</td>
<td>Debris flow</td>
<td>-</td>
<td>40 killed, 400 houses</td>
</tr>
<tr>
<td>Kure, Japan</td>
<td>1945</td>
<td>Earthquake-triggered</td>
<td>-</td>
<td>1154 killed</td>
</tr>
<tr>
<td>Tadzhikistan</td>
<td>July 1949</td>
<td>Various</td>
<td>-</td>
<td>Buried or destroyed 33</td>
</tr>
<tr>
<td>SW of Tokyo, Japan</td>
<td>1958</td>
<td>Loess flows</td>
<td>-</td>
<td>deaths unknown</td>
</tr>
<tr>
<td>Ranrahira, Peru</td>
<td>10 June 1962</td>
<td>Ice and rock avalanche</td>
<td>13</td>
<td>3500+ killed</td>
</tr>
<tr>
<td>Vail, Italy</td>
<td>1963</td>
<td>Rockslide into reservoir</td>
<td>250</td>
<td>about 2600 killed</td>
</tr>
<tr>
<td>Aberfan, Wales, UK</td>
<td>21 Oct 1966</td>
<td>Flowslide</td>
<td>0.1</td>
<td>144 killed</td>
</tr>
<tr>
<td>Rio de Janeiro, Brazil</td>
<td>1966</td>
<td>-</td>
<td>-</td>
<td>1000 killed</td>
</tr>
<tr>
<td>Rio de Janeiro, Brazil</td>
<td>1967</td>
<td>-</td>
<td>-</td>
<td>1700 killed</td>
</tr>
<tr>
<td>Virginia, USA</td>
<td>1969</td>
<td>Debris flow</td>
<td>-</td>
<td>150 killed</td>
</tr>
<tr>
<td>Japan</td>
<td>1969-72</td>
<td>Various</td>
<td>-</td>
<td>519 died, 7328 houses</td>
</tr>
<tr>
<td>Yungay, Peru</td>
<td>31 May 1970</td>
<td>Earthquake-triggered debris avalanche-debris flow</td>
<td>-</td>
<td>up to 25,000 killed</td>
</tr>
<tr>
<td>Chungar</td>
<td>1971</td>
<td>-</td>
<td>-</td>
<td>259 killed</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>June 1972</td>
<td>Various</td>
<td>-</td>
<td>138 killed</td>
</tr>
<tr>
<td>Kamijima, Japan</td>
<td>1972</td>
<td>-</td>
<td>-</td>
<td>112 killed</td>
</tr>
<tr>
<td>Southern Italy</td>
<td>1972-3</td>
<td>Various</td>
<td>-</td>
<td>about 100 villages</td>
</tr>
<tr>
<td>Mayanmarca, Peru</td>
<td>25 Apr 1974</td>
<td>Debris flow</td>
<td>1000</td>
<td>town destroyed, 451 killed</td>
</tr>
<tr>
<td>Mantaro Valley, Peru</td>
<td>1974</td>
<td>-</td>
<td>-</td>
<td>450 killed</td>
</tr>
<tr>
<td>Mount St Helens, USA recorded</td>
<td>1980</td>
<td>Earthquake-triggered</td>
<td>2500</td>
<td>largest historically</td>
</tr>
<tr>
<td>Mount Semeru</td>
<td>1981</td>
<td>-</td>
<td>-</td>
<td>landslide, c.60 killed</td>
</tr>
<tr>
<td>Yacitan, Peru</td>
<td>1983</td>
<td>-</td>
<td>-</td>
<td>500 killed</td>
</tr>
<tr>
<td>Western Nepal</td>
<td>1983</td>
<td>-</td>
<td>-</td>
<td>233+ killed</td>
</tr>
<tr>
<td>Dongxiang (Salashan) killed</td>
<td>1983</td>
<td>-</td>
<td>3</td>
<td>4 villages destroyed, 227</td>
</tr>
<tr>
<td>China</td>
<td>Nov 1985</td>
<td>Lahar (mudflow)</td>
<td>-</td>
<td>about 22,000 killed</td>
</tr>
<tr>
<td>Catak, Turkey</td>
<td>June 1988</td>
<td>-</td>
<td>-</td>
<td>66 killed</td>
</tr>
<tr>
<td>Kaimipit, Papua New destroyed</td>
<td>Sept 1988</td>
<td>Rock fall-debris</td>
<td>2000</td>
<td>74 killed, 1 village</td>
</tr>
<tr>
<td>Guinea</td>
<td>June 1990</td>
<td>Flow</td>
<td>-</td>
<td>2 villages partly buried</td>
</tr>
<tr>
<td>Western Iran</td>
<td>Oct 1998</td>
<td>Earthquake-triggered</td>
<td>2000</td>
<td>40-50,000 killed</td>
</tr>
<tr>
<td>Casita Volcano, Nicaragua</td>
<td>Dec 1999</td>
<td>Rainfall-triggered rockslide-debris avalanche + lahar runout flow</td>
<td>0.2</td>
<td>c. 2000 killed, two towns destroyed</td>
</tr>
<tr>
<td>Northern Venezuela</td>
<td>Dec 1999</td>
<td>Rainfall-triggered mudflows</td>
<td>-</td>
<td>Estimated 30,000+ deaths, c.90,000 homes destroyed</td>
</tr>
</tbody>
</table>

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Implementation strategy for landslide hazard preparedness
Table 2: Factors likely to cause future increase in the frequency and magnitude of landslide hazards in the developing world

<table>
<thead>
<tr>
<th>Factors influencing the frequency and magnitude of landslide hazards</th>
<th>Implications for increased vulnerability to landsliding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population growth and displacement of people to urban centres</td>
<td>- Rapid urbanisation and intense pressure on land</td>
</tr>
<tr>
<td></td>
<td>- Expansion of land holdings and building onto progressively more difficult terrain</td>
</tr>
<tr>
<td></td>
<td>- Increasing development of infrastructure across marginally stable ground</td>
</tr>
<tr>
<td></td>
<td>- Radical changes of land use and increasingly complex patterns of commercial activity</td>
</tr>
<tr>
<td>Economic development pressures</td>
<td>- Deforestation, etc. may trigger significant episodes of slope failure unless carefully planned and managed</td>
</tr>
<tr>
<td></td>
<td>- Increasing colonisation of remote, under-developed mountainous regions and highly dissected terrain, often characterised by intense geomorphological activity (e.g. erosion, major rock avalanches and debris flows, etc)</td>
</tr>
<tr>
<td>Resource exploitation and strategic considerations</td>
<td>- Population, buildings and infrastructure brought into more frequent contact with major threatening landslide events</td>
</tr>
<tr>
<td>Global warming</td>
<td>- Changing patterns of storm rainfall and alterations in the magnitude, frequency and distribution of tropical storms and hurricanes</td>
</tr>
<tr>
<td></td>
<td>- May increase landslide potential in some areas</td>
</tr>
<tr>
<td>Landslide-prone terrain</td>
<td>Implications for slope instability</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------------------</td>
</tr>
</tbody>
</table>
| Areas subject to seismic shaking [e.g. Countries bordering the 'Pacific Rim'; northern & eastern Africa, southern Europe & Mediterranean region; eastern, central & southern Asia; Caribbean] | - Earthquake shocks may trigger widespread landslides in almost all geological materials and terrains.  
- A wide variety of landslide types may be initiated, of which rock falls, rock avalanches (+debris flows), rock slides and soil slides are the most common.  
- In steep terrain, widespread failures can form numerous landslide-dammed lakes which on breaching can result in flood wave hazards downstream.  
- Landslides arise directly from seismic shaking or as indirect failures some time after the seismic event.  
- Failure is due to increases in shear stress due to horizontal accelerations; cyclic loading resulting in liquefaction of clays, sands and silts; reduction of intergranular bonds; and ground cracking.  
- Limiting threshold for majority of failures appears to be Modified Mercalli Intensities IV-VI generated by shocks with magnitude of at least 4 on the Richter Scale (Keefar, 1984). However, slope failures may be triggered by lower magnitude shocks where ground motion is amplified by factors such as unconsolidated superficial deposits, high water tables and topographic features such as ridges, convex hills and escarpments. |
| Areas subject to frequent periods of intense rainfall, such as monsoonal environments and zones of tropical storms and cyclones [e.g. Central and South America; Caribbean Islands; India, eastern China; Taiwan; south east Asia, Philippines, Hong Kong; Indonesia; Papua New Guinea; island states of the South Pacific] | - Intense rainfall frequently triggers widespread initiation of small to medium-sized landslides in weathered slope materials.  
- Earth-slumps and earth/mud-flows are likely in clay terrains; debris-flows may develop in steep terrain where abundant granular debris mantles slopes.  
- Landsliding is likely to be most severe where original vegetation cover has been removed (e.g. deforestation). |
| Mountainous environments with high relative relief and over-steepened slopes due to recent glaciation or intense incision resulting from recent or contemporary uplift [e.g. Highland region of Papua New Guinea; Andes region of South America; Himalayas; other high mountain areas of the world] | - High energy environments, prone to a wide variety of landslide types and scales in response to topographic, climatic, geological and tectonic factors.  
- Prone to widespread rockfall activity and debris flows due to abundance of easily mobilised slope debris.  
- Highly destructive, but relatively infrequent, rock avalanche-debris flows occur in this terrain, many of which are probably triggered by earthquakes. |
| Steep and highly weathered igneous and volcanic terrains in tropical/sub-tropical climatic zones [e.g. Volcanic island states of the Caribbean and South Pacific; Philippines; Hong Kong; Indonesia; Colombia; Central America] | - Prone to widespread small to medium-sized landslides, and occasional large landslides, involving deeply weathered regolith (saprolite, residual soil) produced by intensive chemical weathering of slope-forming materials.  
- Variety of landslide types may be initiated, mainly by intense rainfall associated with tropical storms and cyclones, of which earth slides (slumps), debris slides and earth/debris flows are the most common.  
- Where active volcanoes are present, areas may be prone to extremely rapid and highly destructive lahars (or flows of saturated volcanic ash) triggered by steam or snowmelt caused by magmatic activity. |
| Areas of moderate relief developed in geologically complex clay-rock strata, such as flysch deposits, melanges and tectonised, or scaly, clays [e.g. Central Europe, Slovakia, Bulgaria; Mediterranean region, central & southern Italy, Cyprus; Barbados; Indonesia; Taiwan] | - Coincidence between Flysch deposits, melanges and the occurrence of landslides is found throughout the world.  
- Associated stiff clays or clay-shales often contain planar and/or random shears caused by tectonic compression or extension during deposition; clays are frequently highly plastic with active clay minerals such as smectite.  
- Most severe landslide problems occur in regions of recent or active tectonic uplift, where slope profiles are steep and landforms are subject to active erosion.  
- Landslides range widely in type, size and extent but earth/rock slides and slumps and earth/mud flows are common.  
- Landslide areas are often complex and may be extensive due to coalescing individual failures; continuous slow post-failure movements and/or seasonal reactivation is of common occurrence. |
| Areas covered with extensive and thick sheets of loess [e.g. Central China, eastern Europe (Ukraine, Slovakia, Bulgaria); northern Argentina] | - Very prone to slope failure where deeply eroded and subject to earthquake shaking or prolonged rainfall.  
- Landslide types may include slides, slumps and flows of varying size (often very large).  
- Rapid failures frequently involve 'collapse' of the metastable, porous loess soil fabric; other failures may be slow and involve continuous movements related to seasonal rainfall/groundwater levels. |

Table 3. Terrains most prone to landslide hazards and implications for slope instability (not mutually exclusive). [Based on information from Jones, 1993a; Esu, 1979; Keefar, 1984; Derbyshire & Mellors, 1986; and other sources]
2.2 Assessment and management of landslide hazards

Landslide hazard assessment provides the basis for identifying hazard zones, indicating areas with varying potential for threatening landslide events. Because the initiation or reactivation of landslides can place individuals or communities at risk, assessment of landslide hazards constitutes a fundamental part of assessing landslide risk, and hence formulating and implementing risk management strategies. A useful relationship between hazard and risk with respect to landsliding, based on Varnes (1984), may be expressed as:

\[ R_S = H \times V \]

Where:

- \( R_S \) = Specific Risk or the expected degree of loss due to a particular magnitude of landslide;
- \( H \) = Hazard or the probability of occurrence of a particular magnitude of landslide within a specified area over a given period of time;
- \( V \) = Vulnerability or the degree of loss to a given ‘element’ or set of ‘elements’, E, (population, properties, infrastructure, etc) at risk from the occurrence of the landsliding event within the area under consideration; and
- \( E \) = Elements at risk or the total value of population, properties, economic activities, etc at risk within the area under consideration.

Total Risk, \( R_T \), is the expected number of lives lost, persons injured, damage to property, or disruption to economic activity. It may be expressed as the product of specific risk \( (R_S) \) and elements at risk \( (E) \), over all of the landslides and potential landslides in the area under consideration:

\[ R_T = \sum (R_S \times E) = \sum (H \times V)(E) \]

Thus, when hazard assessments and vulnerability assessments are combined, it is possible to develop estimates of potential loss and hence assess risk. The most effective assessments of landslide risk ideally require information that forecasts the location, magnitude and timing of landslide events. Such information, based on probabilistic analysis, is a difficult task and may only be feasible in specific situations. Moreover, problems are also associated with quantitatively determining the vulnerability of the ‘elements’ at risk. These complexities make it hard to achieve an accurate risk assessment. Therefore, it is not surprising that attention is currently focused on landslide hazard assessments, which, by means of hazard maps, delineate zones of landslide hazard potential.

Landslide hazard assessments may be undertaken on a local or regional basis. Local assessment concerns site-specific work, often associated with a proposed construction project, and normally follows a well-established methodology involving surface and sub-surface investigation, instrumentation, testing and analysis. A factor of safety approach is generally

1 Engineers describe slope stability using the term ‘factor of safety’, which may be defined as the ratio of the forces (or stresses) which resist movement to the forces (or stresses) that tend to disturb or destabilise the slope material. A slope is stable when the balance between resisting and disturbing forces favours the resisting forces. The slope
used in which the stresses acting on a slope (destabilising forces) and the shear strength of the slope materials (resisting forces) are calculated. Determination of the location and nature of any pre-existing slip, or shear, surfaces and the measurement of groundwater pressures acting upon them, are crucial in such assessments (Hutchinson, 1993). Such techniques are generally too expensive and time-consuming to be employed in regional hazard assessments.

The assessment of landslide hazards at a regional scale provides a tool to aid preliminary reconnaissance and planning and to assist in the mitigation of losses to life and property. The logic of the approach to regional landslide hazard assessment is that the occurrence and distribution of identifiable past landslides reflects the occurrence of combinations of factors that resulted in the slope failures. If those causal factors can be identified, recorded, measured and mapped, then comparison of the distributions of different factors allows the identification of areas with varying potential for future landsliding. A variety of hazard assessment techniques exist which should be applicable in a wide range of situations, depending on the extent of the area under consideration, the type of landsliding and available baseline data. Methodologies for rapid landslide hazard assessment have been developed that are suited to a variety of terrain conditions and enable preliminary hazard maps to be prepared quickly and at reasonable cost. They are described in the present study and are of particular relevance to developing countries.

Such assessments provide a sound basis for strategic and regional planning aimed at mitigating the effects of threatening landslide events. However, in the developing world, the applicability of landslide hazard assessment in formulating and implementing hazard preparedness strategies has not always been recognised and the techniques have not often been applied in a systematic way. This arises for a number of reasons, but the situation may be redressed, at least in part, by:

- Improving general awareness of the nature, distribution, causes and significance of landsliding;
- Improving awareness of the potential of landslide hazard assessment for formulating hazard preparedness strategies and reducing landslide losses;
- Improving the accuracy and applicability of landslide hazard assessments for use by decision makers and planners;
- Transferring knowledge, expertise and technology to developing countries such that national awareness and capabilities with respect to landslide hazards may be raised and sustained.

These points are considered in the following sections of this report.

### 2.3 What is a landslide?

'Landslide' is a convenient term employed to describe a wide range of gravity-dominated mass movement processes that transport earth materials (rock, soil or debris, and including artificial fills and dumped waste) down slopes. All slopes are under stress due to the force of gravity. Should the forces acting on a slope exceed the resisting strength of the materials that form the

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would then have a factor of safety greater than 1.0. A slope becomes unstable when the balance between resisting and disturbing forces shifts to being equal or slightly in favour of the disturbing forces. The slope would then have a factor of safety of 1.0 or less. A slope with a factor of safety of 1.0 (resistance equals disturbing force) is at the point where movement will occur and is considered to be in a state of limiting equilibrium.
slope, the slope will fail and a landslide occurs. As stated by McGill (1965), it is as natural for land to slide as for water to run downhill. As such, landslides constitute one of the most common and important erosional processes that shape the earth’s landscape.

Displacement of the material involved in landslide movements is achieved by one or more of three main mechanisms:

(i) **falling** (detachment of blocks or masses of material from steep slopes or cliffs which descend by free-fall, bouncing or rolling);
(ii) **sliding** (movement of materials as a coherent body over a basal discontinuity or shear surface); and
(iii) **flowing** (turbulent motion of wet or dry material that moves as a viscous fluid which may or may not be bounded by a basal shear surface).

In reality, these processes produce a bewildering spectrum of slope movement landforms and behaviours. Size varies enormously and displacements may range from a few metres to tens of kilometres. Some movements are rapid while others occur very slowly. In some cases the majority of displacement may be achieved in a single, short-lived event, whilst in other circumstances movement may be gradual, cyclical or pulsed. Sometimes the displaced material moves in well-defined masses to create a familiar irregular terrain of scars, ridges, humps and hollows. In other situations it may appear to lose coherence completely and run away from the sites of initial failure like dry sugar (e.g. in dry sands and silts) or freshly-mixed wet concrete (e.g. mudflows). Occasionally, a single movement mechanism may operate alone, but more usually several mechanisms occur in the same tract of unstable ground (a landslide complex). Alternatively, the mechanism of movement may change down slope to give what is known as a 'complex' landslide.

A number of schemes for classifying landslides have been proposed. Because of the variable combination of slope forming materials, agents responsible for movement and the spectrum of possible movement types, it is not surprising that a single, all-embracing and globally acceptable scheme has still not been produced. Many schemes have been developed for a particular purpose or end use, and although acceptable locally they are often inappropriate when applied to other areas or situations. However, a valid classification scheme provides the essential framework whereby appropriate names can be applied to the various landslide types and it is a pre-requisite for field identification and applying reasoned generalisations about the occurrence of different landslide classes. Most importantly, a clearly identified classification scheme facilitates communication between earth scientists, other specialists (engineers, planners, etc.) and the general public concerned with, or affected by, landslide problems. One of the most widely used classification schemes is that of Varnes (1978) which primarily uses the type of movement and nature of the displaced material to define different landslide types. Style and rate of movement and other characteristics are employed to define further, discrete sub-categories (Table 4, Figure 1). The terminology applied to landslide types throughout this report is based on this classification scheme.

The Varnes’ scheme is also used as a basis for landslide classification as recommended by the International Geotechnical Societies (IGS) and United Nations Educational, Scientific and Cultural Organisation (UNESCO) Working Party on the World Landslide Inventory (WP/WLI, 1993a,b). The IGS/UNESCO scheme also incorporates some concepts and terms from the classification scheme of Hutchinson (1968, 1988; Skempton & Hutchinson, 1969). The major distinction between Hutchinson’s and Varnes’ schemes is the difference in status accorded to
flow movements; that is, slope movements which are initiated by shear failure but which subsequently achieve most of their movement by flowage. However, both schemes have tended to converge over the years, particularly in terminology. One significant difference between the Varnes’ and the IGS/UNESCO classification schemes is that whereas Varnes’ scheme recognises complex landslides as a distinct movement type (Table 4), the IGS/UNESCO scheme does not. However, the term complex is retained as a description of the style of activity of a landslide and complexity can be indicated by combining the five main movement terms (fall, topple, slide, spread and flow) in the landslide description. For example, a complex rock topple-rock slide, indicates a complex landslide involving a sequence of movements initially involving rock toppling followed by rock sliding.

**Table 4.** Landslide classification scheme (after Varnes, 1978)

<table>
<thead>
<tr>
<th>TYPE OF MOVEMENT</th>
<th>TYPE OF MATERIAL</th>
<th>ENGINEERING SOILS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BEDROCK</td>
<td>Predominantly coarse (DEBRIS)</td>
</tr>
<tr>
<td>FALLS</td>
<td>Rock Fall</td>
<td>Debris Fall</td>
</tr>
<tr>
<td>TOPPLES</td>
<td>Rock Topple</td>
<td>Debris Topple</td>
</tr>
<tr>
<td>SLIDES</td>
<td>ROTATIONAL</td>
<td>Rock Slump</td>
</tr>
<tr>
<td></td>
<td>FEW UNITS</td>
<td>Rock Block Slide</td>
</tr>
<tr>
<td></td>
<td>TRANSLATIONAL</td>
<td>Rock Slide</td>
</tr>
<tr>
<td>LATERAL SPREADS</td>
<td>Rock Spread</td>
<td>Debris Spread</td>
</tr>
<tr>
<td>FLOWS</td>
<td>---</td>
<td>Debris Flow</td>
</tr>
<tr>
<td>COMPLEX</td>
<td>Combination of two or more types of movement</td>
<td></td>
</tr>
</tbody>
</table>

Landslide description may be made more precise by further qualification of:

- Material particle size
- Degree of saturation of the moving mass
- Style of movement (single or multiple movements)
- Rate of movement (extremely rapid to extremely slow)
- State of activity (active or inactive)
- Dimensions of the landslide (incl. estimated depth of movement)
Figure 1. Examples of landslide types and terminology based on Varnes’ classification.

Falls - Mass detached from steep slope/cliff along surface with little or no shear displacement, descends mostly through the air by free fall, bouncing or rolling; Topple - forward rotation about a pivot point; Rotational slides - sliding outwards and downwards on one or more concave-upward failure surfaces; Translational (planar) slides - sliding on a planar failure surface running more-or-less parallel to the slope; Flow - slow to very rapid mass movements in saturated or dry materials which advance by viscous flow, usually following initial sliding movement. Some flows may be bounded by basal and marginal shear surfaces but the dominant movement of the displaced mass is by flowage; Complex slides - slides involving two or more of the main movement types in combination.
2.4 Landslide causes

Landslides occur when the stress acting on a slope exceeds the resisting strength of the slope-forming materials. The displaced material moves to a new position so that equilibrium can be re-established between the destabilising forces and the residual strength of the rock or soils along the surface of movement. A landslide, therefore, is a process that tries to change a slope from a less stable state to a more stable state. This is usually achieved by the initial slope failure but, if the triggering conditions persist, further failures may follow despite the increase in stability. The strength of the slope-forming materials may be reduced by internal changes (e.g. weathering, removal of cements, groundwater changes). The stress acting on a slope can be increased by external factors (e.g. slope steepening due to erosion or excavation, slope loading due to dumping or construction, extreme rainfall events, earthquake shocks, etc.). These factors may combine to stabilise a slope over time in two ways. Firstly, they may make it increasingly susceptible to failure, without actually inducing movement (when they act as preparatory factors). Secondly, they may sufficiently alter the balance of forces so as to initiate movement (acting as triggering factors). Thus, changes in both the short-and long-term are important to slope stability, and many of these changes can be the result of human activity.

The failure of a slope does not necessarily resolve the landslide hazard. Following initial landsliding, renewed or repeated movements of the displaced material may continue at locations where active erosion causes undercutting or the continued removal of the lower parts of the slipped mass (e.g. adjacent to river channels or coastal cliffs). In many inland areas, further landslide movements may be initiated by loading, unloading or groundwater changes, often following periods of relative inactivity lasting hundreds or even thousands of years. A major problem with very old pre-existing landslides is that their features are often degraded and vegetated or superficially remodelled by later events, making recognition difficult. A significant hazard associated with these landslides is their unexpected reactivation due to human interference. Hutchinson (1993) has observed that, in general, slipped masses that have suffered only moderate displacements on clayey failure surfaces tend to have a factor of safety against further sliding close to unity. That is, the slipped material is only marginally stable and is often affected by slow, continuing seasonal movements. However, where landslides have involved rapid movements and large displacements (such as rapid debris flows with long run-outs over gentle slopes), the resulting slide debris tends to have a high long-term overall margin of safety against renewed movement. In these cases, significant post-failure movements are usually absent and the factor of safety against further sliding usually remains high even when erosion or excavation removes large parts of the slide toes. Thus, in areas of existing landslides, observations of the type of movements and the materials involved in those movements may allow very broad estimates of the present degree of stability of the landslide debris. These estimates can then be incorporated into regional landslide hazard assessments.

2.5 Landslide hazard maps

Landslide hazard maps display the extent of potentially threatening landslide events across a region. Based on the statistical analysis of baseline spatial data sets (landslide inventory and identified controlling factors) they show divisions or zones reflecting the scale or intensity of the landslide hazard (hazard zonation). These maps are also referred to as landslide potential...
maps or landslide susceptibility maps. The hazard or susceptibility zones are usually classified into at least four categories, for example:

(a) Areas of high landslide susceptibility  
(b) Areas of moderate landslide susceptibility  
(c) Areas of low landslide susceptibility  
(d) Areas of minimal or no landslide susceptibility

The hazard map should also indicate areas of existing landslides which, if data are available, can be distinguished by type (e.g. rotational slides, debris flows, etc) or character (e.g. whether deep-seated or shallow; active or inactive). It is important, however, that the map categories are kept few and simple in order that the information can be better understood by non-specialist end-users.

Landslide risk maps are significantly different from landslide hazard maps because they involve the assessment of the potential losses that may be incurred through the impact of landslide hazards on vulnerable elements in society or the community. Vulnerability assessment focuses on the targets of the hazard and involves evaluation of the expected performance of structures, infrastructure, institutions and the safety of human lives under the impact of landslide events. When hazard assessments and vulnerability assessments are combined, it is possible to develop estimates of potential losses and hence a quantitative or semi-quantitative assessment of risk. Areas subject to the same hazard (e.g. landsliding) can face a variety of consequences depending on land use. Therefore, several risk maps may have to be developed for the same area. The simplest and most common approach to risk map preparation is through the overlay of a hazard map with a land-use map, or more explicitly with a map reflecting property values. However, such maps would not only be politically 'sensitive' but may also oversimplify the information. For this reason, in many cases actual risk maps are not produced and decision-makers and planners proceed directly from the hazard map to actions involving regulatory management or technical countermeasures (Einstein, 1997).

2.5.1 Use of landslide hazard maps

Landslide hazard maps are of great value to development planning as they present a spatial division of the ground into areas of different levels of potential threat (landslide hazard zones). It is these divisions which provide the essential framework for land-use planning, building regulations and engineering practices. For planning and mitigation purposes, landslide hazard assessments provide a basis for addressing three broad concerns (Jones, 1992):

- to assess the reasons for widespread or repeated losses affecting a broad range of interests;
- to assess hazard potential with regard to proposed developments so that future losses can be minimised by relocation (hazard avoidance) or the adoption of protection measures; and
- evaluation of the likelihood of hazardous events occurring as a consequence of proposed developments (environmental impact assessments)

The susceptibility maps together with information on existing or expected vulnerability can also be used to compute landslide risk. For example, it is possible to estimate the risk associated with critical facilities, such as the road network, hospitals, water pipelines, etc., in landslide-prone areas. Such information may be evaluated and used to make decisions regarding 'acceptable risk' for a facility (or facilities), the need for relocation or the application of appropriate remedial measures.
2.5.2 Limitations of landslide hazard maps

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

The zoning presented on hazard maps, determined by the analysis of areal landslide distributions in relation to perceived factors controlling those landslides, is only applicable to regional planning. Such maps are unsuitable for use in site-specific stability assessments, determining the siting of individual structures or in engineering design. More detailed local hazard assessments are required for these purposes. Thus, regional hazard maps in no way replace or reduce the need for new developments to be designed on the basis of appropriate geotechnical investigation. Rather, the maps serve to focus attention on likely problem areas which, prior to new development, should be assessed in greater detail using site-specific geotechnical techniques.

The scale of landslide hazard maps will depend on the purpose for which they are intended, the extent of the area under consideration and data availability. A general summary relating the scale of hazard map to planning use is summarised in Table 5, modified using information provided by van Westen (1993) and Soeters and van Westen (1994).

2.5.3 Accuracy of landslide hazard maps

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

The fundamental assumptions underpinning landslide hazard map preparation are that: (i) the estimation of future slope instability can be based on the assessment of conditions that led to slope failure in the past; (ii) the main factors that cause landsliding can be identified; and (iii) the relative significance of these factors can be estimated. Let us examine these assumptions. Firstly, the basic premise that the conditions leading to past and present slope instability will apply equally well in the future is only valid in general terms. Both climate change and human intervention influence the stability conditions of slopes over time. Moreover, past landsliding may lead to changes in the landforms that induce stability. Secondly, although the main factors that influence landsliding may be identified (e.g. geology, soil type, vegetation cover, etc.), other relevant parameters are often excluded from regional hazard assessments because the data do not exist or due to the difficulty of measuring them over a whole region. For example, the thickness and character of weathered colluvium, detailed lithological variation and variable joint and fracture spacing would all influence slope stability but are extremely time-consuming and expensive to map. Similarly, data on groundwater flow patterns in steep mountainous terrain may prove impossible to collect for meaningful assessments on a regional scale. Thirdly, it is not always possible to assign relative levels of significance to landslide causes with a high degree of confidence, especially in those situations where complex rock sequences are involved in failure. All these considerations will effect, to a greater or lesser degree, the accuracy of the delineated hazard zones.

One of the most important influences on the accuracy of hazard map zonation is the reliability of the landslide inventory map which is the key element in estimating the significance of the identified factors controlling landslide occurrence and distribution. Any deficiencies in the
inventory will be transmitted to the susceptibility map. The main reason for such deficiencies is the difficulty of recognising past landslides, even for experienced investigators. This is most acute in areas of old degraded landslides and/or steep, rugged terrain with a more-or-less continuous vegetation cover. Recognition problems are exacerbated in tropical regions where high relief and severe rainfall events lead to the widespread development of small- to medium-sized landslides. In these areas, re-growth of the vegetation cover is remarkably rapid and may severely obscure evidence of failures after about five to ten years. The problems of landslide recognition are particularly important where the landslide inventory map is compiled primarily by aerial photograph interpretation with limited field checking. This fundamental procedure for the rapid assessment of landslide hazards, used in this and earlier related studies (Greenbaum, et al., 1995 a & b), requires appropriate aerial photographic coverage, competent interpretation skills and targeted field checking.

Accuracy of hazard zonation is also sensitive to how the mapped landslides are statistically analysed. Specifically, this relates to whether individual landslides are analysed in terms of their ‘complete’ areal extent, source area only or as initiation points. Each technique has its merits and limitations, depending on the type of landslides prevalent in the region under consideration and the data able to be acquired when compiling the landslide inventory. The procedures adopted for compiling landslide inventories and undertaking statistical analysis for hazard zonations in the contrasting terrains assessed in the present study are discussed fully in the later sections of this report.

Provided the limitations in use and accuracy of landslide susceptibility maps are appreciated, they represent the most effective basis for landslide hazard management and land planning. Current experience and knowledge of the main factors controlling and triggering slope instability and advances in remote sensing techniques and Geographic Information System (GIS) technology now make rapid and cost-effective production of these maps viable. By following an established methodology, rapid assessment of areas with limited existing data, leading to the production of ‘preliminary’ or ‘first-stage’ susceptibility maps, is possible. GIS capability allows map accuracy to be readily updated, or the scale of production changed, as additional data are acquired. For developing countries or landslide-prone regions where basic information pertaining to landslide hazards is scarce, these maps can provide an essential framework for developing and implementing effective landslide hazard preparedness strategies.

2.6 The need for a national landslide hazard preparedness strategy

Over the past 25 years, a number of countries in the developed world have incorporated the results of landslide hazard assessments into national or regional hazard preparedness strategies. In some cases this has led to associated legislation governing new development in landslide-prone terrain, the most notable examples being parts of the United States (especially California), Japan, Austria, and Tasmania (Varnes, 1984). Legislative policies range from the provision of guidance, such as the need for appropriate geotechnical investigation to assess site-specific stability conditions, followed as necessary by the construction of preventative engineering work, through to restrictions on land use in certain zones. The latter may involve controls on the density, size and type of building or the prohibition of all building works.

For many countries in the developing world, the traditional response to the threat of landsliding has tended to focus on post-event clearance, remedial measures and reactive engineering, rather than anticipatory planning. The paucity of landslide hazard assessments in land-use planning...
reflects general ignorance of the nature of landslide hazards and the potential offered by hazard assessment techniques. There is also the assumption that emergency action and response measures are cheaper and more cost-effective. In other words, why invest scarce resources in preparing for an uncertain ‘random’ event, compared with a response strategy that clearly relates expenditure to need, especially when the possibility exists of external financial assistance from relief and aid?

Such a retrospective approach suffers from a number of severe limitations:

1. No provision is made to limit injury or loss of life of the local population
2. No provision is made to safeguard the homes or livelihoods of the population (e.g. farmsteads, factories, etc.)
3. No provision is made to safeguard institutions, infrastructure or basic utilities (e.g. water supplies, power or access routes) which may be of crucial importance for post-disaster response, clearance and remediation.
4. External aid may not be forthcoming. For example, whereas major disasters involving severe loss of life may be considered aid-worthy, such events are infrequent. However, widespread initiation of small to medium landslides (such as those triggered by intense rainstorms) or the slow seasonally-reactivated movements of old existing landslides are extremely common and of frequent occurrence. Such movements may result in few, if any, fatalities but cause significant economic loss and disruption over considerable areas. Such events rarely attract external aid.
5. Post-event response measures relating to stabilisation or rebuilding are often directed to individual sites that generally take no account of the regional causes of landsliding. Such site-specific works may result in inadequate protection against, or may even initiate, further movements, resulting in additional costs and safety implications.
6. Ill-informed, post-event response may also lead to the displacement of local populations and post-failure avoidance strategies that may be unwarranted.

The assumption that responsive strategies are more cost effective than those aimed at prediction and prevention is not borne out by the limited cost-benefit analyses that are available. Particularly low cost-benefit ratios described for areas such as California can be explained by high property values and encroachment onto marginal hillside terrain (Alfors et al., 1973; Leighton, 1976; Hansen, 1984). However, these data demonstrate the importance of landslide hazard assessment and planning initiatives that can be applied to landslide-prone terrain elsewhere. Just as the landslide hazards themselves make no distinction between developed and developing countries, neither should sensible hazard preparedness planning.

Regional landslide hazard assessment and the production of hazard zonation, or susceptibility, maps may be used to:

- Recognise geographical areas where landsliding has already occurred and future landsliding is most likely. In other words, the maps help in understanding the constraints on land use and the scale of the landslide problem, and thus can assist in land-use planning by relating land-use zonation to hazard zonation.
- Adopt appropriate strategies for dealing with the problems that may arise because of landslides on marginally stable slopes;

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• Prepare for, modify, and/or mitigate the often disastrous effects of landslides on communities and infrastructure by means of appropriate engineering practice and building codes;

• Regulate new development in hazardous areas through planning controls; and

• Enhance public education

Hazard zonation maps, if properly appreciated, understood and applied, form the basis for hazard preparedness planning. This, in turn, allows those charged with addressing the problems facing present and future development in landslide-prone areas to deal with them in an informed and cost-effective manner.

2.7 A hazard preparedness strategy

All too often, national and regional organisations tend to consider preparedness and mitigation planning only following major disasters. The gathering of information on landslides, and slope failures more generally, is often initiated in response to catastrophic landsliding events which cause loss of life and damage to infrastructure. Often at such times, emergency actions are taken to assess and remediate the damage to buildings and access roads in particular. This leads to local and regional authorities putting in place plans to study the scale and vulnerability of the region to all kinds of slope failures. A hazard preparedness strategy should seek to put in place systems that can provide essential information prior to the event.

Although earth scientists and engineers may undertake assessments of landslide hazard, the responsible government authorities or departments must apply the available information through appropriate planning policies and other precautions. It is beyond the scope of this report to recommend in detail how this may best be achieved for specific countries or regions but some general principles of landslide hazard reduction strategies are universally applicable and are outlined below. Some important implementation issues for developing, and maintaining, a landslide hazard preparedness strategy are discussed further in Section 4.

The first stage in developing a landslide hazard preparedness strategy requires an appreciation of the scale of the existing landslide problem by government administrators and the general public, and of the benefits and limitations of landslide hazard assessment. To this end, and to ensure that the study results can be applied, it makes good sense to involve the users in all stages of the hazard assessment programme. Those who will be called upon to implement the findings of landslide hazard assessments should participate in each stage of the process, leading from the definition of the problem, through the methods of investigation to the conclusions reached. In this way users will be able to identify with the investigations and their outcome and will be motivated to apply what they have learned. In particular, the form and content of hazard zonation and particularly the manner of presentation should be appropriate to the users needs and capabilities.

Ideally, hazard zonation studies and maps should directly assist the user in taking decisive action concerning practical preventative or corrective measures; they should aid land-use planning, the design of proposed construction, environmental impact assessments for proposed engineering works and legislation. However, as noted earlier, the accuracy or completeness of regional hazard zonations depends on the availability, quality and extent of existing data and the cost implications of acquiring more detailed information for enhanced accuracy.
Preliminary rapid hazard zonation maps, which form the focus of the present study, provide a valuable basis for initial regional hazard mitigation planning but can not be applied to site specific problems. Therefore, an appreciation of the limitations of hazard zonation maps is as important as recognition of their benefits.

Although landslide hazard reduction can be undertaken as an ‘individual’ exercise, it must also be recognised that landslides often occur as a result of interrelated multiple natural-hazard processes in which an initial event triggers one or more secondary hazard events. Examples are combinations of volcanic eruptions, earthquakes, hurricanes or extreme rainfall events, and landslides. The resulting multiple-hazard problems require a shift in perspective from mitigation of individual hazards to a broader framework that takes into account the characteristics and effects of all the processes involved. Therefore, in planning landslide hazard reduction programmes, attention should be paid to possible relationships between landslides and other hazards. For example, a building that is moved from a hillside to lower lying, flatter ground to avoid landslides might be at increased risk from floods. Mitigation planning should consider all possible modes of hazard likely to affect the area under consideration.

The actual development and implementation of a national hazard reduction strategy by the responsible government authorities or departments may hinge on a number of important issues, that could include:

- The level of occurrence of different natural hazard events in a region (including landslides, earthquakes, volcanic eruptions, severe rainfall events, floods, or various combinations of these hazards).
- The existing level of co-ordination between agencies or regional authorities in applying mitigation procedures.
- The need for proper land-use planning and practices for sustainable development.
- The need to sustain a ‘robust’ economy (that is, one not repeatedly setback by successive disasters).

Thus, a number of diverse technical, economic, political and human issues need to be considered in the development and implementation of a national hazard management strategy. This may appear to be a daunting task, but precedents have been set by several countries in both the developed and the developing world. On the basis of collective experience from these national experiences, and as reviewed by Swanston and Schuster (1989), a successful unified national programme of landslide hazard reduction conceivably would include the following key elements:

1. Identification of a central organisation for management of a landslide loss-reduction programme.
2. Establishment of limits of responsibility of national, regional, local, municipal authorities and private sector organisations in dealing with landslide hazards.
3. National efforts to identify and map hazards, define process characteristics, and determine degree of vulnerability and risk.
4. Development of guidelines for the application of reduction techniques to the identified hazards.
5. Development of minimum standards of application and professional practice (standards should be created by professional societies in collaboration with regional and national governments).

6. Regulation of minimum standards of application and professional practice (in conjunction with professional societies) through periodic review and upgrading of practice guidelines, building codes, and land-use practices.

7. Strong support of university research and regional and national government dealing with process mechanics, reduction techniques and warning systems.

8. Provision of a central clearinghouse for collection and distribution of publications and guidelines to professionals, agencies and local authorities.

9. Relief and compensation programmes through regional, national and private insurance funds.

A comprehensive national hazard reduction production programme must clearly be tailored to both the severity of the hazard(s) and what can be achieved within funding constraints. A planned approach is to be recommended that sets out considered, realistic goals and tasks for making landslide studies, evaluating and mapping the hazard, disseminating the information to potential users, and subsequently evaluating the use of the information.
3. HAZARD MAP PREPARATION

The following sections describe the remote sensing and GIS concepts involved in rapid, hazard map preparation. These techniques have been developed during several, sequential, country-specific case study projects carried out in four contrasting landscapes:

- Papua New Guinea, where massive landslides are caused by seismicity and heavy rainfall. (Reported in Greenbaum and others, 1995a).
- Fiji, where much smaller landslides occur that are triggered by rainfall (Reported in Greenbaum and others, 1995b).
- Jamaica, where medium landslides occur preferentially on the steeper slopes. (Reported in Northmore and others, 2000).
- Slovakia, where a more subtle problem of disturbed ground is associated with certain rock types. (Reported in O'Connor and others, 2000).

The reader is referred to the appropriate report for more details on the specific case studies and the particular problems associated with each study site. This report concerns the generalities that have emerged during these studies.

3.1 Concepts of the remote sensing and spatial analysis approach

Remote sensing covers a range of techniques that involve the acquisition of information about the surface of the earth by satellite- or aircraft-borne sensors. The use of remote sensing, combined with other existing data, provides a practical means of mapping the land surface and of deriving information about changes which result directly or indirectly from dynamic geological, climatic or human activity. In the context of landslide hazard modelling, the need is for a landslide inventory providing information on where landsliding has occurred in the past. Where such information already exists from historical data or ground surveys this may suffice but usually such information is lacking or incomplete, and it is here that remote sensing can provide a cost-effective, rapid solution. The underlying assumption of the landslide modelling approach is that past events, resulting from inherent ground and terrain instabilities ('controlling factors'), provide an indication of what is most likely to occur in the future. The landslide inventory is, in itself, a simple form of hazard map.

Repeatable and affordable optical and radar earth observation data with global coverage has been available to the scientific community for over 15 years and, as sensor technology has advanced, the nominal ground resolution has accordingly improved. The applicability of various forms of remote sensing data to the study of landscape development depends on the scale of the slope failures. For example, whereas conventional satellite data is useful for identifying large landsliding events such as those that occur in Papua New Guinea, for most types of smaller mass movement either very high resolution satellite data or aerial photography is required.

Although remote sensing offers a convenient method for deriving a basic landslide inventory, there are many uncertainties in this approach. It assumes that: (1) landslides can be reliably identified; (2) controls and/or triggering mechanisms remain essentially constant with time; and
(3) that areas previously affected by landsliding continue to be unstable. The landslide inventory obtained in this way can be supplemented by other existing data on landslide occurrence or by undertaking field checks ('ground truthing') to confirm the identification of supposed mass-movement features and iterating the interpretation based on this knowledge.

The use of a Geographic Information System (GIS) in landslide hazard modelling allows the superimposition of geographically referenced and thus co-registered data sets of various types. This means that the relationships between the data sets, either singly or in combination, and the observed landsliding can be tested. A GIS permits the ready combination of remote sensing data with various other digital information e.g. geology, land-use, forestry, soils, rainfall etc. Once registered, the GIS allows complex spatial correlations to be carried out with ease. Hazard analysis relies on determining the significance or otherwise of each factor, or combination of factors, and assigning quantitative weighting values to them. These factors may then be combined to derive a hazard susceptibility map. The analysis can be approached in a number of ways depending on the information held and the availability of supporting field or geotechnical evidence. The process of statistical spatial correlation is best carried out using raster-based GIS tools. Here, every point within the study area has a classified value for each attribute, thus making the analysis of spatial relationships more straightforward. The modelling approach, even if it is over-simplistic, has the advantage of being objective and does not rely on any prior knowledge of causes.

A schematic representation of the stages involved in landslide hazard modelling and map preparation is shown in Figure 2.

![Diagram of landslide hazard modelling stages](image-url)
3.2 Developing the landslide inventory

The preparation of a landslide inventory relies primarily on the interpretation of remote sensing data, informed and modified by information obtained from existing, archival sources or from new field investigations. The following procedures are involved:

1. Determine what remote sensing data are appropriate and available. Use the World Wide Web or a local remote sensing supplier to establish satellite image availability. Obtain aerial photography, preferably of multiple date origin and at different nominal scales, from local sources. Consider commissioning new aerial surveys using infrared film for detecting changes in forest or grassland vegetation.

2. Review the literature and maps. Consult with other agencies and organisations (e.g. land survey, forestry, universities etc.) to obtain all available and relevant topographic, geological, land use, forestry, hydrogeological and hydrological, etc. data.

3. Devise a procedure for classifying and annotating landslide features. This will depend on the type(s) of remote sensing data used and the terrain. Alternatives are: (i) polygons defining the landslide scar; (ii) polygons defining the combined area of the landslar scar plus landslide runout; or (iii) a point locating the approximate landslide ‘initiation’ towards the top of the scar (plus, possibly, a second point defining the base of the scar or farthest extent of the runout). The choice will depend on the type of analysis to be later carried out.

4. Process digital remote sensing data as necessary. Carry out preliminary interpretation(s) of landslide and other mass-movement features using all remote sensing data. Obtain preliminary confirmations of satellite imagery interpretations from comparison with aerial photographs and fieldwork, and confirm detailed aerial photograph interpretations by reference to published information and through field checking. Use such ancillary information to revise and update the preliminary remote sensing interpretations.

5. Transfer interpretation based on any uncorrected aerial photography to an orthorectified base map or to geocorrected imagery.

6. Unless already captured digitally, digitise and attribute the landslide inventory and convert to a raster format suitable for GIS analysis.

3.2.1 Remote sensing data types

As indicated earlier, various types of remote sensing data exist and the initial task is to determine what data are available and fit for purpose. Most of the older commercial earth observing optical satellites acquire data at ground cell resolutions of between 10 and 30 m. These images are useful for detecting larger mass-movement features such as major avalanche-type landslides that can occur in tropical regions e.g. Papua New Guinea (Greenbaum et al. 1995) but are less useful for identifying smaller scale landslides. The latest, commercial, satellite systems provide optical data at higher spatial resolution. The Indian IRS optic sensor, for example, has a nominal resolution of 5 m. Still higher spatial data, ranging from 4 to 8 m, is obtainable from the Russian photographic cameras. The long-awaited high-resolution satellites giving 1 m or better ground cell resolution have only recently been launched; the commercial Ikonos-2 satellite was launched successfully in September 1999. This sensor has in-track stereo imaging capability, allowing stereo images to be made for viewing using appropriate dual-
processor computers and photogrammetric software. Besides 1 m panchromatic data it also provides 4 m multispectral imagery.

A limiting factor of optical satellite data is its inability to penetrate cloud cover and where this is persistent, as in many tropical regions, it may prove difficult or impossible to obtain useful imagery. An alternative is to take advantage of radar, which has all-weather capabilities. This data type is available from satellite systems at ground-cell resolutions of between 8 and 25 m. The disadvantages of radar are its inherent geometric distortions, intense shadows (which unlike aerial photographs contain no information at all), and the speckled nature of the data. All these factors make the images more difficult to interpret. Appropriate processing can overcome some these problems but the data types available currently are probably only of use for mapping large-scale mass-movement events. Higher resolution systems are planned and these may become available in the not-too-distant future. A further aspect of radar that could be useful to these studies is its ability to detect very small ground movements, based on changes that can be detected between two successive images. This technique, known as interferometry, has not yet been applied successfully to landslide studies for a variety of reasons.

Detection of typical, small scale landslide features requires remote sensing data that can be interpreted at a scale of 1: 25 000 or better, and only very high-resolution satellite imagery or aerial photography can address this need. Most countries have archives of aerial photographs but these vary considerably in type, age, quality and nominal scale. The most common photography is panchromatic (black and white), which was used by many countries as the basis for topographic mapping and land use/land cover studies and planning. Despite its age, archive photography is often still the most appropriate data for landslide studies. Indeed, older photography may have the added advantage of providing information on an area before modern development which, in conjunction with later photographs, can be used to identify changes that have occurred in the recent past. Aerial photographs have the advantage of stereoscopic viewing, which greatly assists the interpretation of terrain features although, of course, this also depends on the experience of the interpreter, the classification criteria used, and local knowledge based on fieldwork. Disadvantages of traditional, analogue aerial photographs at the regional scale include the large numbers of photographs needed to cover an area, the slowness of the interpretation and the slowness of accurately transferring the information to a planimetric base map. These problems can increasingly be overcome by using digital photogrammetry to correct large blocks of photography and allow on-screen interpretation in real-world projections. Another innovative method of data transfer involves the visual annotation of georeferenced satellite data on screen or hard copy from the air photo interpretation. Direct interpretation of the new stereo, very high-resolution satellite imagery, such as Ikonos-2, will be a strong challenger to aerial photography in these applications. It has many advantages including the possibility of direct capture of landslide information in map-accurate digital format. The downside, however, is that the imagery has to be specially requested, data costs are high, and its visualisation in stereo requires specialist software. These limitations are likely to diminish with time as more data become available and prices fall.

### 3.2.2 Image processing

Before digital imagery can be interpreted, the data need to be processed using an image analysis (IA) system. If not already geocorrected, the first stage in image processing is the rectification of the data to the map projection and spheroid of the country under study using topographic maps or suitably spread GPS (Global Positioning System) data. This process involves selecting a series of points that are readily identifiable on both the image and topographic map. Once
collected, the image processing software is used to establish least squares polynomial equations between the image and map co-ordinates. These equations are then used to transform the entire image to the map projection. The process primarily involves a rotation of the scene with respect to grid north, and an internal re-sampling to adjust for distortions within the scene. During this process, the image can be re-sampled to a pixel size commensurate with other data to be used in the modelling and rotated onto a new grid orthogonal to the map base.

Once geometrically corrected, the image needs to be enhanced to emphasise the features of interest. The main stages of image enhancement are ‘edge enhancement’ and ‘contrast stretching’. Edge enhancement emphasises high spatial frequency, local contrast differences whilst retaining the broad, low frequency brightness information, thereby enhancing the fine detail within the image. This compensates for image blurring caused by the electronic sampling by the sensor, which averages the intensity across each ground pixel. 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 emphasised and the overall image appears sharper. Edge enhancement is especially important for structural (e.g. lineament) interpretation, or when generating large-scale photographic enlargements. It is not yet clear whether this will be a required stage in the processing of the new, very high-resolution satellite imagery.

Contrast stretching involves redistributing the raw data brightness (DN or digital number) 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 that 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. Although automatic enhancements may be applied, it is often better to expand each of the bands independently, balancing the colour tones visually to achieve the maximum discrimination between surface materials. For optical data, 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. Radar data require more specialised processing. These processes, whilst quantitative, rely 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.

3.2.3 Data interpretation

Satellite imagery and aerial photography can provide information on older and more recent landslides, geological faults and fractures (‘lineaments’), bedding and other lithological structures, recent erosional/deposition processes, habitation (including cultivation), infrastructure and roads. Each form of remote sensing data has its own advantages and disadvantages as cited above.

In general, the interpretation of satellite imagery follows a standard procedure regardless of data type. Either of two basic approaches may be taken: the interpreted information can be annotated onto a transparent overlay attached to the photographic print; or it can be directly digitised on the computer screen using the image analysis or GIS system. One advantage of the former approach is that the interpreter sees the entire image at full resolution at all times so that, for example, the relationships between structures can be more easily recognised. It also allows the image to be viewed in all orientations. However, the interpretation must then be digitised as a
separate operation. The alternative approach of interactive on-screen interpretation is possible only if a suitable image analysis or GIS system with vector graphics is available. In the case of stereo data, special digital photogrammetric viewing hardware and software are required. The principal advantage of this is that the data are captured directly in digital form with true x,y,z co-ordinates.

Several types of stereoscope are available for the interpretation of hard copy aerial photographs but the most useful for systematic desk-based work is the mirror stereoscope. This allows the observer to view the complete 'stereo model' (the area of overlap between adjacent photographs) at low magnification. It also 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, as mentioned earlier, from the difficulty of accurately transferring interpreted information to a base-map.

Usually, alternate photographs in a run are used for compiling 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 particularly in areas where the relief is significant. Other approaches to transfer include the raster scanning of the interpretation followed by digital warping, but this is time consuming and cannot be justified in most investigations. If appropriate, the use of aerial photographs may be restricted to examination of particular landslides or for validating/understanding the information provided by the low- to high-resolution satellite imagery.

Until the latest very high resolution space data become more widely available and affordable, perhaps the optimum strategy is to use aerial photographs as the basic interpretation source and low resolution digital satellite imagery as the plotting base. This provides a detailed interpretation whilst at the same time bringing all of the image data into a digital layer for further analysis in a GIS.

3.2.4 Ground verification

Remote sensing interpretation, even for an experienced photogeologist, involves many uncertainties and ideally needs to be supported by ground truthing and verification through reference to other existing information. Such information is then used to inform and correct the initial interpretation. Field investigations are frequently carried out along roads and tracks as this is often the only available access, especially in tropical terrain. These should attempt to delineate landslides and identify landslide-prone areas in order to begin to understand the controlling and triggering factors. They should also seek information, as far as is practicable, on the physical properties of soils, regolith, bedrock and groundwater regime. Landslides can occur in almost any upland landscape if the conditions permit (e.g. appropriate geology, moderate/steepest slopes, high moisture content, low vegetation cover, human intervention). However, experience shows that landslides are common in some landscapes partly or wholly governed by geological controls and rare in others. Certain landscapes, often but not always controlled by their underlying geology, are vulnerable to slope failure. These include: areas of steep ground; cliffs and river banks undercut by stream or wave action; areas of drainage concentration and seepage zones; areas of hummocky ground; and areas of fracture and fault intensity. Special attention may be given to these types of terrain when examining maps and aerial photographs in addition to the field studies.
Besides their obvious value in locating landslides, aerial photographs have other uses in this type of survey. They can provide a unique, three-dimensional overview of the terrain in which the interrelations between slope, drainage, surface cover, rock type and human intervention in the landscape can be assessed.

3.3 GIS hazard modelling

3.3.1 Concepts

The likelihood that a landslide will occur at a given location depends on a number of conditions that may be separated (1) controlling factors and (2) triggering events. Controlling factors may be broadly divided into material properties (rock or soil type; \textit{in situ} and post-movement strength; etc.) and terrain conditions (slope angle; fracturing; cultivation; etc.). Triggering events include earthquakes, intense rainstorms and possibly new construction, development and cultivation. In theory, if all the controlling factors in an area are understood and comprehensive ground information on them is available, it should be possible to 'predict' where landslides are most likely to occur given a particular triggering event. Unfortunately, such information is rarely, if ever, to hand. However, even an imperfect knowledge of the controlling factors can provide an indication of the probability of new landsliding events occurring.

As stated before, the fundamental assumption underpinning rapid landslide hazard assessment is that the distribution of past landslides provides a guide to the location of future events. Secondly, the method assumes that remote sensing images can be interpreted reliably to provide a landslide distribution inventory map for an area. If these assumptions are met, even partially, the landslide distribution inventory map can be itself considered a simple hazard map. A third assumption is that the controlling factors and/or triggering mechanisms remain essentially constant over time.

Given that the emphasis of the approach is on the \textit{rapid} assessment of hazard, it is not usually possible to have a complete knowledge of all the potential controlling factors. Instead, data that already exist and are easily available are used in conjunction with remote sensing and spatial analysis to prepare a preliminary landslide hazard map. The use of a GIS enables the analyst to examine potential controlling factors and to quantify their apparent significance to landsliding in the study area. The most commonly available data include geological, topographic, pedological and land cover information, which together can be regarded as providing a limited description of the overall controlling factors. Building a database in a GIS can be time consuming but once available allows different models to be developed and tested easily. New information can be readily incorporated and an updated model generated.

3.3.2 Basis of analysis for rapid landslide hazard assessment

Spatial analysis, as provided in different proprietary GISs, uses a number of terms to describe aspects of the same entity. In what follows the following terms are used:

\textbf{Theme} \quad A map illustrating the characteristics of a particular spatial variable; for example, the geology map - geology being the theme.

\textbf{Class} \quad A sub-division of a theme; for example, limestone is a class within the geology theme.
This section outlines the suggested analysis techniques. For a more formal description of their use and a comparison with other similar techniques, see Appendix A.

The analysis examines the correlation between the landslide inventory map and the various themes in the database using the technique of cross tabulation. For this to work the themes must be represented in raster format by nominal data.

Maps in raster format consist of a regular grid of cells each of which contains a number representing the value of the theme in that cell. An advantage of raster data is that neighbourhood queries, spatial operations, such as filtering, and overlay operations to combine information from different themes, can be performed rapidly and efficiently.

Nominal data (e.g. rock or soil types identified by name) simply use numbers as codes to represent the categories. For example, in the geology theme limestone might be represented by the code value 1, and granites by the value 2. The correspondence between the code value and the category will be held separately within the database. Not all theme types can be represented by nominal data. Thus, topographic height and slope angle are numeric measurements on a (nearly) continuous scale. These must be converted to nominal data before the analysis. The most common way to do this is to divide the overall range of theme values into convenient number of classes. In the case of the height information each resulting class might represent a range of 100 m: e.g. 100 m - 200 m becomes code value 1; 200 m - 300 m becomes code value 2 etc. It is important that the range of each class is chosen carefully. If a class has too wide a range it will incorporate too much of the inherent variation in the data into one that class and so mask any underlying correlations. Conversely, the statistical validity of the correlation will be reduced by choosing too narrow a class width since each band will produce classes with very small areas. Recoding data in this way is sometimes called density or level slicing.

3.3.3 Building the database

Building the database is the most time consuming operation of landslide hazard modelling. Ideally, the database comprises all of the information ‘layers’ that potentially influence the occurrence and location of landslides. In reality, not only is there a lack of detailed knowledge of what controls are actually important but the information available is limited and of variable quality or detail. Since the emphasis is on ‘rapid’ techniques, new data gathering is not usually an option, so the best must be made of what data exist. This can be a major limitation and can significantly affect the reliability and usefulness of the results.

In the general case, the approach is to gather all sources of information that can be expected to exert an influence on landsliding. This will include topographic relief (elevation, slope angle, slope aspect), geology (lithology), structure (faults and joints), soils (type, depth), hydrogeology, land use, roads, etc. As a minimum, information on topography and geology must be available for the analysis to be feasible. Other information will add to the reliability of the model. Fieldwork and past studies can significantly assist by providing firm information on factors of local importance.

In most instances, the information available will exist as hard copy – usually paper maps – possibly produced at different projections and scales. For GIS analysis, all data must be converted to an appropriate resolution digital raster and be spatially co-registered. The
requirements of each information set will need to be considered separately and treated accordingly. Some general comments on the different data layers are given below:

**Topographic relief**: This is an essential data set since all landslides are controlled to a greater or lesser extent by slope (i.e. they move under the influence of gravity). Once in digital format (Figure 3), elevation data can be used to generate secondary data sets on slope angle (Figure 4) and slope aspect (direction) (Figure 5), either/both of which may have a separate influence on landsliding. The elevation data may also be used to create shaded relief visualisations of the land surface that can be useful as a means of presenting the results. Digital height information is becoming increasingly available in the form of digital elevation (or terrain) models (DEM or DTM) derived either from the original map contours or directly from space imagery. If a DEM of adequate resolution is known to exist, it is recommended that this be purchased. The alternative is to generate a DEM in-house by digitising and converting map contour data. However, this is a complex, time-consuming and thus costly (in terms of labour) task and one that is likely to require specialist software. Various approaches to this are possible. Either the contours (or a sub-set of them) may be line-digitised by hand or the image can be scanned. Scanning is best done using a separate plot of the contours, if such is available from the national mapping/lands agency. If it is not, then special software may be needed to separate the contour data from other line information contained on the map. Some software allows a degree of automation in this process. Once digitised, the vectors need to be checked and corrected to remove any breaks in continuity, taking particular care at boundaries where map sheets have been joined. Contours must be then fully attributed with height values. In some software, the vectors then need to be converted to a raster and this information finally used to interpolate height values at every grid cell of the raster representing the analysis area. Other systems, such as Erdas Imagine, can create DEMs from contours directly. Whichever package is used, care needs to be taken to establish a grid whose resolution matches that of other data (including the landslides).

**Geology**: Although it may not be possible to include all the detail in the digital version, a large scale (1: 250 000 to 1: 50 000) geological map is required initially to ensure that the information is as accurate as possible. The important thing is to retain information on lithological differences that are likely to affect landsliding and to capture the information at a resolution appropriate to the analysis. Consequently, where lithological units are judged to have similar geotechnical properties these may be combined into a single class. This is a subjective decision that will benefit significantly from a knowledge of the causes of landsliding in the area. The geological units are digitised as raster polygons and attributed according to class. An example showing the digitised geology for the Jamaica test area is shown in Figure 6.

**Structure**: Faulting and jointing (fracturing) can potentially influence landsliding as they represent zones of rock weakness. Fractures may be digitised from the geological map and/or interpreted from a satellite image. In general, published maps only show the more important or well-defined structures. By contrast, it is often possible to identify a much larger number of ‘lineaments’ on satellite imagery. Since a line drawn on a map has no real thickness it cannot easily be used in the analysis. Consequently, it is usual to generate a ‘corridor’ about the line representing an assumed zone of weakness surrounding the main structural discontinuity. This is easily done using raster GIS tools. This may be left to the modelling stage at which time appropriate corridor widths can be tested by experimentation. An example of the corridors generated about the lineaments for Jamaica is shown in Figure 7.
Figure 5

Aspect (Rio Minho Watershed)

Figure 6

Geology (Rio Minho Watershed)

Implementation strategy for landslide hazard preparedness
Distance to faults (Rio Minho Watershed)

Soils (Rio Minho Watershed)

Figure 7

Figure 8
Soils: This information is only occasionally available. Enquiries should be made with the national forestry or agricultural department, or with universities. As in the case of geology, it may be appropriate to simplify the soil categories by combining those considered to possess similar engineering properties. This judgement is cross-disciplinary and may require discussion between appropriate experts (e.g. pedologists and engineering geologists). An example of the digitised soils map for Jamaica is shown in Figure 8.

Hydrogeology: Depth to water table and other information on the hydrogeology are potentially highly important but it is unlikely that detailed, continuous information will be available across the area. This lack of information can be a major weakness in the modelling approach. The use of hydrogeological data will depend on its nature. If related to a ‘continuous’ survey, it may be digitised as contour values; however, if tied to specific lithologies or other categories, then the categories may be digitised as polygons.

Land use: Land use data are often important to landsliding, for example in relation to areas of vegetated as compared to cleared ground. In some cases, land use or forestry/agricultural maps may be available, perhaps derived from the ‘classification’ of satellite imagery. Alternatively, a classification of the remote sensing data could be undertaken as part of the project using standard image processing classification software supported by any available ground truth information. In either case, the data so produced will be in digital form and so easily included in the database. Alternatively, if such information exists as a paper map, it will need to be digitised in a similar way to the geology.

Roads: Cuttings associated with the building of a road may themselves cause instability and hence landsliding. The road network may be digitised from existing maps, possibly augmented by reference to a recent satellite image. As in the case of lineaments, it is a simple matter to generate a (narrow) corridor around the road network and use this as part of the analysis. However, it is probably inappropriate to do so in most cases as road construction is more akin to a triggering effect than an inherent ground factor. In any case, the road network (digitised as a vector string) is a valuable addition to the final hazard map output and may provide an explanation as to why certain landslides occur where they do.

It cannot be stressed enough that all data sets must be co-registered to a common map projection. If differences still exist in the data due to variations in the original sources (due to map projection, inaccuracies or distortion of paper maps), these must be reconciled by geometric warping.

3.3.4 Cross tabulation

The first phase of the analysis examines the amount of landsliding within every class of each theme. This is best done by cross tabulation. An area cross tabulation is a two-dimensional table summarising the extent of overlap between all possible class combinations of two input theme maps. The landslide distribution inventory map, which consists of two classes (landslide or not landslide), is cross tabulated with each theme map in turn. The resulting table gives the areas affected and not affected by landslides for each class. An example is given in Table 5.
In this example, there are 827 landslides over the whole study area, representing about 0.55% of the total land area. The incidence of landslides in any individual class can be assessed from the percentage values; those greater than the average represent classes more susceptible to landsliding than would be expected if landsliding were a purely random event.

<table>
<thead>
<tr>
<th>Rock type (Class)</th>
<th>Landslide</th>
<th>Not Landslide</th>
<th>Total</th>
<th>Landslides as percentage of class area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td>6</td>
<td>7908</td>
<td>7914</td>
<td>0.08 %</td>
</tr>
<tr>
<td>White Limestone</td>
<td>13</td>
<td>12366</td>
<td>12379</td>
<td>0.11 %</td>
</tr>
<tr>
<td>Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Limestone</td>
<td>86</td>
<td>27239</td>
<td>27325</td>
<td>0.31 %</td>
</tr>
<tr>
<td>Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guinea Corn Frm.</td>
<td>34</td>
<td>7048</td>
<td>7082</td>
<td>0.48 %</td>
</tr>
<tr>
<td>Arthurs Seat Frm.</td>
<td>113</td>
<td>24557</td>
<td>24670</td>
<td>0.45 %</td>
</tr>
<tr>
<td>Total</td>
<td>827</td>
<td>149388</td>
<td>150215</td>
<td>0.55 %</td>
</tr>
</tbody>
</table>

Table 5. Area cross tabulation between the landslide inventory and geology maps for the Rio Minho, Jamaica study area. Values are in number of pixels which can be converted to area by multiplying by the pixel area of 2 500 m². Shaded classes have a higher than average incidence of landslides.

Whereas the incidence of landsliding compared to the area average can be assessed from the cross tabulation, it is important that the significance of these values is estimated in a consistent way. Two aspects of significance need to be addressed:

1. Significance of a theme to landslides (e.g. how important is the geology theme for predicting landslides?). This measure can then be used to determine whether a theme is a controlling factor, and if so how much weight it should be given in the final model.

2. Significance of each class within a theme (e.g. does alluvium host more or fewer landslides than other classes in the geology theme?). This measure is then used firstly to generate a hazard map for that individual theme, and secondly to combine all the themes into a final landslide hazard model.

3.3.5 Significance of a theme

The method chosen in the test areas was Cramer’s co-efficient, V. This is described in more detail in Appendix A. Cramer’s V varies from 0, representing independence, to a maximum value of 1. Using Cramer’s V, themes having a high correlation with landslides can be given more weight in the hazard model. For example, in Jamaica geology has V = 0.038 whereas aspect has V = 0.024. This indicates that in this study area geology is the
more important of these two, possible controlling factors and can be given more weight in constructing the final hazard model.

3.3.6 Significance of each class within a theme

The method suggested, here called association \((\alpha)\), was proposed by Yule (Fleiss, 1991). Again, this is described in more detail in Appendix A. Association values range from \(-1\) (maximum negative correlation) though \(0\) (independence) to \(+1\) (maximum positive correlation). Using the cross tabulation example given above (Table 5) the corresponding association values are shown in Table 6:

<table>
<thead>
<tr>
<th>Rock type (Class (k))</th>
<th>Landslide</th>
<th>Not Landslide</th>
<th>Total</th>
<th>Landslides as percentage of class area</th>
<th>Association ((\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology Map (Theme 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td>6</td>
<td>7908</td>
<td>7914</td>
<td>0.08 %</td>
<td>-0.469</td>
</tr>
<tr>
<td>White Limestone Group</td>
<td>13</td>
<td>12366</td>
<td>12379</td>
<td>0.11 %</td>
<td>-0.408</td>
</tr>
<tr>
<td>Yellow Limestone Group</td>
<td>86</td>
<td>27239</td>
<td>27325</td>
<td>0.31 %</td>
<td>-0.162</td>
</tr>
<tr>
<td>Guinea Corn Fm.</td>
<td>34</td>
<td>7048</td>
<td>7082</td>
<td>0.48 %</td>
<td>-0.036</td>
</tr>
<tr>
<td>Peladon Hills Fm.</td>
<td>113</td>
<td>24557</td>
<td>24670</td>
<td>0.45 %</td>
<td>-0.054</td>
</tr>
<tr>
<td>Total</td>
<td>827</td>
<td>149388</td>
<td>150215</td>
<td>0.55 %</td>
<td></td>
</tr>
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Table 6. Association values between geology theme classes and the landslide inventory for the Rio Minho, Jamaica study area from area cross tabulation. Shaded classes have a higher than average incidence of landslides.

Cross tabulation and subsequent assessment of significance are performed for each theme in the data set. The themes are then reclassified, within the GIS, using the association value for each class, to produce a map showing the degree of landslide susceptibility for the theme.

3.3.7 Combining data sets to form the landslide susceptibility model

Having assessed each theme separately, it is necessary to look at their combined effect on landsliding. Logically, if two themes individually 'explain' landsliding (in some undefined way), then the two taken together should provide an even better predictor.

The individual hazard maps can be combined in the GIS. The reclassified theme / landslide association maps are weighted by the Cramer’s V (i.e. multiply the theme by V)
and then summed. The result is normalised by the sum of the Cramer’s coefficients. The landslide susceptibility model thus produced should provide values in the range -1 to +1 that can be interpreted in the same manner as the association values.

3.3.8 Summary of procedures

A illustrative summary of the generic analysis procedure is given below:

1. Create landslide inventory map

Landslides can be represented in a number of ways and this will affect the analysis and the resulting model. The options include: (a) point representing the assumed landslide inception location; (b) polygon representing the scar only; (c) polygon representing the scar plus runout; or (d) polygon generated as a corridor around a line joining the inception point and toe of runout. The differences may be considered in the following example:

   Typical small landslide A covers 20 pixels
   Typical large landslide B covers 1000 pixels

both contained entirely within one class of the geology theme (e.g. alluvium consisting of 7914 pixels).

Considered as a percentage of the class area:

   Landslide A = 20/7914 * 100 = 0.25%
   Landslide B = 1000/7914 * 100 = 12.64%

In this example, landslide B is heavily weighted compared to landslide A (50 small landslides are required to cover the same area as 1 large landslide). This results in a model that identifies factors responsible for large landslides but pays little attention to small landslides.

The use of points rather than polygons gives all landslides the same weight (i.e. 1 pixel). This has some advantages but it negates the greater significance of the larger events. A possible compromise model would give slightly more weight to larger landslides by using a corridor generated about a line joining the inception point to the toe. In this approach, the large landslide might comprise 15 pixels compared to 3 pixels for the smaller slide. A judgement as to which approach to use will depend on the nature and variability of landsliding in the study area.

2. Perform cross tabulation of the individual themes with the landslide inventory map

3. Calculate the significance of each theme (Cramer’s V)

   Import cross tabulation results into the spreadsheet designed to perform calculation of Cramer’s V

4. Calculate association values for all classes in each theme
Import cross tabulation results into the spreadsheet designed to perform calculation of association

5. **Reclassify each theme using the association values calculated in step 4.**

6. **Add the reclassified themes on a cell-by-cell basis and normalize by the number of themes.**

   The relative significance of the themes can be included by weighting each theme by its corresponding Cramer’s V statistic, summing, and normalizing by the sum of the Cramer’s V statistics.

7. **Verify the model**

   Providing an objective measure of the success of the model is difficult. There are two options:

   - compare the results of the modelling with the landslide inventory, either visually or using cross tabulation analysis
   - compare the results of the modelling with landslides identified by fieldwork (does not have to be a complete dataset), either visually or using cross tabulation analysis

3.3.9 **Hazard map outputs**

There are various options for presenting the results.

Interim hazard models may be conveniently output as simple colour plots at A4 or A3 size. This is usually good enough for comparing and assessing alternative models. When combined with the landslide inventory, such plots may be used, at least subjectively, to validate the success of a model. An example plot for Jamaica is shown in Figure 9.

For practical purposes, the final hazard information should be output in the form of a true map (i.e. including appropriate cultural and geographical reference information). Hazard map output can take various forms depending on the data itself and the capabilities of the software and plotting systems being used. The components of the final map are:

- **Hazard zones:** An output from the raster GIS usually comprising three or four levels each with an assigned colour held as a raster image.
- **Topography:** Topography may be represented either as contours (vector line strings) or as a shaded relief image (raster): see below. The shaded relief image can be generated from the DTM.
Map data: This will include some/all of the following: roads, rivers, towns/villages symbols, hospitals, police stations, water tanks, map grids (e.g. Lat/Long or UTM) etc held as vectors plus text (names; map projection; credits etc). It may additionally include image ‘objects’ such as the legend (map explanation), location inset map etc.

The map may be thought of as comprising a ‘backdrop’ of the raster hazard zones, together with any other raster information and image objects (as above), overlain by cultural and locational vector information and text. A major consideration is how to represent the topographic information. Conventionally, topography is displayed on maps as contours. If vector contour information is held on the database, then this may be directly plotted on the map. If vector contours are not held, then they may be generated, using an appropriate interval, from the DTM using either image analysis or raster GIS software. However, contours can be difficult to understand, especially for those not familiar with maps, or may crowd the presentation. An alternative is to represent the relief as a grey-scale shaded relief image (generally best when illuminated from the northwest) which provides an easily understood visualisation of the ground. The shaded relief image can be generated from the DTM, again using either image analysis or (in some cases) raster GIS software. The next problem is how to display two raster layers together; this can be approached in at least two ways depending on the software options available. One approach (available, for example, in the Erdas Imagine image analysis package) is to adjust the ‘opacity’ of the hazard colours so that the grey scale shaded relief is visible through them. For best results the shaded relief image should be reduced to only a few (e.g. 6 or 8) grey levels and should be quite contrasty. The alternative method is to carry out an intensity-hue-saturation transformation, a process that is available on most image analysis systems using the two images as inputs. This effectively modulates the colour hazard zones based on the intensity of the shaded relief. Both approaches will give similar results but each requires experimentation to achieve the best result. An example hazard map for Jamaica (reduced to A4 and thus lacking some details of the original 1:75 000 map) showing the hazard zones draped onto a shaded relief image is shown in Figure 10.

Final map compilation may be carried out in the IA or vector GIS environment. A summary of the stages involved in hazard analysis and map generation is given in Figure 11.

As mentioned above, the map should include a legend (or explanation) written in terms that are understandable by the non-specialist. This should describe in general terms how the map was produced, what the different colour zones represent, and how the map should – and should not – be used. An example legend of this type is shown in Figure 12.

3.4 Discussion

A principal limitation of the method is likely to be the incompleteness of the database. In the Slovakian case study, for example, although most of the landslides occurred in the weathered surface layers, no physical property data was available for this weathered zone. Consequently, information about an important controlling factor was not included in the analysis. This omission must affect the accuracy of the resulting landslide hazard model to an unknown extent. However, an advantage of the GIS approach is that, once the database is established, the analysis is easily repeatable. If and when additional information becomes available, a more accurate, updated model can be produced. Nevertheless, it should be
recognised that in most instances regional landslide hazard maps produced using this method will be imperfect to varying degrees and will only approximate the ‘truth’.

The analysis combines information by adding the themes recast as association values. This assumes that when different themes/classes that are individually associated with landsliding combine, they result in an area that has an even higher susceptibility to landsliding. Conversely, themes/classes which impart stability (i.e. have a negative association with landsliding) will act to reduce the effect of other themes/classes which are positively associated with landsliding. Although this would seem to be a reasonable hypothesis, there is little definitive evidence for or against it. Moreover, even if the assumption that susceptibilities do combine in some way is correct, it does not follow that the effects are purely linear. Indeed, in a previous study using a slightly different (and in some aspects less rigorous) modelling approach, Greenbaum (1995a and 1995b) found indications that the combination of weightings was far from linear. For example, a soil and a particular rock type may not pose a hazard in isolation but they may do so in combination, if that soil overlies that rock type. There are ways of modelling these effects by using the union of the two themes, but this has not yet been attempted.

Another uncertainty in the use of statistics is the question of the independence of the classes and themes. Most statistics require that the variables are independent of one another but this is unlikely to be the case with landsliding. For example, soil types and possibly relief and slope are each likely to be related to the underlying geology so that their separate correlation with landsliding cannot be linearly additive. The approach adopted takes no account of this.

One difficulty in using the final output is the lack of any real indication as to the reliability of the resulting hazard map. One way to assess reliability is to perform a cross tabulation between the hazard map and the landslide inventory map, and quantify the level of agreement between the two distributions using significance statistics. An alternative approach might be to perform the hazard analysis using the information for one half only of the study area and then applying the results to the other. This would test the predictive power of the model. It requires that similar ground and terrain conditions pertain in both halves of the study area. (This approach would also provide an indication of whether the model might be extended to areas of similar ground beyond the limits of the landslide inventory provided the appropriate database existed). Finally, the hazard analysis could be performed a number of times using randomly selected sub-sets of the landslide inventory. This would allow the ‘stability’ of the modelling to be assessed. None of these techniques gives an indication of how the model changes with the inclusion/exclusion of themes within the database or due to the omission of information.

3.5 Using landslide hazard maps

Various comments about the use (and misuse) of landslide hazard maps have been made in the above sections but it is perhaps worth re-iterating here some of the do’s and don’ts.
Figure 10 Landslide hazard zones draped onto shaded relief (For explanation, see Figure 12)
SCHEMATIC SHOWING THE COMPONENTS OF HAZARD MAP PRODUCTION
EXPLANATION

The map divides the area into broad zones representing the relative potential for landslide hazards (that is, the likelihood that landslides will occur). It is based on the concept that landslides result from a number of factors that, in combination, produce unstable ground conditions. These include controlling factors such as the type and nature of the rocks and soils forming the slope, and the steepness of the slope, and triggering factors such as heavy rainfall, earthquakes or man-made excavations. Using a computer, the locations of identified existing landslides (both recent and ancient) have been compared against a range of factors that may contribute to ground instability. Where correlations were found, these were used to predict broad zones of varying susceptibility to future landslide events. The zones are very broad and within each there will be locations where the risk of landslides will be higher or lower than in dictated depending on local circumstances. The map provides only a general indication of landslide susceptibility and cannot be used as an indicator of ground instability at any specific location. The map indicates the extent and relative severity of probable landslide hazard and may be used as a tool to assist planners in the preliminary selection of areas for housing and infrastructure development or emergency services considering response actions.

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

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

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

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

Existing landslides are present in all zones and should be avoided for development purposes unless made stable by appropriate engineered remedial works. The vulnerability of current development and infrastructure on or near existing landslides should be assessed as a matter of priority and the stability conditions of the landslide deposits and adjacent slopes ascertained prior to design and implementation of any corrective measures. Avoidance is advised where corrective measures, and their continued maintenance are, too costly.

- **Road**
- **River/Drainage**
- **Waternet**
- **Police Station**
- **School**
- **Landslide**
- **Hospital**
- **Church**
- **Community Centre**
- **Town Village**

**User responsibility**

The map provides only a general indication of landslide susceptibility and must not be relied upon as a source of detailed information about specific areas or as a substitute for site investigations or ground surveys. Users must satisfy themselves, by seeking appropriate professional advice and carrying out ground surveys and site investigations, that ground conditions are suitable for any particular land use or development. The map is released on the condition that the British Geological Survey (BGS), the Department for International Development (DFID) or the Unit for Disaster Studies (UDS) may not be held responsible for any damages resulting from any authorized or unauthorized use of this information.

Figure 12
The approach described in this report for producing regional landslide hazard maps is very simplistic and the resulting outputs are consequently rather restricted in terms of the information they contain. This limits the uses to which the maps should be put. Users need to be aware that if they require information on specific locations then the maps will not address their needs and it would be inappropriate to use them in this way. The main danger is that the maps will be read and used at the local level by individuals who are not fully aware of this 'health warning' and who will thus draw wrong conclusions about the local hazards. An informative map explanation (Figure 12) can help prevent this happening but there will always be those who fail to read or fully understand the information provided.

Regional hazard maps should be regarded principally as a source of general information about the area as a whole. The maps will inform users as to which parts of the area are likely to be at most risk but (1) they cannot be taken to imply that all locations within a particular zone are equally hazardous and (2) that areas of similar hazard do not, in fact, fall outside the indicated zone. In other words, the maps are in all probability only a first approximation of the true situation.

There are at least two important uses for regional hazard maps. First, they can be used to support decisions requiring more detailed, conventional ground engineering surveys to be conducted over sites (including the routes of new roads) identified for new developments. Here, they will help flag the need for local authorities to ensure that adequate investigation is done as part of the planning application procedure. Second, the maps can be used for regional disaster planning by the emergency services. In this case, the maps should provide a basis for 'modelling' different disaster scenarios, such as the consequences of particular roads being blocked by landsliding, and developing contingency strategies based on the results.

The importance of producing maps that are understandable by a range of users has already been mentioned. Thus, the use of shaded relief instead of contours to indicate relief will assist comprehension and location. Other visualisation approaches are also possible using the power of the computer, either interactively or as printed output. The main technique involves the use of perspective views of the ground in which the map area, or part of it, can be viewed obliquely from different vantage points and at different angles to the horizon, creating 'bird's eye' views of the terrain. This is based on techniques of draping the hazard zones over the DTM. Such presentations can be especially helpful in scenario testing and public education.
4. SOME IMPLEMENTATION ISSUES

4.1 Developing a strategy

Previous sections of this report have outlined the technical approach to landslide hazard mapping. The description is necessarily general, and any geological survey or other organisation considering implementing a project will need to develop a detailed plan based on their own particular needs and resources. The purpose of this section is to highlight some of the practical considerations and constraints in deciding whether a landslide hazard mapping project is viable.

Landsliding is a significant problem in many developing (and developed) countries. It has been estimated that up to 25 per cent of all deaths from natural hazards are the result of landslides (Hansen, 1984). However, the physical nature and importance of the problem vary greatly from country to country so that before anything else it is necessary to decide whether the need justifies the effort involved. In a ideal world, landslide hazard maps would be available for most urban and many rural areas, but realistically the resources (both human and financial) needed to make this happen are not likely to be realised in the foreseeable future. Ground surveys are simply too expensive for this to happen. On the other hand, rapid regional hazard maps can be produced at moderate cost and within a short time frame. Even so, given the limitations of such maps, it is relevant to ask whether such information will be of practical use in a particular situation. Consequently, it is important to understand – and to inform all those concerned in the decision process – as to the limitations of the method. Regional hazard maps provide information on the statistical likelihood of landsliding at a very coarse scale: they cannot provide information useful at the detailed (site-specific) level. They provide a useful starting point for: (a) initial, pre-development planning (e.g. new road routes; pipelines); (b) identifying areas where conventional ground investigations may be required; and (c) developing disaster response plans. A decision on whether to develop a hazard mapping project requires the informed input of all potential users and this will require broad consultation among interested parties. The importance of a Steering Committee is further discussed below.

Having decided that hazard maps are needed, priority areas must be decided and investigations undertaken to establish whether sufficient data exist to make the project possible. Since the technique depends on the analysis of ground and terrain factors which influence landsliding, the existence of reliable data on geology, relief, soil type, land use, etc. is critical. In most cases, the information will not exist in digital form but this should not be a deciding factor.

At this point, detailed consideration should also be given to the availability of resources including suitably qualified staff, computing and other facilities, and funding.

4.2 The skills base and training needs

The techniques described for hazard modelling call for a range of expertise. Organisations will need to consider their skills’ base and training needs in order to assess costs and benefits, to ensure the approach taken realistically matches resources.

Remote sensing: The basis of landslide modelling is a landslide inventory derived from the interpretation of remote sensing data, perhaps supplemented by ground survey information. The
skills required to build this vital data set are varied. The work is best undertaken by a geologist, preferably one with a geotechnical background and certainly with experience of interpreting aerial photography and/or satellite imagery. If satellite imagery is to be used in the study, then it is preferable that this is processed in-house so that topographic, textural and tonal details can be optimally enhanced for landslide identification. Ideally, the operator should be an experienced image analyst. There is no reason why, if s/he has a geological background, the same person cannot also carry out the interpretation; alternatively, this could be undertaken by another member of the team. If standard satellite imagery is the main data type to be used in the study, then examination of stereo aerial photography may also be required. This will require someone with good geological and especially geomorphological knowledge as well as photointerpretation skills and experience.

If required, training in image analysis and/or photogeology (with an emphasis on geomorphology and terrain analysis) can be provided through short training courses that are available from various research and academic centres worldwide, including BGS. Acquiring experience and confidence takes a little longer but can be achieved on the job, especially when image interpretation is interspersed with field checking. An ideal candidate for such training would be a geologist with a geotechnical background who already has basic computing skills. Again, there is no reason why the image analysis specialist might not be the same person responsible for databasing and GIS modelling (see below).

**Databasing & GIS modelling**: Building the digital database is a major activity. How it is approached will depend on the nature/format of the input data and the software/hardware being used. Database design is important and requires specialist knowledge: this might be provided by the GIS expert (see below) who would then have the advantage of fully understanding data requirements in terms of the later modelling to be carried out. The digitising work itself might be more cost-effectively undertaken by junior staff under supervision from the database manager. Quality control is, however, an important consideration.

The GIS expert is an important member of the team who must work closely with the geologist who has overall responsibility for the project. Creation of a landslide hazard map calls on a range of GIS skills including experience of raster GIS for modelling operations and vector/cartographic GIS for production of the final output. Alternatively, the latter might be achieved using the GIS capabilities of the image analysis system. The GIS expert will need to have a basic knowledge and understanding of statistics/mathematics. GIS modelling is not a ‘blind’ operation; it requires interaction and the assessment of results to ensure that the end product is realistic.

Databasing and GIS skills can be obtained through specialist degree or post-graduate training courses. IT skills are important in many areas of geoscientific work in modern geological surveys, so that investment in training will undoubtedly bring wider benefits to the organisation. It is not essential that the IT expert has a background in geology: indeed, someone with a computing background may require less training overall. However, anyone coming from a non-geological background should be given at least basic, on-the-job, geological/geotechnical training.

The long-term sustainability of the programme will, amongst other things, depend on the retention of skilled IT staff. This can prove to be a difficult problem since IT specialists are increasingly in demand and may have attractive job opportunities in the commercial world, both within geology and beyond. Government organisations may find it difficult to compete on
salary, so that the best way to prevent critical staff loss is probably a combination of job satisfaction, good working conditions and payment of a skills/retention allowance. An ongoing trainee IT programme should be implemented as a fallback.

4.3 Computer hardware and software requirements

The following is a list of the main stages of landslide hazard modelling, and the essential computing requirements at each stage for data entry, processing and output.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Hardware</th>
<th>Software</th>
</tr>
</thead>
</table>
| Data entry           | Digitiser                       | Digitiser software
                                                                          Vector to raster conversion |
|                      | Scanner                         | Line-following software                            |
| Image processing¹    | Workstation or high-level PC    | Image analysis (processing) software (e.g. Erdas Imagine, ER Mapper, ENVI) |
| GIS modelling¹       | Standard PC (high-resolution monitor) | Raster GIS (e.g. Idrisi, ILWIS)                   |
| GIS presentation¹    | Standard PC (high-resolution monitor) | Vector GIS (e.g. MapInfo, ArcView) |
| Output               | Colour plotter                  |                                                   |

¹. Image analysis packages increasingly feature advanced GIS functionality, and vice versa

4.3.1 Hardware Requirements

Most requirements, other than the workstation or high-level PC required to run the image processing (analysis) software, are standard items that may be already available. In this case, they can be used without incurring additional cost, other than software and possibly upgrading of memory and disk storage. However, if it is necessary to purchase hardware, then this should be considered in terms of the broader benefits that the extra computing facilities would bring to the organisation. Similarly, in the case of the image analysis system, although costs have reduced significantly in recent years, the total hardware/software requirement may still be substantial. The investment (including the training of an operator) would possibly not be justified if landslide mapping were the only application and any such decision should be taken in the context of the needs of the organisation as a whole. Digital remote sensing has many applications such as geological mapping, mineral exploration, environmental monitoring etc. Alternatively, organisations not able to make this investment should consider whether it is
feasible to make use of the facilities of another institution (e.g. a university) on a collaborative basis.

4.3.2 Software Requirements

Software offers many choices and will be determined by several factors, not least of all cost. It is not critical that any particular software package is used: the only requirement is that it has the functionality to achieve the task and deal efficiently with the data sets. If GIS or image analysis software is already available to the project, then it might be appropriate to make use of this. If new software is to be purchased then consideration needs to be given to various local issues, such as: compatibility with systems already in use in the organisation or country; the presence of a local agent; support/maintenance; and the likely supplementary uses to which the systems will be put. Furthermore, although the above table implies that the three operations of image processing, GIS modelling and GIS presentation are separate activities carried out using different systems, software systems are rapidly moving towards a point where they can perform more than one of these tasks. Some image analysis systems have the capability to perform all three operations – although not necessarily in the most efficient manner. In a similar way, the latest GIS packages now offer the functionality of both raster and vector GIS (e.g. ArcView Spatial Analyst) and promise increased operational efficiency at low cost. Indeed, the trend in software development is increasingly to integrate image processing with fully functional GIS packages. This will serve to further streamline operations, will avoid the need to convert data formats between software packages, and will allow all software to be run on a single hardware platform (workstation or high-level PC). Such an integrated software system would have significant advantages at the map output stage, as it would permit the rapid generation of one-off, customised map products on demand.

4.4 Project planning

Good project planning is always important, and this is especially true in the case of landslide hazard mapping where the output is intended to be used by various outside individuals and organisations. The need to establish a Steering Committee has already been mentioned. This should begin as a pre-project action and include all parties from regional and local government who have a potential interest, together with representatives of academic institutes and commercial firms, if appropriate. The active interest and involvement of outside parties serves a number of purposes. Firstly, it guarantees the relevance and hopefully take-up of the eventual products. Secondly, it conveys a sense of 'ownership' to all concerned. Thirdly, it raises the profile of the project sufficiently (as a result of multi-party endorsement) to help in the fight to win funding – possibly from multiple sources.

The aim of early consultation is to ensure that the scope and objectives are clearly defined so that the eventual products are both useful to, and used by, those they are intended for. The Steering Committee will include members with little technical appreciation of the geological problem and limited understanding of the scientific approach, so it is important to explain the limitations of the method and how the product can and cannot be used. No one involved should be under the illusion that regional landslide hazard maps are the answer to detailed site planning. A range of potential users will undoubtedly have varied requirements but, described earlier, the limited validity of the outputs should be made clear: that (1) they can provide a first indication as to whether a site falls within a high, medium or low hazard zone and therefore whether further geotechnical ground studies are needed; and (2) that they can provide emergency services with the basis for developing regional contingency plans based on the...
The likelihood of landsliding events. Effective use of the information may ultimately require changes to the law and thus the involvement of government decision-makers from the outset might be helpful.

The result of this pre-project planning phase, should be an outline design specification for hazard map production. This will indicate the types of plots (and/or maps) and scales to be produced and a list of what locational, cultural and infrastructural information is to be included. Consideration should also be given to other forms of output (e.g. interactive; video) that might form part of an educational package. Although this preliminary specification will undoubtedly change, it will provide an initial target strategy. The pre-project phase will also lead to the identification of study areas. Commonly, urban areas will be nominated as priority targets: although the method will not provide detail at the level required for urban sites, their inclusion is acceptable where the area forms part of a broader regional study.

Having defined the products and identified priority areas, the project resources – in terms of both facilities and professional staff – must be considered and costed so that a detailed project proposal can be prepared. Various formalised approaches to project planning exist and no specific recommendations will be given here. What is important is to have clear and realistic ideas about the project objectives and time scales. Some of the general elements of any project plan are listed below (based in part on the Project Cycle / Logical Framework approach). Not only will consideration of these ensure a focused, practical project, but they will also help convince potential funding agents that the project is worthwhile and achievable.

**Goal**

This is the higher level objective to which the project will hopefully contribute. It is useful to state this as it may help funding departments to justify the award of funds in terms of their own policy objectives (which the project proposers would be well advised to consult). It may be little more than a ‘motherhood’ statement, perhaps along the lines: ‘Protect populations and infrastructure from natural and man-made disasters’.

**Purpose**

The Purpose should clearly define the sustainable benefits to be gained from the successful implementation of the project. These may include effects beyond the immediate control of the project itself (e.g. ‘to make available information on potential landslide hazards for use in development planning and disaster contingency/mitigation’).

**Outputs**

Unlike the above objectives, the project is held accountable for delivering the Outputs (of which there may be several). An Output is not exactly the same as a ‘deliverable’ and may be better thought of as an immediate desired effect (e.g. ‘improved knowledge of landslide hazard probability’ or ‘better informed decision makers, planners and emergency services’). The tangible deliverables (the maps themselves, or the databases, or perhaps educational workshops) may be considered as ‘verifiable indicators’ (see below) of the Outputs.

**Activities**

These are the specific actions to be undertaken in order to achieve each of the stated Outputs. Usually, there will be one main Activity for each Output with each then subdivided into an ordered series of individual tasks. Besides stating these in a narrative, they should be shown graphically on some form of bar (Gantt) chart where each is given a time...
frame, milestone(s) and team member responsible. For potentially long-running projects, each component (e.g. a hazard map for a specific region) may be described as a separate phase.

Indicators

Project progress and the achievement of milestones are best measured against what may be termed ‘verifiable indicators’. These should be provided for each Activity, as well as for each Output (see above) and take the form of specific interim products, actions or tangible records. Verifiable indicators should be quantifiable (e.g. ‘digital data capture for X map sheets completed by Month Y’ or ‘preliminary hazard maps for Z map sheets reviewed by Steering Committee by Month T’).

Assumptions

Awareness of factors (often external to the project) that can influence the success should be considered and listed. In order to guarantee success to at least the Output level, no uncontrolled event should be so damaging that an appropriate contingency plan cannot be devised to deal with it.

Team

The manpower (in terms of skills/specialisms) necessary to successfully carry out the project should be described together with a management and responsibility structure. The plan should identify whether the staff are available in-house, or whether they will need to be specially recruited or existing staff given training. Linkages with outside bodies and the role of the steering committee should also be stated.

Resources

The detailed requirements of the project in terms of facilities, equipment and data need to be specified.

Finances

The project should be fully costed to take account of all elements. This will include: staff costs (including overheads); training; field costs (including transport); computing hardware/software (including ongoing maintenance); purchase of imagery/photography; consumables etc.

The actual form that the proposal takes will depend on the requirements of the department or funding agency. It should be remembered that, a good project plan, besides being a requirement for securing funding, should also be a tool for managing the project. However, the plan should not be so inflexible that it cannot be adapted to deal with events/delays as they occur. In a phased project, experience gained in the early stages will help improve the planning for subsequent phases.

4.5 Public awareness

For the project to be successful, the results must not only be applied in some practical way but the concept must gain acceptance across the wider community. The value of having an active and enthusiastic Steering Committee, both before and during the project, has already been discussed. It may also serve another important function – and that is in the area of public awareness and understanding. Publicity is important and can act for the good of the project provided it is planned and not merely responsive. However, one of the pitfalls of informing the general public about hazards is that the information is easily open to misinterpretation and ‘bad press’, which can result in public alarm and even ‘blight’ of certain areas. Therefore, just as it is
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APPENDIX A: Description of analysis


A1 Methodology

A1.1 Cross Tabulation

The first phase of the analysis assesses the degree of landsliding within every class of each theme. This is most easily achieved by cross tabulation. An area cross tabulation is a two-dimensional table summarising the extent of overlap between all possible class combinations of two input theme maps. In this study, the landslide distribution inventory map, which consists of two classes (landslide or not landslide) is cross tabulated with each theme map. The resulting table gives the areas affected and not affected by landslides for each class. An example is given in Table A1.

In the example cross tabulation (Table A1) there are 827 landslides over the whole study area, representing about 0.55% of the total area. The incidence of landslides in any individual class can be assessed from the percentage values; those greater than the average are more susceptible to landsliding.

<table>
<thead>
<tr>
<th>Rock type (Class)</th>
<th>Landslide</th>
<th>Not Landslide</th>
<th>Total</th>
<th>Landslides as percentage of class area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology Map (Theme 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td>6</td>
<td>7908</td>
<td>7914</td>
<td>0.08 %</td>
</tr>
<tr>
<td>White Limestone Group</td>
<td>13</td>
<td>12366</td>
<td>12379</td>
<td>0.11 %</td>
</tr>
<tr>
<td>Yellow Limestone Group</td>
<td>86</td>
<td>27239</td>
<td>27325</td>
<td>0.31 %</td>
</tr>
<tr>
<td>Guinea Corn Frm.</td>
<td>34</td>
<td>7048</td>
<td>7082</td>
<td>0.48 %</td>
</tr>
<tr>
<td>Arthurs Seat Frm.</td>
<td>113</td>
<td>24557</td>
<td>24670</td>
<td>0.45 %</td>
</tr>
<tr>
<td>Total</td>
<td>827</td>
<td>149388</td>
<td>150215</td>
<td>0.55 %</td>
</tr>
</tbody>
</table>

Table A1 Area cross tabulation between the landslide inventory and geology maps for the Rio Minho, Jamaica study area. Values are in number of pixels which can be converted to area by multiplying by the pixel area of 2 500 m². Shaded classes have a higher than average incidence of landslides.
A1.2 Significance

Whilst the incidence of landsliding compared to the area average can be assessed from the cross tabulation it is important for the significance of these values to be estimated in a consistent way. The simplest way is to normalize the percentage landslide area by the regional average. There are, however, a number of other statistics which can be calculated from the information in the cross tabulation to help improve the understanding of the information content of the data.

To assist the calculation of significance measures consider the following table for a single class:

<table>
<thead>
<tr>
<th>Landslide</th>
<th>Class (e.g. Rock Unit)</th>
<th>Present</th>
<th>Absent</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T_{11}$</td>
<td>$T_{12}$</td>
<td>$T_{1*}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{21}$</td>
<td>$T_{22}$</td>
<td>$T_{2*}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{*1}$</td>
<td>$T_{*2}$</td>
<td>$T_{**}$</td>
</tr>
</tbody>
</table>

Table A2 Contingency table of unique conditions from the cross tabulation of a class map and the landslide inventory map.

The T values in Table A2 are the areas of the various combinations between the presence/absence of the class and landslides. They represent:

- $T_{11}$: the area within the class affected by landslides
- $T_{12}$: the area of landslides outside the class
- $T_{21}$: the area within the class not affected by landslides
- $T_{22}$: the area outside the class unaffected by landslides
- $T_{1*}$: total area of landslides
- $T_{2*}$: total area unaffected by landslides
- $T_{*1}$: total area of class
- $T_{*2}$: total area of study outside the class
- $T_{**}$: the total area of the study

When performing a cross tabulation between a theme with more than one class and the landslide inventory it is more convenient to present the information with the class information in the rows of the table. It must be remembered that we are trying to use the class as a predictor for landslides and that the class is the controlling factor. The table will not display some of the T values and these have to be calculated (see Table A3 below).

The notation used in Table A2 above can be applied to the full cross tabulation as $T_{ij}$ where $i=1,2$ landslide classes (presence/absence) and $j=1,2,...,n$ classes in the theme. The marginal totals are defined as $T_{i*}$ for the sum of the $i$-th row, $T_{*j}$ for the sum of the $j$-th column and $T_{**}$ for the grand total summed over all rows and columns.
A common measure of association is the chi-squared statistic which compares the observed area of landsliding with the expected area. The expected area of landslide within the class is given by:

\[ T_{ij}^* = \frac{T_{ii}T_{jj}}{T_{..}} \]  

(1.1)

Then the chi-squared statistic is defined as

\[ \chi^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{(T_{ij} - T_{ij}^*)^2}{T_{ij}} \]  

(1.2)

the familiar \((\text{observed} - \text{expected})^2/\text{expected}\) expression, which has a lower limit of 0 when the observed areas exactly equal the expected areas and the two maps are completely independent. As the observed areas become increasingly different from the expected areas, the chi-squared increases in magnitude and has a variable upper limit. The chi-squared value is a goodness-of-fit measure and should only be used in a descriptive manner since it has a variable upper limit. Equation (1.1) gives an estimate of the significance of landslides within each class whereas the chi-squared value from Equation (1.2) indicates the overall significance of the theme.

An alternative measure is that of Cramer's co-efficient, \(V\), in this case defined as

\[ V = \sqrt{\frac{\chi^2}{T_{..}}} \]  

(1.3)

Cramer's \(V\) varies from 0, representing independence, to a maximum value of 1. This statistic can be used to compare the overall correspondence of each of the themes in the data base to landsliding.

An alternative measure of significance, here called \(\alpha\), was proposed by Yule (Fleiss, 1991). Using the single theme class notation of Table A2 it can be calculated thus:

\[ \alpha = \frac{\sqrt{T_{11}/T_{21}} - \sqrt{T_{12}/T_{22}}}{\sqrt{T_{11}/T_{21}} + \sqrt{T_{12}/T_{22}}} \]  

(1.4)

Like a correlation co-efficient, \(\alpha\) ranges in value between -1 and +1. A value of 0 implies that the distribution of landslides and the class are independent. This means that within the class the area of landsliding is no more than would occur by chance which is represented by the regional average. A negative suggests that the class is more stable than average whereas a positive value indicates that the class has a higher incidence of landslides.

Expanding (1.4) to the general case with cross tabulation between the landslide inventory and a multi-class theme map, when some \(T\) values have to be calculated, gives the class association \(\alpha\):
where \( k \) is the class.

Using the cross tabulation example given above (Table A1) the corresponding association values are:

\[
k \alpha = \frac{\sqrt{k T_{11}} / k T_{21} - \sqrt{(T_{1k} - k T_{11}) / (T_{2k} - k T_{21})}}{\sqrt{k T_{11}} / k T_{21} + \sqrt{(T_{1k} - k T_{11}) / (T_{2k} - k T_{21})}} \tag{1.5}
\]

Table A3 Association values between geology theme classes and the landslide inventory for the Rio Minho, Jamaica study area from area cross tabulation. Shaded classes have a higher than average incidence of landslides.

Cross tabulation and subsequent assessment of significance is performed for each theme available in the data set. The themes are then reclassified, within the GIS, using the association value for each class to give a map showing the degree of landslide susceptibility for the theme.

Another means of assessing the significance of each class is the calculation of weights-of-evidence. These measures are related to the probability of landsliding and can be calculated from the cross tabulation results. Two weights, \( W^+ \) and \( W^- \), are calculated for each class where (using the above notation):

\[
k W^+ = \ln \left[ \frac{k T_{11} T_{2k}}{k T_{21} T_{1k}} \right] \tag{1.6a}
\]
\[ W^* = \ln \left( \frac{(T_{1w} - T_{2w}) T_{2w}}{(T_{2w} - T_{21}) T_{1w}} \right) \] (1.6b)

Weight \( W^* \) relates to the probability of landsliding within the class whereas weight \( W \) is related to the probability that landslides occur outside the class. A fuller explanation of the approach is given in Bonham-Carter (1994). Clearly, weight \( W^* \) can be compared to the association values described above as an indication of landslide susceptibility. When \( W^* \) is positive then \( W \) is negative, and vice versa. A comparison of the different measures of significance for the geology theme in the Rio Minho study area is given in Table A4. The main use of the weights-of-evidence is in the combination of the various themes and arose from mineral exploration.

**A1.3 Combining datasets**

Having assessed the themes separately, it is necessary to consider their combined relationships to landsliding. Logically, if two themes individually relate to landsliding, in some undefined way, then the two taken together should provide a still better predictor. Such combinations may, for example, help explain, and model, particular spatial patterns evident in the landslide distribution resulting from multivariate interactions.

**A1.3.1 Association**

The combinations of themes can be produced in the GIS. Firstly, each class of each theme is reclassified in terms of its corresponding association value. Secondly, the resulting theme/landslide association maps are then summed. Finally, the result is normalized by the number of themes used in the summation. The landslide susceptibility model thus produced should range in value between -1 and +1 and can be interpreted in the same manner as the association values.

**A1.3.2 Weights-of-evidence**

Weights-of-evidence values give an indication of how well each theme class can be used as a predictor of landslides. They are related to the probability of landsliding and can be combined using Bayes' Rule. Consider a single class as a predictor of landsliding, then the probability of there being a landslide given the presence of the class can be expressed by the conditional probability:

\[ P(L|C) = \frac{P(L \cap C)}{P(C)} \] (1.7)

It can be shown that the probabilities \( P(L \cap C) \) and \( P(C) \) are represented by the area of landslides within the class and the area of the class itself.

If we now have two predictive classes \( C_1 \) and \( C_2 \) then the conditional probability of a landslide occurring becomes:
Table A4. Association values between geology theme classes and the landslide inventory for the Rio Minho, Jamaica study area from area cross tabulation. Shaded columns are given by cross tabulation, rest are calculated from these values. Shaded classes have a higher than average incidence of landslides.
\[ P\{U \cap C_r \cap C_2\} = \frac{P\{L \cap C_r \cap C_2\}}{P\{C_r \cap C_2\}} \quad (1.8) \]

Assuming conditional independence this can be re-arranged to give:

\[ P\{U \cap C_r \cap C_2\} = P\{L\} \frac{P\{C_r|L\} \, P\{C_2|L\}}{P\{C_r\}} \, P\{C_2\} \quad (1.9) \]

effectively separating the conditional probabilities of each individual class \(i\).

These probabilities can be recast in terms of logarithmic odds, or logits, such that:

\[
\text{logit}\{L|C_r \cap C_2 \cap C_3 \cap \ldots \cap C_n\} = \text{logit}\{L\} + \sum_{i=1}^{n} W_i^+ \quad (1.10a)
\]

\[
\text{logit}\{L|\overline{C}_r \cap \overline{C}_2 \cap \overline{C}_3 \cap \ldots \cap \overline{C}_n\} = \text{logit}\{L\} + \sum_{i=1}^{n} W_i^- \quad (1.10b)
\]

The value of \(\text{logit}\{L\}\) can be found from the prior probability of the occurrence of a landslide in the area thus:

\[ P\{L\} = \frac{T_{w}}{T_{\infty}} \quad (1.11) \]

(Prior probability of landslides is simply the average density of landslides across the area)

\[ O\{L\} = \frac{P\{L\}}{1 - P\{L\}} = \frac{T_{w}/T_{\infty}}{1 - T_{w}/T_{\infty}} \quad (1.12) \]

(Prior odds of landslides)

\[ \text{logit}\{L\} = \ln O\{L\} = \ln \left(\frac{T_{w}/T_{\infty}}{1 - T_{w}/T_{\infty}}\right) \quad (1.13) \]

(Prior logit of landslides).

A fuller explanation of this derivation can be found in Bonham-Carter (1994).

A2 Procedure

The generic analysis procedure is given below:
Step 1 Cross tabulation of the individual themes with the landslide inventory map. Results held as text files.

Step 2 Calculation of significance measures for each theme. Cross tabulation results imported into spreadsheet designed to perform calculation of association, weights-of-evidence, chi-squared and other statistics. Results held as text files.

Step 3 Import significance measures as tables in the GIS database.

Step 4 Calculation of association. Reclassify each theme using the association values from the database tables. Add the reclassified themes on a cell-by-cell basis and normalize by the number of themes. Relative significance of the themes can be included by weighting each theme by its corresponding Cramer's V statistic, summing, and normalizing by the sum of the Cramer's V statistics.

Step 5 Calculation of posterior probability. This requires a separate processing sequence:

i Calculate the prior probability of landslides. Estimate from the average landslide density over the study area.

ii Convert prior probability to prior odds and take the natural logarithm to give the prior logit.

iii Treat each class in each theme as a binary map showing presence or absence of the class. Where the class is present set the value to the $W^*$ of the class, everywhere else set to $W$. Sum all the reclassified themes. (This can be achieved either by creating and recoding $n$ binary maps, where $n$ is the number of total classes in the database which can be large, or by nested conditional and recoding statements in the GIS processing algorithm. The former is easier to implement but produces more intermediate files and requires additional processing time, in the second a complex processing algorithm must be defined.)

iv Add the prior logit to the result of Step 5iii to give the posterior logit.

v Convert posterior logit to posterior odds by taking the inverse natural logarithm (exp function) and transform to posterior probability.

Step 6 Assess validity of hazard models by comparing with landslide distribution either visually or by cross tabulation analysis.

The specific procedure will depend on the capabilities of the GIS used for the analysis and should be developed from the generic procedure.

A3 Comments and discussion

In the case of the Jamaica and Slovakia trials, association was used in preference to weights-of-evidence. In general, association is simpler and easier to implement. Encouragingly, when both methods were tested for Jamaica, they produced similar results.

Another concern is that in order to use the weights-of-evidence approach a necessary assumption is that of conditional independence between the predictor classes. This means that the probability of
one class being present is independent of whether another class is present or absent. This may be satisfied between themes but unlikely to be so between classes within the same theme. For example, whereas there may be little association between the location of forests and slope aspect (i.e. it is not possible to predict the presence/absence of forest from the direction the slope faces or vice versa), in the land cover theme, areas of trees preclude other cover types such as pasture (thus, given the presence of coniferous forest it is possible to predict the absence of pasture and vice versa). The degree by which conditional independence is violated can be tested by a pairwise chi-squared test between all the possible pairings of the classes (Bonham-Carter, 1994). If the validity of the posterior probability map is reduced, due to a high degree of conditional independence, then those themes which cause the problem can be omitted from the analysis or modified to reduce the problem. One way to modifying the themes is by grouping together classes which have a positive association with landsliding to form a single large class. This regrouped theme is then cross tabulated with the landslide inventory map and the analysis repeated.

A4 References


