

The Tasmanian Landslide Hazard Map Series: Methodology

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Introduction

All societies are affected by natural hazards in one form or another. Whilst landslide hazard is not the most significant hazard in Tasmania (Gilmour, 2003) the cost to the community from economic and social perspectives is considerable. Furthermore, the Thredbo disaster in New South Wales has raised awareness of the consequences of landslide activity in Australia. Fortunately, only one person in Tasmania has lost their life to this hazard, but the potential exists for catastrophic failures with lethal consequences.

For much of Tasmania there is no information source which the community can use to assess and manage landslide risk. In 2005 the first of a new series of landslide hazard maps was published by Mineral Resources Tasmania to begin to address this information deficiency.

The purpose of this report is to provide a companion document that fully outlines the methodology used to create the hazard maps. The first part details the purpose of the maps, how they should be used by stakeholders, and outlines the roles of the various parties involved. The second part provides a technical description of the landslide methodology which underpins the maps. This document is targeted at the geoscientific community (e.g. geologists, civil engineers, etc.) to allow them to assess the inherent assumptions, strengths and weaknesses of the hazard model. Hopefully, planners and other professionals in councils should be able to understand much of this material.

While the document attempts to be generic for the whole of Tasmania, it is likely that minor changes and/or additions will occur as each area is studied. Therefore this text should be considered a living document subject to change if and when additional information becomes available.

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Part One: Project Outline

Aim

To produce a set of landslide hazard maps throughout Tasmania following a standard methodology that utilises modern hazard identification techniques, and conforms to Australian best practice hazard and risk principles. A pilot area, roughly coinciding with the Hobart municipality, was chosen to refine an existing methodology.

The map series is designed to show areas where landslides have been identified and areas that are judged to have a potential for instability.

The information is made available so that appropriate risk assessment and management activities can contribute to a safer and more resilient community.

Scope

The scope of the landslide hazard maps is confined to rockfalls, debris flows and deep-seated landslides. While it is acknowledged that expansive soils and soil creep are widespread hazards in Tasmania, they are not part of this project. The scale of the project is limited to 1:25 000 although some contributing data are collected at more detailed scales.

Background

During the 1970s to 1980s the Tasmania Department of Mines (as Mineral Resources Tasmania (MRT) was then known) was a world leader in landslip zoning studies. The Department of Mines undertook regional landslide hazard mapping as well as a considerable amount of site-specific investigation. Since that time, some important changes have occurred in the way that landslide issues are managed.

- Management approaches based on risk assessment have been established as good practice in dealing with landslide issues.
- Geographic information systems are now freely available for the manipulation of spatial data and the generation of maps.
- Geotechnical consultants have become established within the Tasmanian community and are now the main providers of geotechnical advice. MRT's resources for landslip issues, in contrast, have significantly reduced.

While the existing MRT landslip advisory maps have served a useful purpose, Baynes (2001a) concluded:

- that the information base is of widely varying levels of quality;
- there is a considerable range in the techniques adopted to formulate the advisory zones, consequently the nature and meaning of the zones varies from region to region;
- there is generally a lack of geomorphological input relative to geological input. The understanding of

the hazard is poorly developed as a consequence of the lack of geomorphological input;

- there are no real concepts of risk embodied in the advisory zones and consequently it is difficult to evaluate the potential impact of landslides of differing levels of activity;
- the resultant planning tools vary widely in effectiveness and consistency and this results in difficulties in the uniform application of the system.

In the face of a demand for hazard information from Local Government and the public in Tasmania, and with the findings of the Thredbo Coronial Enquiry in mind (Hand, 2000), MRT concluded that the implementation of new landslide methodology was necessary. After seeking expressions of interest, Dr Fred Baynes was contracted to do this work. Under his direction an initial report *A strategy for future landslide risk assessment in Tasmania* (Baynes, 2001a) was produced. His report (see Appendix 1) provides advice on possible approaches to landslide risk assessment, a review of the approaches used within Tasmania in the past (partly outlined above), and a recommendation for a useful approach in the future. The recommendations included:

- Systematic collection of geological and geomorphological information and an inventory of geotechnical information.
- When this information is compiled, heuristic transforms should then applied to the information base to [eventually] produce advisory maps. Establishing hazard zones should be the first major objective and risk assessment could be undertaken at a later stage.
- A trial in a prototype area is essential to establish the practicalities of the approach.

Based on these recommendations, Baynes (2001b) developed a hazard assessment methodology using the Hobart area as a test. The results of the trial and the methodology were discussed at a workshop in 2001 for people within the geological and geotechnical community. Although a variety of opinions were presented at the meeting, the methodology was left unchanged. A summary of the meeting was prepared by Dr Baynes in a letter to MRT (see Appendix 3).

A later trial of the methodology was undertaken in a contrasting geological setting to the Hobart area at Windermere/Pleasant Hills (Baynes, 2002) where minor modifications to the approach were undertaken.

As part of the process of developing the landslide methodology, a software package called LHARA (Land Hazard and Risk Assessment) was developed for MRT to provide the modelling tools for the GIS part of the analysis. Unfortunately LHARA proved unsatisfactory and alternative tools were developed in-house. MRT wishes to distinguish between the landslide methodology developed for MRT (referred

hereafter as the 'Baynes methodology') and the LHARA software package, which has not been used in the preparation of the new hazard maps.

MRT has, in large part, adopted the kernel of the Baynes methodology to produce the first of its landslide hazard maps for the Hobart area. However, in the process of compiling the data, aspects of the Baynes methodology and corresponding computer modelling techniques have been adjusted where deemed necessary. Statistical and deterministic approaches have been incorporated into the MRT methodology in order to automate the method and to reduce the sole reliance on expert judgement. The final methodology and resulting hazard maps are therefore the responsibility of MRT alone. As a final quality control exercise of the methodology, the Hobart map and the accompanying report were internally and externally reviewed.

Hazard and risk defined

The new hazard map series conforms to *Landslide Risk Management Concepts and Guidelines* prepared by the Australian Geomechanics Society (AGS, 2000). It is strongly recommended that the users of the maps make themselves familiar with this document. Parts of the explanation below are derived from the AGS text.

The terms hazard and risk are often erroneously interchanged by society. Risk is defined as the chance of something happening, in a specified period of time, that will have an impact on considered objects, such as people or structures and is usually measured in terms of consequences and likelihood. A (geological) hazard refers to a process that may have unwelcome consequences.

The Varnes risk equation provides a simple means to understand the relationship between the two:

RISK = Hazard Vulnerability Elements at Risk

A hazard therefore is the source of the risk, such as a landslide, that includes properties such as magnitude, frequency and spatial variability (adapted from EMA, 2002).

There is widespread acceptance in the geohazard community that landslide hazard at a regional scale is particularly challenging to quantify compared to other hazards. Because of the difficulties, the maps produced in this study have not attempted to fully quantify the hazard and have instead concentrated on showing the spatial extent. Given the risk definition above and the limitations outlined, it is apparent that the MRT landslide hazard maps are just part of the equation to calculate risk.

Roles and responsibilities

Because the new regional hazard maps are only part of the equation for risk assessment and management, it is critical that this is understood by all potential users. The emergency management process model (fig. 1) provides a useful example of the risk management

process (which is the ultimate goal). This model demonstrates the need for ownership of key roles by relevant organisations and cooperation amongst them. Note that the model describes an ongoing process of review and feedback and is therefore not a one-off event.

Technical approach

A pragmatic approach has been taken to balance the immediate needs of key stakeholders for landslide information against the limited resources, technology and data available to MRT. It must be realised that predictive maps are never finished, or definitive. This is because the uncertainties involved with the process of compiling maps are such that it is prudent to periodically review them and make amendments, when additional data and new modelling techniques come to hand.

Project development

During the development of this new project methodology a number of key steps were recognised (Table 1). Each of these steps involved risks which needed to be addressed to ensure a successful outcome.

Intended users

The hazard map series has been designed primarily, but not exclusively, for local government in Tasmania. The maps are public documents and other parties are encouraged to make use of them, provided they understand the strengths and limitations of the information. The technical component of the maps means that lay people (without geotechnical and or earth science education) may have difficulty understanding the maps. This is an unavoidable consequence of the approach and it emphasises the need for involving properly trained and experienced people in the process of interpreting such information.

Application

A landslide hazard map serves to raise awareness about potential and actual problem areas based on historical records and modelling. If used properly, the maps will be useful for planning and other forms of risk management within local government, as well as other organisations and individuals. For example, with this knowledge, local government may avoid problem areas before development, via avoidance or the imposition of strict controls. For areas already populated, it may serve to help councils manage potential problem areas in a safer way. The document *Planning Safer Communities* (EMA, 2002) provides useful guidelines for this process. Studies such as *Community Risk in Cairns* by Granger *et al.* (1999) provide excellent examples of hazard and risk studies involving research organisations and key stakeholders. While this is the ultimate aim in Tasmania, the process here is being done in a staged

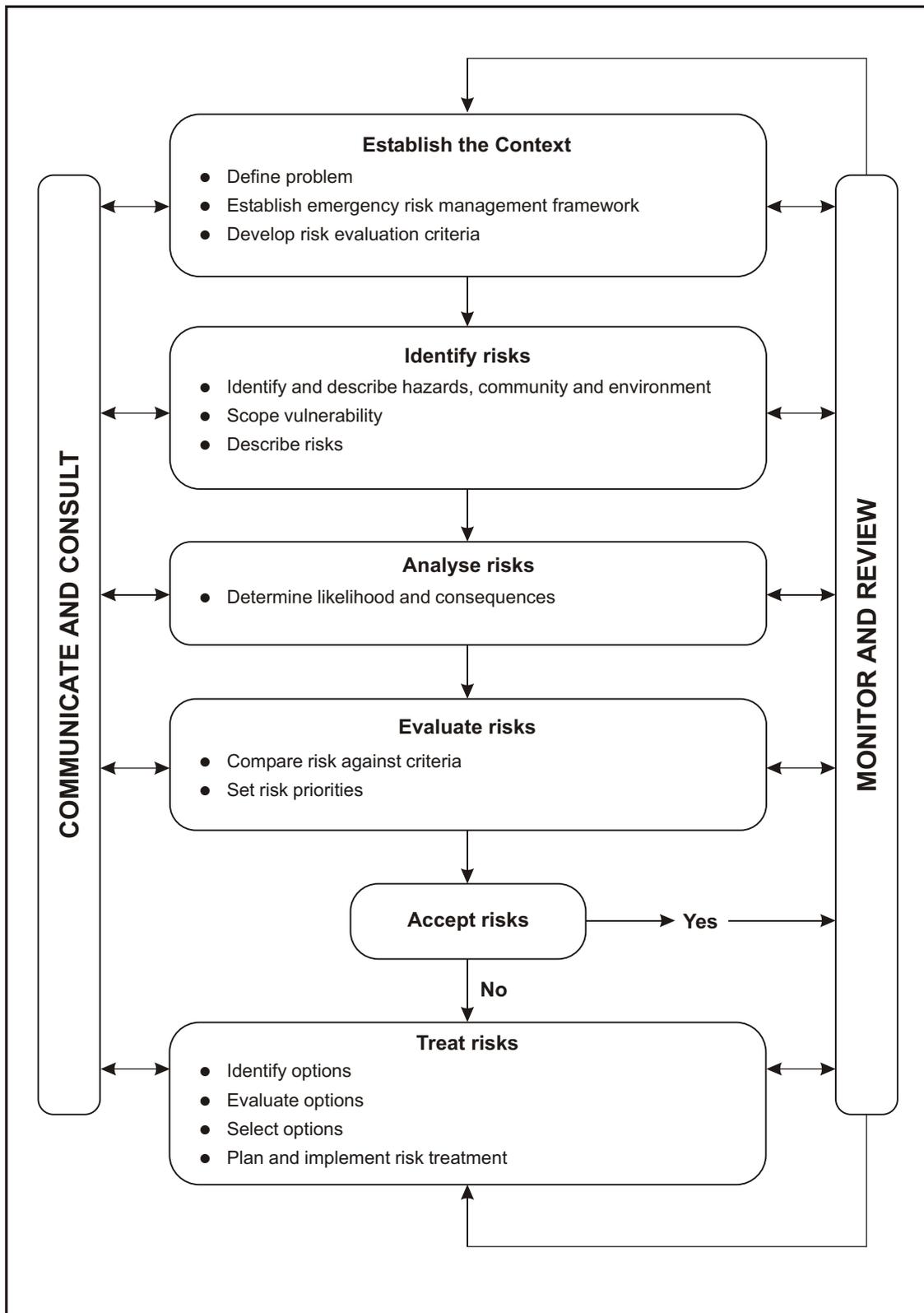


Figure 1
Emergency management process model.

Table 1*Key steps in development of project methodology*

Description of activity	Measures taken to minimise risk	Issues
Develop landslide methodology.	Employed recognised expert, and consulted stakeholders.	
Implement and refine methodology.	Recruited necessary skills, provided training and resources.	
Funding and human resources.	Successfully applied for external funding and additional persons assigned to project (including external recruits).	
Acquisition of all relevant data.	Requests sent to Councils to obtain further information. Discussions with geotechnical community.	<p>Responses varied. Privacy and ownership of geotechnical information raised as significant obstacle to providing data to MRT.</p> <p>However both MRT and Hobart City Council (HCC) sought legal opinions that cleared way (through partnership agreements) for HCC to provide data to MRT providing HCC reports are placed on closed file. Data can be extracted from these reports and entered into databases.</p> <p>Difficulty in extracting data from councils because of resource issues and limitations of their filing systems means that information gaps may exist. Process needs to be developed whereby geotechnical reports are routinely passed on to MRT.</p>
Quality assurance of pilot study.	Conduct internal and external peer review.	Changes were made to methodology and additional field work undertaken to address issues raised.
Communication of information to Local Government and geological and engineering community.	Organised hazard seminars and other presentations to educate users, seek feedback and establish joint working committees.	Partnerships between Local Government and State Government to be strengthened. Working group to be formed from volunteers at seminars.
Public access to information.	Information to be put on internet and published. Councils and other stakeholders supplied with digital data in GIS format.	Format and metadata standards developed.
Risk and planning maps.	Development of derivative map/products is outside of current scope of project.	Could be developed after hazard maps are completed but primary responsibility is on Local Government and other stakeholders to develop.

manner with most of the initial effort being undertaken by MRT.

Limitations

The following caveats apply and should be read, and understood, before the maps are used.

- The hazards identified are based on imperfect knowledge of ground conditions and models that represent only our current understanding of the landslide process. As this knowledge improves, our perception of the hazard, and the depiction of the zones on the map, may also change.
- These maps can be used as a guide (or flag) to the need for specific assessment in potential hazard areas.
- Planning decisions should not be made solely on the basis of the hazard zones delineated on the map.
- The scale limitations of the data (1:25 000) should be considered at all times. Exceeding this limit could lead to inaccurate decisions about hazards.
- Specific assessment of landslide hazard and risk should be undertaken by suitably qualified and experienced practitioners in the fields of engineering geology and geotechnical engineering.
- Practitioners undertaking specific assessments should read the text and appendices attached to the maps and obtain a thorough understanding of the methodology and limitations of the maps.
- Areas where no hazard is shown can still have issues with slope instability.
- Development within proclaimed Landslip A and B zones must follow existing regulatory requirements.
- At all times safe hillside practices should be followed in conjunction with good engineering practice.
- Anthropogenic influence on slopes cannot be predicted and the occurrence of slope instability

resulting from this is specifically excluded from these maps.

- The identification and performance of cut and filled slopes have not been specifically considered in this analysis and their scale is such that they often cannot be resolved on the maps. The presence of such slopes should always be considered in specific assessments.

Reasonable attempts were made to assemble information relevant to land stability and to ensure it was quality controlled. However, it is recognised that much more information exists in council records that could not be easily retrieved. The hazard identification technique is underpinned by available factual data but the limited number of ground control points necessitates the use of modelling techniques to predict ground conditions beyond these areas.

All reasonable care was taken to produce the maps (including limited field checking), but qualified people undertaking subsequent risk analysis should critically examine the information portrayed. Various forms of depicted ground control points (e.g. regolith observations on the debris-flow map, structural measurements on the geology map) serve to provide an indication of where data has been observed versus where it is was inferred.

Peer review

The hazard map methodology was originally devised by a respected expert in land stability in Australia, Dr Fred Baynes, and benefited from additional scrutiny from the geotechnical community at a workshop in 2001. This provides a good foundation for the process. However, putting the methodology into practice by actually producing a real map requires interpretation and adaptation by MRT. As a final step in providing quality assurance to stakeholders, the first of the new map series has undergone an external and independent peer review process. The findings of the peer review (Coffey Geosciences, 2004) have, as much as possible, been incorporated into the methodology.

Part Two: Technical Methodology

This section of the report provides the technical description of the landslide hazard methodology. While some background explanation is given for the lay reader, a certain level of familiarity with geological processes is assumed. Readers wishing to gain background knowledge of generic landslide processes, and an understanding of landslides in Tasmania, are directed to the report by Telfer (1988) and a number of key references that are listed in that report.

Separating hazard according to landslide type

Landslide hazard identification requires an understanding of slope processes and the relationship of those processes to geomorphology, geology, hydrogeology, climate and vegetation. There are several different types of landslides recognised in Tasmania but previous advisory maps produced by MRT did not separate them. The new methodology addresses rockfall, debris flow and deep-seated landslides individually – each of these is considered to pose a real risk to persons and structures within parts of Tasmania. A standardised methodology is adopted to predict where land failure could occur (source areas) and what areas are likely to be affected (source and runout/setback areas).

Resolving the components of hazard

Hazard can be broken down into the following components:

- Spatial – *where does it occur?*
- Temporal – *how often does it occur?*
- Intensity – *what energy levels are involved (consideration of mass and velocity)?*

The current methodology depicts the likely spatial occurrence of each of the studied landslide processes, but the other pieces of the puzzle listed above are in many cases poorly understood. While thorough risk assessment requires quantification of all these factors, the risk assessment process can begin with more limited information.

The frequency of landslide events can be assessed through understanding the processes that trigger them. Climatic events are the most likely natural triggers in Tasmania, given that the likelihood of strong ground shaking associated with earthquakes (an important trigger in many other parts of the world) is probably much lower for most, if not all of Tasmania. The probability of short-term high-intensity rainfall events that trigger debris flows was quantified (Jordan, 2004) and is shown on the related map. Antecedent rainfall probability was also studied to provide an indication of deep-seated landslide frequency. Human activities may also contribute to landslide activity but in this case, the frequency is difficult to quantify as it is not related to any type of

non-random process. Instead, the user should be aware of human activities that increase or decrease the likelihood of landslides when calculating risk.

The potential for destruction from landslides in Tasmania can be judged from knowledge of past events, both historical and prehistoric (many of which are held in the Geohazards database compiled by MRT), and also by reference to international case studies.

Rockfalls are considered in this study because their likely mass and velocity are sufficient to cause injury or death to unprotected persons and damage to vehicles and structures from direct hits. An anecdotal record of this occurred on the Pinnacle Road, Mount Wellington, in the 1990s when a campervan was hit by a rockfall. Rockfall debris on roads can also be a serious traffic hazard.

Debris flows are also potentially dangerous to unprotected persons and structures but mass and velocity can vary significantly, so consequently the effects will also vary. Historical records suggest damage ranges from minor damage to houses at the lower end of the scale to the flash flood in 1872 in Humphrey Rivulet, Glenorchy. In this latter event, large trees and boulders were rapidly transported from Mt Wellington down the rivulet into the Glenorchy area with the loss of one life and the destruction of several buildings. According to Leaman (2002) the source zone on Mt Arthur contains evidence of previous failures; only the time intervals are unknown. Because the 1872 event was triggered by exceptional rainfall it may be possible, with further work, to provide probability curves based on size and frequency to assist with future risk assessment.

Records of deep-seated landslides in the Hobart area are mainly confined to the failure of clay-rich Tertiary sediments. Based on knowledge of the behaviour of landslides that occur in this unit, such features are very slow to extremely slow according to the AGS (2000) scale. The likelihood of death in this setting is very low (e.g. Moon and McDowell, 2002) and (depending on position) many houses will not suffer significant damage (Figure B3 in AGS, 2000). Despite this structures situated across the surface expression of failure planes can be significantly damaged, with houses being abandoned and demolished, as has occurred at Rosetta in Glenorchy City. Infrastructure supplying – or passing through – the area can be damaged, requiring costly and ongoing maintenance. Overall, the economic and social costs on communities affected by landslips of this nature can be considerable.

Geographical Information System (GIS)

The landslide methodology relies heavily on a GIS and therefore it is considered useful to make brief comment on what software was used. However the document

will use generic GIS principles, to reflect the fact that other brands of GIS software could have been used to achieve the same result and to indicate that MRT is not seen to endorse one particular product. All GIS digital datasets created can be viewed by a range of software products.

The principal GIS software used was *ArcMap-Arcview* 8.3 and 9.0 using *Spatial Analyst* and *3D Analyst* extensions. Modelling scripts were written in VBA language, run as macros, while a standalone equivalent was written in VB (by Peter Slater of MRT). *ArcMap Modelbuilder* routines significantly automated compilation processes. Debris flow source prediction, using SHALSTAB (Montgomery and Dietrich, 1994), was undertaken in *Arcview* 3.X. Map publication was undertaken in Unix workstation *ArcInfo* 8.X. Note that all of the software listed are copyrighted brand names of Environmental Systems Research Institute, Inc. (ESRI).

Compilation process

The compilation process for the maps is summarised in the following list with fuller explanations following:

1. Geological mapping
2. Geomorphological mapping and analysis
3. Landslide and engineering data compilation
4. Construction of digital elevation models
5. Modelling debris flows
6. Modelling rock falls
7. Modelling deep-seated landslides
8. Validation Procedures

1. Geological Mapping

Geological maps are a fundamental component of the hazard map series for several reasons. Firstly, most deep-seated landslides in Tasmania occur in low strength Tertiary sedimentary and volcanic rocks. Therefore mapping the distribution of these rocks becomes important for hazard analysis.

Secondly, the physical act of field inspection allows slope processes to be understood that cannot be easily deduced in any other way. Furthermore, it allows for new discoveries to be made, such as previously unrecorded landslides and new outcrops, showing that the previous geological map may need modification.

Method

Geological mapping at a scale of 1:25 000 was undertaken to complete the coverage of the Hobart City Council area as a test for the pilot study. This mapping was entered into a GIS format and added to the seamless 1:25 000 scale digital geological map of Tasmania managed by Data Management Branch of MRT. The stratigraphic legend attached to the

geological map is simplified for reasons of space but the reader can make reference to previously published maps, such as Taroona and Hobart. It is normal MRT practice not to provide geological discussion with its 1:25 000 scale geological maps but summaries can be found in a number of texts, such as Hofto *et al.* (1991). Details of the geology pertaining to slope stability can be found in a later section of Hofto *et al.* (1991).

The geological map presented with this report (fig. 2) is based on a classical approach to mapping that generally favours the depiction of bedrock geology over surficial deposits. In contrast, Hofto *et al.* (1991) produced an engineering geology map of the Hobart area that showed features such as predicted regolith thickness and site measurements (e.g. Atterberg limits). While it can be argued that an engineering geology map would be highly desirable in this study, all of Hofto's data has been entered into a database and localities checked. Unfortunately, many of Hofto's primary observations have not been documented and consequently it is difficult to evaluate the reliability of his map without further work, particularly the regolith component. To overcome this limitation, information on regolith thicknesses, as recorded in the field by MRT geologists involved with the Hobart pilot study, has been entered into a database. This information is depicted on the debris flow map.

Discussion and limitations

In an ideal situation, the geological mapping philosophy in MRT would be varied to show surficial and bedrock units separately and equally. With a GIS this can be done as a multi-layered approach and should be considered for the second generation of hazard maps.

The reader should be aware that geological maps are hypotheses based on imperfect knowledge at the time of compilation. As further data become available the maps may require change. In the case of Hobart, the geological map presented displays significant changes in the distribution of geological units from the previous map (Hofto *et al.*, 1991). Some of the areas mapped as Mesozoic and Palaeozoic units by Hofto *et al.* are in fact Tertiary sediments containing boulder beds with clasts derived from the former lithologies. The change of geological interpretation has obvious implications for the perception of landslide hazard.

2. Geomorphological mapping and analysis

Geomorphology is the study of landforms and the processes which created them. In the pilot study there are several aspects to the geomorphological analysis; recognition of broad-scale geomorphic terrains, understanding the processes that operate in each of these terrains, and defining areas within each terrain that are critical to the hazard model. This report does not contain a full geomorphic discussion but rather makes brief mention of the principal concepts relevant to the hazard identification process.



Figure 2

Example of a portion of the geological map. Geological polygons, fault lines and structural measurements are visible.

Methodology

In undertaking the Hobart pilot study, available aerial photographs (generally 1946 era) were analysed and information compiled onto orthophoto plots at a scale of 1:5000. This allowed the recognition and mapping of such features as landslides, areas of fill, quarries, talus slopes, structural surfaces and cliff lines. Where scale permits, a number of these features are depicted on *Map 1: Landslide Inventory and Geomorphology* of the hazard series for the area.

Terrains

The landscape in the Hobart area can be divided into two main terrains; the lowland terrain representing gently sloping areas beside the Derwent estuary and the generally steeper upland terrain representing the remaining area, but which in places extends down to the Derwent estuary. The boundary between the

terrains is typically gradational and difficult to delineate at a detailed scale, but is largely controlled by graben boundary faults that have displaced the geological units by hundreds of metres.

Processes

It is generally understood that the Earth's climate over the last two million years has been changing between glacial and interglacial regimes. The climate around Hobart was cooler and dryer during the predominant glacial periods than in the interglacials. These changes in mean temperature and sea levels (eustasy) have controlled the rate and relative importance of the various mass-wasting processes operating in the area. For example the rate of toppling and rockfall was probably much faster in glacial times than at present. Conversely, debris flow processes may have accelerated in interglacial regimes when the climate was wetter.

Eustatic changes have caused the shoreline to shift seawards during glacial times and landwards during interglacial periods. During glacial times, when sea level was about 120 m lower than present, the base levels of the rivers adjusted their profile to match. The consequence of this is that the streams in the lowland area were deeply incised and transported sediment further out on the continental shelf. During the interglacial periods sediment was deposited much closer to source.

From a theoretical point of view the process of incision, when triggered by a rapid change of base level such as eustasy, creates nick points that progressively migrate headward and extend into the upland terrain. When such features are well developed they can separate mature (unadjusted) landscape with generally lower slopes, from more youthful landscapes with steeper slopes. In some cases, the boundaries between the two landscapes will coincide with hazard boundaries. Baynes (2001b) attached special importance to nick points in his Hobart trial in terms of the modelling process. However, the author and others have had difficulty recognising such features in the area concerned, and for this and other reasons nick points have not been factored into the modelling process.

Figure 3 provides a process diagram summarising the influence of changes of climate, vegetation and human activity on erosion processes in the Hobart area.

Lowland terrain processes

The lowland area is currently affected by coastal and fluvial processes. In much of this terrain, the landscape

can be regarded as mature, with very low slopes that are well below their threshold value of instability. Exceptions are the former and current coastal cliffs that are, or were, eroding due to wave attack, and some segments of river courses with active bank erosion. Rates of coastal retreat have not been investigated in this report although it may be an important contribution to future hazard and risk assessment.

Upland terrain

Most of the upland terrain is regarded as an immature landscape, characterised by deeply incised streams, waterfalls and moderate to steep slopes where, in many cases, the rock units approach the threshold of instability. Fluvial incision and mass wasting processes (e.g. landslides) dominate the landscape in this terrain.

In the most elevated areas, such as on the top of Mt Wellington, periglacial and possibly glacial processes have had a substantial effect on the form of the landscape, especially during the cooler regimes of the Quaternary. One major effect of these processes has been to weaken and fracture the dolerite rock mass in the near surface through freeze and thaw processes. This process leads to topple failure and rockfall, with the development of talus slopes. Snow and debris avalanches may have also operated in these cool conditions.

The main geological layers that form the Hobart area are well expressed in the landscape of the upland terrain. Dolerite sheets are generally a much more competent and erosion resistant unit than the rocks

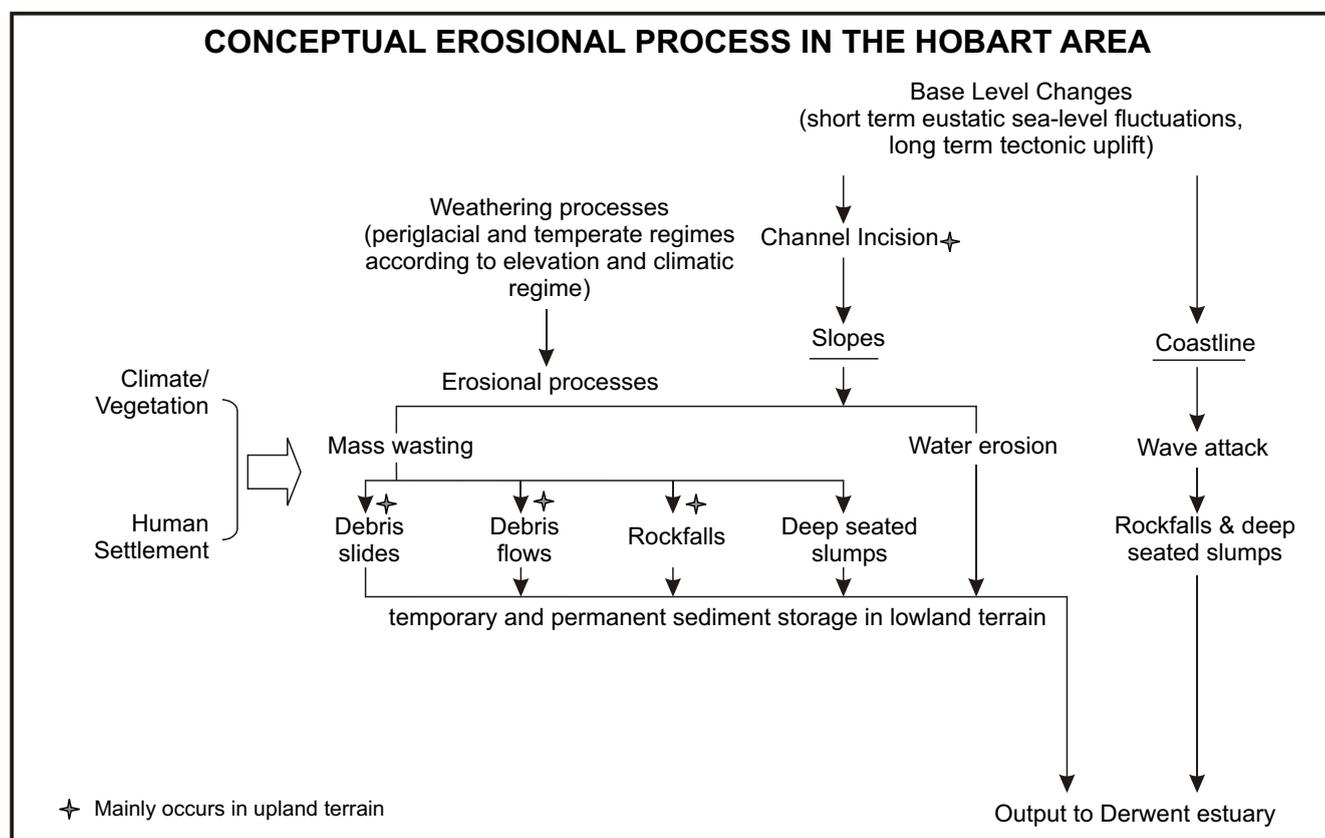


Figure 3. Conceptual erosional process in the Hobart area in time and space.

they intrude, as shown by the impressive bluffs flanking Mt Wellington. The remnants of gently rolling landscape surfaces concordant with the top of subhorizontal dolerite sheets are preserved in a number of places on top of the lower hills and on Mt Wellington. In general dolerite outcrops are not significantly weathered. The 1872 landslide scarp provides a rare exposure of highly weathered dolerite (4 m thick) underlying an extensive area of slope deposits on Mt Arthur. The distribution of this low strength weathered material is not well understood.

The Parmeener Group landscapes are reasonably steep and are controlled to some degree by the subhorizontal layering of rocks of varying composition, such that the sand-rich lithologies typically are associated with steeper slopes than the mud-rich units. This causes the landscape to have a terraced appearance in places. For example the Risdon Sandstone is a cliff-forming unit that can be identified in the landscape as it occurs between two mud-rich units. Landscapes developed on Tertiary boulder beds and sediments are typically much more subdued than the Parmeener Group or Jurassic dolerite landscapes, reflecting their poor lithification and the presence of swelling clays. Deep-seated landslides are typically associated with this unit in the greater Hobart area and many other places, and have occurred on very low slopes.

Slope deposits

Many hillsides, generally in the upland terrain, are mantled with slope deposits reflecting mass wasting processes. Dolerite-dominated talus derived from rock falls and topples mantles the flanks of mountains such as Mt Wellington, and is known to range up to 15 m thick.

Some of the boulder deposits are probably old as they are highly weathered and infilled with a clay matrix. Others are composed of unweathered loose boulders with little or no matrix, suggesting that they are either much younger or have had their matrix removed.

While rock fall and topple failure are primary transport mechanisms on the upper slopes, stream action, debris slides, debris flows, soil creep and sheetwash are responsible for moving material into the lowland.

In areas where the dolerite-dominated slope deposits are absent, soils are usually much less than two metres thick, composed of colluvial material resting with sharp contact on relatively fresh bedrock. The variation of thickness within these deposits can be judged from the debris flow map.

The forests on the upland terrain serve to limit erosional processes such as rock falls and debris flows, through a variety of processes. The removal of forests through land clearance, fire or during glacial periods can, and has, accelerated these processes.

Mapping methodology

In the pilot area, four layers of information were collected and displayed on the *Landslide Inventory and Geomorphology Map* (fig. 4).

Surficial deposits were simply extracted from the geology layer and reclassified according to depositional environment. The features are polygons that reveal landscape-forming processes, both of natural and artificial origin. The features comprise alluvial fans, alluvial, beach and dune, estuarine, slope and swamp deposits together with artificial fill and refuse and mine deposits. Unfortunately, features such as strath surfaces (e.g. river terraces without deposits) have not been depicted in the pilot study but some can be inferred from the map as gently sloping to flat landforms close to the River Derwent. Regolith thickness information was collected to convey an impression of the range of values that exist over the study area, with this information being displayed on the debris-flow map.

Linear landscape features have been captured mainly through the use of topographic maps and aerial photography interpretation. Features shown on the map comprise convex breaks in slope that are generally cliff tops such as the top of marine cliffs, escarpments, quarry headwalls and embankments. Some effort was used to consistently identify such features through the use of curvature commands in a GIS. Although not shown on the published map, the linear features are classified with multiple attributes such as sharpness and origin that allows intelligent searching and more complex symbology.

The location of quarries is depicted by extracting data points out of the MRT TIGER (Tasmanian Information on Geoscience and Exploration Resources) system. On their own, and in association with headwall cliff tops, they indicate areas of artificial disturbance that may not always be obvious.

Slope categories, mostly of 10° increments, have been blended with a hillshade model in order to visualise the morphology of the landscape.

3. Landslide and engineering data compilation

Design

As part of TIGER, two key databases were created in 2003 to store information for the landslide hazard project: the Geohazards and the Groundwater and Engineering databases. These databases are important and underpin the landslide hazard identification process; showing where landslides have been recorded that in turn helps identify the conditions in which landslides occur. It should be realised that the databases are currently incomplete, but with time and the support of stakeholders, they will grow in value.



Figure 4

Example of geomorphology and landslide inventory map. Slope categories (coloured areas), cliff lines, surficial units (patterned areas), quarries (quarry symbol) and landslides (point and polygons) are visible. Landslides are colour coded according to type.

Data Entry

All landslides in the study area have been checked and attributed by experienced geologists. This is a necessary component for each subsequent study area. The landslide database is linked to the GIS, from which thematic queries permit various types of landslide to appear on the appropriate hazard maps. The system is designed so that as data is routinely entered into the Geohazards database, the map can be readily refreshed. In time this database will be web-enabled making it possible to see landslide information throughout Tasmania independent of the landslide hazard maps.

Most of the engineering data available in the Hobart pilot area is derived from the Hofto *et al.* (1991) report and from more recent Hobart City Council records, and is stored in the Groundwater and Engineering database. The amount of groundwater and

engineering data available is surprisingly limited, despite Hobart being the most developed area in Tasmania. While Hobart may be relatively impoverished in data, Launceston (a future study area) has an abundance of information and there the database will allow for statistically meaningful analyses.

Analysis

The level of analysis for the Hobart pilot study was rather rudimentary because the available records were extremely limited. Future studies should make much more use of the data to statistically validate the predictive models. For example by using a GIS coupled to the landslide database, it will be relatively simple to produce tables and graphs summarising the properties of landslides in areas such as the Tamar Valley and the North West Coast.

4. Construction of digital elevation models

Background

An accurate digital model defining the elevation of the landscape is an essential component of any hazard study. Such features are generally called **Digital Elevation Models**, or DEM for short. A DEM generally refers to a cell-based (raster) feature containing elevation values that approximates the Earth's surface. For the purposes of this discussion the term DEM will be expanded to include **Triangular Irregular Network(s)** (TINs) that, as the name suggests, are not true raster layers.

There are several techniques for building DEMs involving different interpolation algorithms, each of which has its strengths and deficiencies. Casadei and Farabegoli (2002) compared the output of three basic techniques; contour-based methods (CBM), rectangular rasters (TOPOGRID) and triangular meshes (TIN). The CBM technique was highly regarded by the authors but the software is not available to MRT, in contrast to the other two methods. Casadei and Farabegoli (2002) considered that the TIN technique produced models closer to CBM than GRID but contend that both TIN and TOPOGRID fail to represent correctly the morphology within gullied hillslopes. Given the limitations of this project, TIN and TOPOGRID techniques remain the only options available to the author.

Wilson and Gallant (2000) contended that simple interpolation techniques will give satisfactory results as long as the input data are well sampled. Sophisticated algorithms are likely to produce unsatisfactory results if applied to poor data. The TIN method is good for honouring slope values but not so with ridge tops and very low gradients with widely spaced contours. TOPOGRID, in contrast, tends to under-estimate the extent of slopes steeper than 40% (Casadei and Farabegoli, 2002) but produces realistic rounded ridges through its interpolation routine.

For both TOPOGRID and TIN techniques there are a number of permutations available that should be appreciated. TIN models can be significantly improved by adding breaklines for streams, ridgelines and breaks in slopes. This prevents triangles from crossing these features and thus creates a more realistic result. If breaklines don't exist in the topographic dataset then they can be created manually by digitising features from topographic maps. Unfortunately this can be time consuming for large areas.

The TOPOGRID function, based on an early version of ANUDEM (e.g. Wilson and Gallant, 2000), was available in the ArcInfo UNIX workstation environment. TOPOGRID attempts to mimic landforms by using spline-based interpolation methods with consideration of hydrology. For example it will assume that ridgelines are rounded in the absence of any topographic control. Spot heights (if they exist) can be used to help control the DEM model,

in which case both contours and spot heights are input layers into the TOPOGRID process. Spot heights are very useful for controlling flat-lying areas and ridges. Useful details of the AML are provided in the ArcInfo online help files.

While TOPOGRID is a standard routine for producing regional DEMs that make great hillshade images (among other things) it can produce unwanted artefacts that are apparent at the detailed scale. For the five metre DEM a striping effect parallel to the contour lines is evident; this is a result of the interpolation process. This not only affects elevations but also slope values. An attempt was made to eliminate this effect by creating intermediate contours from the DEM and then rebuilding the DEM with effectively a double density of contour data. Unfortunately, this proved unsuccessful and the user is therefore cautioned to the limitations of the model.

A critical decision in the creation of a DEM is determination of the appropriate cell size. The smallest grid size possible produces slope values (derived from the elevation grid) that are closer to reality than a larger grid size, which tends to average the slope masking the high frequency changes. For example, a small area with a steep slope (potential rockfall source) surrounded by a low slope may not be identified if the grid is too large. However, there are limitations to the minimum size determined by the scale of input data. A rule of thumb is to divide the scale of the input data by 1000. Therefore 1:5000 scale topography can be reduced to a five metre cell size. A cell size smaller than this will not offer any advantage. Furthermore, as the effect of reducing cell size dramatically increases the file size, it may exceed the limitations of the modelling software. The 32-bit operating system of the PC used (Windows XP) poses a limit to the maximum number of cells that can be modelled in a single process. A solution to this problem is to divide the given study area into smaller parts for the modelling and combine them at the end. Defining the smaller areas can be very time consuming because the area has to consider catchment boundaries which are never simple polygon boundaries. After some consideration, and with the benefit of discussions with other people familiar with the subject, a 10 m cell size has been adopted for the working model.

Once a DEM is created a number of derivative raster layers can be created as routine operations in a GIS. The principal layers referred to in this report are *hillshade* (this is a pseudo-landscape image with shadow effects that is used primarily for visualisation purposes), *slope* (representative slope value for each cell, usually in degrees), *aspect* (direction of maximum slope in degrees), *flow direction* (indicates the neighbouring cell that best represents the downstream direction – eight cardinal directions are used) and *flow accumulation* (indicates the catchment area upstream for each cell considered and can be calculated in a variety of ways with different results).

Method

The input dataset for the Hobart pilot study was a blend of mainly five metre topographic contours (1:5000 scale) and ten metre topographic contours (1:25 000 scale) sourced from the cartographic branch of the Department of Primary Industries, Water and Environment (DPIWE). The 1:5000 scale data was specially purchased for the project but unfortunately did not cover the entire area. This deficiency was overcome by a splicing together of the two data sources which required manual adjustment of the 1:25 000 scale contours in a GIS to snap to the corresponding 1:5000 contour. Splicing is a necessary process to prevent unwanted artefacts forming along the seam. In some cases a 10 m horizontal shift of the 1:25 000 scale contour was necessary to join the appropriate contour lines. This mismatch serves to illustrate the accuracy limitations of the datasets. (It was also noted that minor misalignments occur within the 1:5000 scale topographic dataset that presumably correspond to mismatches along internal tiles).

The 1:5000 scale topographic dataset did not have a systematic spot height layer for the area and very few stream lineaments were provided, in contrast to the 1:25 000 scale dataset. Unfortunately, because of imprecision, it is not acceptable to simply add the 1:25 000 scale spot heights or streams to areas underlain by 1:5000 scale data. As a result of not having spot heights or streams in the model, the accuracy of ridge tops and stream positions has been degraded. However this should not significantly affect the hazard analysis given the final scale of the output.

Both TIN and TOPOGRID DEMs were created from the contour data. Because a TIN model should identify slope values in steeper country better than TOPOGRID, it is useful for delineating rockfall source areas. The TOPOGRID model was used for runout analysis of rock fall and debris flows because of its superior hydrological integrity.

5. Modelling Debris flows

Definitions

Debris flows are defined as mass movements involving rapid flowage of debris of various kinds, generally with a clay component, and are usually triggered by heavy rains. The debris flow hazard map contains *source areas*, defined here as the areas where potential debris flows can be derived from. *Runout* is defined as the area where a landslide travels from its source to its eventual resting place. In the case of debris flows the distance travelled can be a considerable, ranging up to several kilometres in the extreme case of the 1872 Glenorchy landslide. *Critical rainfall threshold* is defined as the minimum value of rain (e.g. a 24 hour rainfall value) that is necessary to trigger a debris flow. A *travel angle* (or beta angle) is an empirical measurement from the headscarp of a debris flow to the extremity of the toe representing the angle defined

by the elevation change and the planimetric distance travelled.

Predicting debris flow source area

The methodology for identifying source areas of potential debris flows, according to Baynes (2001b), was expert judgement based on geomorphological criteria.

The judgement relied on the underpinning observation that 'debris flows occur from steep long slopes on which there is evidence of landslides, previous debris flows or active accumulation of slope deposits'. In analysing the results of the Hobart trial, it was clear that Baynes positioned the lateral boundaries of source areas at the shoulders of rounded ridges and included most areas of talus deposits. In addition, most of the slopes identified were relatively steep with little profile curvature. However Baynes provides no guidance on what threshold slope values should be used. While the underlying concept Baynes has used is not disputed, the definition is vague and likely to vary according to the opinion of each potential practitioner.

Expert judgement is acceptable for delineation of hazard zones providing definitions and methodology are clearly stated and adhered to. Furthermore, if there is no other valid or proven approach available, then it may be the only viable option. The author has investigated alternative methods utilising GIS technology in an attempt to minimise the subjective judgement component and to be able to apply the approach consistently over all of the future map sheets.

According to Montgomery and Dietrich (1994), shallow landslides (which includes debris flows) result from a combination of interacting factors including topography; soil thickness, hydraulic conductivity and strength properties; rainfall intensity and duration; subsurface flow orientation; bedrock fracture flow; and vegetation surcharge and root strength. Given the number of variables concerned and incomplete knowledge of the distribution of each of these spatial variables, it is a huge ask to accurately predict where landslides will in fact occur.

Over the last decade a factor of safety technique – the Infinite Slope Model – has been successfully adapted into a GIS environment with generally favourable reviews (e.g. Shaw and Vaugeois, 1999). A factor of safety (FOS) calculation involves dividing the resistance of the soil to failure (shear strength) by the forces promoting failure (shear stress). A factor of safety value of unity (the condition of failure) would indicate that the site is in a critical state and failure is imminent, while a factor of safety greater than one indicates stable conditions.

A freely available Arcview extension called SHALSTAB (Dietrich and Montgomery, 1998) was tested to predict the source areas of debris flows in the Hobart area. SHALSTAB is a deterministic approach

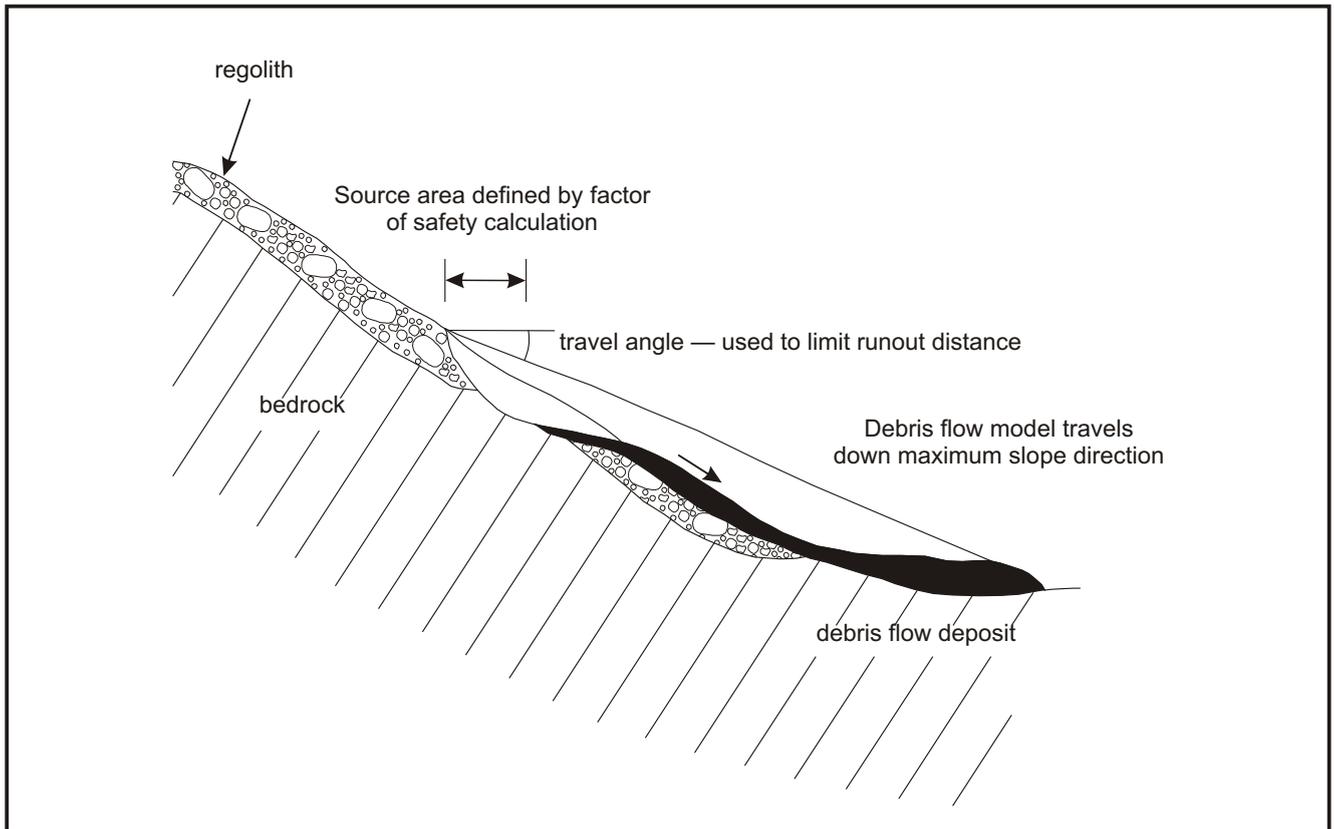


Figure 5

Conceptual diagram showing components of hypothetical debris flow.

that performs a FOS calculation for each cell in the area considered without regard to neighbouring cells. The program uses a DEM to derive slope and flow accumulation rasters used in the calculations. An interface allows soil parameters to be entered, but only as spatial constants. The general assumption that these soil parameters are spatially constant is obviously not true in nature but the authors of SHALSTAB provide convincing reasons for maintaining this approach. When soil parameters are kept constant the interplay of slope and wetness can be judged from the stability diagram below (fig. 6).

The Hobart trial used the TOPOGRID DEM and, in the first attempt, adopted default values provided in the software: cohesion = zero, friction angle = 45°, one metre of soil/regolith and an assumed uniform threshold rainfall of 200 mm/day. The authors of SHALSTAB provide a justification for making cohesion lower than reality (zero) and compensating by increasing the friction angle. A threshold value of <-3.1 was chosen from the q/T plot as defining the source area.

The trial predicted a number of potential source areas that included all of the known translational debris landslips in the study area; the 1872 Glenorchy debris flow, Knights Creek and Mt Stuart landslips. The immediate success of the trial indicates that the technique may be the best way to delineate source areas for debris flows for the Tasmanian landslide project. It is assumed in this approach that the method

will predict debris slides as well, as they may be a precursor failure mechanism to debris flow.

Later experimentation with SHALSTAB utilised more realistic soil parameters gathered from field inspections and subsequent lab testing by MRT. Shear strength data were obtained from testing several colluvial soil sites adjacent to Mt Wellington (dominated by dolerite derived material). The averaged results place friction angle at ~31.5°, and cohesion at 2.5 kPa. Soil density was placed at 2000 kg/m³ and soil thickness adjusted upwards to 1.5 m to match observations of the minimum thickness from four inspected debris flows in the Mt Wellington area.

Soil thickness data are sparse in the Hobart area and only sweeping generalisations can be made about soil thickness distribution. The talus slope areas high on the mountain are generally much thicker than one metre but in lowland areas the thickness is typically less than one metre. Obviously, in the course of more detailed studies, if soils are found to be absent in a predicted source area then there is no material to fail and the hazard can be eliminated.

Variations in vegetation cover, rainfall distribution and groundwater discharge are also important spatial variables influencing soil strength locally and these should be considered in future studies. Despite these uncertainties the resultant SHALSTAB model correctly predicted all of the actual debris flow locations in the map.

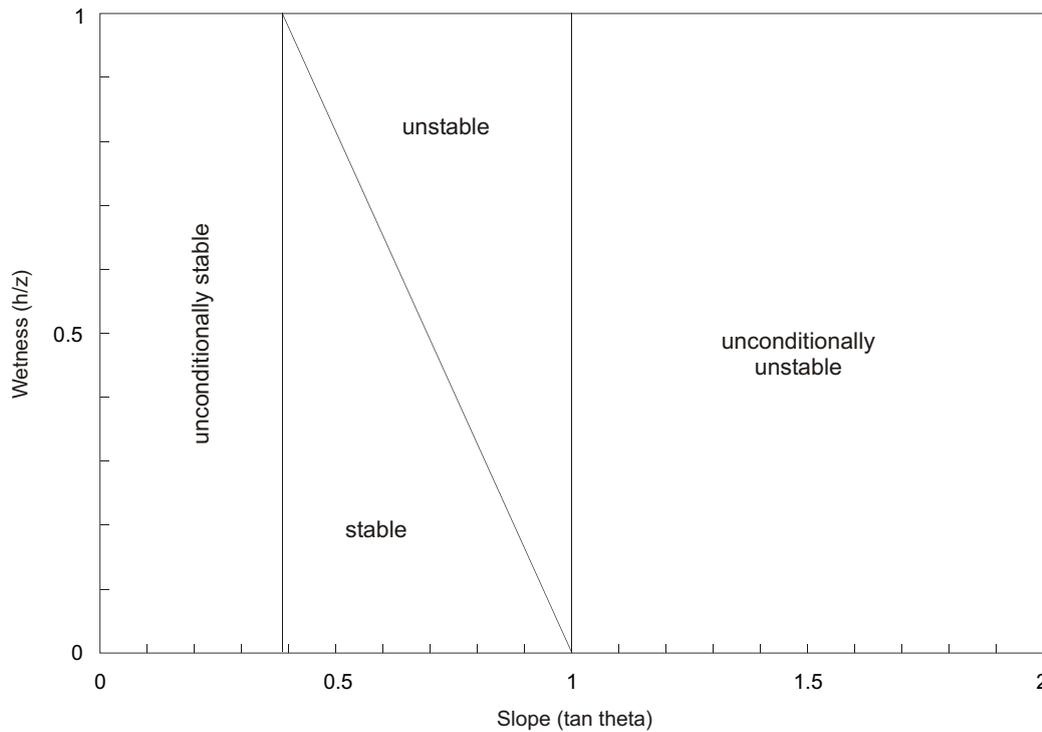


Figure 6

Stability concept model adapted from Montgomery and Dietrich (1994). Note that for intermediate slopes the failure threshold (stable/unstable boundary) at any point in the landscape depends on slope angle and wetness.

Inherent in the SHALSTAB model is the concept of a critical rainfall threshold value that is necessary to trigger a debris flow. International reviews of landslide triggering rainfall events (e.g. Caine, 1980) indicate a range of threshold values depending on local conditions. In the Hobart area, an indication of likely triggering rainfall magnitude can be crudely gained by studying the 1872 and 1960 storms. In both cases rainfall rates are likely to have exceeded 200 mm/day in the area of the failures, based on consideration of daily rainfall records and the extrapolated intensity distribution (e.g. Jordan, 2004).

According to Montgomery and Dietrich (1994) and assuming a simple system (e.g. uniform ground properties, i.e. soil and vegetation), as daily rainfall approaches 100 mm/day using the SHALSTAB model, zones of predicted instability spread to steep, low order channels, topographic hollows, and the base of steep side-slopes. Further increasing the simulated rainfall to 200 mm/day expands the zones of predicted instability away from channels, towards drainage divides, and into topographically divergent hillslopes where debris flow initiation is rare.

For reasons stated above, and for simplicity with using the SHALSTAB software, a 200 mm/day value was chosen to identify source areas in the Hobart area. Whether this value is an over-prediction or under-prediction of potential source areas is difficult to assess given the data limitations. More detailed studies should make an attempt to refine this value but for now it is accepted as a first order approximation. The 200 mm/day value was subsequently used to

indicate the probability of such events occurring spatially throughout Tasmania by Jordan (2004). This information is depicted on the debris flow hazard map of Hobart and Glenorchy.

Predicting debris flow runout area

A somewhat simplistic method has been employed to track the path and extent of debris flows using raster-based deterministic modelling tools and empirically derived limit values.

A runout path has been determined for each source cell, assuming that the material will behave like a liquid and follow the direction of maximum slope. In the modelling process, the path of a hypothetical debris flow starts from the central point in each source cell and follows the direction of maximum downhill slope, defined by an *aspect raster* created from the TOPOGRID DEM. The program performs a series of iterations and checks. Each iteration in the process steps across the landscape at a distance chosen to be the cell size of the raster and the coordinates of each step are calculated using simple trigonometry. Because the new coordinate will seldom equal the exact centre of a cell, the program identifies the nearest cell. However, the 'real coordinates' are used to identify the next cell in the iteration rather than the central point of each of the identified cells. The process iterates until a limiting travel angle value is reached (described later) after which the program goes on to the next source cell to repeat the process.

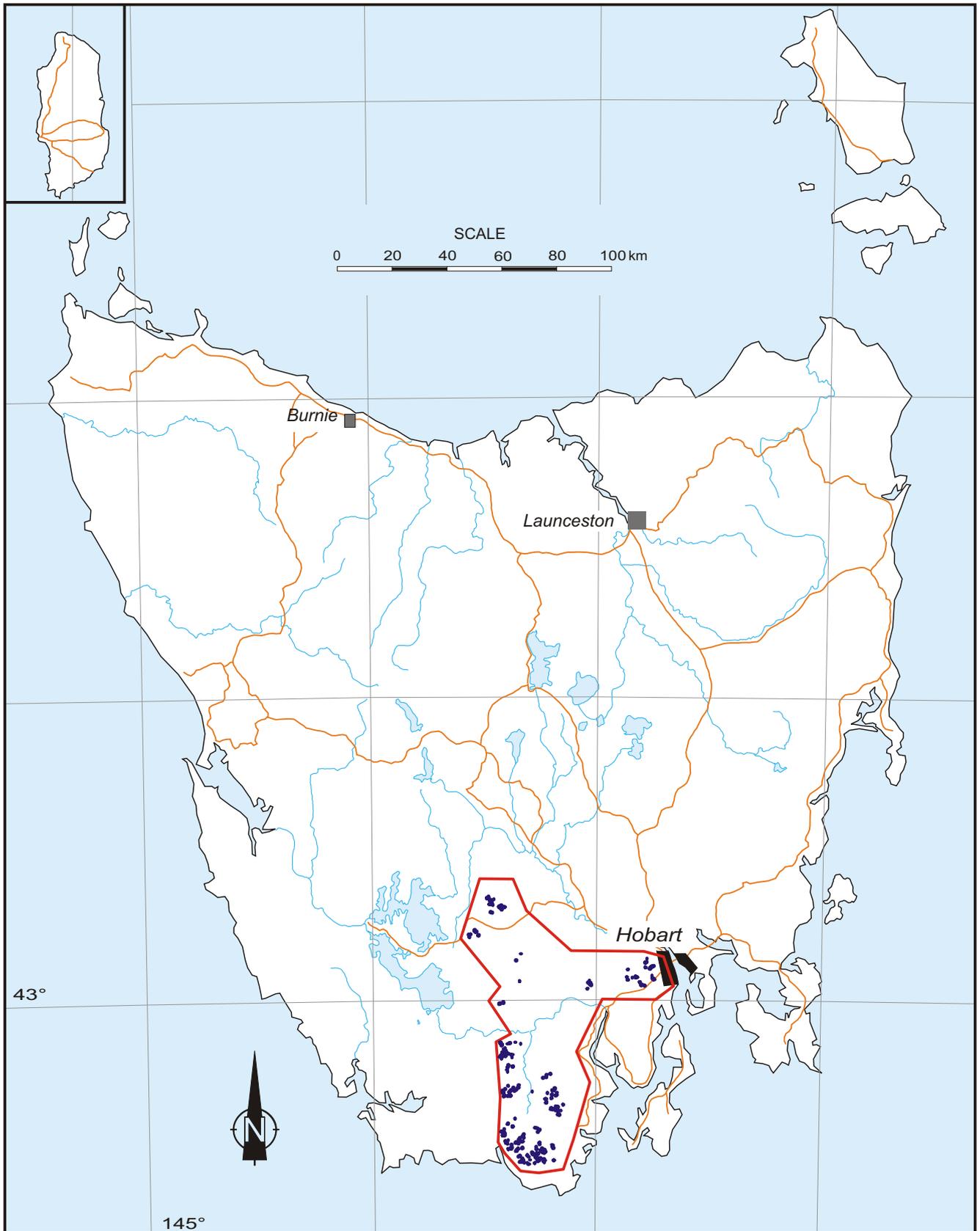


Figure 7

Debris flows identified in aerial photograph reconnaissance study by Clive Calver and showing boundary area.

The technique described above using the aspect raster has a significant advantage over the *flow direction raster* method (as used in the LHARA program). Because flow direction grids can only flow in multiples of 45° (eight cardinal directions) they tend to create unrealistic travel paths that are particularly obvious on long planar slopes. However, the aspect method has a disadvantage in that it will be 'hung' by an obstacle where the path alternates between two approximately opposed cells; this effect is observed on some of the low gradient channels in the lowland. The flow direction method does not experience this problem because of the inherent hydrological integrity. In order to overcome these issues, the runout script was designed to start each cell runout using the aspect technique but switching to the flow technique when a recognised stream channel is encountered. This, on visual evaluation, produces acceptable results.

There are two obvious limitations of the modelling technique employed. Firstly, the software does not account for angular momentum forces where changes of direction are encountered. This could be significant if the debris flow is fast moving. Secondly, it produces unrealistic paths in wide/non-incised channels. In

these settings the runout path should spread laterally over the floodplain rather than being confined to the principal channel. While this limitation should be appreciated by the map user, in most cases debris flows have seldom reached lowland floodplains where the effect is most obvious.

The concept of *travel distance angle* (see Fell *et al.*, 2000), here shortened to *travel angle* (also known as 'shadow angle'; AGS, 2000), is invoked to limit the distance that the flow will reach. Travel angle is defined in this study as a calculated value using the arctangent of change in elevation divided by distance travelled. It is admitted that the modelling technique is a very crude method, but considered to be pragmatic, given that there are so many variables which may influence the debris during its motion that have not been accounted for. Four travel angles have been chosen in the pilot area (30, 26, 22, and 5 degrees) that represent empirically derived population quartiles of an aerial photograph study of approximately 270 debris flows occurring on dolerite mountains of southern Tasmania (fig. 7, 8) by Clive Calver of MRT. These runout values were used in the final debris flow map to define hazard zones of decreasing probability.

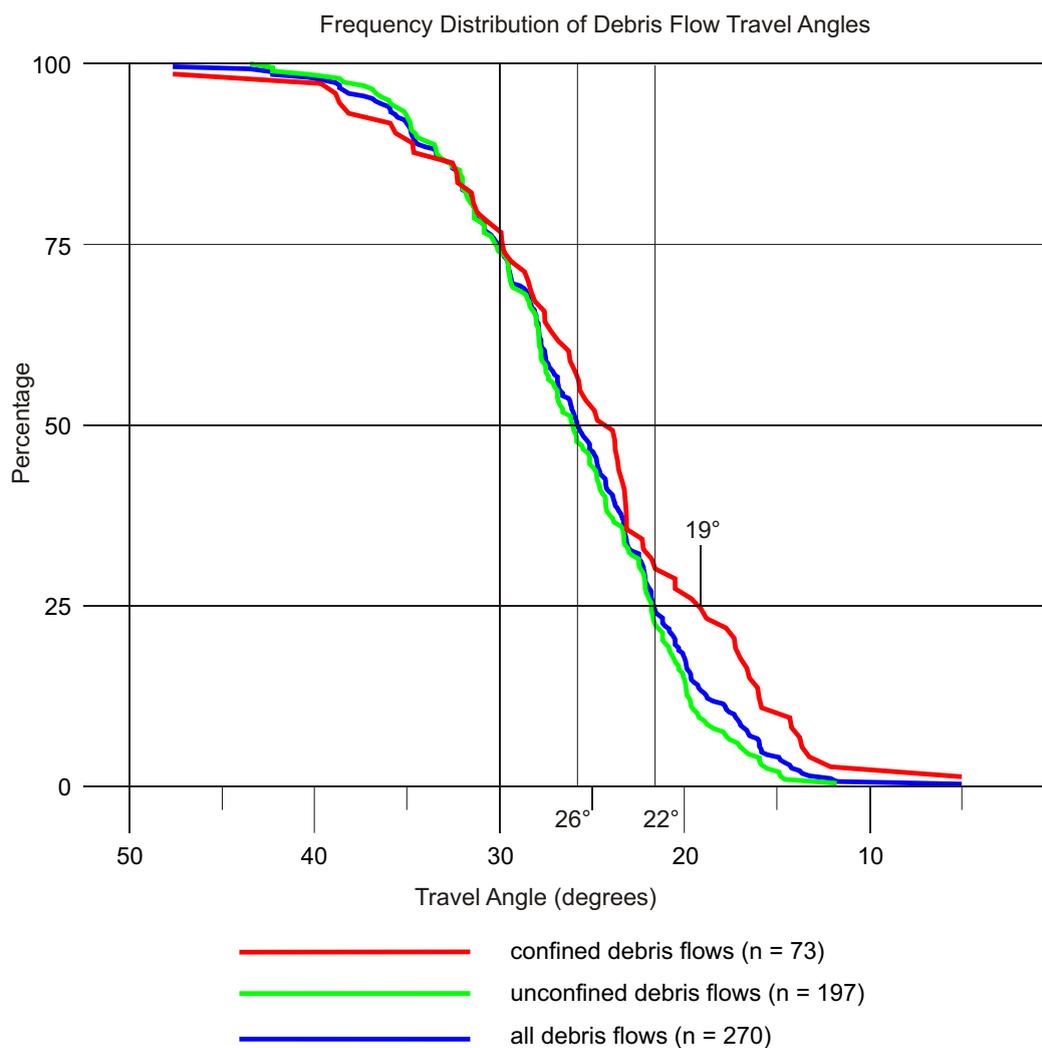


Figure 8

Debris flow travel angles compiled by Clive Calver with percentage quartiles indicated.

Debris-flow modelling procedure

1. Compile debris flow records into spatial database.
2. Establish statistical distribution of debris-flow travel angles.
3. Assemble soil parameters for likely areas of failure.
4. Run SHALSTAB (infinite slope failure model) to identify stability zones. Choose appropriate soil parameters with adjustment to incorporate known landslips in failure zone.
5. Create source raster from stability map defining likely source area as -3.1 .
6. Remove areas 45° from source raster (as no soil will accumulate here).
7. Model runout tracks from source raster using the four travel angle values.
8. Compile source and runout rasters into single raster in the following order of priority: source, 30, 26, 22, and 5. The 5° runout was buffered by one cell width to improve visual recognition on the published map.
9. Apply mask to areas that should be excluded from hazard zone such as quarry headwalls where soil material has been removed.

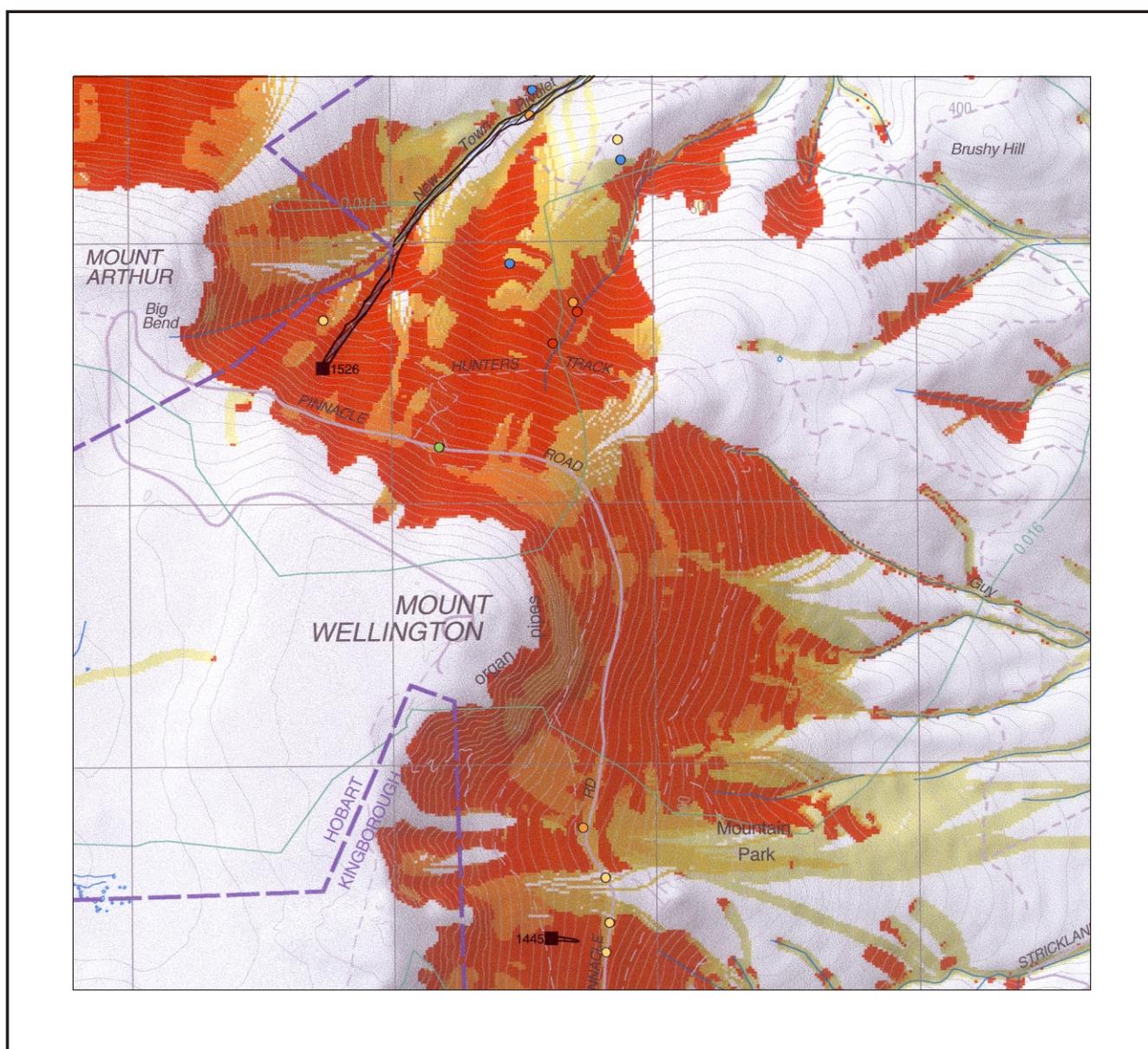


Figure 9

Example of debris flow hazard map. Potential source area and four runout models (30, 26, 22 and 5 degrees) are shown in colours ranging from dark red to yellow respectively. Two landslides are also visible.

6. Modelling rockfalls

Definitions

A rockfall is defined as the independent movement of rock or soil fragments through free fall, bouncing, rolling and, to a lesser degree, sliding. The rocks are usually sourced from cliffs or escarpments and are the fastest moving type of landslide. The rockfall hazard map contains *source areas*, defined here as the areas from where potential rockfalls can be derived. A *threshold slope value* is used to define the minimum hillside slope from which a rockfall is likely to be initiated. *Runout* is defined as the area where the rockfall material travels from its source to its eventual resting place. A *travel angle* (or beta angle) is an empirical measurement from the headscarp of a rockfall to the extremity of the runout path, representing the angle defined by the elevation change and the planimetric distance travelled.

Predicting rockfall source area

Rockfall source areas occur on steep slopes. While Baynes (2001b) suggested a value of 45° should be a general threshold slope value to identify rockfall sources areas, this study adopts a slightly lower value of 42° which coincides with the maximum angle of repose of dolerite talus (see Caine, 1983). The lower value ensures that unstable talus slopes are also include in the modelling. The author is not implying that rockfall will not occur on lower slopes, but that it becomes steadily less likely with reduced slope angle.

Potential source areas can be easily identified by performing a raster query in the GIS. A DEM created from a TIN model was used to identify cells with a slope greater than and equal to 42°.

Predicting rockfall runout area

Rockfall runout is a complex process and any raster-based modelling approach cannot easily factor in obstacles that are not part of the controlling DEM, such as trees and small mounds, which may impede the path of each hypothetical boulder. There are several regional rockfall modelling approaches in the literature ranging from highly simplistic to moderately sophisticated. At the high end of the scale is STONE (Guzzetti *et al.*, 2002) that tracks three dimensional trajectories of particles with consideration of coefficients of restitution for various rock types in the path of the particle. Unfortunately this program was unavailable to the author at the time of writing.

A much simpler modelling approach was developed for this study that merely follows the path of greatest slope from each source cell. The path of a hypothetical boulder starts from the central point in each source cell and follows the direction of maximum downhill slope, defined by an *aspect raster* that is created from the TOPOGRID DEM. The program performs a series of iterations and checks. Each iteration in the process calculates a step at a set distance chosen to be the cell size of the raster. Because the new coordinate will seldom equal the exact centre of a cell, the program

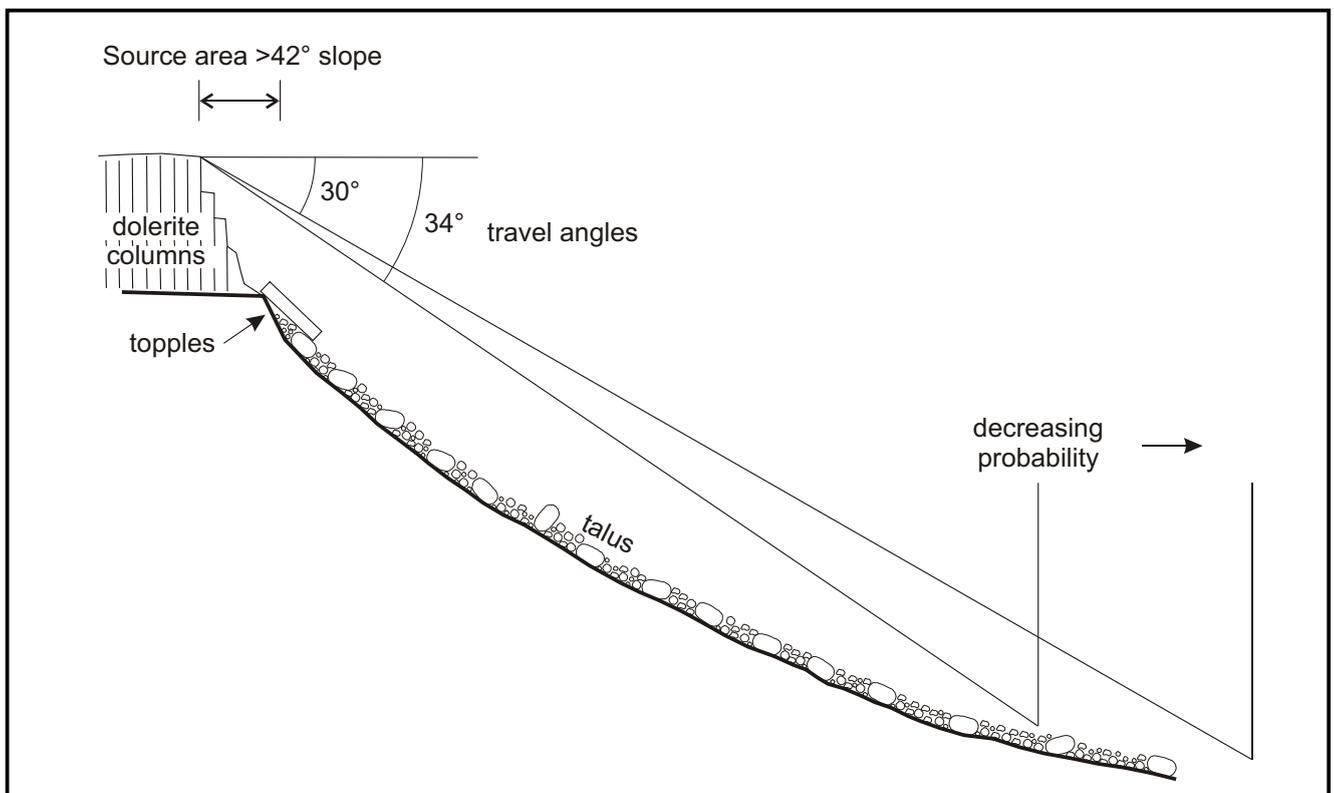


Figure 10

Conceptual model of rockfall process and associated parameters used in landslide modelling.
The setting in this example is based on a dolerite talus slope.

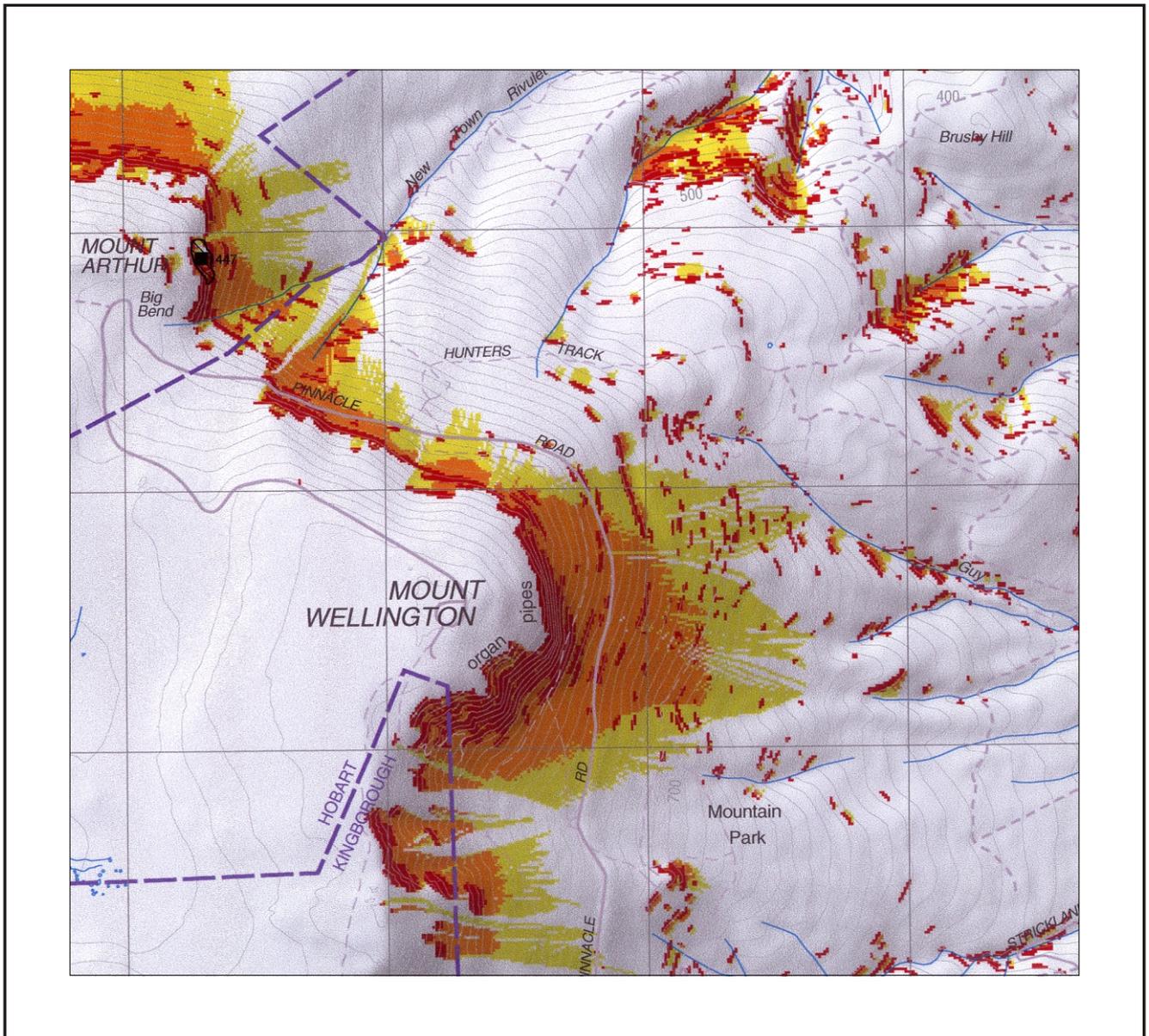


Figure 11

Example of rockfall hazard map. Potential source area, and two runout models (35 and 30 degrees) are shown as dark red, bright red and yellow respectively.

identifies the nearest cell and gives it a positive value. The 'real coordinates' are used to identify the next cell in the iteration rather than the central point of each of the identified cells. The program differs from the LHARA method that used the *flow direction raster* to identify the appropriate cell. There are advantages and disadvantages with both approaches. The flow direction approach is hydrologically correct so any modelled runout path will find a path into the lower catchment. The disadvantage of the flow direction raster is that it creates raster artefacts that are unrealistic (i.e. all travel is in multiples of 45°). The aspect raster model overcomes the raster artefact problem but its main disadvantage is that it can get 'hung' by a topographic obstacle (where the model will keep iterating between two opposing cells – cells that approximately face each other). For a regional study it is considered that the 'hanging' effect makes little difference to the overall model.

The travel angle method is a well accepted and simple approach for limiting the extent of rockfall boulders when undertaking computer modelling. It is a parameter that generally can be easily determined from field observations of real rockfalls. From a review of published literature, there would appear to be two main geomorphic settings for understanding rockfall runout; slopes dominated with talus and slopes largely without talus. Conceptually, runout characteristics and hence travel angles, will differ between the two.

For talus slopes, there are at least two types of travel angle method used in published rockfall analyses; the *rockfall fahrboschung method* (used by Baynes, 2001a and adopted in this study) and the *minimum shadow angle method* (summarised in Evans and Hungr, 1993). The former method uses the highest point of the rockfall source scar and the stopping point of the longest run-out boulder for any given rock fall. Onofri and

Candian (1979) used this method and found the limits of the beta angle to be between 28.34° and 40.73°. In this and another study by Toppe (1987) the distribution of boulders was determined as a percentage over a range of beta angles.

Unfortunately the results vary between studies and it would appear that the discrepancy may be due to the difficulty of calculating the beta angle when the source area is not well defined. To address this uncertainty a small field investigation was undertaken by the author and co-workers on dolerite talus slopes to derive likely travel angle parameters. Talus slopes in the Hobart area were not considered suitable for detailed analysis because the slopes appear to have formed as the result of multiple processes, not simply restricted to rockfall. For this reason, an area on the flank of Ben Lomond (Stonjeks Lookout) was identified between the escarpment and a large toppled block as a more suitable place to study. In this area, a predominant slope angle of 34° was determined (see also Caine, 1983) while a value of 30° approximately represents the lower range of travel angle values recorded.

Slopes not dominated by talus deposits with measurable rockfall boulders that can be related to a source are rare. Field observations at a number of sites, including Bradys Lookout and the Cataract Gorge in the Launceston area, indicate that beta values are generally steeper than 30°.

Given that the Hobart area is dominated by dolerite talus slopes it was decided to adopt beta values from the Ben Lomond area as empirical parameters to determine the hazard zones.

Rockfall modelling procedure

- Create source grid by extracting triangle polygons from TIN model for slopes $> 42^\circ$. Convert polygons to raster (one metre cells), expand by half final raster cell size (10 m) to ensure all source areas in TIN will be captured in final raster. Resample raster to ten metre cells.
- Convert geomorphic layer (quarries and marine cliffs) to a raster. Combine with source raster above to form a final rockfall source raster (binary format).
- Run aspect runout model at 34° and 30°.
- Combine source and runout rasters in order of precedence.
- Apply mask to areas that should be excluded from hazard zones such as retaining walls and other artificial structures.

7. Modelling deep-seated landslides

Definitions

Deep-seated landslides are defined here as failures that are generally deeper than about five metres below the surface and involve bedrock units beneath surficial regolith.

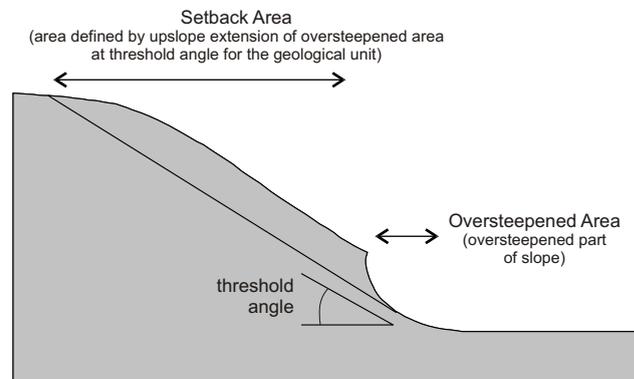


Figure 12
Conceptual model of deep-seated landslide and associated parameters.

The concept of *threshold angle* is used here to represent a slope value at which a given geological unit is likely to fail. An *oversteepened area* is defined as an area where the threshold value is exceeded. A *setback area* defines the upslope extension of an oversteepened area by projecting upslope at a value equalling the threshold value.

Predicting oversteepened areas

The hazard map presented has two main components; *known landslides* (from available records) and *predicted hazard areas* (areas where there is higher probability of failure occurring). To predict hazard areas it is considered necessary to analyse known landslides, geomorphology and have an understanding of soil and rock behaviour.

Baynes (2001b) summarised standard engineering understanding by stating that “each geological unit may contain materials of low strength, either as strata or defects, which could form a shear plane on which a landslide could occur. On the basis of soil and rock mechanic principles, the likely shear strength of such materials, known as a ‘phi angle value’ in terms of effective stress, may be assessed from knowledge of the rock or soil materials typical of the stratigraphy and structure of the units”.

A nominated threshold angle (phi) for a given rock unit should be viewed as a generalised value, given that rock and soil properties vary naturally from site to site for a variety of reasons. In this document three approaches are used to establish the threshold value. Where possible they are checked against other and refined accordingly:

1. Analysis of existing failures in each rock type.
2. Engineering data applied to soil and rock mechanics theory.
3. Frequency analysis of slopes for each rock type

1. Landslide analysis

An analysis of landslides and their surrounds is probably the most reliable guide to understanding the slope conditions that lead to failure. An estimate of the

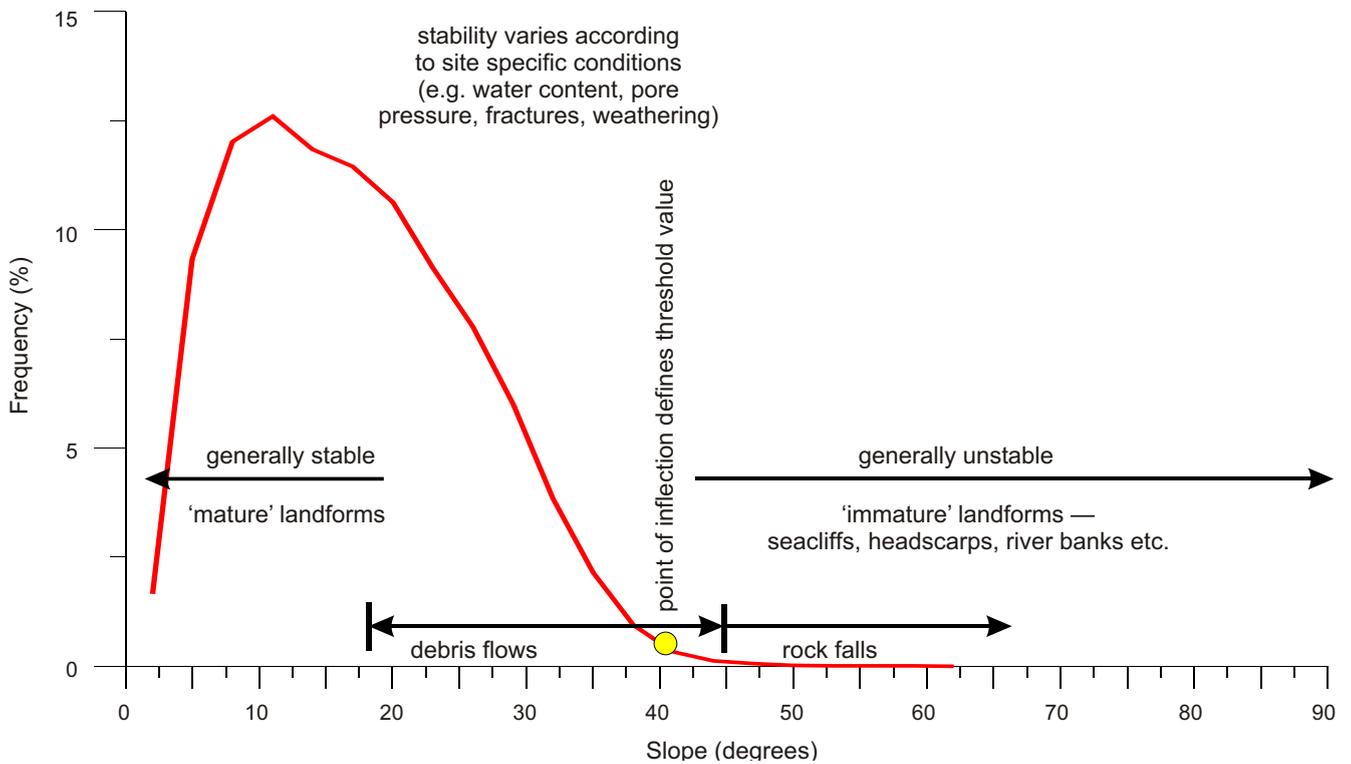


Figure 13

The slope-frequency analysis technique for identifying threshold slope values for specific geological units behaving according to rock mechanics principles.

pre-existing slope on which the failure occurred has been the key parameter to use as the threshold value. For the pilot area of Hobart and surrounds, the number of known landslides is very limited and most of these are in one rock unit, the Tertiary sedimentary units.

2. Soil and rock mechanics

From simple soil mechanics theory, a long continuous slope undergoing shear failure parallel to the surface will have a factor of safety approaching unity (the condition of failure) if the slope is steeper than 50% of the phi value, providing the groundwater level is at the surface. Likewise the factor of safety against shear failure will approach unity if the slope is steeper than the phi value and the slope is drained (adapted from Baynes, 2001b).

3. Slope frequency analysis

The frequency analysis technique has been developed by the author to identify the uppermost range of slope values for a given rock unit. From geomorphological considerations, this range represents very young or immature landforms such as sea cliffs and eroded river banks. In areas of totally 'mature' topography where slopes have 'slackened' this approach may not identify the appropriate threshold value.

A script was written to produce slope frequency histograms for each geological unit. The threshold value corresponds to where a change in gradient occurs in the upper end of the histogram (fig. 14). While the validity of this technique has yet to be

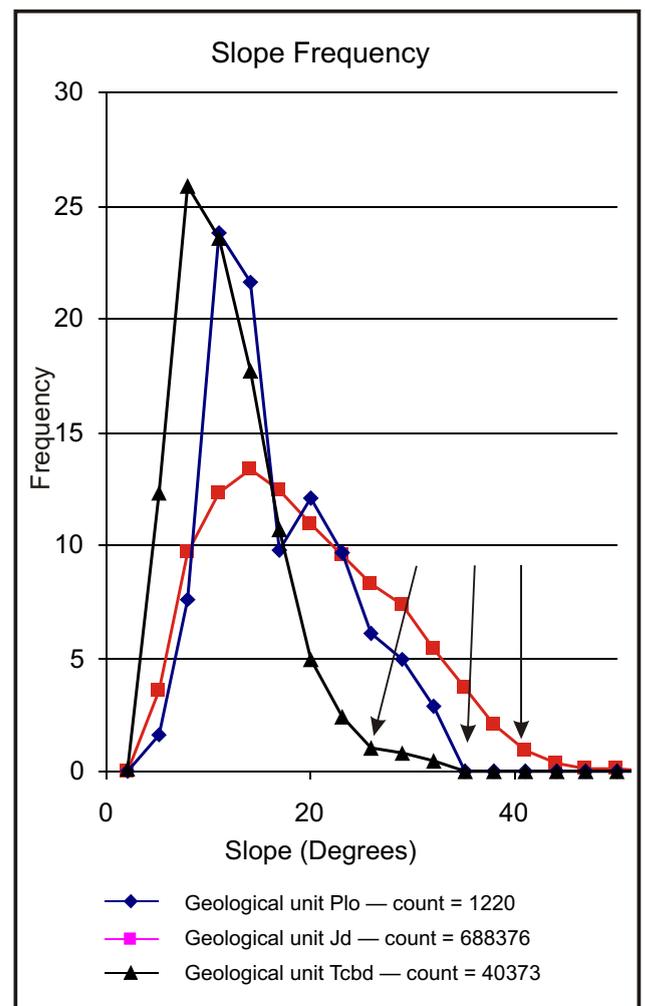


Figure 14

Chart from the histogram tool comparing Tertiary boulder beds (Tcbd), Jurassic dolerite (Jd) and a Permian siltstone unit (Plo). Inflection points from which threshold values are obtained are arrowed.

rigorously tested, it has statistical integrity and produces values that are in accord with expert judgements provided in Baynes (2001b). Given the paucity of other forms of information, the slope frequency approach forms the basis of the majority of threshold values.

The threshold value is used in the GIS to identify predicted *oversteepened* areas where the ground slope equals or exceeds the threshold value for the underlying geological unit. Analysis of the Hobart pilot map shows that only a small percentage of the area is identified as being in a potentially *oversteepened* area. This is in accord with the low incidence of deep seated landslides, which in itself may be used to argue that most of the rock (as opposed to the soil) units are in a reasonably stable state (under present conditions).

While the slope-frequency approach appears satisfactory for the units behaving according to rock mechanics principles, it is apparent that the approach is not appropriate for units behaving more like soils; viz. the Tertiary sedimentary rocks. Known landslides, such as at Tarooona, Rosetta and Casuarina Crescent, are failing at much lower angles than the slope-frequency derived value (24°) predicts. This discrepancy may be due to the heterogeneity of the geological unit in question. In this case, the soil mechanics approach (described earlier) was also used to identify threshold values based on published residual friction angle values of failure planes for the unit (Donaldson, 1991; Latinovic *et al.*, 2001). The adopted threshold slope value of 6.5° was used to represent the worst-case scenario of fully saturated soils failing at approximately half the friction angle. This value has some validity in that it matches the failure angle of the Tarooona landslide complex. A higher threshold value of 10° is also used to represent the Rosetta scenario.

From a hazard zoning perspective, the two approaches and scenarios used to define *oversteepened* areas essentially depict the probable range of values given the varying properties that may exist in any unit from site to site.

Predicting setback area

Once an *oversteepened* area is identified, regardless of method, a raster modelling script, developed by the author, was used to define the *setback* area. The *setback* area represents the uphill extent of a hypothetical failure plane from each source cell (*oversteepened* area). The model defines the uphill direction as being the opposite direction to the aspect raster for the source cell. While the plan direction stays constant, in the vertical plane the angle is defined by the threshold value for each cell. The effect of this is that the failure plane will be generally planar but will alter if a change of threshold value is encountered. This is a realistic departure from the LHARA model where the setback analysis would stop if a change of threshold value was met.

The setback area approach varies from Baynes (2001b; 2002) in two main ways. In the Baynes approach, the setback routine is only performed in areas which experience contemporary undercutting such as coastal cliffs and nick points, whereas this system is applied to all areas. The justification for this departure is based on practicality and consideration of other landslips. While it is an easy process to define an area such as an eroding coastal cliff, other geomorphic settings are more difficult. For example, in river valleys, it is often difficult to subdivide valley segments into eroding and non-eroding parts given the scale limitations of the aerial photos available and a general lack of knowledge about erosional rates along the channel and on opposite banks of each stream. The other justification for a departure from the Baynes approach is that it would also fail to identify the full extent of landslips triggered by human influence, such as at Rosetta.

Runout

The modelling technique used in this study identifies only *oversteepened* and setback areas. A *runout area* is not considered useful to model because the distance most deep-seated landslides travel is insignificant at a regional scale.

Faults

Faults can affect the stability of slopes adjacent to them. For example, rock units are often more fractured, more weathered and thus weaker in the vicinity of a fault. Faults may also have an important influence on hydrogeological conditions that may result in a reduction of slope stability locally. For example fault lines can, in certain circumstances, act as conduits for water flow. In other cases they may be barriers to flow that serve to raise pore pressure. Unfortunately, without detailed local knowledge, the variables are such that landslide hazard is difficult to predict when comparing sites.

The approach adopted in this study is to show where such features (faults) occur on the map so that they flag areas of potentially enhanced instability. It should also be realised that the exact position of a fault may not be determined accurately in the course of mapping due to limited exposure. The width of a given fault zone can also vary markedly and unpredictably along its length and no assumption about the width should be made.

Ranking logic

Baynes (2001b) adopted a five-fold ranking logic to qualitatively classify areas of deep-seated landslide hazard. However, in the writer's opinion, this implies a level of knowledge that is rarely justified. Such knowledge can only be gained by more detailed investigation. Instead the depiction of hazard is here based on presenting the results in a manner which identifies each of the methods used but does not necessarily imply any judgement about the relative level of hazard.

Deep-seated landslide modelling procedure

1. Clip statewide 1:25 000 scale geology layer (vector format) to extent of map.
2. Edit geology polygon layer to merge (remove) surficial deposits in critical areas with underlying bedrock geology.
3. Determine threshold values.
4. Attach threshold values to each geological unit in polygon layer.
5. Convert geology layer from vector to raster using threshold angle as value field to create failure raster.
6. Query slope raster to identify cells where it equals or exceeds failure raster. The output raster becomes the source raster for the setback analysis.
7. Run setback routine using source, failure, elevation and aspect rasters to create a setback raster. Run model twice to produce two scenarios for the Tertiary units. The rest of the rock units are only modelled with one threshold value.
8. Combine source raster with setback rasters, with the former being the priority. The higher angle setback raster for the Tertiary units takes priority over the lower angle.

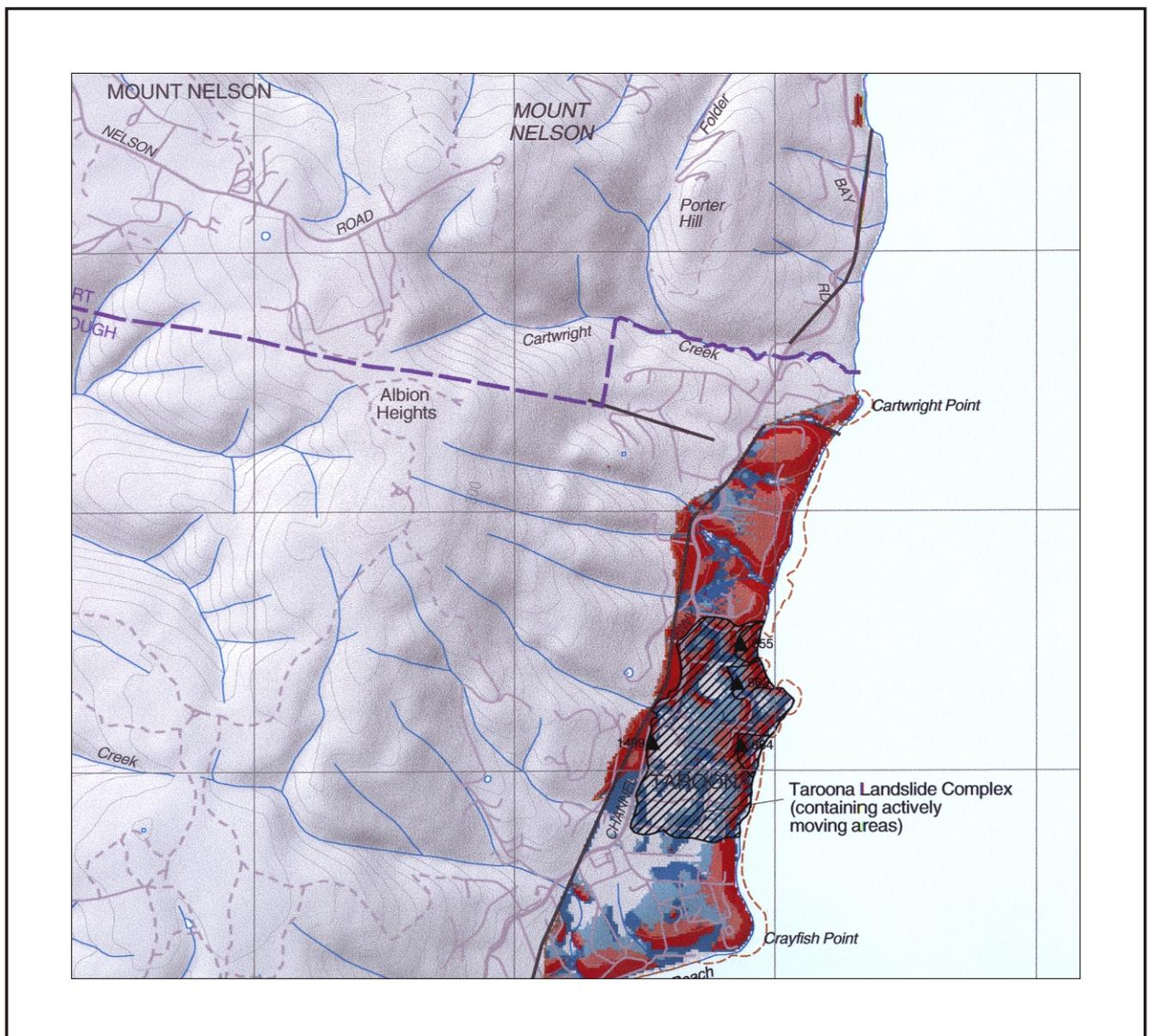


Figure 15

Example of deep-seated landslide hazard map. Red and blue colours represent Rosetta and Taroona landslide scenarios respectively. The Taroona Landslide Complex is shown as hatched area.

8. Validation procedures

Validation is an important aspect of hazard assessment to test the modelling assumptions employed. Validation will either confirm the modelling assumptions or highlight where revisions are required. For much of the modelling the results were checked as a desktop exercise with existing data such as the landslide database and orthophotos.

A further aspect of validation is a walkover inspection. The peer review by Coffey Geosciences (2004) recommended that a selection of boundary types and areas be checked in a methodical manner. In addition they recommended that the results of the walkover be documented within this report.

For Hobart, various field inspections have occurred over the two years the project took to complete. As the maps approached a final state further checking was undertaken. The field check involved consideration of the following criteria:

- Identify obvious errors and omissions particularly in:
 - Sensitive areas (e.g. residential suburbs, important structures);
 - Frequently visited areas (e.g. beaches, parks);
 - Critical infrastructure.
- Collate a list of corrective and containment measures.
- Evidence of land instability not previously recognised.
- Field indication of whether a gross over-estimation or under-estimation of the hazard has occurred.

The inspections were undertaken principally by Dr C. Calver, A. Ezzy and S. Forsyth. The opinion of these people was that the maps were a good guide as a predictor of landslide hazard. A polygon layer was created to record where inspections occurred and this will be put on internal file. There were few instances where it was decided to modify the maps. For example on the debris-flow map, solid-rock quarries were masked as there was no debris that could be potentially mobilised. For the rockfall hazard map, masks were created for artificial structures such as retaining walls.

Conclusions

Five thematic maps have been produced for the pilot study area of Hobart: geomorphology and landslide inventory; geology; potential debris flow hazard; potential rockfall hazard; and potential deep-seated landslide hazard. These maps represent the first of a new landslide hazard map series in Tasmania produced with a methodology that will be used in other parts of the State. The purpose of the maps and the methodology used have been outlined in this report. The users of the maps should familiarise themselves with this supporting document.

Hazard maps are based on assumptions and models that may change with time. The maps are merely tools that should be routinely questioned and tested when undertaking detailed investigations. Ideally, any deficiencies with the model or suggestions for improvement should be reported back to MRT with the view that the maps are updated as necessary.

Acknowledgements

The author is grateful to a number of persons who contributed to the project. The geological mapping was undertaken by Clive Calver, Steve Forsyth and Andrew Ezzy. Nizama Latinovic and John McDougall entered data into the Geohazards database and Miladin Latinovic contributed much of his knowledge to underpin this project. Jo-Anne Bowerman did a remarkable job of the cartographic aspects of the project using ArcInfo. Peter Slater provided invaluable programming assistance. Richie Woolley undertook laboratory testing of soil samples.

Information supplied by Hobart City Council was critical for the success of the project. In particular I wish to thank Stephen Ashton and Barry Holmes for their support and assistance.

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Finally I wish to thank my manager, Ms Carol Bacon, and the Director of MRT, Dr Tony Brown, for their support of the project.

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[8 August 2005]

APPENDIX 1

A strategy for future landslide risk assessment in Tasmania

F. J. Baynes

1. INTRODUCTION

This advice on a strategy for future landslide risk assessment in Tasmania was prepared at the request of Adrian Waite of Mineral Resources Tasmania (MRT).

The advice was initially prepared during November and December 2000. The advice was submitted as a provisional draft for discussion in December 2000, to meet planning deadlines and to generate interactive development of the advice. A final version of the advice was submitted in March 2001.

2. SCOPE

The scope was stated in Purchase Order MRPO 00936 dated 12 October 2000 as follows:

“Preparation of a methodology for landslide risk assessment”

This was interpreted as preparing advice on possible approaches to landslide risk assessment, a review of the approaches used within Tasmania in the past, and a recommendation as to what would be a useful approach in the future.

3. BACKGROUND

The purpose of landslide risk assessment is to provide technical information to the community, the regulators and to geotechnical consultants, in order that the social and economic impacts of landslides can be reduced. The reduction is achieved by way of an informed community, a suitable planning and legislative framework within government, and the application of sound landslide engineering practice.

During the 1970's the Mines Department of Tasmania (as MRT was known), was a world leader in landslide zoning studies. The work was carried out under the guidance of Peter Stevenson and wide variety of experimental techniques in landslide hazard zoning were pioneered (References 1 & 2). Since that time, some important changes have occurred in the way that landslide issues are managed:

- Management approaches based on risk assessment (risk being the product of probability and consequence) have been established as good practice in dealing with landslide issues (Reference 3).
- Geographic information systems (GIS) are now freely available for the manipulation of spatial data and the generation of maps.
- Geotechnical consultants have become established within the Tasmanian community and can provide advice on landslide engineering, although there will always be a reliance on MRT to provide overview of geohazard advice. However MRT has recently become so under-resourced that the skill base is rapidly falling below the critical mass necessary to provide such advice effectively.

4. LANDSLIDE RISK ASSESSMENT METHOD

The idealized process of landslide risk assessment is illustrated as a succession of different maps in Figure 1. Each map is derived from the preceding map via the addition of more information.

The process starts off with a basic geological map in which the bedrock and superficial geology and structure are described. Onto that map is added knowledge of the geomorphology, which relates to the landforms and surface processes. It is essential that hydrogeological information indicating groundwater conditions is also added. The results of geotechnical site investigation information such as bore holes and laboratory tests, and also any direct knowledge of landslides, such as movement rates or incidents, are then added to produce an inventory map. The first three maps in the succession represent the compilation of information.

MRT has traditionally produced good quality geological maps of the State and this reflects the high level of geological expertise of the staff. Geomorphological expertise is poorly developed in MRT and consequently geomorphological maps of the State are not readily available, and geomorphological knowledge is lacking. Inventory maps collate available geotechnical information and MRT has only carried out such studies in a limited fashion in few areas.

The three **information maps** are compiled and then *transformed* to produce three **advisory maps**. This is a critical step on the landslide risk assessment process (Reference 4).

The advisory maps relate to hazard, risk and planning (Reference 5). Hazard maps depict the distribution of landslides and the probability of the landslide processes occurring. Risk maps depict the probability and consequences of the landslide processes in terms of impacts on people and property. Planning maps depict zones where activities are controlled in order to reduce landslide impacts. The planning maps are used by government agencies to manage land usage.

The way that the geological, geomorphological and geotechnical information is transformed into the hazard risk and planning maps may be differentiated depending upon the nature of the transform adopted. The types of transforms that are applied to generate advisory maps are presented in Table 1 (Reference 6 & 7).

TABLE 1
Different transforms from information to advice

<i>Technique</i>		<i>Basis for transform</i>
Inventory		The mapped areas of landslide activity define the hazard zones.
Heuristic – expert opinion used to identify, classify, interpret, recommend	Geomorphological opinion	Recommendations with regard to hazard are based on geomorphological understanding and expertise but with no elaboration of the analytical basis.
	Qualitative weighting	Weighting values are assigned to mappable attributes and the combination of the values gives the level of hazard.
	Geomorphological model	A slope evolution model is used to anticipate the controls on landslide development and occurrence and those controls become mappable attributes to assess hazard.
Statistical – based on consideration of contributing factors	Bivariate	Selected weighted attribute maps are combined to assess hazard.
	Multivariate	All relevant factors are sampled and related to landslide occurrence using multiple regression or discriminant analysis.
Deterministic		Factors of safety are calculated for slope facets using soil mechanics models with input data generated from GIS.

5. EXISTING APPROACHES TASMANIA

Since the pioneering work in the 1970's a number of different approaches have been adopted in Tasmania to establish advisory maps. The approaches may be divided into those based on descriptive zones, which are based on geological and geomorphological attributes and have been used to develop advisory zones for planning purposes, and those based on proscriptive zones, which have a legislative basis and are used to declare zones of landslide risk (Reference 1).

5.1 Descriptive Zones

The quality of selected examples of descriptive zone systems used in different parts of Tasmania is evaluated in Table 2.

TABLE 2
Evaluation of examples of descriptive zones in Tasmania

	Information basis			Advisory status		
	Geological	Geomorphological	Inventory	Hazard Assessment	Risk Assessment	Planning Zones
Burnie (1963 & 1998)	3	3	1	2	1	2
Blackstone Heights (1989)	4	2	5	1	1	4
Hobart (1991)	3	1	5	1	1	1
Launceston Geodata (2000)	4	1	1	2	1	2
Lilydale (1978)	4	3	1	2	1	2
Penguin (1964 & 1998)	3	3	1	2	1	2
Tamar valley (1974)	4	2	1	2	1	3
Glen Lusk (1976)	3	2	1	2	1	2

Subjective Score: Excellent – 5, Good – 4, Reasonable – 3, Poor – 2, Non-existent – 1

It should be noted that this evaluation is purely judgmental and based on the limited documentation that was made available. In carrying out the evaluation the quality of depiction of the following aspects of each part of the system formed the criteria for the score:

- Geological inputs – stratigraphy, structure, choice and distribution of units.
- Geomorphological inputs – landform classes, landform evolution, choice and distribution of units.
- Inventory inputs – geotechnical site investigation data, landslide history, events, impacts.
- Hazard maps – landslide processes, potential impact zones, distribution, probability of occurrence.
- Risk maps – elements at risk, probability of consequences, levels of risk, distribution of risks.
- Planning maps – prescriptive advice, clarity, usefulness, distribution.

It is also possible to assess the existing approaches that have been used in Tasmania by considering the transforms that have been applied to the information bases to produce advisory maps. The various techniques used to transform the information are indicated in Table 3.

TABLE 3
Transforms used in examples from Tasmania

	Inventory	Heuristic			Statistical		Deterministic
		Geomorph	Qualitative	Model	Bivariate	Multivariate	
Burnie	✓	✓					
Blackstone Heights	✓	✓					
Hobart	✓						
Launceston Geodata	✓				✓		
Lilydale	✓	✓					
Penguin	✓	✓					
Tamar valley		✓			✓		
Glen Lusk	✓				✓		

I have the following comments on the descriptive approaches evaluated in Tables 2 and 3:

- The information base is of widely varying levels of quality.
- There is a considerable range in the technique adopted to formulate the advisory zones, consequently the nature and meaning of the zones varies from region to region.
- There is generally a lack of geomorphological input relative to geological input. The understanding of the hazard is poorly developed as a consequence of the lack of geomorphological input.
- There are no real concepts of risk embodied in the advisory zones and consequently it is difficult to evaluate the potential impact of landslides of differing levels of activity.
- The resultant planning tools vary widely in effectiveness and consistency and this results in difficulties in the uniform application of systems across the State.

5.2 Proscriptive Zones

The proscriptive zones are based on Section 43 IA of the Local Government Act 1973, in which it states:

“The Governor may, by order in Counsel made on the recommendation of the Director of Mines, declare any area of a municipality which is subject to earth movement by reason of inherent instability, as a landslip area to be known as an A landslip area, or a B landslip area and define it by reference to a Plan ”

The important words are *“subject to earth movement by reason of inherent instability”*. The wording *“inherent instability”* is open to interpretation and was questioned when the Mines Department attempted to prescribe a Zone B at Rosetta. It may be interpreted as indicating a condition where slope instability is a permanent or characteristic attribute of the ground. This is not necessarily the case where Zones A and/or B have been proclaimed, or may in the future be proclaimed. It follows from this that the wording of the Act should probably be changed. One possibility would be to replace the words *“subject to earth movement by reason of inherent instability”* with *“subject to significant risk from landslide”*. This would also introduce risk concepts into the proscriptive scheme, which would bring it up in line with modern practice.

It is understood that Zone A and B have not been rigorously or uniformly applied across the State. There are many anomalies to my knowledge where established landslides have not been proclaimed as Zone A or Zone B.

At this stage this advice cannot address the proscriptive zones in any further detail.

6. RECOMMENDED APPROACH

The recommended approach to landslide risk assessment in the future is as follows:

- The production of landslide risk assessments for areas within the State should follow the idealised approach epitomised by the set of maps in Figure 1 ie. there should be a systematic collection of geological information, geomorphological information and an inventory of geotechnical information. When this information has been compiled it should be transformed to produce advisory maps which describe the hazard and the risk and can be used for planning purposes.
- The current level of geological information within the State is perfectly adequate for the development of landslide risk assessments, although certain stratigraphic subtleties may have to be either grouped or divided, to produce stratigraphic divisions which are more suited to engineering geological purposes.
- There needs to be an increase in the input of geomorphological knowledge to the landslide risk assessment process. This will involve producing geomorphological maps and assessments for each of the areas and should culminate in the development of maps and slope evolution models to allow the inclusion of those aspects of the geomorphology that contribute to landslide development.
- All of the geotechnical information suited to compiling an inventory exists within MRT, it simply needs compiling and this needs to be done for each area.

If nothing else was achieved the above actions would create a very powerful tool for landslide risk assessment (Reference 8).

Using compiled information base, heuristic transforms should be then progressively applied to the information base to generate advisory zones in the following manner.

- Using geological information and threshold slope angle information, broad advisory zones should be established in which there is some potential for landslide risk. This is very similar to the existing systems and by and large they will suffice, however, they do need to be checked for robustness and intellectual rigour.
- Geomorphological slope evolution models need to be established which will provide knowledge to anticipate areas of landslide risk and define those attributes which are associated with landslide risk. Those attributes can then be combined with knowledge of geology and slope angle to establish hazard zones. This is the main thing that is missing from the existing evaluations.

The use of complex statistical transforms based on sophisticated manipulation of GIS data is not recommended. It is my opinion that effective landslide risk assessment must be based on a good, practical field based understanding of the geological and geomorphological controls on landslide occurrence.

I consider that establishing landslide hazard zones should be the first major objective of the strategy for future landslide risk assessment, and that this objective is realistic and achievable.

If that objective were to be achieved, then by looking at the hazard zones and identifying areas where there are high risks (in other words, potentially high impacts on property, or impacts on individuals leading to loss of life), then potential risk zones can be established for further attention. At that stage the relatively sophisticated risk assessment approach outlined in Reference 3 may be applied on specific areas of concern.

Where high risk zones are identified proscriptive Zones A and B can be used to control development within them. For instance, it would not be worthwhile applying a Landslide A Risk Zone to an empty paddock, but it would be worthwhile gazetting such areas if they are likely to be sub-divided, and thus represent potentially higher risks. Note that in order to achieve this purpose it will probably be necessary to modify the wording to Section 431A of the Local Government Act.

This information can be then progressively disseminated within the community in the knowledge that it is robust and defensible.

8. MRT LANDSLIDE RISK ASSESSMENT ACTION PLAN

In order to progress with this matter the following actions are required:

1. MRT should adopt a policy for future landslide risk assessments that reflects this recommended approach and plan to upgrade existing zoning systems to a uniform level based on current best practice. This will require management commitment, a budget, skilled resources and a programme to deal progressively with each area of concern.
2. It will be essential to trial this approach on a prototype area to establish the practicalities, develop the techniques and determine the levels of work that are involved in generating maps. It is only when maps are generated that the information can be disseminated. Based on such a prototype approach, improvements can then be made to the overall process.
3. A programme in time can then be developed to deal with all areas that require landslide risk assessment and budget developed and resources allocated to achieving the objectives within the time-frame.

A very provisional plan to prototype the Greater Hobart Area is outlined in Appendix A. **This plan will need considerable further discussion and refinement prior to being activated.**

9. CLOSURE

The findings of an engineering geological report are based on observation, interpretation and opinion derived from limited site investigations. The inherent uncertainty in the findings should be recognized. It will be essential to review and perhaps revise the findings of this report if the nature of the project changes, or if the use of the report, or the conditions encountered, differ from those anticipated.

10. REFERENCES

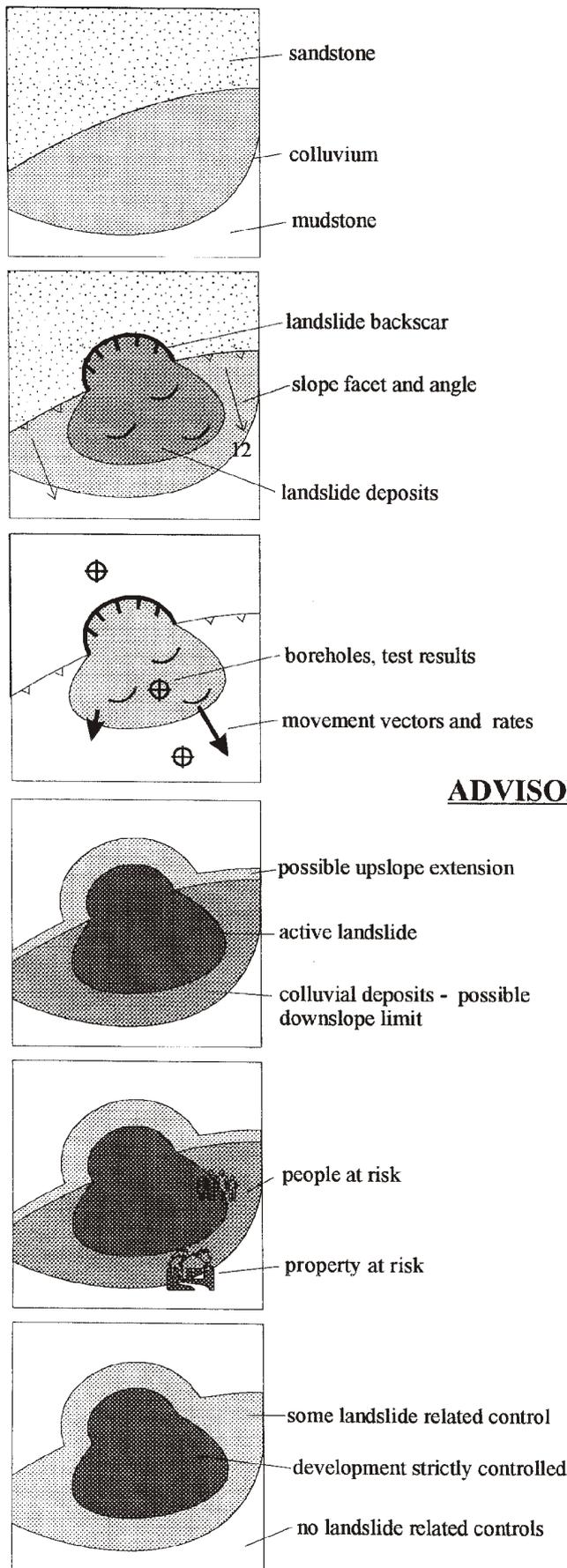
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**APPENDIX A
PROVISIONAL WORK PLAN
LANDSLIDE RISK ASSESSMENT FOR THE GREATER HOBART AREA**

Aim – to establish landslide hazard zones for the Greater Hobart area.	
Method – as per the activities described below, note estimates of resource requirements are provisional only	
<i>Objective</i>	<i>Activity and comments</i>
Develop overview of the controls on landslide distribution, potential and activity	Half day brainstorming session.
Generate simplified geological base map depicting the stratigraphy and structures of significance	Collation of existing mapping required then presentation as GIS layer. One day for the consultant, several days for the GIS operator.
Research existing information then generate a geomorphological sketch map and slope evolution models for the area.	Viewing of several different generations of aerial photos required, map to be generated, digitised, and presented as GIS layer, models to be devised, model controls to be formulated and incorporated onto GIS. Several days work for the consultant and the GIS operator.
Inventory of landslides and geotechnical data	Largely completed by Hofto, additions based on geomorphological mapping. Existing Hofto spreadsheet data to be incorporated into GIS. Several days work for the GIS operator.
Choose transform method	Use geomorphological models to transform. Based on consideration of controls on landslide distribution, potential and activity. Attributes defined and incorporated into GIS model. One day for the consultant, several days for the GIS operator.
Generate landslide hazard maps, initial documentation.	A few days for a GIS operator.
Ground truthing of hazard maps	A few days for the consultant.
Revision of the maps to optimize the transform	A few days for the consultant and the GIS operator.
Full documentation	A few days for the consultant.

INFORMATION MAPS



GEOLOGICAL MAPS

Observations and interpretations of bedrock and superficial geology

GEOMORPHOLOGICAL MAPS

Observations and interpretations of landforms and surface processes

INVENTORIES

Spatial presentation of information relating to landslide processes and associated engineering geological characterization

ADVISORY MAPS

HAZARD MAPS

Probability of landslide activity occurring within a polygon (probability is H)

RISK MAPS

Risk (R) is the probability of consequences such as impact on life and property and depends upon the elements at risk (E) and their vulnerability (V), thus $R = H \times V \times E$.

PLANNING MAPS

Indicate development constraints within different zones

APPENDIX 2

Mineral Resources Tasmania policy on Geohazards, 2005

Large tracts of land throughout Tasmania are subject to landslide hazard and these areas need to be identified prior to consideration for development approval, particularly where housing development is concerned. About 60 houses have been destroyed by landslides throughout Tasmania from the late 1950's to the present.

Mineral Resources Tasmania has produced advisory landslide hazard zone maps for a number of areas. Some small areas have been proclaimed as landslide areas under provisions of the *Mineral Resources Development Act 1995*. These areas represent only a few hundred hectares of the several hundred square kilometres of land that is currently subject to landslide movement, has signs of past movement, or is regarded as posing a significant landslide hazard.

MRT will produce regional advisory landslide hazard maps, at a scale of 1:25 000, to give guidance to planners, developers, property owners and potential purchasers of the geohazards on a regional basis. The advisory maps do not remove the need for site-specific investigations before development approval is given.

For areas that have been proclaimed there are clear procedures which have to be followed. For declared 'A Landslip' areas, new development is limited to an insubstantial shed (up to 25 square metres in area) or an addition to an existing house under some circumstances. For declared 'B Landslip' areas, construction of houses can take place using a special building code in which there are restrictions relating to house size, position, excavation and fill depth, drainage, vegetation removal and water storage.

Geohazards other than landslide risk need to be considered when approvals for development are required. These hazards include reactive or expansive clay soil, earthquake, subsidence, low bearing capacity, flood (including sea level rise), corrosive soils, contaminated sites and radioactivity. Codes have been developed for some of these issues, for example reactive soils (AS2870) and building to withstand effects of earthquake, and these codes should be adopted in the process of giving approval for development.

This Divisional policy relates only to land stability.

Policy Provisions

Local government, the main planning and approval authority should, within a set period, have landslide-prone land indicated on their planning schemes for the whole of each municipality. Initially, this may only be on a broad scale, which will be refined over time as more information becomes available.

Prior to subdivision approval, assessment should be made of stability conditions and any special precautions outlined (e.g. siting, excavations, drainage, etc.) that are required for development to proceed in a safe manner.

In approving building on undeveloped lots within previously approved subdivisions, an assessment of stability should be made before approval to proceed is given.

Landslide risk assessments should be undertaken by competent geotechnical practitioners who have relevant qualifications and experience in stability problems (e.g. engineering geologists, civil engineers, etc.). They should carry an appropriate level of indemnity insurance.

Assessments may be at various levels and may only require an inspection of land stability information on the planning scheme or from some other source, and/or a brief inspection of the area before advice can be given. In areas where risk is determined to be other than very low, an appropriate investigation, which may include any one or all of the following, should be undertaken:

- detailed surface examination;
- subsurface investigation and soil testing;
- stability analysis.

All landslide information (regional surveys, specific studies at particular locations) should be held in a central register. The most appropriate location is the body responsible for recommending the declaration of landslide areas, currently Mineral Resources Tasmania. A ready source of information will then be available from this register for the use by planning authorities, other government agencies, stability assessors and the public.

APPENDIX 3

Summary of MRT Landslide Risk Assessment Workshop

F. J. Baynes

This letter summarises my views of the findings of the workshop held at Mineral Resources Tasmania (MRT) on 18 September. The aim of the workshop as originally set out by MRT is attached as Appendix A and the Agenda that I defined is attached as Appendix B. The list of attendees is attached as Appendix C.

1. THE MRT INITIATIVE

The MRT Policy Initiative that outlines the overall approach being adopted by MRT is summarized as follows:

"To develop geoscientific information databases for infrastructure development, land management and local council planning schemes which incorporates geohazard risk assessment".

The initiative consists of two parts and is to be carried out over a two year period:

- Development of geoscientific databases for infrastructure and land management.
- Geohazard risk assessment using up to date techniques.

2. WORKSHOP FINDINGS

My views of the workshop findings are summarised under the following headings:

- Issues and policy
- End users views
- Strategy
- The GIS Engine
- Input/Output and Q.A.
- Dissemination

3. POLICY AND ISSUES

MRT policy was outlined by Dr Tony Brown as being the production of regional maps depicting landslide hazards at a scale 1:25 000 using approaches that are based on the Australian Geomechanics Guidelines for landslide assessment. A distinction was drawn between the provision of regional geohazard information which is MRT's responsibility and the assessment of landslide risks for owners and developers which is to be managed by Councils and funded by the end users.

The MRT strategic plan to implement this policy was explained, and the work in progress on the Hobart Sheet was described. The following considerations were generated by the workshop:

- There was concern that the maps should portray other geohazards besides landslides, i.e. reactive soils, river bank erosion, sources of contaminants etc. This is a matter of policy for MRT to consider.
- There were strong representations from individuals involved in council work that maps at a scale of 1:25 000 were not suited to planning needs and that maps at a scale of 1:10 000 were actually required.
- The need to revise the wording describing the proscriptive zones A and B was discussed.
- It was felt that MRT, as managers of the Initiative, should clearly enunciate the aims, methods budget and programme.

4. END USERS VIEWS

The workshop discussed end-users needs and formed the following views:

- The requirements of the end users should be more clearly defined and used to outline the whole process.
- Simple planning maps needed to be produced from the geohazard maps and this was the prerogative of MRT.
- Guidelines in the use of the maps needed to be produced, to be used uniformly throughout the State by the different councils within Tasmania.
- The maps and the guidelines needed to be presented within some kind of uniform framework (the universal legend) so that there were no inconsistencies between different maps.

- The functionality of the maps and guidelines needed to be related to any existing or proposed legislation in order to provide a uniform approach throughout the State.

5. STRATEGY

The overall strategy was discussed at some length and the following findings were made:

- The need for a strategic division of information maps (geology, geomorphology, inventory) and advisory maps (hazard, risk and planning) was accepted. The desirability of presenting all of the information as different accessible layers together with ultimate planning maps was indicated.
- The heuristic approach proposed by the strategy was generally considered to be the most suitable way of generating these maps but the possibilities of adding both deterministic and multi-variant statistical information to the heuristic approach was considered to be useful.
- In general the workshop could not form a consolidated view that the Terms of Reference had been met by the pilot study of the Hobart area. There were some concerns about the level of detail on the maps, the reliability of the inputs, whether or not the maps would be widely acceptable and universally applicable. Nevertheless, the workshop in general supported the overall strategy and approach.
- The need to rigorously separate information maps from advisory maps and hazard risk and planning maps was endorsed by the workshop as being a critical activity.
- The need for feedback from end users was identified as being a critical activity.
- It was felt that geoscientists should be involved in all stages of the mapping including the planning.

6. THE GIS ENGINE

The "GIS engine" that was developed for the Hobart exercise was described at the workshop and was generally considered to be a suitable approach. However, the following considerations were generated by the workshop:

- The need to recapture existing information, manage the data acquisition process, periodically revise data and obtain feedback and data from users was clearly identified.
- The need for legislation requiring the collection of useful investigation data generated in the commercial sector was discussed.
- The need to be able to see through the hazard maps into the different layers of information was discussed. The following information layers were proposed as the minimum:
 - Demographics
 - All landslides
 - Topography (the best available)
 - Geological information.
 - Hydro-geological information, both rainfall and groundwater
 - Geomorphological information
 - Geotechnical properties
 - Historical occurrences of landslides
 - Other geohazards
 - Seismic activities
- Incorporation of other specific models such as micro-climate, reactive clays or dip and strike was discussed.

7. INPUT/OUTPUT and Q.A.

The quality control of the GIS engine was discussed at great length and the following views formed:

- Field verification and the compilation of real data was considered to be critical.
- Scale problems to do with GIS were an issue because if information is presented in electronic vector form it can be viewed at any scale.
- The need for peer review of any findings was discussed and endorsed.
- Parameter choice was discussed and the possibility of developing slope histograms to determine threshold angles following the example of the approach adopted by Colin Mazengarb from the Institute of Geological and Nuclear Sciences in New Zealand was identified.

- The need to attach metadata statements to the information was discussed.
- The depiction of geological boundaries as they are recorded rather than following property boundaries was discussed and the policy of following the geological boundaries rather than the property boundaries was agreed upon.

8. DISSEMINATION

The dissemination of risk assessment information was discussed in the context of MRT policy and the associated legal liabilities. Clear distinction between opinion and facts was chosen by the workshop as being a critical factor. Some concerns were expressed as to the way that risks may be allocated to different parties:

- Conflict between different State Government departments was alluded to.
- The need for MRT to be involved in both the planning and knowledge areas of the map was alluded to.
- It was generally felt that local government and developers needed to concentrate on the planning side of the maps rather than the knowledge side of the maps.
- It was generally felt that owners and consultants needed to be involved in both the planning and knowledge side of the maps.

9. CONCLUDING COMMENTS

1. In general the workshop participants supported the approach adopted in implementing the MRT Initiative. There were no major areas of dissent.
2. Alternatives to the approach were discussed and whilst some improvements were outlined, there was no real alternative to the approach being adopted.
3. A need for greater clarification and definition of MRT's policy, strategy and implementation plan in regard to the initiative was indicated.
4. The GIS engine needs to be revised in order to incorporate the many useful points made by workshop participants. This should include the establishment of a "universal legend" which could be applied to many of MRT's existing maps.

I trust that these views are in accord with your own and look forward to progressing this project by addressing points 3 and 4 above.

Fred Baynes

Director, Baynes Geologic Pty Ltd

**APPENDIX A
LANDSLIDE RISK ASSESSMENT WORKSHOP**

Mineral Resources Tasmania has recently had developed a strategy for future landslide risk assessment in Tasmania. The work has been carried out by a national authority on the subject, Dr Fred Baynes. The strategy incorporated a proposed methodology for uniform assessment of landslide hazard and risk, using modern concepts of these terms, as set out in the paper "Landslide Risk Management Concepts and Guidelines" (Australian Geomechanics Society, 2000).

A pilot study using this methodology, to map landslide hazard on the western shore of the River Derwent, has recently been carried out using a GIS predictive model to assign preliminary levels of hazard, which require confirmation by field checking. Both the model and the map require further work for finalisation.

The methodology is required to be as robust as possible in its application. Its principles should be acceptable to a wide selection of expert opinion and should also be sufficiently all-embracing to be applicable throughout the State, such that the hazard classification schemes in each area are uniform. Any numerical values used in constructing predictive GIS systems should also reflect real ranges for the parameters concerned.

A workshop is proposed to critically examine the new methodology. The workshop will be formed of participants from the geotechnical profession in Tasmania, the Australian mainland and overseas. The workshop will be chaired by a representative from MRT.

Some of the issues proposed for the workshop to address are as follows:

- Is the mechanism proposed in the methodology a true reflection of the assessment process?
- Do the transforms and mapping types listed in the methodology represent all the stages necessary to generate landslide advisory maps?
- Should the assessment by geoscientists finish with identification of levels of hazard?
- Is it possible to link past studies with the methodology and, if so, to what extent is this possible?
- What numerical criteria should be used in carrying out the transforms (e.g. threshold angles) and what are suitable representative values?

Proposed invitees to the workshop are:

Dr Fred Baynes	Baynes Geologic Pty Ltd
Mr Alan Moon	Coffey Geosciences Pty Ltd
Mr John Sloane	Sloane Weldon Pty Ltd
Mr Ralph Rallings	Pitt & Sherry Pty Ltd
Dr Owen Ingles	
Mr Miladin Latinovic	Mineral Resources Tasmania
Mr Ric Donaldson	
Mr Adrian Waite	Mineral Resources Tasmania
A representative	Institute of Geological and Nuclear Sciences, New Zealand
Mr Neil Benson	Golder Associates Pty Ltd
Dr David Leaman	Leaman Geophysics Pty Ltd

The outcome of the workshop will be a set of recommendations indicating the strengths of the methodology, its deficiencies, and suggestions for resolving the deficiencies.

The proposed date for the workshop is Monday, 17 September 2001, to be held at the Government offices, Rosny Park.

APPENDIX B
MRT LANDSLIDE WORKSHOP
AGENDA

Workshop to be convened and chaired by Dr Fred Baynes.

- 10.00 am Introductions, Terms of Reference
 MRT policy and programme (Carol Bacon)
- 10.30 A Strategy for Landslide Risk Assessment in Tasmania (Fred Baynes)
 Discussion
- 11.00 The Hobart Landslide Hazard Assessment (Fred Baynes)
 The GIS based Landslide Risk Assessment Engine (Hydro Tasmania)
- 11.30 Contributions by prior arrangement (limited to 10 minutes)
 Cairns regional LRA (AGSO - Marion Leiba)
 New Zealand Experience (Colin Mazengarb)
 Making landslide risk management decisions (Coffeys - Alan Moon)
 Problems evaluating probability (David Leaman)
 Hobart City Council experience (Stephen Ashton)
- 13.00 LUNCH
- 13.30 Workshop Session – to develop and summarise the views of attendees under the following
 general headings:
 - The issues and MRT policy
 - The proposed strategy as a response
 - The views of the end users
 - The GIS methodology, system architecture
 - Inputs, outputs and QA
 - Dissemination
- 15.00 Summing up
- 15.30 FINISH

**APPENDIX C
LIST OF ATTENDEES**

Ric Donaldson - (ex MRT)
Marion Leiba - (AGSO)
Miladin Latinovic - (MRT)
Alan Moon - (Coffeys)
Adrian Waite - (MRT)
Clive Calver - (MRT)
Stephen Forsyth - (MRT)
Barry McDowell - (Coffey)
Wojciech Grun - (MRT)
John Pemberton - (MRT)
Geoff Green -(MRT)
Ken Bird - (MRT)
Peter Stevenson - (ex MRT)
Colin Mazengarb - (GNS)
David Leaman - (Leaman Geophysics)
Owen Ingles - (Coffey)
Carol Bacon - (MRT)
Andrew Ezzy - (MRT)
Ralph Rallings - (Pitt & Sherry)
Chris Potter - (Consulting Engineer)
Stephen Ashton - (HCC)
Hayden Foley - (Hydro Tas.)
Bill Cohen - (Hydro Tas.)