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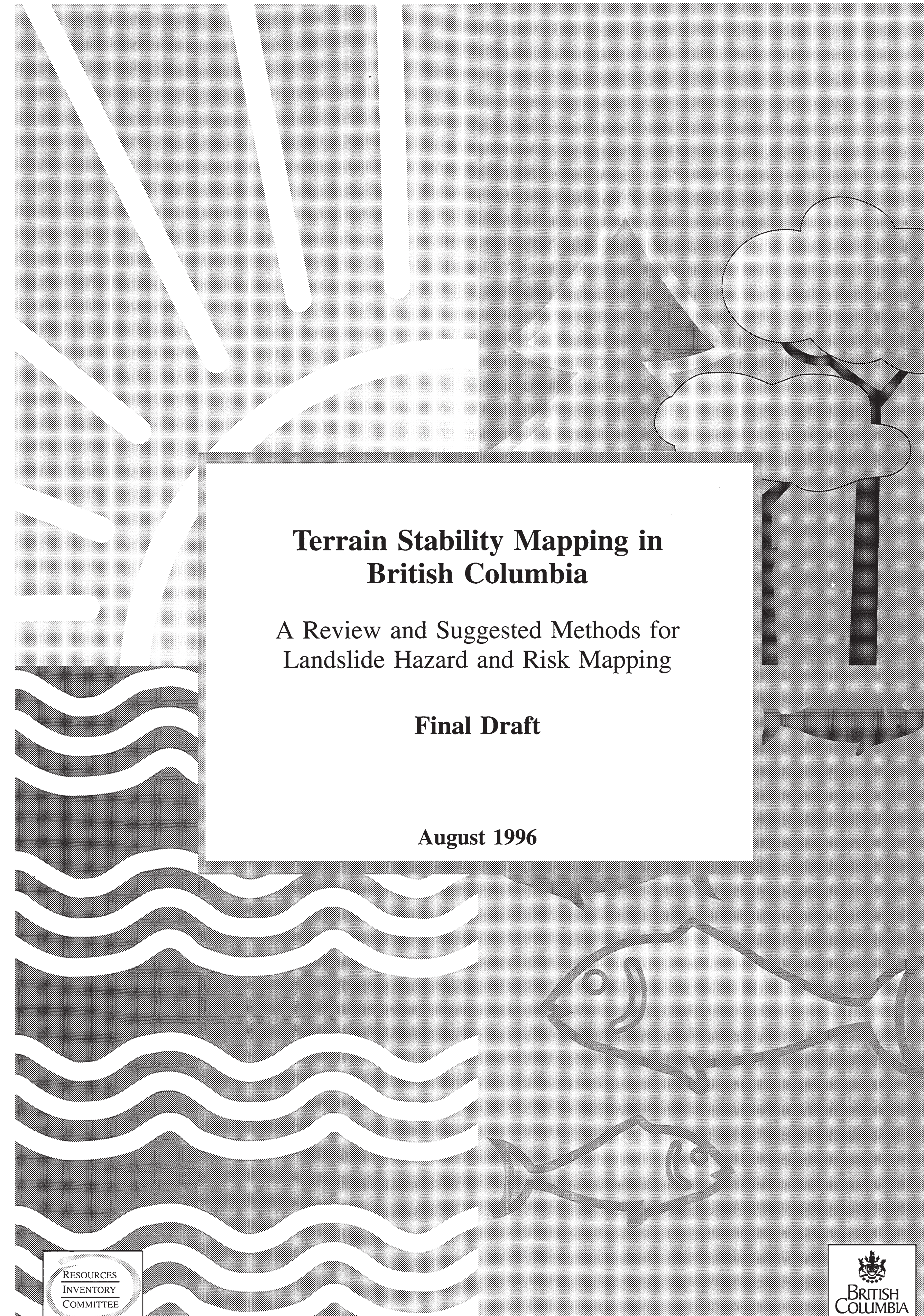

Terrain Stability Mapping in British Columbia

A Review and Suggested Methods for Landslide Hazard and Risk Mapping

Final Draft

August 1996

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BRITISH COLUMBIA

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TERRAIN STABILITY MAPPING IN BRITISH COLUMBIA

A REVIEW AND SUGGESTED METHODS FOR LANDSLIDE HAZARD AND RISK MAPPING

Final Draft

by

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Government of British Columbia

Slope Stability Task Group
Earth Sciences Task Force

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TABLE OF CONTENTS

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TABLE OF CONTENTS continued

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1. INTRODUCTION

1.1 General

Terrain stability mapping involves mapping the terrain to delineate areas that are stable and areas of existing and potential landslides, assessing the probability of those landslides occurring, and may include assessing the associated landslide risks. Landslide hazard and risk mapping, or simply landslide hazard mapping, are other terms commonly used to describe terrain stability mapping.

In British Columbia terrain stability mapping is used for resource development planning (for example in the forest industry); for land use and development planning; and for planning of linear projects such as for roads, railways, pipelines, and transmission lines.

The Earth Science Task Force of the British Columbia Resources Inventory Committee retained Thurber Engineering (Robert Gerath and Oldrich Hungr), in association with VanDine Geological Engineering (Doug VanDine), to review terrain stability mapping methods currently used in British Columbia, the Northwest United States and elsewhere in the world, and to suggest methods appropriate for a wide range of uses. This report is a summary of the review and the suggested methods.

The purposes of establishing standard methods are:

- to define reasonably uniform procedures, levels of effort and expertise for professionals involved in mapping projects;
- to develop common terminology, classifications, and symbols to improve communications among professionals involved in mapping, and between mappers and non-professionals who use such maps; and
- to prepare for technological changes, such as the introduction of computerized data bases and Geographical Information Systems (GIS).

1.2 Method and Scope

The review included a literature review and discussions with individuals experienced in terrain stability mapping and with map users. The suggested methods are based on the findings of the literature review, the discussions, and the collective experience of the authors.

Chapter 2 introduces landslides and the concepts of landslide hazards, consequences and risks. Chapters 3 and 4 provide a summary of the findings of the review. Chapter 5 presents general aspects of the suggested terrain stability mapping methods. Chapter 6 discusses specific aspects of terrain stability mapping in the context the forest industry, land use planning and linear project planning. The documents reviewed and referenced are listed in the bibliography in Chapter 7. Throughout the text a number of examples are referenced. The referenced examples are by no means exhaustive, and have purposely been limited.

Terrain stability mapping is based partly on scientific principles and partly on the intuition and experience of the mapper. It is therefore difficult to codify and standardize. The most valuable insights in terrain stability mapping are often obtained by experienced mappers with a flexible imagination. The suggested methods outlined in this report are intended to aid the work of the mapper, not stifle it by the imposition of rigid procedures. The authors hope that this report will serve as a summary of useful procedures and as a guide for improved communication between mappers and map users.

Although this report specifically addresses landslide hazards, many of the findings and suggestions can be applied to other forms of mass movement, such as snow avalanches and surface soil erosion, as well as other natural hazards.

The authors wish to acknowledge the numerous individuals who have contributed to this study and report in many different ways.

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2. LANDSLIDES, HAZARDS, CONSEQUENCES AND RISKS

This Chapter introduces landslides in general (Section 2.1), landslides in British Columbia (Section 2.2), and the concepts of landslide hazards, consequences and risks as they pertain to terrain stability mapping (Section 2.3).

2.1 Landslides

A landslide event is defined as "the movement of a mass of rock, debris or earth down a slope" (Cruden 1991). The word 'landslide' also refers to the geomorphic feature that results from the event. Other terms used to refer to landslide events include 'mass movements', 'slope failures', 'slope instability' and 'terrain instability'. In spite of the simple definition, landslide events are complex geological/geomorphological processes and are therefore difficult to classify. The classification system most commonly used in North America, and used in this report, is modified from Varnes (1978) to reflect the common usage in British Columbia (Table 2.1). The classification is based upon material type and type of movement, and is similar to the updated classification of slope movements suggested by Cruden and Varnes(1996).

2.1.1 Material Type

The material involved in a landslide is classified into two groups, 'bedrock' and 'soil'. Soil, which is generally unconsolidated surficial material, is further subdivided into 'debris' and 'earth' depending upon its texture.

Bedrock refers to earth materials that have lithified by some rock-forming process. Its strength depends not only on the rock type but also on the degree of weathering and the density and orientation of the discontinuities, which are generally the planes of weakness in the rock mass. For instance, if a strong, hard granite contains many fractures, the rock mass may be no stronger than a coarse grained soil.

Debris is composed of predominantly coarse grained soil (bouldery through to gravel and sand-sized materials), or as mentioned above, can also include highly fractured bedrock. The strength of coarse grained soil is generally derived from friction between the grains. Woody debris such as trees or logs, or other organic material, is sometimes incorporated with the inorganic debris.

Earth refers to predominantly fine grained soil (primarily of silt and clay sized materials). The strength of fine grained soil is generally derived from cohesion, the chemical and electrical bonding between the small particles.

2.1.2 Type of Movement

Falls take place rapidly by free-fall, bouncing, or rolling, and may develop into either slides or flows.

Topples consist of the rapid rotation of a unit of rock or soil about some pivot point. Toppling may not lead to either falls, slides or flows.

Slides involve the movement along one or more distinct surfaces. Slides are subdivided into 'rotational slides' and 'translational slides', depending upon the shape of the failure plane.

> ***Rotational slides***, also referred to as slumps, involve movement along a curved failure plane. Often the failure plane did not exist before movement occurred. Rotational slides usually involve relatively few distinct rock or soil units.
>
> ***Translational slides*** involve the movement of many rock or soil units along a plane. If few distinct units are involved, the movement is referred to as a 'translational block slide'. Often the failure plane existed before movement occurred.

Most rotational and translational slides occur rapidly, however, some earth slumps and slumps in weak rocks can occur slowly, over many days or even years.

Lateral spreads are dominated by lateral extension of the ground, accompanied by shear or tensile forces, and a general subsidence of the ground surface. They generally occur relatively slowly.

Flows describe movement that resembles a viscous fluid. Some flows occur slowly, others occur rapidly. Velocity within the flowing mass is usually decreases with depth and laterally. In most cases, water is an integral component. Creep is a type of flow that occurs very slowly.

Complex landslides involve the combination of two or more types of movement. Commonly one type of movement starts the material moving, such as a debris slide, and once underway the material takes on the character of another type of movement, such as a debris flow. The name of the complex movement is a combination of the types of movement, in order of occurrence, such as a debris slide-debris flow. The rate of movement depends on the types of movements and material types involved.

2.2 Landslides in British Columbia

At present there is no comprehensive inventory of landslides in British Columbia, however, most types of landslides occur in the province. A number of the publications that review landslides in the province include Eisbacher (1979); Evans and Gardiner (1989); Evans (1991); Evans (1992); VanDine (1992); BC Ministry of Energy, Mines and Petroleum Resources (1993), and BC

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Ministry of Transportation and Highways (1996). The following are examples of common landslide types in British Columbia.

Rock falls and rock topples are associated with steep, near vertical or overhanging natural bedrock bluffs and steep bedrock excavations. Where they occur frequently, the bedrock is usually moderately to highly fractured with intersecting fractures. Rock falls and rock topples vary in size from a single piece of rock to many thousands of cubic metres. They often occur rapidly without warning. Rock falls and rock topples occur in all areas of British Columbia. Small rock falls are common along many of the province's transportation routes.

Debris and earth falls and topples are associated with steep, near vertical or overhanging natural soil bluffs or excavations. They vary in size from a single boulder or block of soil to many hundreds of cubic metres. They often occur rapidly and without warning. Debris and earth falls and topples occur throughout the province, wherever the appropriate vertical relief exists. They are common in the dryer southern interior and are a concern along a number of the interior transportation routes.

Rock slumps most frequently involve large tracts of land, up to several kilometres across. They are usually located along river banks or along steep valley sides and are generally associated with weak, fine textured bedrock types. Glacier unloading is postulated as one triggering mechanism of rock slumps. They can occur moderately fast, all at once, or slowly and progressively. Large slow-moving rock slumps are commonly found bordering river valleys, in particular in northeastern British Columbia, for example along the Peace River and Laird River valleys.

Rock block slides and rock slides are generally associated with stronger rock types that fail along pre-existing planes of weakness. They usually occur rapidly in strong rocks and more slowly in weak rocks. Once the initial failure has occurred they can continue to move slowly and/or intermittently. They can vary in size from very small, involving one or several blocks of rock, to extremely large.

Rock block slides and rock slides occur in all mountain ranges within the province. An example of a large rock block slide is Downie Slide north of Revelstoke along the Columbia River valley. Hope Slide east of Hope, which occurred in January 1964, is an example of a large rock slide. Some rock slides can have extremely long runout zones and become debris flows. The resulting complex landslide is often referred to as a 'rock slide-avalanche', or simply a 'rock avalanche'. An example of a rock slide with a long runout is the 1959 Pandemonium Creek rock avalanche in the Southern Coast Ranges which travelled nearly 8 km along a stream valley inclined at only 6^o to 9^o.

Earth slumps are usually located along river banks, road cuts or steep valley sides. They can involve the displacement of one or more rotational blocks of weak, predominantly fine grained soil. They can occur extremely slowly to rapidly, all at once, or slowly but progressively. They can stabilize then remobilize, and often retrogress with time. Earth slumps vary in size from small, involving several cubic metres, to large, involving many hundreds of thousands of cubic metres.

Earth slumps are common in glaciolacustrine sediments along the interior valleys of the province, in particular the Thompson, Columbia and Okanagan valleys. Many spectacular examples of large rapid earth slumps were triggered by flood irrigation of silt benches at the turn of the century. With today's restrained irrigation techniques, landslides of this type occur less frequently. Earth slumps also occurr underwater, as submarine earth slumps, within delta fronts. Examples are those which occurred along Howe Sound and Douglas Channel, near Kitimat.

Debris slides are common in areas with steep slopes and high rainfall. They often occur during periods of intense rainfall. They tend to be shallow failures and usually occur along planes of weakness between looser, overlying soil such as colluvium or weathered till, and denser, underlying material, such as unweathered till or bedrock. Debris slides are also common along road fills. They vary greatly in size from very small, involving an area a few square metres, to large, involving up to many hectares. Once started, they usually travel rapidly and can develop into debris flows. Debris slides are ubiquitous in all parts of the Coast Mountains, Vancouver Island and the Queen Charlotte Islands. They also frequently occur in the wetter parts of the interior of the province, such as the Columbia Mountains.

Debris flows can occur on open slopes or in pre-existing channels. Open slope debris flows are also referred to as 'debris avalanches'. Channellized debris flows have in the past been referred to as 'debris torrents'. Both open slope and channelized debris flows involve the rapid movement of liquefied, predominantly coarse grained soil and sometimes large organic debris, on steep terrain. They may be initiated by debris slides or rock slides. The volume of the debris often increases downslope as a result of slope erosion and/or channel scouring. Debris flows occur in surges and often come to rest many hundreds to thousands of metres from the initiation zone. Debris flows are common in all mountain regions of British Columbia. They can vary from small, involving several tens of cubic metres, to large, involving many thousands of cubic metres.

Earth flows are large, slow or rapid moving landslides of predominantly fine grained soil and/or weathered volcanic bedrock. They usually involve relatively large tracts of land. Earth flows are common in the Interior Plateau. The 1993 Mink Creek slide near Terrace is an example of a rapid earth flow in glaciomarine sediments.

Soil creep is a shallow, slow-moving form of an earth flow involving thin layers of near-surface soil. Where permafrost is involved, the movement is referred to as 'solifluction'. Soil creep is found throughout the province, while solifluction is found in northern British Columbia and in the higher alpine regions of the province.

2.3 Landslide Hazards, Consequences and Risks

The following summarizes some of the terms relating to terrain stability or landslide hazard and risk assessment. It is adapted from Morgan et al (1992), Fell (1994) and Sobkowicz et al (1995). Common abbreviations are included in parenthesis.

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2.3.1 Landslide Hazards

The word 'hazard' is derived from the Arabic word for 'a die' (singular of dice) and is often related to 'chance or probability', as in the phrase 'to hazard a guess'. This definition is reflected in the United Nations definition of natural hazard: "the probability of occurrence of a potentially damaging natural phenomenon" (Varnes 1984). In reference to landslides, Fell (1994) defines 'hazard' as "the magnitude of the event times the probability of its occurrence".

In British Columbia, however, 'hazard' is also often used to describe the damaging phenomenon, as in 'natural hazard', 'geological hazard', 'landslide hazard', or a specific type of landslide hazard, such as, a 'debris flow hazard'.

Hazard (H), as used in this report, is a condition or event that puts something or someone, in a position of loss or injury, or in a position of potential loss or injury. A landslide hazard results from a potential or actual landslide occurrence.

Probability of occurrence (P) is the chance or probability that a landslide hazard will occur. It can be expressed in relative (qualitative) terms or probabilistic (quantitative) terms. Examples of relative terms are 'very high', 'high', 'moderate' and 'low', or 'very frequent', 'frequent', 'infrequent' and 'seldom'.

Probability of occurrence can be expressed as an 'annual probability of occurrence' (P_a), or a 'long term probability of occurrence' (P_x), where '$_x$' is a given number of years. The following statistical equation converts P_a to P_x:

$$(P_x) = 1-(1-(P_a))^x$$

For example, the probability of occurrence of a landslide hazard in a 50 year period given an annual probability of occurrence of 1 in 475 is:

$$\begin{aligned}(P_{50}) &= 1-(1-(1/475))^{50}\\ &= 0.10\\ &= 10\%\end{aligned}$$

For natural hazards that occur frequently in the same location such as floods, a statistical probability of occurrence can be determined by rigorous analysis. Landslide hazards, however, usually occur infrequently in a given location, therefore an estimated probability of occurrence is often determined by judgement combined with empirical evidence. Such estimates may be arrived at by consensus among a number of specialists and are referred to as Bayesian-like prior probability estimates, or simply 'Baysian-like estimates'. True Baysian estimates can only be tested if events have a relatively high frequency of reoccurrence, for example snow avalanches (McClung and Tweedie). Baysian statistics are described in texts such as (Freund 1973 and Lapin 1983).

The results of Bayesian-like estimates are often presented as ranges. The ranges presented in Table 2.2 are useful benchmarks in that they decrease in a regular stepped manner and they relate to some physical factors as well as to existing hazard acceptance.

Magnitude (M) is the volume of displaced material involved in a landslide hazard. The magnitude can be expressed qualitatively by words such as 'small', 'medium' or 'large', or quantitatively as an actual volume or range of volumes. It should be emphasized that some landslide events, such as debris flows, may take place as a number of separate smaller events or surges, and the magnitude of the surge versus the total magnitude of the event must be differentiated. From air photos it is often difficult to estimate the actual or potential thickness of a landslide Therefore the area affected by the landslide hazard, with some assumption of thickness, is sometimes used as a rough estimate of magnitude.

As in earthquake engineering, the magnitude of a landslide hazard can be related with the probability of occurrence of that hazard. An example of a single 'magnitude-probability of occurrence' relation is:

> a colluvial fan that is subject to debris flow with an estimated magnitude of 10,000 m^3, with an estimated annual probability of occurrence of 1:200.

Intensity (I) is a collection of physical parameters that describe the destruction or destructive potential of a landslide hazard, such the downslope velocity, the thickness of the landslide debris and/or the impact forces. Intensity can also be expressed qualitatively, by words such as 'slow', 'moderate', and 'fast', or 'low', 'moderate' and 'high', or quantitatively. Intensity varies with location along and across the path of the landslide and therefore it should ideally be described using a spatial distribution function.

As in earthquake engineering, the intensity of a landslide hazard at a given location can be related to probability of occurrence of that hazard. An example of a single 'intensity-probability of occurrence' relation is:

> a specific site on a colluvial fan that is subject to debris flows with estimated velocities $\geq$ 5 m/sec and an estimated debris deposition thickness $\geq$ 2 m, with an estimated annual probability of occurrence of 1:400.

For a range of magnitudes or intensities, and the corresponding range of probabilities of occurrence, the relation can be graphed (Figures 2.1). The two curves represent the ranges in confidence or uncertainty in assigning the parameters. The area beneath the magnitude (or intensity)-probability of occurrence curve is the product of the magnitude (or intensity) and the probability of occurrence, and represents the 'total hazard' as defined by Fell (1994).

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2.3.2 Landslide Consequences

Landslides hazards can result in a wide variety of downslope consequences, including environmental, social and/or economic. To have a consequence, there must be something or someone vulnerable to loss or injury, as described below.

Elements at risk (E) include any land, resources, environmental values, buildings, economic activities and/or people in the area that may be affected by the landslide hazard. The elements at risk can be quantified by placing a dollar value, or some other form of value, on them. Specialists are often required to identify and/or evaluate certain elements at risk. For instance a fisheries biologist should determine whether or not a stream is a fish stream and detemine the value of that resource.

Vulnerability (V) is the degree of damage caused by a landslide hazard to the elements at risk. It is usually expressed in relative terms, using words such as 'no damage', 'some damage', 'major damage', 'and total loss', or by a numerical scale between 0 (no damage) and 1 (total loss). An assessment of vulnerability often requires specialist input, such as engineers for structures and resource managers for natural resources.

Vulnerability can also be subdivided, for example into spatial vulnerability (V_s -- will a particular area be affected by the event?), temporal vulnerability (V_t -- will the area be occupied by a person at the time of the event?), and life vulnerability (V_l -- will there be loss of life due to the event). When expressed by a numerical scale, the subdivided vulnerabilities can be multiplied together to obtain the total vulnerability ($V = V_s \times V_t \times V_l$) (Morgan et al 1992).

Consequence (C) is the resulting loss or injury, or the potential loss or injury. It is the product of the elements at risk and the vulnerability (E x V), and can be quantified if the element at risk is expressed as a value and the vulnerability is expressed numerically.

When a consequence is expressed qualitatively, it is sometimes referred to as a 'consequence rating'. The phrase, 'there is a high probability that landslide debris will reach the creek, cause siltation and damage fish habitat', is an example of a consequence rating.

2.3.3 Landslide Risks

Landslide risk considers both the landslide hazards and the consequences. Simply stated, risk is the product of the probability that a landslide hazard will occur and the consequence of that occurrence:

$$R = P \times C$$

Specific risk (R_s) is the product of the annual probability of occurrence and the vulnerability ($R_s = P_a \times V$) for a specific element at risk. Depending on the quality of the data and the methods used to express annual probability of occurrence and vulnerability, specific risk can be expressed qualitatively or quantitatively.

Total risk (R) is the sum of the specific risks, or the sum of the product of the annual probability of occurrence, the elements at risk and the vulnerability ($R = P_a \times E \times V$). As for specific risk, depending on the methods used to express annual probability of occurrence, elements at risk and vulnerability, total risk can be expressed qualitatively or quantitatively.

Risk cost (R_c) is the annual cost, or annualized cost, of the expected losses from the landslide hazard.

In many cases involving landslide hazards, public safety is an overriding consideration. The following 'risk to life' concepts are modified from Morgan et al (1992).

Probability of death of an individual (PDI), also known as 'risk to life', is the probability that a specific person will be killed as a result of a specific landslide hazard. It is a variation of the risk procedures described above. PDI is the product of the annual probability of the hazard, the person being spatially in the path of the event when it occurs, the person being temporally in the path of the event when it occurs and the person being killed as a result. Mathematically, PDI is expressed as:

$$PDI = P_a \times P_s \times P_t \times P_l$$

where

P_a = annual probability of occurrence of the hazard;

P_s = spatial probability of impact: that is, if the hazard occurs, the probability that the path of the event intersects the location where the person could be;

P_t = temporal probability of impact: that is, if the hazard occurs and if the path of the event intersects the location where the person could be, the probability that the person is there; and

P_l = probability of loss of life: that is if the hazard occurs, if the path of the event intersects where the person could be, and if the person is there at the time, the probability that the person would die.

If a given area is potentially subject to more than one type of independent landslide hazard, the individual PDIs are additive.

Probability of death of a group (PDG) is the probability that a specific hazard will result in a minimum number of casualties. Because the numbers of people vary in space and time, PDG is much more complex to determine.

Severity (S) is sometimes used in association with PDI and PDG, and is the product of $P_s \times P_t \times P_l$, described above. It is somewhat analogous to consequence (C).

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As for the other parameters, PDI, PDG and severity can be expressed qualitatively by words such as 'low', 'moderate' or 'high', or quantitatively as an actual number.

For a range of consequences or severities, and the corresponding range of probabilities of occurrence, the relation can be graphed (Figures 2.2). The two curves on each figure represent the ranges in confidence or uncertainty in assigning the parameters. The area beneath the consequence (or severity)-probability of occurrence curve is the product of the consequence (or severity) and the probability of occurrence, and represents the 'total risk' as defined by Morgan et al (1992) and Fell (1994).

The final stage in landslide risk assessment is to determine the acceptability of the estimated risk. In the case of environmental or economic risks, acceptability is often carried out by means of a cost-benefit analysis, comparing estimated annual risk costs with annual capital and maintenance costs of any or all remedial measures. In the case of risks to life, comparisons of estimated PDI or PDG are made against accepted societal standards. It is the responsibility of the terrain stability mapper to provide technical input. It is not the mapper's responsibility to determine the acceptability of the risk.

2.3.4 Applications and Limitations

As discussed above, many of the landslide hazard, consequence and risk parameters can be expressed in relative (qualitative) or numerical (quantitative) terms. If reliable data is available quantitative terms are preferred, as they provide the most precise, objective mapping. Because landslide hazards occur relatively infrequently in the same location, unlike other natural hazards such as floods, probabilities of occurrence and other quantitative assessments cannot be based on standard statistical methods, and are usually based on Baysian-like estimates--essentially 'subjective estimates' that cannot be tested, but can be critically reviewed. Even when quantiative terms are used, numerical ranges are useful to convey the degree of uncertainty perceived by the mapper. For example, a statement such as 'moderate sized debris flows, with a magnitude range of 10,000 to 20,000 m^3, can occur frequently, with an estimated annual probability of occurrence of 1:100 to 1:500', conveys the degree of uncertainty. Quantitative results can easily be applied to cost-benefit analyses to aid decision making.

Unless users of such quantitative assessments understand the limitations of the methods, however, they may be misguided by the apparent precision provided by the numbers.

With less reliable data, qualitative estimates can be made and qualitative terms can be used to express the landslide hazard and risk parameters. If using a qualitative scale, it is recommended that the same principles of landslide hazard and risk assessment should be kept in mind. A drawback to using qualitative terms is that terms such as 'low', 'medium' and 'high' mean different things to different people, and hence map users may interpret different meanings than intended by the mapper.

Table 2.1 Abbreviated Classification of Landslides

Material Type Type of Movement	Bedrock	Predominantly Coarse Grained Soils (Debris)	Predominantly Fine Grained Soils (Earth)
Falls	Rock falls	Debris falls	Earth falls
Topples	Rock topple	Debris topple	Earth topple
Slides Rotational Translational	Rock slumps Rock block slides Rock slides	Debris slumps Debris block slides Debris slides	Earth slumps Earth block slides Earth slides
Lateral spreads	Rock spreads	Debris spreads	Earth spreads
Flows	Rock flows (deep creep)	Debris flows	Earth flows (soil creep, solifluction)
Complex	Combination of two or more types of movement		

(Modified from Varnes 1978)

Table 2.2. Example of Relative Terms and Ranges of Annual Probability of Occurrence

Relative Term of Probability	Range of Annual Probability of Occurrence (P_a)	Comments
Very high	>1/20	P_a of1/20 indicates the hazard is imminent, and well within the lifetime of a person or typical structure. Landslides occurring with a return interval of 1/20 or less generally have clear and relatively fresh signs of disturbance.
High	1/100 to 1/20	P_a of 1/100 indicates that the hazard can happen within the approximate lifetime of a person or typical structure. Landslides are clearly identifiable from deposits and vegetation, but may not appear fresh.
Moderate	1/500 to 1/100	P_a of 1/500 indicates that the hazard within a given lifetime is not likely, but possible. Signs of previous landslides, such as vegetation damage may not be easily noted. 1/475 is used by BC Ministry of Transportation and Highways as an acceptable probability of occurrence for life-threatening hazards, and is used by BC Hydro to define the Design Basis Earthquake for dams.
Low	1/2500 to 1/500	P_a of 1/2500 indicates the hazard is of uncertain significance. A similar probability was at one time used to define the Maximum Credible Earthquake for dams, but this definition has been dropped.
Very low	<1/2500	

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Table 6.3. Approximate relationship between Terrain Stability Class, frequencies and likelihood of landslides following timber harvesting and road construction for BC coastal conditions.

Terrain Stability Class	Likelihood of Landslide Initiation following Timber Harvesting or Road Construction	Polygons with Landslides following Timber Harvesting or Road Construction (%)	Landslide Frequencies following Road Construction (#/km)	Landslide Frequencies following Timber Harvesting (#/ha)
I	Negligible	0%	0	0
II	Very Low	5%	0<0.1/km	<0.02/ha
III	Low	5-30%	0.1-1/km	0.02-0.10/ha
IV	Moderate	30-70%	1-3/km	0.10-0.50/ha
V	High	70-100%	>3/km	>0.50/ha

These relationships are generalized from limited data for several coastal study areas, for the period 5 to 15 years after logging (Howes 1987, Rollerson 1992, and Rollerson and Sondheim 1985). They may not be applicable to other climatic regions or longer time periods. The table addresses landslides ≥ 0.05 ha, and sidecast road construction practices. Some terrain types will have a different likelihood of failure for road-building compared to timber harvesting. (modified from BC Ministry of Forests 1995a)

3. TERRAIN STABILITY MAPS

This Chapter summarizes various aspects of terrain stability maps: uses (Section 3.1), types (Section 3.2), terrain attributes (Section 3.3), map scales (Section 3.4), and map units (Section 3.5). The following Chapter summarizes various methods of terrain stability mapping.

3.1 Uses

Terrain stability maps are used for a variety of purposes that can be compiled into three groups:

- resource development planning;
- land use and development planning; and
- linear project planning.

3.1.1 Resource Development Planning

Presently in British Columbia, of all resource industries, the forest industry makes the greatest use of terrain stability maps for development planning.

The forest industry uses these maps:

- to assist with establishing cutblock boundaries, road alignments, and timber harvesting systems to minimize future landslides;
- to predict areas where landslides may occur and/or to predict the severity of landslides in response to road construction, or during or following logging;
- to assist with road deactivation plans; and
- to locate forestry camps, mill sites and other facilities.

The first systematic method of terrain stability mapping in British Columbia was developed by MacMillan Bloedel Ltd for coastal areas (Bourgeois 1978). Over the years the BC Ministry of Forests and other forest companies have adopted and adapted similar mapping methods. The "Mapping and Assessing Terrain Stability Guidebook" associated with the Forest Practices Code (BC Ministry of Forests 1995a) has recently summarized and standardized this method of mapping. Similar methods are used elsewhere in the Pacific Northwest. See for example Duncan (1989).

Since the early 1980s, research has been carried out in coastal British Columbia on the prediction of landslides in clear cut areas based on the study of a variety of terrain attributes. Examples include Rollerson and Sondheim (1985), Howes (1987) and Rollerson (1992). It is anticipated that such 'terrain attribute studies' will help refine the methods of pre-logging terrain stability mapping.

Gully sidewall and channel stability, as well as erosion and sediment delivery to streams, are also concerns of the forest industry. Methods have been suggested in the province and elsewhere to map and assess gully sidewall and channel stability, and erosion potential and the potential for sediment delivery of the eroded material to streams. Examples include Hogan and Wilford (1989) and the California State Board of Forestry (1990). These methods, although not yet routine, are gaining general acceptance. The "Gully Assessment Procedure Guidebook" associated with the Forest Practices Code (BC Ministry of Forests 1995b) is an initial attempt to standardize the assessment of gully sidewall and channel stability.

Recently terrain stability mapping in the forest industry has been included as a component of the multi-disciplinary approach to 'cumulative effect' assessments that also include sediment production, effects on wildlife and vegetation, fire hazards, soil degradation and other environmental concerns. Examples include Acres International Ltd (1993) and Washington Forest Practices Board (1993). Landslide hazards constitute one of the most important components of cumulative effects of forestry activity.

3.1.2 Land Use and Development Planning

The purpose of terrain stability mapping in land use and development planning is to delineate areas where existing and/or land development may be affected by landslide hazards, and where land development may affect slope stability. These areas include land on steeper slopes, at the breaks in slope, along the base of slopes and land on colluvial and alluvial fans. The ultimate aim of such mapping is to assist with the planning or regulation of land use and development.

Many regional terrain stability mapping programs for land use planning were implemented in Europe and the United States in the 1970s and 1980s. Tippett and Roberts (1992) reviewed such programs in Austria and France. Since 1975, Austria has required the preparation of plans of natural hazards including debris flows, snow avalanches and flooding. France in the late 1970s published a series of terrain stability maps at 1:10,000 to 1:25,000 scales, locally referred to as ZERMOS (zones exposed to risk of soil and sub-soil movement) maps. Since 1982 a French law has required natural hazard prediction (PER) maps at 1:2,000 to 1:10,000 scales be prepared for areas prone to natural hazards. Each map is accompanied by a report and four additional maps: a land use map, a process inventory map, a probability of occurrence map, and a 3-class zoning map (Perrot 1988).

In San Mateo County, California in the early 1970s a detailed terrain stability map using a 7-class zoning system was prepared to reduce new development in hazardous areas and to encourage site specific studies (Brabb et al 1972). The program was extended to include the entire San Francisco Bay region. Separate zoning maps addressed landslides (Brabb 1991), debris flows (Mark 1992) and seismically triggered landslides (Wieczorek et al 1985).

Table 6.1 Reconnaissance Terrain Stability Classification

Reconnaissance Terrain Stability Class	Interpretation
S can be unspecified	• Stable. There is a negligible to low likelihood of landslide initiation following timber harvesting or road-building.
P	• Potentially unstable. • Expected to contain areas with a moderate likelihood of landslide initiation following timber harvesting or road construction.
U	• Unstable. Natural landslide scars present. • Expected to contain areas where there is a high likelihood of landslide initiation following timber harvesting or road construction.

(Modified from BC Ministry of Forests 1995a)

Table 6.2 Detailed Terrain Stability Classification

Detailed Terrain Stability Class	Interpretation
I	• No significant stability problems exist.
II	• There is a very low likelihood of landslides following timber harvesting or road construction. • Minor slumping is expected along road cuts, especially for 1 or 2 years following construction.
III	• Minor stability problems can develop. • Timber harvesting should not significantly reduce terrain stability. There is a low likelihood of landslide initiation following timber harvesting. • Minor slumping is expected along road cuts, especially for 1 or 2 years following construction. There is a low likelihood of landslide initiation following road-building. • A field inspection by a terrain specialist is usually not required.
IV	• Expected to contain areas with a moderate likelihood of landslide initiation following timber harvesting or road construction. Wet season construction will significantly increase the potential for road related landslides. • A field inspection of these areas should be made by a qualified terrain specialist prior to any development, in order to assess the stability of the affected area.
V	• Expected to contain areas where there is a high likelihood of landslide initiation following timber harvesting or road construction. Wet season construction will significantly increase the potential for road related landslides. • A field inspection of these areas should be made by a qualified terrain specialist prior to any development, in order to assess the stability of the affected area.

The classification addresses landslides $\geq$0.05 ha. (Modified from Chatwin et al 1994 and BC Ministry of Forests 1995a.)

application was originally intended for residential areas and had limited application for agriculture,

industry, forestry and recreation. Around the linear segments of a reservoir, BC Hydro's 'impact lines' delineate the potential upslope and downslope extent of various hazards such as flooding, erosion, groundwater and landslides.

For existing or proposed residential areas adjacent to a reservoir where lives may be threatened, the 'landslide impact line' is defined as the boundary landward of which there is less than a 1:10,000 annual probability of occurrence of the area being subject to landsliding, either due to the reservoir, or due to existing instabilities not affected by the reservoir (BC Hydro 1993). The effects of toe erosion and seismic activity on slope stability are also considered. BC Hydro realizes that to determine an annual probability of occurrence of 1:10,000, extensive geotechnical investigations are required. BC Hydro suggests that "different", presumably greater, annual probabilities of occurrence may be selected for specific projects.

In non-residential areas, BC Hydro suggests the landslide impact line be determined in a similar manner as for a residential area, but that it can have a lesser degree of confidence, and presumably a greater probability of occurrence, due to less data and non-life threatening consequences. The degree of confidence and annual probability of occurrence can vary with land use, but if land use changes, the impact line should be reviewed.

BC Hydro (1993) suggests that for reservoir projects, shoreline stability should initially be classified in terms of existing, pre-flooding stability. For preliminary studies, post-flooding shoreline stability can be derived from judgement based on experience from existing reservoirs. As studies advance from preliminary to final design and with more data, numerical factors of safety determined by stability analyses can be determined for typical or critical shoreline segments. These, along with experience, can be used to classify the stability of shoreline segments for first flooding of the reservoir, normal reservoir operation and for rapid reservoir drawdown.

It is possible to extend BC Hydro's 'impact lines' by showing degrees of confidence and annual probabilities of occurrence on the map as a band or series of lines. Impact line maps can also be used as the basis for cost-benefit analyses to aid with the planning and design processes.

- Both corridor and linear segment terrain stability mapping should be carried out using a phased approach going from a regional (medium scale), through to a project (large scale), to a detailed scale.
- For corridor mapping, terrain stability maps should address both the initiation and runout zones, and address how the landslide hazards will change once the project has been constructed and is in operation.
- For linear segment mapping, terrain stability mapping, similar to 'impact line mapping', as described by BC Hydro (1993) for existing and future reservoirs, should be considered an appropriate method.

In British Columbia, the BC Ministry of Transportation and Highways, which has jurisdiction over subdivisions in unorganized areas, carried out a number of pilot terrain stability mapping projects in the 1970s and 1980s. For examples see Buchanan (1977, the South Thompson Valley) and Haughton (1978, the Columbia Valley).

In organized areas of the province, residential subdivision and building permit approval procedures are mandated by the Municipal Act. This act is implemented by the appropriate ministries, regional districts and/or municipalities. Currently joint provincial-community funding supports terrain stability mapping for communities that adopt Official Community Plans (OCP). Terrain stability maps are used to delineate areas where restrictions should be applied under the act and where site specific assessments are required. For example see Cave (1992, Fraser-Cheam Regional District).

The extensive 1:50,000 scale terrain mapping carried out by the BC Ministry of Environment in the 1970s and 1980s, following Environment and Land Use Secretariat (1976) and Ryder and Howes (1984), has been used to derive terrain stability information for land use planning. For examples see Maynard (1979) and Ryder and MacLean (1980). This derived information is intended for guidance, without direct administrative or regulatory implications.

Many site-specific terrain stability mapping projects have also been carried out throughout the province, usually by geotechnical engineers and geoscientists, to aid land use planning and regulation.

3.1.3 Linear Project Planning

Terrain stability maps are usually produced prior to the location of a linear project, such as a road, railway, pipeline or transmission line, to help choose the optimal alignment. Examples include Buchanan (1990, a highway), Thurber Engineering Ltd (1989, a resource road), and Pacific Hydro Consultants Ltd (1989, a transmission line). These types of terrain stability maps often include project-specific interpretative comments.

Terrain stability maps are also often produced for planning purposes along linear geomorphic features such as streams, shorelines and reservoirs. Such mapping has been applied to BC Hydro's reservoir shorelines since the early 1970s to assess existing terrain stability and to predict terrain stability after reservoir flooding. Examples include Morgan (1982), Enegren and Moore (1990) and BC Hydro (1993). These maps often delineate a 'safe line', 'break line', and/or 'impact line' (described in Section 6.3) along the crests or toes of bluffs, or along existing or future shorelines.

Snow avalanche 'atlases' serve similar planning purposes. Several have been prepared for specific highways in the province by the BC Ministry of Transportation and Highways, for example the Coquihalla Highway (BC Ministry of Transportation and Highways 1980), and by Environment Canada, for example the Rogers Pass section of the Trans-Canada Highway (Schleiss 1989).

Linear terrain stability maps are also prepared during the operation of certain facilities to help monitor landslide activity and establish priorities for maintenance. An example is the rock fall hazard map for an active French road, produced by the French Road Research Laboratory (Einstein, 1988).

3.2 Types

There are a number of different types of maps that can provide information on terrain stability. For the purpose of this study they are grouped into seven types. Types 1 through 5 are maps that delineate the distribution of particular landslide data, or terrain attributes, and may be accompanied by some form of data base. When interpreted or combined with other information these map types can become, or can be used as, terrain stability maps that address either landslide hazards or risks. Type 6 is a specific type of terrain stability map that addresses landslide hazards. Type 7 is a specific type of terrain stability map that extends the landslide hazard assessment by considering the consequences of the hazards, and therefore is a landslide risk map.

Type 1 -- Geology maps delineate bedrock and/or surficial geology units, usually on the basis of relative geological age. Certain map units, specific symbols and/or marginal notes may indicate, or be used as a rough guide to indicate, the distribution of landslide hazards.

Bedrock structure and lithology are often significant in controlling the character of large bedrock landslides. In glaciated terrain, landslide hazards commonly occur in association with certain surficial geology units.

Type 2 -- Terrain maps delineate surface units based on a number of terrain attributes, including material genesis and texture, surface expression and geomorphic process. Several terrain mapping systems have been developed in Canada, beginning with Fulton et al (1974), and in other countries, for example Finlayson (1984, Australia).

In this province, the BC Terrain Classification System (Howes and Kenk 1996; Resources Inventory Committee 1996a) is the provincial standard and is a versatile system to produce terrain maps from a scale of 1:10,000 to 1:250,000. An early data base format for this system was introduced by Kenk et al (1987). Resources Inventory Committee (1996b) summarizes the most recent data base format.

Medium scale terrain maps (1:20,000 to 1:50,000) can be used as preliminary terrain stability maps with suitable annotation of landslide hazards for each type of unit. Ryder and MacLean (1980), Howes and Swanston (1994) and Resources Inventory Committee (1996a) provide examples for use with the BC Terrain Classification System.

Type 3 -- Engineering geology maps delineate, interpret and annotate surficial or bedrock units or terrain units to provide information relevant to engineering issues, such as material usability, soil plasticity, foundation conditions, groundwater conditions, swelling potential, and/or landslides.

approach is taken, it should be carefully justified in the project report. Particular situations, such as undercutting or piping, will also require that downslope hazards and risks should also be investigated.

- Terrain stability mapping methods, similar to those for areal land use planning, should be used for linear project planning.
- Landslide hazards and risks upslope and downslope of a proposed alignment or linear feature should also be mapped if appropriate.

Both corridor mapping and linear segment mapping should be carried out using a phased approach going from a regional (medium scale) through to a project (large scale) to a detailed scale.

Corridor terrain stability mapping is often used to select the best route for the linear project. Such maps should address the initiation zone and runout zone, and how the landslide hazard will change once the project has been constructed and is in operation. Depending on the requirements of the mapping project, subjective geomorphic or rating analyses, or relative univariate, probabilistic univariate or probabilistic multivariate analysis are considered acceptable methods in the initiation zone (refer to Section 4.1). Any of the mapping methods described in Section 4.2 can be used in the runout zone.

Project or detailed corridor mapping requires consideration of large or detailed scale base mapping, and proposed project alignment plans, profiles and cross-sections. The BC Ministry of Transportation and Highways regularly carries out these sorts of mapping projects for locating new or realigned highways.

For some large scale projects, magnitude (or intensity)-probability of occurrence and/or consequence (or severity)-probability of occurrence relationships are produced in association with the mapping. Such mapping can be used for cost-benefit analyses that can be used to evaluate corridor or alignment alternatives, and to compare possible passive versus active mitigative measures. An example of a relatively simple risk assessment procedure for forestry road corridors is described in BC Ministry of Forests' "Engineering Manual" (1993).

Linear segment terrain stability mapping addresses hazards and risks along linear geomorphic features. From the early 1970s to the early 1990s, such mapping was used by BC Hydro to delineate a 'break line' and a 'safe line' along a proposed reservoir shoreline. The 'break line' was defined as the maximum anticipated extent of shoreline regression by erosion, beaching and/or landsliding. The 'safe line' was defined as a conservatively located line placed along the shoreline, landward of which security or residents and their belongings could be reasonably assured. See Morgan (1982) for an example. The concepts of break line and safe line can be adopted for any other types of linear segment mapping.

In the early 1990s, BC Hydro replaced the 'safe line' concept with the 'impact line' concept (BC Hydro 1993). BC Hydro felt the term 'safe line' could be misunderstood, and its conservative often either the initiation or runout zone is outside the study area. Subjective geomorphic or rating analyses, or relative univariate, probabilistic univariate or probabilistic multivariate analysis are considered acceptable methods in the initiation zone (refer to Section 4.1), although at this scale these methods should be calibrated with some form of stability analysis. Any of the mapping methods described in Section 4.2 can be used in the runout zone, although the hazard consequence analysis is less desirable.

For some projects at the large or detailed scales, magnitude(or intensity)-probability of occurrence and/or consequence (or severity)-probability of occurrence relationships are produced in association with the mapping. For many projects these are used to determine the probability of damage to property and resources (structural, environmental, or economic) and probability of death of an individual or group. The BC Ministry of Highways and Transportation suggests that a 10% long-term probability of occurrence of a landslide (other natural hazard) over a 50 year period should be considered as a guideline for approval of subdivision permits. This is equivalent to an annual probability of occurrence of 1:475. The Fraser Valley Regional District applies this same probabilitiy of occurrence to building permit approvals unless remedial or protective works are practical.

Such landslide risk mapping can be used for cost-benefit analyses that can be used to evaluate development alternatives, and compare possible passive versus active mitigative measures. This sort of detailed mapping is developing rapidly in British Columbia at the present time. See for example Morgan et al (1992), Hungr and Rawlings (1995), Sobkowicz et al (1995).

- A phased approach to terrain stability mapping for land use planning should be considered. Mapping should proceed from regional, to subdivision to detailed mapping, with increasing mapping scales with emphasis shifting from landslide hazard mapping to landslide risk mapping.
- Changes in existing conditions must be considered, including changes beyond the area of interest.
- Landslide risk mapping should be considered for use in cost-benefit analyses to evaluate development and/or mitigative alternatives.

6.3 Linear Project Planning

Terrain stability mapping for the planning of linear projects, such as roads, railways, transmission lines, and pipelines is referred to as corridor mapping. Mapping carried out for planning along linear geomorphic features such as along streams, shorelines and reservoirs is linear segment mapping. Both use methods that are similar to general land use planning, except that terrain attributes and terrain stability are focussed along a linear corridor or a linear segment.

Landslide hazards upslope of a proposed alignment or linear feature should also be mapped because these areas may initiate events that can affect the linear zone of interest. In some cases, such as debris flows moving down pre-existing channels, there is sometimes a tendency to avoid mapping the upslope areas and to concentrate on the assessment of the defined paths. If this

Engineering geology maps are produced at a variety of scales, from medium (1:20,000 to 1:50,000) to detailed (1:5,000 or larger). Methods for engineering geology mapping including symbols to represent landslide areas have been summarized by the International Association of Engineering Geology (1976, 1981a and 1981b).

Type 4 -- Terrain attribute maps delineate the distribution of one or more specific terrain attributes, such as overburden depth, soil type or soil moisture. For terrain stability mapping, two terrain attributes, slope gradient and drainage network, are most useful and discussed further below. Using a GIS, individual terrain attribute maps can be combined as a series of overlays to produce a multi-terrain attribute map.

Slope maps show the distribution of slope gradients. These maps can be prepared at scales as small as 1:50,000 but larger scales are preferable. Simple slope maps may have only two slope categories, for instance areas <50% and areas >50%. More complex slope maps may have several slope classes that are determined to be significant. Slope maps can be used to prioritize areas for more detailed mapping, especially if background data and/or funding are limited.

Traditionally slope maps are produced by measuring the distance between topographic contour lines. Recently Digital Terrain Models (DTM) and Digital Elevation Models (DEM) have become available. To produce satisfactory results, however, DTMs and DEMs must be sufficiently detailed. It is important to note that photogrammetrically derived contours on heavily forested slopes often underestimate local slope angles.

Drainage network maps show permanent and ephemeral drainage paths and can be produced at a variety of scales. A potential use in terrain stability mapping, besides the depiction of drainage density, is to indicate potential paths of debris or sediment movement, and potential locations of erosion. Drainage network maps have traditionally been produced manually, and may require considerable field checking if produced at a large scale especially in a heavily forested area. Drainage network maps produced from DTMs require a very high quality terrain model.

Type 5 -- Process inventory maps delineate the distribution of one or more geomorphic processes, such as snow avalanching, erosion and landsliding. Such processes can be shown by polygons, feature outlines, linear symbols and/or point symbols. Landslide inventory maps are produced for a variety of purposes including:

- to delineate different types or sizes of landslides;
- to distinguish active, or recently active, landslides from those which are dormant;
- to document landslide damage incurred in a region from a specific event, such as a rain storm or earthquake;
- to guide research or mitigation spending within a region; and/or
- to calibrate and provide detail to other types of terrain stability maps.

Landslide inventory maps, at scales larger than 1:5,000, often use elaborate systems of feature outline symbols (see Section 3.5) to indicate internal detail of large landslides, such as scarps, ridges, and tension cracks.

Landslide density maps, an extension of landslide inventory maps, use contours to join areas with equal densities of landslides (isopleths), and are useful in areas that contain a relatively large number of relatively small landslides. See for example DeGraff (1985).

Some countries are attempting to establish a national landslide inventory mapping program accompanied by a data base. A world-wide standard for the reporting and inventorying major landslides is being prepared by the UNESCO Working Party on World Landslide Inventory (1990a, 1990 b, 1991, 1993a, 1993b, 1995 and in prep).

Other examples of landslides inventory maps include Kienholz (1978, a single valley in Switzerland), VanDine and Evans (1992, a regional study of Vancouver Island), and Radbruch-Hall (1982, the entire United States).

Type 6 -- Landslide hazard maps can be derived by interpreting one or more of the map types described above. They are often produced, however, specifically for use as landslide hazard maps and have a wide range of forms and present a wide range of information.

Landslide hazard maps are most commonly directed toward landslide initiation zones and are sometimes referred to as 'landslide initiation maps'. They often delineate areas of equal probability of landslide initiation, such as the probability of occurrence, or the probability of occurrence combined with magnitude and/or some other characteristics of the landslide. In runout zones, landslide hazard maps delineate the probability of certain areas being affected by the runout of landslide debris. Some landslide hazard maps consider both the initiation and runout zones. The probability in both the initiation and runout zone can be expressed either qualitatively or quantitatively (refer to Section 2.3).

Type 7 -- Landslide risk maps extend the information shown on landslide hazard maps to include consequence associated with the hazard. They are usually prepared for the runout zones and are sometimes referred to as 'landslide runout maps'. Occasionally landslide risk maps are prepared for the initiation zone.

Risk may be expressed either in qualitative or quantitative terms. In some cases spatial distribution functions are used to determine the variability of landslide risks over a specific geographic area. Landslide hazard maps that are annotated with simple consequence ratings can be considered as simplified qualitative landslide risk maps.

The responsibility of the mapper, as discussed in Section 5.5, should be kept in mind for terrain stability mapping associated with land use planning. It is the responsibility of the mapper to produce terrain stability maps and/or estimates of probabilities of occurrence, magnitude, intensity, elements at risk, vulnerability, consequence and risk. Individuals, agencies or authorities, such as landowners, governments or courts, who incorporate appropriate socio-economic and environmental factors into their decisions, are responsible for determining the acceptability of the landslide hazard or risk.

- Terrain stability mapping for land use planning should be carried out uniformly over a study area and as objectively as possible.
- Quantitative approaches of terrain stability mapping are preferable over qualitative approaches to minimize potential misunderstanding, however, complex analytical methods should be simplified for public presentation.
- The responsibility of the mapper, as discussed in Section 5.5, should be kept in mind for terrain stability mapping associated with land use planning.

Unlike the British Columbia forest industry, except for a few provincial regional districts there are no standards or guidelines for terrain stability mapping and reporting for land use planning. A phased approach to mapping is often preferred. In all cases changes in existing conditions must be considered. Will the slopes above be crossed by a road, will they be logged, will development at the top of the slope increase the water discharge onto the slope? It is often difficult to take all possibilities into account, but a range of possibilities should be considered. If necessary a series of terrain stability maps should be produced to show how the hazards and risks change under different changed conditions.

Regional terrain stability mapping, usually carried out at a medium scale of 1:20,000 to 1:50,000, can be used to identify hazardous areas requiring further, larger scale, mapping. Regional mapping is usually focussed on the initiation zone. Subjective geomorphic or rating analyses, or relative univariate, probabilistic univariate or probabilistic multivariate analysis are considered acceptable methods (refer to Section 4.1). The latter three methods are more objective and quantitative, but require more data.

Subdivision terrain stability mapping is usually large scale mapping carried out at scales ranging from 1:5,000 to 1:20,000. Subdivision mapping may be used to establish landslide hazard or risk zones for bylaws and regulations and should consider both hazards and risks in the initiation zone and the runout zone. Subjective geomorphic or rating analyses, or relative univariate, probabilistic univariate or probabilistic multivariate analysis are considered acceptable methods in the initiation zone (refer to Section 4.1). Any of the mapping methods described in Section 4.2 can be used in the runout zone. As mentioned previously, the more objective and quantitative methods are preferred, however, they require a great deal more data, time and resources.

Detailed terrain stability mapping for land use planning, at scales of 1:500 to 1:5,000, is usually associated with surveyed legal boundaries such as restrictive covenants, and almost always considers both the landslide hazards and risks in the initiation zone and the runout zone. Quite

6.1.3 Field Terrain Stability Assessments

The purpose of an field terrain stability assessments as described by BC Ministry of Forests (1995a) is to identify the probability of occurrence and potential effect of a landslide in a specific area, and to recommend mitigative measures. These assessments are carried out at scales considered to be detailed mapping scale described in Section 3.4, however, the field assessments described by BC Ministry of Forests (1995a) should not be considered as either landslide hazard or risk mapping. The terrain stability of specific areas should be clearly and concisely described on a map and in a report. Terrain stability classes should not be used.

Generally for resource development planning detailed scale mapping is not carried out, but can be done using TSIL A if required. Such terrain stability mapping requires a great deal of field checking, and possibly, depending upon the intended use, surveys of terrain features and map boundaries.

Field mapping along proposed or existing forestry roads at 1:5,000 scale can use the linear mapping methods described in Section 6.3.

- Field terrain stability assessments for the forest industry should be carried out following the 'field assessment' standards and procedures described by BC Ministry of Forests (1995a).
- Terrain stability classes should not normally be used for field assessments.
- Detailed scale terrain stability mapping is not usually carried out for resource development planning, but can be carried out using TSIL A and possibly surveys of terrain features and map boundaries.

6.2 Land Use and Development Planning

Terrain stability mapping in land use and development planning usually delineates areas where existing and/or future land development may be affected by landslide hazards, either under existing or changed conditions. The understanding and confidence of citizens, developers, elected officials and government agencies are required for acceptance of terrain stability maps and any resulting regulations, restrictions or specific recommendations in land use planning process.

The intensity of land use planning can vary dramatically in area from a single property to a subdivision to an entire region. Investigation of a landslide on a particular property is generally considered a geotechnical or geological engineering investigation, rather than mapping, and therefore is not discussed further.

Terrain stability mapping for land use planning can have a great impact on property values and, therefore, to the extent possible, it should be carried out uniformly over the study area and as objectively as possible. Quite often quantitative approaches of mapping are preferred because there is less misunderstanding among citizens, developers, elected officials and government agencies. Complex analytical methods, however, should be simplified for public presentation.

3.3 Terrain Attributes of Landslide Hazards

Landslides are exceedingly complex phenomena that are controlled by, or associated with, many physical factors, or terrain attributes. Hutchinson (1992) summarized the main 59 terrain attributes, both preparatory and triggering, into 13 categories. His summary is reproduced as Table 3.1. Popescu (1994) formulated a similar list.

The ideal terrain stability map would record information on all the terrain attributes in Table 3.1. The resulting map, however, would of course be unrealistically complex. Furthermore, not all terrain attributes are important in all circumstances. Therefore, any practical terrain stability mapping system must select a relatively small group of relevant terrain attributes.

The selection of such attributes can be based on individual judgment, or on an analysis of actual landslides. This study examined twelve different terrain stability mapping projects from different parts of the world to determine which terrain attributes were selected and why. In eight of the twelve projects the terrain attributes were selected subjectively. In the other four, statistical analyses were used to select statistically 'significant' terrain attributes. The mapping projects examined are listed in Table 3.2.

The projects examined show that the only terrain attribute common to all projects is slope gradient. Evidence and frequency of past instability were used in seven of the twelve projects. Besides slope gradient and past instability, a wide variety of terrain attributes were selected by the mappers as being relevant. The revelance of certain terrain attributes was found to be very different, and sometimes contradictory. To some extent this was dependent on the local or regional terrain and geology. For example, bedrock lithology tends to be important in regions of weak argillaceous rocks, but insignificant in areas of stronger rocks, or areas covered by glacially derived soils. It was noted that different groups of terrain attributes were sometimes responsible for different types of landslides in the same geographic area. Rollerson (1992), for example, determined that a different group of relevant terrain attributes were responsible for landslides triggered by road building, than for landslides associated with clear cut logging.

3.4 Map Scales

The scale of presentation of the terrain stability map is very important to communicate the appropriate level of detail for the intended use. The presentation scale should be dependent upon the actual scale of mapping and the methods and intensity of field checking -- sometimes referred to as the terrain survey intensity level (TSIL) (discussed further in Chapter 5).

The following classification of scales of map presentation is modified from Van Westen (1993).

Synoptic or territorial scale maps (>1:50,000) are often process inventory maps, used by planning agencies to direct allocation of funds, develop emergency preparedness plans and similar tasks. An example is the overview map of the United States produced at a scale of 1:7,500,000 (Rudbruch-Hall 1982).

Medium scale maps (1:20,000 to 1:50,000) are generally used for preliminary or regional landslide hazard assessments and feasibility studies, to be followed by more detailed work. The 1:50,000 scale terrain maps using the BC Terrain Classification System are examples.

Large scale maps (1:5,000 to 1:20,000) are generally used for planning of land use in urban areas or resource development in rural areas. Depending on the use, large scale maps quite often must be supplemented by detailed site investigations or on site assessments. In British Columbia, detailed terrain stability maps prepared for forest management are prepared at 1:20,000 scale (BC Ministry of Forests, 1995a)

Detailed scale maps (1:5,000 to 1:500) are usually prepared as part of a landslide hazard assessment of a specific site and should be accurate enough to guide layout of individual structures or specific operations, or to plan mitigation. Engineering plans at these scales can also be used to derive design parameters. In the BC forest industry, areas with moderate or high probabilities of landslide hazard, identified from the 1:20,000 scale mapping, are examined on the ground at the 1:5,000 scale . The findings from these field assessments are used to help locate cutting boundaries and roads (BC Ministry of Forests, 1995a).

3.5 Map Units

Map units on terrain stability maps delineate the terrain attributes, such as slope, soil drainage, and material texture, and/or the hazard and risk parameters, such as probability of occurrence, magnitude and specific risk. They can be referenced to the map in a number of different ways.

A regular rectangular map grid is sometimes used to approximate a continuous variation of terrain attributes or parameters over an area defined by a regular grid. This is similar to the mathematical process of making a continuous function discrete by assuming that the function is constant within each elementary area.

A regular grid of points can be used to display the average terrain attributes or parameters at a point, usually defined on the basis of a regular grid.

Polygons are used to delineate areas which are approximately uniform in terms of one or more terrain attributes or parameters. Polygons can be delineated subjectively or objectively by using a map overlay process. The BC Terrain Classification System (Howes and Kenk 1996; Resources Inventory Committee 1996a) uses subjectively delineated polygons based on material genesis and texture, surface expression, and geomorphic process. The polygon system provides greater flexibility and scope for use of geological knowledge than the above grid systems.

Linear segments are used to map linear geomorphic features such as shorelines, stream channels or gullies.

mapping as described in Section 3.4 and is used for forest development planning and to identify areas requiring on-site assessments prior to the approval of cutblocks and/or road construction. Detailed terrain stability mapping was previously referred to as 'Level 2' mapping.

Detailed terrain stability mapping should be done at TSIL C, or in certain circumstances, TSIL B (refer to Table 5.1). It is recommended that 1:20,000 scale base maps be used wherever possible. Polygons, and linear and point map symbols, are used to delineate the surficial material (genesis), texture, surface expression and geological processes as described by the BC Terrain Classification System (Howes and Kenk 1996; Resources Inventory Committee 1996a), as well as slope gradients or classes and soil drainage classes.

Subjective rating analysis is used to interpret the terrain data, and to place each polygon in one of five terrain stability classes. The five relative and qualitative classes are summarized in Table 6.2. The criteria for classifying the terrain is uniform throughout the map area but can change between map areas due to regional differences such as terrain and climate. An example class criteria is presented in Table 5.7. Table 6.3 is an example of how probabilistic univariate analyses can be used to help define the class criteria.

The terrain stability classes suggested by BC Ministry of Forests (1995a) provide a relative ranking of the probability of occurrence of a landslide in the initiation zone after forestry activities only. They provide no quantitative predictions of probability of occurrence and no indication of magnitude of potential landslides. As mentioned previously, however, they can be extended to include landslide-induced stream sedimentation which does address some aspects of effects in the runout zone. They can also be interpreted for surface erosion potential and the potential for any eroded material to reach a drainage course. The latter two type of maps are examples of simple landslide risk maps.

For uses other than the forest industry and beyond what is suggested BC Ministry of Forests (1995a), it is possible to extend the suggested five class system to include quantitative probabilities of occurrence, potential magnitudes in the initiation zone, and possible effects in the runout zone. These extensions require substantially more data. Detailed terrain stability mapping as described above can also be modified and used for mapping of existing conditions, as opposed to conditions following logging operations.

- Large scale terrain stability mapping for the forest industry should be carried out following the 'detailed terrain stability mapping' standards and procedures described by BC Ministry of Forests (1995a).
- For other resource development planning the standards and procedures for detailed terrain stability mapping can be modified, if necessary.

6.1.1 Reconnaissance Terrain Stability Mapping

Reconnaissance terrain stability mapping (BC Ministry of Forests 1995a) identifies unstable or potentially unstable areas following road construction or timber harvest over a large region for long-range planning purposes. Based on the map scales described in Section 3.4, reconnaissance terrain stability mapping is considered to be medium to regional scale mapping. Reconnaissance terrain stability mapping was previously referred to as 'ESA' (Environmentally Sensitive Area) mapping, 'Es1 and Es2' mapping, and/or 'Level 1' mapping.

It is recommended that reconnaissance terrain stability mapping be carried out at terrain survey intensity level (TSIL) D (refer to Table 5.1). The map units are polygons, delineated primarily by air photo interpretation supplemented by limited helicopter reconnaissance and field checking. Linear and point map symbols can be used to show the locations and type of landslides, and other indicators of unstable terrain too small to be mapped as separate polygons.

The entire map area is not mapped, but only those areas predicted to be 'unstable' or 'potentially unstable' following forestry activities. A qualitative, relative subjective rating analysis is used to map two terrain stability/landslide hazard classes: 'unstable and 'potentially unstable'. A third class, 'stable', is assumed for all remaining areas and is often not mapped. Table 6.1 summarizes the three classes.

The mapping is not accompanied by terrain mapping, but terrain symbols, geomorphic processes and slope gradients or classes relevant to terrain stability are recorded for the unstable and potentially unstable polygons. Most reconnaissance terrain stability maps address landslide hazards in the initiation zone, but can be supplemented by codes to indicate effects on the runout zone and thus become landslide risk maps.

Reconnaissance terrain stability mapping as described above can be modified, if necessary, for use with other resource development planning.

- Medium to regional scale terrain stability mapping for the forest industry should be carried out following the 'reconnaissance terrain stability mapping' standards and procedures described by BC Ministry of Forests (1995a).
- For other resource development planning the standards and procedures for reconnaissance terrain stability mapping can be modified, if necessary.

6.1.2 Detailed Terrain Stability Mapping

Detailed terrain stability mapping (BC Ministry of Forests 1995a) collects and presents data on a number of terrain attributes using an extended version of the BC Terrain Classification System, then interprets that data for terrain stability following timber harvest or road construction. In community watersheds, this level of mapping is extended further to include interpretations of landslide-induced stream sedimentation and surface erosion hazards. It is considered large scale

Contours of a terrain attribute are used to display the variation of a specific terrain attribute or parameter. For example, slope maps are often presented as polygons with a range of specific slope gradients.

Feature outline symbols are used to display detailed features of landslides such as tension cracks, slump blocks, and headscarps, and are therefore usually limited to large landslides and/or detailed scale maps.

Linear and point symbols are generally used to delineate small features. The definition of a small feature is determined by the map scale.

Table 3.1 Main Terrain Attributes Associated with Landslides

Bedrock Geology
Lithostratigraphy and sedimentology
Structure: fold, flectural shear, faults and joints
Fabric and layering
In situ stresses

Quaternary Geology
Glacial and proglacial
Glaciotectonics
Precipitation (pluvial)
Periglacial
Glacio-eustasy and glacio-isostasy

Geomorphology
Slope morphology and gradient
Slope aspect
Former landslides and other mass movements
Energy and state of development of landscape

Weathering
Physical, chemical and biological
Endogene and exogene, past and present
Regolith thickness, rate of formation

Erosion and Deposition
General erosion, knick points, fronts of aggression
Erosion of toe and face of slopes
Deposition at head of slopes
Surface erosion, gullying
Seepage (internal) erosion

Climate
Precipitation
Evapotranspiration
Freeze-thaw
Heat expansion and cracking

Vegetation and Pedology
Vegetation types, root strength, etc
Palaeosols, datable indicators of past stability and instability

Hydrogeology
Runoff and infiltration
Snow drifting, snow melt
Groundwater pressures in fissures, soil pipes, burrows
Artesian and perched groundwater
Positive and negative porewater pressures
Groundwater pressure variations with depth
Groundwater chemistry

Geotechnics
Index properties, mineralogy, clay content and cementation
Geochemistry
Shear strength: peak, fully softened and residual, anisotropy, stress history, progressive failure
Presence or absence of pre-existing shears
Brittleness, rate effects on shear strength
Metastable structure, porosity
Swelling and shrinkage
Permeability: profile and anisotropy
Unit weight, variation with rain infiltration

Volcanic Activity
Lava flows, diversion of drainage
Ash accumulations
Steam emissions, forming intense rainfall
Hydrothermal alteration

Neotectonics and Seismicity
Tilting, uplift and enhanced erosion
Earthquake, shaking

Natural Dams
Landslides
Lava flows
Glaciers and ice sheets
River ice

Human Activity and Land Use
Cuts and fills
Mining
Afforestation and deforestation
Irrigation and leakage
Other hydrogeological modifications
Impounding, drawdown and critical pool effects

(Modified from Hutchinson 1992)

6. SUGGESTED METHODS OF TERRAIN STABILITY MAPPING -- SPECIFIC ASPECTS

Chapter 5 summarized general aspects of terrain stability mapping. This chapter summarizes a number of the specific aspects directed toward the three broad groups of uses described in Section 3.1, resource development planning (Section 6.1), land use and development planning (Section 6.2) and linear project planning (Section 6.3). As in Chapter 5, the suggested methods are highlighted in a series of boxes.

6.1 Resource Development Planning

The British Columbia forest industry is the most frequent user of terrain stability mapping. Similar maps are used by the mining industry, usually associated with mine site development. Since 1995, all resource roads on crown land are now under the jurisdiction of the Forest Practices Code of British Columbia

Landslide hazard mapping, and to a lesser extent, landslide risk mapping is usually carried out to assist with forest management, and quite often is used to predict the stability of the terrain after road construction or timber harvest. Since forest practices can influence the potential landslide hazards, mappers should be familiar with various logging road construction techniques and timber harvesting practices, and make themselves aware of specific proposed development plans.

In British Columbia three levels of terrain stability mapping are used in the forest industry:

- 'reconnaissance terrain stability mapping' identifies unstable or potentially unstable terrain from a broad perspective;
- 'detailed terrain stability mapping' provides a more comprehensive assessment of terrain stability within a specific forest development area; and
- 'field terrain stability assessments' focus on specific areas of concern for a cutting permit or road location.

BC Ministry of Forests' (1995a) 'Mapping and Assessing Terrain Stability Guidebook' outlines in some detail the standards and procedures for carrying out the three levels of mapping. The reader is referred to that document and Ryder et al (1995) for specific details. The following comments put these three levels of mapping into the broader context of terrain stability mapping as described in this document.

- Terrain stability mappers associated with resource development planning projects should be familiar with how the development of the resource can influence landslide hazards. For example in the forest industry, the mapper should be familiar with various logging road construction techniques and timber harvesting practices.

Table 5.7 An Example of Terrain Stability Class Criteria, Subjective Rating Analysis

Terrain Stability Class	Example Class Criteria
I	• Floodplains and level to undulating coastal plain areas • Most terrain with slopes <20%. Exceptions are noted in higher classes
II	• Most gently sloping (20-40%), poorly to well drained lower slope landforms. Exceptions are noted in higher classes • Moderately sloping (40-60%), well to rapidly drained surficial deposits
III	• Moderately sloping (40-60%), imperfectly to poorly drained surficial deposits that are not marine or lacustrine • Level to gently sloping (0-40%), imperfectly to poorly drained deep marine clays and lacustrine deposits • Moderately sloping, deeply gullied surficial deposits that are not of lacustrine or marine origin
IV	• Steeply sloping (≥60%), well drained, deeply gullied surficial deposits • Steeply sloping, poorly drained surficial deposits • Moderately sloping, deeply gullied, or imperfectly to poorly drained lacustrine or marine deposits
V	• Any areas where natural landslide scars are visible on air photographs or in the field • Very steeply sloping (≥70%), imperfectly to poorly drained, deeply gullied surficial deposits

Caution: These criteria are examples only and mappers should develop suitable criteria for each mapping project.
(Modified from B.C. Ministry of Forests 1995a)

Table 5.8 Example of Terrain Stability Class Criteria, Probabilistic Univariate Analysis

Material	Slope (%)	Shape	Process	Drainage	Terrain Stability Class
colluvium	>36	uniform	gullied	rapid	high
till; till/colluvium	>33	uniform	gullied	rapid-moderate	high
unconsolidated scarp	>33	uniform		rapid-moderate	high
colluvium	>36	uniform		rapid	moderate
till; till/colluvium	>33	uniform		rapid-moderate	moderate
till; till/colluvium	26-33	uniform	gullied	rapid-moderate	moderate
colluvium	29-36	uniform	gullied	rapid	moderate
fluvial	20-33	uniform		rapid-moderate	low
till; till/colluvium	26-33	uniform		rapid-moderate	low
colluvium	39-36	uniform		rapid	low
rock/colluvium	>30	uniform		rapid	low
till	>26	uniform		moderate-rapid	very low
fluvial	>20	uniform	active flooding		very low
colluvial	>36	uniform	active fans		very low
fluvial	>20	uniform		rapid-moderate	very low
till of colluvium	>20	uniform		rapid-moderate	very low
till or colluvium	variable	irregular		rapid	very low
fluvial over till	<33	uniform		rapid-moderate	very low

(Modified from Howes 1987 in Neimann and Howes 1992)

Table 3.2 References Examined for Selection of Terrain Attributes

Terrain attributes selected subjectively

Reference	Geographic Area
Anbalagan (1992)	India
Bourgeois (1978)	Vancouver Island, British Columbia
Brand (1988)	Hong Kong
Chang (1992)	Taiwan
Hammond et al (1992)	Pacific Northwest, United States
Howes and Swanston (1994)	British Columbia
Neilsen and Brabb (1977)	San Francisco Area, California
Rollerson and Sondheim (1985)	British Columbia

Terrain attributes selected by statistical analysis

Reference	Geographic Area
Carrara (1983)	Italy
Carrara et al (1991)	Italy
Pack (1985)	Utah, United States
Rollerson (1992)	Queen Charlotte Islands, British Columbia

Table 5.6 Some Indicators of Past and Potential Slope Instability

- recent landslide scars
- revegetated landslide scars or partially revegetated strips
- linear strips of even-aged vegetation or trees

- jack-strawed trees, leaning trees, 'drunken' trees, especially in groups
- split trees
- pistol butt (recurved) trees (may also indicate snow creep)

- fresh rock or soil surfaces on a steep faces
- fresh rock or soil on lower slopes or at the base of a steep slope
- talus/scattered boulders at base of slope
- bulging in the lower portion of a slope
- rock or soil piled on the upslope side of trees
- hummocky ground, sag ponds

- mixed or buried soil profiles
- poorly developed soils relative to other comparable slopes

- steeply dipping bedrock discontinuities and/or intersections that parallel the slope

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- tension cracks
- crescent shaped or curved scarps or depressions
- shallow, linear depressions
- step-like benches or small scarps
- ridged marine deposits
- terracettes across the slopes, solifluction lobes
- displaced or disrupted stream channels

- recently scoured gullies
- exposed soil on gully sides
- debris fans or piles at the mouths of gullies or streams
- trim lines, levees along gully
- no or new vegetation in gully bottoms
- vegetation in gully much younger than the adjacent forest
- poorly developed soils on gully sides relative to adjacent slopes

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- numerous springs at toe of slope
- sag ponds
- poorly drained or gullied, fine textured materials, <3 m deep on slopes >50%
- poorly drained or gullied, coarse textured materials on slopes >50%
- shallow, wet, organic soils on slopes >40%
- wet site vegetation on slopes >50%

- disrupted roads, fences, or other linear features
- bulges in road, signs of repair such as fresh pavement

(Modified from Chatwin et al 1994; BC Ministry of Forests 1995a; BC Ministry of Transportation and Highways 1996)

Slow mass movement	**F**	Slow downslope movement by sliding, flowing or creeping
Rapid mass movement	**R**	Rapid downslope movement falling, rolling, sliding or flowing
Snow avalanches	**A**	Rapid downslope movement of snow and ice, as well as incorporated rock, surficial material and vegetative debris by sliding or flowing
Gully erosion	**V**	Modification of the surface by processes such as running water, mass movement and snow avalanching resulting in the formation of long narrow ravines
Washing	**W**	Modification of the surface by wave action or running water resulting in lag deposits formed by the removal of fines
Piping	**P**	Subterranean erosion by flowing water resulting in the formation of underground conduits

Subclass modifiers	Symbol	Definition
rock fall	**b**	descent of mass or masses of bedrock by falling, bouncing and rolling
surficial material fall	**f**	descent of mass of earth or debris by falling, bouncing and rolling
rock slump	**m**	sliding of an internally cohesive mass of bedrock on a rotational failure plane
surficial material slump	**u**	sliding of an internally cohesive mass of earth on a rotational failure plane
rock slide	**r**	sliding of a mass of bedrock on a relatively straight inclined failure plane
surficial material slide	**s**	sliding of a mass of debris on a relatively straight inclined failure plane
debris flow	**d**	rapid flow of saturated debris (inorganic and organic); can be located on an open slope or in a pre-existing channel
earth flow	**e**	flow of material containing a high proportion of silt and clay
soil creep	**c**	slow movement of surficial material
rock glaciers (rock creep)	**g**	slow movement of angular debris under periglacial conditions
lateral bedrock spread	**p**	lateral extension, predominantly horizontal, of a fractured mass of bedrock
lateral surficial spread	**j**	lateral extension, predominantly horizontal, of a mass of surficial material
tension cracks	**k**	open fractures or fissures, commonly near the crest of the slope

(Modified from Howes and Kenk 1996)

4. TERRAIN STABILITY MAPPING METHODS

The previous chapter summarized the uses, types, terrain attributes, map scales and units of terrain stability maps. Because of the many terrain attributes and parameters involved, there are many possible methods to produce a terrain stability map. Nine of the methods are applied to landslide initiation zones and discussed in Section 4.1. Four of the methods are applied to landslide runout zones and discussed in Section 4.2.

Useful reviews of terrain stability/landslide hazard and risk mapping methods have been prepared by Hansen (1984), Brabb (1984), Varnes (1984), Brand (1988), Hartlen and Viberg (1988), Hutchinson (1992), Gee (1992), Van Westen (1993) and Wu et al (1996).

4.1 In the Initiation Zone

In the initiation zone, landslide hazard mapping is most common type, although landslide risk mapping is sometimes carried out. Landslide hazard mapping usually involves, among other things, predicting and expressing the probability of a landslide occurring. The approaches vary from qualitative to quantitative. The following Methods A through I, modified from a classification proposed by Van Westen (1993), review the main aspects of these methods. A summary of the methods is provided in Table 4.1.

Method A -- Landslide distribution analysis requires the preparation of a process inventory map for individual landslides such as debris slides or debris flows, or for a group of landslides. The process inventory map is a simple, objective, but qualitative, form of a landslide hazard map. It shows the distribution and magnitude of recent landslide events by the number and size of landslides. It can then be used for more elaborate landslide hazard analysis. If used to calibrate other types of terrain stability maps, or by themselves, process inventory maps must be used cafefully, as they record only past landslide activity within a specific time interval. They provide no information on the landslide potential of areas other than those that experienced landslides during the time interval used for the study.

Some types of landslides, such as those involving the failure of thin colluvial material, are cyclical in nature. When such landslides occur at a given site, a period of stability follows while the forest regenerates and new surficial material develops. A landslide distribution analysis usually records those sites which failed recently, but ignores those which are mature and 'primed' for a landslide. Thus, a thorough landslide hazard assessment should also consider factors other than landslide distribution.

Landslide distribution analyses are particularly unreliable if a prediction of landslide hazards is required for changed conditions, such as following road construction, clear cut logging or reservoir flooding. In such cases, it is necessary to use statistical or judgmental extrapolation from areas that have already undergone such change, described below as a probabilistic univariate analysis.

The bibliography lists approximately 20 publications concerned specifically with landslide distribution analyses. These range from maps of large rock avalanche sites, for example Abele (1974) and Cruden et al (1988), through maps of debris slides, for example Rood (1984), to snow avalanches, for example Scheiss (1989).

Method B -- Landslide activity analysis is a refinement of the landslide distribution analysis, by which information is included on a process inventory map from several different time periods. Landslide activity analysis maps show changes in landslide sites with time. The objective, qualitative data are usually obtained from the interpretation of air photos from several different years. Landslide activity analysis still may not recognize areas which have not been active, but are potentially unstable.

The most useful landslide activity analyses are carried out for areas of slow movement where it is possible to distinguish sequential activity. An example of this method of mapping applied to land use planning in Switzerland is Bonnard and Noverraz (1984). A special application of landslide activity analysis is the comparison of landslide occurrence before and after a certain activity, such as timber harvesting, for example Swanson et al (1982).

Method C -- Landslide density analysis is a second possible phase in the processing of landslide distribution or landslide activity, and is used to calculate some form of landslide density, and therefore, although objective like the former two methods, is somewhat quantitative. This calculation may be done in three ways:

- average the number of landslides per unit area in a map unit, for example Howes (1987);
- calculate the percentage of unstable area in a map unit, for example O'Loughlin (1972); or
- draw contours of equal landslide density (isopleths), for example Wright et al (1974), DeGraff (1985) and DeGraff and Canuti (1988).

The first method of calculation is suitable for medium or small scale mapping. The second is more appropriate for larger map scales, especially where the size of the unstable areas varies. The isopleth method is more suited to areas of weak rocks or fine grained soils, characterized by abundant and relatively deep seated landslides.

Landslide densities are sometimes subjectively grouped into 'susceptibility classes', for example Hicks and Smith (1981).

The limitations of landslide distribution and landslide activity analyses apply equally to landslide density analysis. The most important use of all three methods is to document past events and to provide calibration for predictive techniques using other terrain stability mapping methods.

Terrain Attribute	Examples (not exhaustive)	Mappable from *
Groundwater		
Soil drainage	rapidly, well, moderate, etc	maps, air photos, ground
Seepage regime	recharge area, discharge area, undrained area, etc	air photos, ground
Permeability	high moderate low, very low, etc	air photos, ground
Depth of limiting layer	shallow, moderately deep, deep, etc	ground, subsurface
Depth to gw table	shallow, moderately deep, deep, etc	ground, subsurface
Precipitation	annual, monthly, extreme daily	records
Vegetation		
Forest type	hemlock, cedar, alder, aspen, etc	maps, air photos, ground
Forest stand age	<10 years, 10-30 years, 30-100 years, >100 years	maps, air photos, ground
Harvest/fire history	logged, unlogged, forest fire plus years since	maps, air photos, ground
Other vegetation	devil's club, skunk cabbage, etc	maps, air photos, ground
Human Activity		
Type	fill at top of slope, road across slope, etc	maps, air photos, ground
Quantity	road length/unit area; ha logged, etc	maps, air photos, ground

* **base map** -- topographic base map; **maps** -- other types of maps; **air photos** -- air photo interpretation; **ground** -- ground checking; **subsurface** -- subsurface investigations

Table 5.4 Summary of Terrain Attribute Headings on Data Base Form

Main Heading	Terrain Attribute Headings
General Project	Project Name; Project Number; Consultant/Department; Mapper; Legend Reference; Map Sheet Number; Terrain Survey Intensity Level (TSIL); Date Mapped; Date Recorded
General Map	Map Sheet; Polygon Number
Terrain Component 1	decile; partial cover relation; surficial material texture; surficial material; surficial material subtype; surface expression; subsurface material texture; subsurface material; subsurface material subtype; subsurface expression
Terrain Component 2	relation; decile; partial cover relation; surficial material texture; surficial material; surficial material subtype; surface expression; subsurface material texture; subsurface material; subsurface material subtype; subsurface expression
Terrain Component 3	relation; decile; partial cover relation; surficial material texture; surficial material; surficial material subtype; surface expression; subsurface material texture; subsurface material; subsurface material subtype; subsurface expression
Geomorphic Processes	first process; first process subtype; first process subclass second process; second process subtype; second process subclass third process; third process subtype; third process subclass
Soil Drainage	first soil drainage class; soil drainage separator second soil drainage class
Slope and Slope Stability	slope: lower limit of first range (% or degree); slope: upper limit of first range (% or degree); slope relation; slope: lower limit of second range (% or degree); slope: upper limit of second range (% or degree); slope stability class; slope stability qualifier for roads
Erosion and Sedimentation	surface erosion potential class; landslide induces stream sedimentation class; potential for sediment delivery from surface erosion sources; bouldery or blocky substrate
Other Data	mean aspect (degrees); Ea -avalanche hazard; reliability of data (low, moderate, high); field checked (detailed, reconnaissance, visual)

(Modified from Resources Inventory Committee 1996b)

Table 5.5 Mass Movement and Erosion Modifiers and Subclass Modifiers

Modifiers	Symbol	Definition

Table 5.3 Relevant Terrain Attributes

Terrain Attribute	Examples (not exhaustive)	Mappable from *
Slope Morphology		
Gradient	typical, average or range	base map, air photos, ground
Uniformity of slope	straight, stepped, benched, concave, convex, etc	base map, air photos, ground
Lateral curvature	broad, narrow, re-entrant, ridge	base map, air photos, ground
Position	near crest, mid-slope, near toe, etc	base map, air photos, ground
Elevation	typical, range	base map
Length	slope length with similar features	base map, air photos
Aspect	quadrant with respect to north	base map, air photos, ground
Identified Processes		
Landslides	rock fall, earth slump, debris flow, etc	maps ,air photos, ground
Erosion	sheet, rill, gully, etc	air photos, ground
Other processes	avalanche, flood, etc	maps, air photos, ground
Age	recent, historic, pre-historic	air photos, ground
Areal extent	width and length	air photos, ground
Depth	shallow, deep, typical, average or range	air photos, ground
Incipient Processes		
Instability signs	jack-strawed trees, tension cracks, disrupted road, etc	air photos, ground
Abundance	signs per area or length	air photos, ground
Surficial Material		
Origin, genesis	glaciofluvial, fluvial, colluvial, etc	maps, air photos, ground
Texture	gravel, sand, silt, clay, till, diamicton or USCS	maps, air photos, ground
Geomorphic expression	fan, apron, cone, landslide, etc	maps, air photos, ground
Geomorphic process	gullying, erosion, failing, etc	maps, air photos, ground
Engng prop of soil	strength, consistency, density, etc	ground, subsurface
Thickness	typical, average or range	ground, subsurface
Bedrock		
Geological classification	granodiorite, siltstone, etc	maps, air photos, ground
Weathering	fresh, slightly weathered, moderately weathered, etc	ground
Structural features	bedding, faults, folds, other discontinuities	maps, air photos, ground
Block size and shape	spacing of discontinuities, cubes, etc	ground
Structural attitudes	strike, dip, dip direction	ground
Engng prop of rock mass	strength, fracture roughness, RQD	ground, subsurface
Contrasting Layers		
Layer description	loose veneer, or pedological type	ground, subsurface
Thickness	typical, average or range	ground, subsurface
Substrate description	dense till, bedrock, frozen ground, etc	ground, subsurface
Nature of contact	weak soil horizon, distinct, etc	ground, subsurface
Streams and Gullies		
Order and status	first, second, third, etc; permanent vs ephemeral	base map, air photos, ground
Channel gradient	typical, average or range	base map, air photos, ground
Uniformity of gradient	uniform, stepped, etc	ground
Channel width	typical, average or range	ground
Channel bed material	inorganic vs woody debris; typical sizes	ground
Channel processes	flood, debris flood, debris flow, etc	air photos, ground
Sidewall height	typical, average or range	ground
Sidewall gradient	typical, average or range	ground
Sidewall material	as for Surficial Material above	ground
Sidewall processes	as for Identified and Incipient Processes above	ground

continued...

Table 5.3 Relevant Terrain Attributes (continued)

Method D - Subjective geomorphic analysis involves the delineation of polygons based on several terrain attributes from air photo interpretation and fieldwork. The mapper then subjectively assigns a qualitative terrain stability/landslide hazard class to each map polygons, based on the air photo interpretation, field observations and his/her experience. The rules of assignment of the classes are not specified and may vary from one polygon to another. Geomorphic recognition of potentially unstable terrain is often strongly guided by observations of existing landslides. Computer-generated slope class maps may be used to focus subjective mapping. Subjective geomorphic analysis is highly flexible and can be very effective at a variety of scales and degrees of effort. Its drawbacks are a lack of repeatability and total reliance on the skills and experience of the mapper.

Kienholz (1978) provides an example of this method. The mapping is at a large scale and complemented by an elaborate system of illustrative geomorphological symbols. The 1:25,000 scale French ZERMOS maps also use a subjective geomorphic method (Champetier de Ribes 1987). The results are translated into a four colour traffic light zoning system: two shades of red distinguish two zones of landslide hazard; orange represents zones of potential, uncertain or minor hazard; and green delineates zones of no perceived hazards. The zone definitions differ from one region to other. Similar mapping was carried out in the 1970s in the United States by the US Forest Service (Bailey 1972 and 1974), and in British Columbia by the BC Ministry of Transportation and Highways (Haughton 1978).

Subjective geomorphic analyses were incorporated into the guidelines for the recognition of environmentally sensitive areas (ESA) by the BC Ministry of Forests (1992). The ESA mapping method provided general guidelines to assist the subjective decisions of the individual mapper, based on geomorphology and recognition of past landslide activity. The ESA mapping method has recently been revised and is now referred to as the 'reconnaissance mapping terrain stability' (BC Ministry of Forests 1995a).

Subjective geomorphic analyses are predominate in snow avalanche hazard mapping, for example Ives and Bovis (1978) and Freer and Schaerer (1980). This method of mapping is supplemented by snow avalanche probability of occurrence analyses on defined paths.

Method E -- Subjective rating analysis is an outgrowth of the subjective geomorphic method where an algorithm for the assignment of terrain stability/landslide hazard classes is established for the entire study area, as opposed to each polygon as in the latter method. The classes are assigned subjectively by judgmental weighting of various relevant terrain attributes, referred to as 'blind' weighting by Gee (1992). Although consistent in a study area, landslide hazard classes may vary between different study areas.

Relevant terrain attributes are usually assigned on the basis of map polygons. The terrain attributes most often used include slope gradient, surficial materials and geomorphic processes. Additional factors such as soil drainage, soil depth, and vegetation cover may also be used. Many subjective rating analyses include the presence of existing landslides as an important factor.

The complexity of the algorithm can vary considerably, from simple qualitative combinations of terrain attributes to complicated quantitative tables of weighting factors. Gee (1992) found that increasing the complexity of the algorithm, however, does not often improve the reliability of the results. Defining a subjective rating algorithm requires a high degree of specific local knowledge and experience. In theory, once an algorithm is defined by an experienced mapper, a less qualified person can be charged with collecting the terrain attributes and determining the landslide hazard classes. The algorithm, however, is not rigid and thus requires continual use of skilled judgement. There is some danger of oversimplification of the analytical results.

An advantage of a subjective rating analysis method is that a record of the procedure exists and the assignment of classes can be independently reviewed. Algorithms should not be exported outside the area in which they were developed and tested.

Many different subjective rating analysis methods have been used in different parts of the world. A few address only one type of landslide, for example Aulitzky (1980) which deals with the relative activity of debris flow fans, while most address the whole spectrum of landslides, for example Gee (1992). This method has been applied in a simple form at the 1:50,000 scale to the BC Terrain Classification System (Ryder and MacLean, 1980; Resources Inventory Committee 1996a).

The method of pre-harvest, 1:20,000 scale terrain stability mapping developed in the 1970s by MacMillan Bloedel Limited (Bourgeois, 1978) is a subjective rating analysis method. Over the years this method has been adapted and adopted by other forest companies and the BC Ministry of Forests (BC Ministry of Forests, 1995a). The terrain stability/landslide hazard classes are defined in terms of expected performance or probability of occurrence of landslides following timber harvesting or road building.

Method F -- Relative univariate analysis uses relative statistical methods to produce an objective, qualitative link between terrain stability/landslide hazard classes and actual observed performance of slopes. The relative correlation is based on the assumption that terrain units that have critical terrain attributes similar to terrain units that have failed in the past are most likely to fail in the future.

Most of the statistical methods reported in the literature are relative methods. This reflects the fact that landslides occur infrequently and therefore it is difficult to assign a numerical probability of occurrence based upon rigorous statistics (refer to Section 2.3). Most relative methods are therefore based on a spatial distribution of occurrence, and are useful in establishing a relative probability of occurrence for areas most likely to generate landslides.

The data of observed slope performance can take two forms:

- landslide density expressed in number of events per unit area (this is suitable for relatively large numbers of relatively small events, especially at medium to small map scales); and

Table 5.1 Terrain Survey Intensity Levels (TSIL)

TSIL	Map Scale	% Polygons Field Checked	Ground-Checks (#/100 ha)	Method of Field Checking	Typical Objectives
A	>1:20,000	75-100	≥1.5	foot traverses	slope stability in sensitive areas residential land planning hazard zonation
B	1:10,000 to 1:50,000	50-75	1.0 to 3	foot traverse vehicle traverse	slope stability assessment
C	1:20,000 to 1:100,000	25-50	0.5 to ≥1.0	foot traverse vehicle traverse some flying	inventory mapping
D	1:20,000 to 1:250,000	0-25	0 to 0.1	vehicle traverse flying	regional planning preliminary mapping
E	any scale	0	none	no field work air photo interp only	general reconnaissance

(Modified from Resources Inventory Committee 1996a).

Table 5.2 Common Slope Classes

Slope class	Range of Per Cent	Range of Degrees
1	0-5	0-3
2	6-27	4-15
3	28-49	16-26
4	50-70	27-35
5	>70	>35

(Resources Inventory Committee 1996a)

- a regional description of physiography, bedrock and surficial geology, vegetation, drainage and geological or geomorphic processes - especially landslides;
- a discussion of the basis of selecting the method of mapping, determining any parameters and any limitations, uncertainties or simplifying assumptions;
- an explanation of the criteria used to develop the terrain stability classes, outlining appropriate assumptions;
- recommendations for follow-up work such as a subsequent level of study or required field checking during site operations or construction.

Examples of other typical report contents are summarized in Resources Inventory Committee (1996a) and BC Ministry of Forests (1995a).

- All terrain stability mapping projects, and any subsequent revisions, should be accompanied by a report, with contents appropriate to the project, that is dated, signed and sealed by the mapper and/or the professional responsible for the mapping.

5.5 Professional Responsibility

All terrain stability mapping projects should be carried out under the direction of a professional registered as a member of the Association of Professional Engineers and Geoscientists of the Province of British Columbia (APEGBC), who is qualified by training or experience to engage in this type of work. Junior mappers can carry out this work under close professional supervision.

It is the responsibility of the mapper to prepare terrain stability maps and/or estimates of probabilities of occurrence, magnitude, intensity, elements at risk, vulnerability, consequence, and risk. It is not the responsibility of the mapper to determine the acceptability of the landslide hazards or risks. Such decisions are reserved for those individuals, agencies or authorities, such as landowners, governments or courts who incorporate appropriate socio-economic and environmental factors into their decisions.

- All terrain stability mapping projects should be carried out under the direction of a professional, registered as a member of the Association of Professional Engineers and Geoscientists of the Province of British Columbia (APEGBC), who is qualified by training or experience to engage in this type of work.
- Terrain stability mappers should not determine, or be expected to determine, the acceptability of the landslide hazards or risks.

- areal density expressed as the percentage of unstable area to total area (this is suitable for larger events and larger map scales).

In relative univariate analyses, the relationship between the performance data and the terrain attributes is examined separately for each attribute. This relationship represents a set of weighting factors which are added, or otherwise combined, to produce a relative terrain stability/landslide hazard class similar in form to the subjective rating analysis.

The relative univariate analysis is a simple and logical method which can be extended to consider more terrain attributes if necessary, however, the amount of work required in overlaying the various parameter maps and combining the weights is considerable. In addition, the analyses require a detailed landslide inventory with a large number of landslide events, otherwise, any calibration may not be statistically significant.

The advantage of the relative univariate analysis is that it allows the influence of individual terrain attributes to be studied. It is therefore useful in studies concerned with the selection of terrain attributes. Van Westen (1993) describes a method of constructing an algorithm by trial and error. The weights of individual terrain attributes were added to the landslide hazard class one by one and the result was examined by statistical comparison to the landslide density maps. Those terrain attributes which did not improve the correlation were rejected. The disadvantage of the relative univariate analysis is that it can only estimate relative probabilities of occurrence, not absolute probabilities of occurrence.

A pioneering example of the relative univariate analysis approach is the landslide mapping of San Mateo County, California by Brabb et al (1972). A detailed geological map and a slope map of the county were prepared. The per cent area within 35 geologic map units covered by landslide deposits was estimated by use of a grid overlay. The geologic map units were then grouped into six classes, from Class I with 0% area covered by landslide deposits to Class VI with 54%-70% covered by landslide deposits, representing the relative probability of landsliding from very low (Class I) to very high (Class VI). The landslide deposits themselves were shown as a separate class, Class L. Each geologic map unit was then further evaluated to determine which terrain attributes were critical for the occurrence of landslides. For example, if few or no landslide deposits formed on low slopes, the class number for the geologic map unit was reduced.

Rollerson (1992) applied a relative univariate analysis to a large sample of landslides in clear cut terrain, mapped at 1:20,000 scale, on the Queen Charlotte Islands. Nine terrain attributes were used in addition to natural and logging-induced landslide densities. About 50% to 80% of the terrain attributes examined were found to have a statistically significant influence on post-logging landslides. Different terrain attributes were significant for clear cut landslides as opposed to road related failures. Rollerson did not combine the individual factor weights into landslide hazard classes. Instead he produced a probabilistic multi-parameter classification, discussed below.

Method G -- Probabilistic univariate analysis uses objective probabilistic statistical methods to produce a quantitative link between terrain stability/landslide hazard classes and actual observed performance of slopes. A quantitative correlation extends the relative univariate analysis by assuming that the probability of future landslides can be predicted from the frequency of landslides in similar failed terrain units over a given time period.

In this method, a statistical correlation is sought between the probability of occurrence and a single terrain attribute or a prescribed combination of several terrain attributes (multi-parameter classification). The probability of occurrence is usually a spatial distribution, although in some cases where the landslide density map can be correlated with a time period, it is also expressed as a temporal probability of occurrence. The probabilistic univariate analysis is usually applied on the basis of terrain polygons.

This method is practical because it is simple to implement and test. Selection of relevant terrain attributes and definition of classes, however, requires careful and thorough work. A potential source of error, which is common to all statistical methods, is the quality and detail of the landslide frequency data on which the correlations are based. A further potential source of error is the delineation and classification of polygons by the mapper during the data collection phase. Because mapping variability can influence the resultant landslide frequencies correlated with a particular multi-parameter terrain class, combining individual terrain types into generalized classes reduces this problem somewhat, and tends to smooth over differences between mappers.

The probabilistic univariate analysis method has been used in a number of forestry related studies in British Columbia, for example Rollerson and Sondheim (1985), Howes (1987) and Rollerson (1992). In the forest industry background data consists of landslide occurrence during the critical 5-15 year time period following logging. The predicted spatial probability of occurrence relates to the same time period and can therefore be converted into a temporal probability of occurrence.

The choice of relevant terrain attributes and their use in establishing the multi-parameter classification is done by judgement or by trial and error by testing different combinations of parameters. The selection of terrain attributes can be guided by a parallel relative univariate analysis of each separate terrain attribute. Rollerson and Sondheim (1985) tried different classifications based on slope, slope morphology, surface material, aspect and the occurrence of natural landslides, and found that different classifications were needed for clear cut and road related landslides. Howes (1987) defined 15 multi-parameter classes based on landform, drainage, soil depth, slope angle and morphology and the presence of gully erosion.

Method H -- Probabilistic multivariate analysis uses objective multiple regression methods to establish a correlation between probability of occurrence and a group of terrain attributes. The method can be applied on a site specific basis, for example Pack (1985), or on an overlay polygon basis, for example Carrara (1983).

The compilation and presentation of the final map should be similar to the format suggested by Resources Inventory Committee (1996a). Compilation includes transferring the data to the base map, preparation of a map legend and summarizing additional information, and preparation of any accompanying data bases.

The use of digital maps, GIS, accompanying data bases and similar tools is encouraged. These techniques should not, however, be considered as a replacement for established scientific methods, diligence and judgement. Such tools should not be imposed on the mapper. Digital format maps, and those compiled using GIS techniques, should follow the appropriate standards. For details on digital map formats and GIS standards for the BC Terrain Classification System, refer to "Terrain Database Manual" (Resources Inventory Committee 1996b). It is important that digital mapping and GIS do not dictate what information is presented on the map. That is the responsibility of the mapper.

The final map should contain all relevant information, but should not be cluttered or so detailed to make it difficult to interpret and use. In certain circumstances, it may be appropriate to present the information as a series of maps using the same base. The final map should be accompanied by a title block, legend and marginal notes including any limitations to mapping. An example layout of a final map and a list of suggested marginal information is presented in Resources Inventory Committee (1996a). An accompanying index map can serve as a reliability map, and should display location access routes, geographic names, access routes, field traverses and observation/sampling sites.

- All terrain stability maps, and any subsequent revisions, should be dated, signed and sealed by the mapper and/or the professional responsible for the mapping.
- With some provisions, the use of digital maps, GIS, accompanying data bases and similar tools should be encouraged. All appropriate standards for these techniques should be followed.
- The final terrain stability map should contain all relevant information, and be presented so the information is easy to interpret for its intended use.
- The final map should be accompanied by a title, block, legend, marginal notes and index map.

5.4.13 Report

Most terrain stability mapping projects, and any subsequent revisions, should be accompanied by a report that is dated, signed and sealed by the mapper and/or the professional responsible for the mapping . The following items should be included in the report:

- the terms of reference and who authorized the project;
- the intended purpose of the project;
- the level of effort and detail of study;
- a description of the work performed in mapping and preparing the map;
- a list of references to all background information examined;
- a list of all air photos examined, giving specific dates, scales, flight lines and frame numbers;

5.4.11 Map Units

Section 3.5 summarized several different methods of presenting terrain stability data on the associated maps. The grid methods are, in theory, highly objective but allow little opportunity for the use of experience and judgement, and are highly dependent on the reliability of the data -- a handicap in heavily forested terrain.

Polygons which can delineate one or more terrain attributes or hazard or risk parameters are preferred as they allow for the greatest flexibility and the maximum use of the experience of the mapper. The information within a polygon can also be analysed using GIS techniques. At least one of the terrain attributes delineated by the polygons should be slope. The polygon boundaries can be delineated by judgement or by overlaying two or more terrain attribute or terrain parameter maps. The minimum polygon size on the final map should not be less than 1 cm^2.

Final polygon boundaries should be such that each polygon can be assigned one unique terrain stability class. If two classes fall within a single polygon, that polygon should identified with the more conservative class. Map scales usually require that small units of one class occur within larger polygons of another class. This should be noted on the map, however, the polygon should be identified with the dominant class.

Linear segments are also a good method to present map units, but are obviously limited to linear geomorphic features, such as shorelines or gullies. A minimum segment length on the final map should not be less than 5 mm.

Feature outline symbols are best suited to larger scale maps to show detailed landslide features that are internal to a landslide. Linear and point symbols indicate features that are important to the terrain stability but are too small to map as polygons or linear segments. Both feature outline symbols and linear and point symbols should complement polygons and linear segments. As much as possible, standard feature outline symbols and linear and point symbols should be used. Suggested symbols and codes are summarized in Resources Inventory Committee (1996a and 1996b). The use of symbols should be limited to avoid cartographic clutter.

- Polygons should be used to show areal terrain stability map units. Linear segments are good for linear features.
- Feature outline symbols and linear and point symbols should be used to complement polygons and linear segments. To the extent possible, standard symbols should be used.

5.4.12 Final Terrain Stability Map

Depending upon the type of mapping, the final terrain stability map will be a landslide hazard map or a landslide risk map. Some maps, with detailed legends, may be stand alone documents. All maps, and any subsequent revisions, should be dated, signed and sealed by the mapper and/or the professional responsible for the mapping.

A simple version of probabilistic multivariate analysis is the matrix approach suggested by DeGraff and Romesburg (1984). Using overlays of maps delineated by terrain attribute polygons, they defined a separate class for each combination of independent terrain attributes. For example, using three terrain attributes, such as bedrock, slope and drainage, with four classes in each, the resulting matrix had $4 \times 4 \times 4 = 4^3 = 64$ possible classes. While conceptually simple, the large number of combination classes, which can result even with a few terrain attributes, requires a detailed data base of landslide occurrences, to achieve statistically significant correlation.

More formal multiple regression and discriminant statistical analyses, using as many as 25 terrain attributes, have been conducted by Carrara (1983, 1991) with the help of a GIS. Van Westen (1993) tested similar procedures on a carefully mapped study area and found that no significant correlations resulted due to insufficient quality of the input data. He found that both relative and probabilistic univariate analyses produced satisfactory results with the same data.

The main disadvantage of the probabilistic multivariate analysis is that it excludes the experience and judgement of the mapper in producing correlations. Thus, the results are totally dependent on the quality of the data.

Method I -- Slope stability analysis methods usually use the infinite slope stability equation to assist with mapping. This equation, of which there are a number of variations, determines the factor of safety of a relatively long shallow slope segment with uniform or assumed characteristics. The factor of safety is used in the engineering sense as the ratio by which the shear strength of the slope material exceeds the shear stresses in the material. A factor of safety of 1 or less indicates that failure is imminent. Some authors suggest using constant material strength properties for a study area. This permits mapping of the variation of the landslide hazard primarily as a function of slope. This technique, however, is only meaningful in very small areas.

Slope stability analyses show either the distribution of the factor of safety (deterministic method) or the distribution of the probability of the factor of safety being less than one (probabilistic method). The deterministic method must be applied at grid points, while the probabilistic method can be applied to polygons (Hall et al, 1994).

The results of such analyses must be interpreted with care. Geotechnical engineers and geoscientists should be aware of the difficulty of obtaining a realistic factor of safety even at a single, thoroughly sampled and instrumented site because of the difficulty in determining the soil strength and groundwater parameters and the failure mechanism. Probabilistic analysis of the parameters is even more difficult and the probabilistic calculation of a factor of safety variation over a large area is as much based on judgement and informed guessing as any of the techniques discussed earlier. The apparent definiteness of the numerical output should not obscure this fact.

In addition, slope stability analyses neglect a number of items, including anisotropy of slope properties, seepage pressures, presence and strength of thin weak layers, effects of non-planar sliding surface, and three dimensional effects. Despite these cautionary remarks, slope stability analysis is a useful tool to improve judgmental assignment of landslide hazard classes, but should be checked against experience and actual performance.

The 'Level I Stability Analysis' (LISA), developed by the US Forest Service (Hammond et al 1992) is a computer-based probabilistic mapping method applied to polygons and is the best developed of the stability techniques. Level I mapping is intended for general resource allocation purposes and normally includes only limited field checking. Level II mapping, carried out in the project planning stage, is intended to predict the response of the terrain to specific treatment. It requires fairly extensive field work. Level III mapping is used for critical site stabilization before and during construction and requires detailed site specific fieldwork (Hall et al 1994).

4.2 In the Runout Zone

The methods reviewed in the previous section are primarily used to determine the spatial probability of occurrence of landslides in the initiation zone. That is, they show the distribution of probability of occurrence, magnitude and/or intensity where landslides are most likely to occur. The effects of the landslides, however, extend downslope, and therefore there is often a need to map the extent and nature of landslide runout. Landslide risk maps can be derived from the landslide hazard maps by including elements at risk, vulnerability and consequence.

Methods of terrain stability mapping in the runout zone are relatively few at present, but can be grouped into four, Methods J to M. The following reviews the main aspects of these methods. The methods are summarized in Table 4.2. It should be noted that landslide hazard mapping in the initiation zone is a pre-requisite for both landslide hazard and risk mapping in the runout zone.

Method J -- Hazard consequence analysis is a subjective extension of landslide hazard mapping applied to the initiation zone by which those zones are annotated to indicate the potential downslope damage should a landslide occur. Therefore, no separate mapping is required beyond the addition of a consequence rating to the landslide hazard polygon or point.

An example is the consequence classification used by Howes (1987) that provides a relative estimate of the potential of debris from a landslide entering a stream or a body of water, should a landslide occur within a particular polygon. In assigning a consequence, knowledge of the runout characteristics of the potential slide is implied, but not directly mapped.

Method K -- Runout zone analysis is used for many landslide and snow avalanche risk mapping projects, where the greatest potential for damage is in the runout zone. The initiation zones are identified and the landslide hazards are determined, but the initiation zones may not appear on the map.

Shallow subsurface sampling using available exposures or portable equipment should be carried out as necessary and as the terrain and access will allow.

It is not possible to suggest a 'standard' method for field checking, as this activity has the character of detective work. Some guidelines are provided in Resources Inventory Committee (1996a).

- The intensity of field work for terrain stability mapping should be based on the terrain survey intensity level (TSIL) as presented in Table 5.1.
- Field work should be organized to direct initial efforts toward more critical areas as determined from the pre-field work, however, the field work should be representative of all terrain in the map area.

5.4.10 Terrain Stability Class Criteria

Throughout the mapping, the mapper should consider possible criteria for grouping the terrain stability into landslide hazard and/or risk classes. Classes are usually based on a combination of the terrain attributes and the hazard and risk parameters such as probability of occurrence, magnitude, and/or specific risk. To a large extent, the method of selecting a criteria is based on the method of mapping (refer to Sections 4.1 and 4.2). For some methods the selection is objective, while for others it is subjective; for some it is highly systematic and quantitative, while for others it is judgemental and qualitative.

In subjective cases, the criteria depends on the knowledge and experience of the mapper, but the mapper should be guided by all available background data including slope maps, drainage maps, process inventory maps (especially landslide inventory maps), terrain maps, terrain attribute studies and field observations.

In establishing any criteria, it is important that a clear distinction be made between terrain stability class criteria for existing conditions and land use, and the criteria assuming changed conditions and/or land use. Examples of the latter include road construction across a slope, residential development at the top of a slope, timber harvesting of a slope, and reservoir flooding.

Two examples of terrain stability class criteria, one based upon a subjective rating analysis (BC Ministry of Forests 1996a) and the other based upon a probabilistic univariate analysis (Howes 1987), are presented in Tables 5.7 and 5.8.

- The criteria for terrain stability/landslide hazard or risk classes should be developed and used with the appropriate method of mapping.
- The terrain stability classes should be developed, either objectively or subjectively, either quantitatively or qualitatively, after consideration of all available data.
- A clear distinction should be made between the criteria for terrain stability classes assuming existing conditions and land use, and those assuming changed conditions and/or land use.

5.4.8 Other Remote Sensing Data

In the past several decades there has been a dramatic increase in remote sensing technology. Some of this technology has application to terrain stability mapping. Examples are the various types of satellite imagery and radar and include:

- Landsat, SPOT, ERS 1, and ERS 2, which can be used as multispectral scanners and thematic mappers; and
- airborne radar, multispectral scanners and imaging spectrometers, such as synthetic aperture radar.

Depending upon the requirements of the project, these and other remote sensing methods, should be investigated to determine their applicability to the project.

- The usefulness of remote sensing methods should be investigated to determine their applicability to the terrain stability mapping project.

5.4.9 Field Work

Field work is carried out to verify or correct terrain attribute data and polygon boundaries or linear segments determined from map interpretation, air photo interpretation and/or other remote sensing interpretations, and to extend the mapping to beyond the level of detail the above methods provide. As presented in Table 5.3, there are a number of important terrain attributes that cannot be obtained or confirmed accurately without field work.

The intensity of field work varies depending on the terrain survey intensity level (TSIL) as presented in Table 5.1. Field access includes fixed wing aircraft and helicopters, vehicles and on foot. During field work observations are made along the traverse route and at specific observation sites. The amount of data collected can vary depending upon the intensity and purpose of the mapping. It can be collected in hand-written form or on data base forms. The latter method allows for later input into a data base. Table 5.4 summarizes the terrain attributes to be collected for the terrain data base in association with the BC Terrain Classification System (Resources Inventory Committee 1996b).

The field work should be organized so as to direct initial efforts toward more critical areas as determined from the pre-field work, however, it should also be representative of all terrain in the map area. The mapper should take maximum advantage of all available clues, particularly soil or rock exposures in cuts, eroded channels, landslide scars and those provided by windthrown trees. Attention should be directed to signs of incipient landslides. A summary of some of indicators of past and potential slope instability is presented in Table 5.6.

In certain locations and under certain conditions, Global Positioning Systems (GPS) are becoming useful for ground navigation and positioning.

The landslide runout zone may be shown simply as having or not having potential for being affected by the landslide hazard, or may be shown by zones based on landslide hazard intensity parameters such as velocity, depth of flow and/or deposits, range of impact pressures, or a combination of several parameters, and associated probabilities. For example, the Swiss national standard for snow avalanche zonation uses a combination of probability of occurrence and maximum impact pressure to define a 3-class "traffic light" system. A similar system was used for debris flow mapping in Colorado by Mears (1977).

In reconnaissance work, runout zones may be defined by a probability of occurrence. All elements within this zone are considered at risk until more detailed, site specific investigations are carried out. This type of runout mapping has been carried out in British Columbia for a number of Official Community Plans. A recent detailed study of debris flow hazards on the Cheekeye Fan near Squamish delineated four runout zones (Hungr and Rawlings 1995, Sobkowicz et al 1995). Each zone was associated with the probability of occurrence of three different size ranges of debris flows, each characterized by qualitative and quantitative descriptions of flow behaviour and likely consequences. The probabilities of occurrence were used to predict the probability of death to individuals (PDI) of the area and to estimate the probability of material damage to development on the fan.

There are a variety of methods for predicting the probability of occurrence, distance and character of landslide and snow avalanche runout. These include:

- analyses of observational data for actual repeated events;
- analyses of historical and dendrochronological evidence;
- analyses of geomorphological and stratigraphic evidence;
- empirical relationships concerning the flow path geometry;
- empirical relationships concerning other parameters such as source area and magnitude; and
- dynamic models of runout.

The methods of runout prediction are presently evolving. A review, oriented towards large rock slides, has recently been carried out by Hungr and Evans (1993). The international geotechnical societies (International Association of Engineering Geology, International Society of Soil Mechanics and Foundation Engineering and International Society of Rock Mechanics) have recently created a working group to prepare a 'suggested method' for the prediction of rapid landslide movement in the runout zone (Sassa 1993).

Method L - Linear path movement analysis includes mapping linear features such as debris flows paths, which generally follow recognizable lines or paths, and the resulting effects of that movement. The Gully Assessment Procedure (BC Ministry of Forests 1995b) begins by defining streams that are susceptible to debris flows. The stream channels are assessed for:

- sideslope and headwall stability which indicates the potential of the sideslopes and headwalls to produce debris slides or flows;
- channel stability determined qualitatively as a combination of available debris and transport capability of the channel; and
- effects of debris flows considering the potential to deliver debris into a stream.

The procedure can be used to produce a qualitative map showing locations where delivery of debris into the stream system is most likely, where along the channel debris flows are likely to initiate, and potential downstream impacts. An extension of this system, which considers movement of erosion products and sediment transport in flowing streams, has been developed by Hogan and Wilford (1989) and is applied to an entire drainage.

Ellen et al (1993) carried out a 1:30,000 scale, GIS supported analysis of debris flows in Hawaii. A landslide hazard map for the initiation zone was prepared by a probabilistic univariate analysis, supplemented by data on average erosion rates of young volcanic terrain. Next a magnitude-probability of occurrence relationship for the initiation of a debris flow was established. The landslide hazard map was sampled at random points to generate random debris flows that followed existing drainage paths. An empirical relationship between erosion and deposition rates in cubic metres per metre of travel, and based on slope angle and degree of confinement, was used to determine the length of runout. The resulting movement lines were then transferred to the map to show the probability of debris flow damage at various points.

Method M - Landslide movement analysis is more general than linear path movement analysis in that it can be used for all types of landslide movement, linear or otherwise. It is a combination of thorough landslide hazard mapping in the initiation zone and thorough landslide hazard or risk mapping in the runout zone. Landslide movement analysis is more frequently carried out retroactively to document specific landslide events that have already occurred, rather than proactively to predict such events and the associated impacts.

There is, in principle, no great difficulty in combining terrain stability maps of the initiation zone, prepared by any of the methods listed in Section 4.1, with terrain stability maps of the runout zones, prepared by described in the previous paragraphs. Such combined maps are rarely prepared, however, perhaps because of the extensive work required in both the initiation and the runout zones.

Several terrain mapping systems are capable of recording many of the relevant terrain attributes. The BC Terrain Classification System, for example, (Howes and Kenk 1996 and Resources Inventory Committee 1996a) does this in a descriptive manner. The "Terrain Database Manual" (Resources Inventory Committee 1996b) provides a data base and procedures for collecting many of the relevant terrain attributes. The headings from that data base are summarized in Table 5.4.

- The selection of a relatively small group of relevant terrain attributes for a particular terrain stability mapping project should be left to the discretion of the experienced mapper.
- Ideally, the mapper should use standard definitions and descriptions of the terrain attributes selected.

5.4.7 Air Photo Interpretation

Air photo interpretation can involve the interpretation of a single terrain attribute, or more practically, the simultaneous interpretation of several of the relevant terrain attributes selected above. The mapper should be experienced in air photo interpretation of the province's terrain. The BC Terrain Classification System is suggested as a good method to capture many of the relevant terrain attributes. Details of the system, and guidelines and standards for terrain mapping, are summarized in Howes and Kenk (1996) and Resources Inventory Committee (1996a). The mapper, however, should not feel constrained to use only those attributes defined by the above system.

Preliminary delineation of terrain polygons and terrain stability classes, should be completed in the office to guide field work. Further refinement of polygon boundaries and assignment of classes should be made on the basis of field work.

The interpreted geomorphic processes from the terrain maps can be re-interpreted to produce a derived process inventory map. Or alternatively, the standard terrain map can be extended by using additional geomorphic process modifiers and/or relevant feature outline symbols and linear and point symbols, such as landslide headscarps, surface drainage paths, bluffs, and lineaments, to produce a more detailed process inventory map. Such methods are explained in Resources Inventory Committee (1996a) and Schwab (1993). Table 5.5 summarizes the geological process modifiers and subclass modifiers (Howes and Kenk, 1996).

Depending upon the scale of the air photos, the detail of mapping required, the size of the landslides, and the density and height of the forest cover, it may be possible to map the outlines of the landslides and their internal features from air photos.

- The mapper should be experienced in air photo interpretation of the province's terrain.
- The BC Terrain Classification System (Howes and Kenk 1996) should be used as the basis of air photo interpretation to capture many of the relevant terrain attributes. Guidelines and standards are summarized in Resources Inventory Committee (1996a).

photography, type of product (black and white, vs colour, vs black and white from colour negatives), and quality of the air photos. These characteristics are described in Resources Inventory Committee (1996a).

The air photo scale should be the same as, or slightly larger than, the scale of the final map. Ideally the scale should never be smaller. The interpretation of air photos with different scales and dates, and even different types of products, is encouraged, because different terrain attributes and landslide features may be emphasized on different sets of air photos. Air photos taken in different years are most useful for age-bracketing specific landslide events, and/or determining the effects of changed conditions, such as timber harvesting.

- Air photos should be selected with the appropriate characteristics for the project. These include scale, focal length of camera, flying height, year of photography, time of year of photography, type of product, and quality of the air photos.
- Ideally, the main air photo scale should be the same as, or slightly larger than, the final map scale.

5.4.6 Terrain Attributes

Table 3.1 lists 59 terrain attributes assocated with landslides. The ideal terrain stability map would record information on all these terrain attributes, however, the resulting map would of course be unrealistically complex. Furthermore, not all attributes are important in all circumstances. Therefore, for a specific terrain stability mapping project a relatively small group of relevant terrain attributes should be selected. The selection should be left to the discretion of the experienced mapper based on regional conditions, however, the mapper should explain why particular terrain attributes were selected. If at all possible, preliminary work should be carried out to identify those terrain attributes most closely linked with landslide activity in the study area.

The mapper should use, to the extent possible, standard definitions and descriptions of the terrain attributes. Standard definitions and descriptions of many terrain attributes are summarized in International Association of Engineering Geology (1981b), Luttmerding et al (1990), Canadian Foundation Engineering Manual (1992), Howes and Kenk (1996) and Resources Inventory Committee (1996a and 1996b).

As discussed in Section 3.3, slope gradient and evidence of previous landslide activity are the two more common terrain attributes. Based upon a review of the literature, discussions with mappers, and the experience of the authors, the terrain attributes most relevant to terrain stability mapping, and readily mappable, are summarized in Table 5.3. This table also indicates whether the attribute is readily mappable from the topographic base map, other types of maps, air photo interpretation, ground mapping, and/or subsurface methods.

Table 4.1 Summary of Terrain Stability Mapping Methods in the Initiation Zone

Method of Analysis	Summary
A - Landslide Distribution	• objective and qualitative • useful data base of existing landslides • no prediction
B - Landslide Activity	• objective and qualitative • useful data base of existing landslides during different time periods • no prediction
C - Landslide Density	• objective and qualitative • useful data base of landslides • no prediction
D - Subjective Geomorphic	• subjective and qualitative • flexible, unspecified terrain stability/landslide hazard class criteria • requires expert skills • useful data base of landslides and some terrain attributes • difficult to review
E - Subjective Rating	• subjective and qualitative to semi-quantitative • flexible, but specified terrain stability/landslide hazard class criteria • requires expert skills • useful data base of many relevant terrain attributes • work can be delegated and checked • danger of oversimplification
F - Relative Univariate	• objective and qualitative to semi-quantiative • relative statistically based • shows effects of individual terrain attributes • data and analytically intensive • relies on quality data
G - Probabilistic Univariate	• objective and quantitative • probabilistic statistically based • simple to implement and test • danger of selection of wrong terrain attributes • data and analytically intensive • relies on quality data
H - Probabilistic Multivariate	• objective and quantitative, precise • probabilistic statistically based • danger of selection of wrong terrain attributes • removes experience and judgement of mapper • very data and analytically intensive • relies on high quality data
I - Slope Stability	• objective and quantitative, precise • can be reviewed • difficult to use for mapping a large area • shows influence of terrain attributes • requires precise estimates of slope geometry, material strength properties and groundwater conditions • danger of oversimplification • conceals lack of knowledge

Table 4.2 Summary of Terrain Stability Mapping Methods in the Runout Zone

Method of Analysis	Summary
J - Hazard Consequence	• subjective and qualitative • simple, no separate mapping required • runout characteristics not mapped
K - Runout Zone	• method can be subjective or objective, qualitative, semi-quantitative or quantitative • simple to complex delineation of risk zones • practical for planning decisions
L - Linear Path Movement	• subjective and qualitative • suited to linear movement • field intensive and analytically intensive • relies on quality data • best for large or detailed scale assessments, • difficult to use for mapping a large area
M - Landslide Movement	• subjective and qualitative • not limited to linear movement • field intensive and analytically intensive • relies on quality data • best for large or detailed scale assessments, • difficult to use for mapping a large area

5.4.3 Previous Work

Before starting a terrain stability mapping project, a thorough review of all relevant mapping and/or studies in the study area and the surrounding region should be carried out. This should include geology maps, terrain maps, engineering geology maps, terrain attribute maps and/or process inventory maps at all scales, and all site-specific geological and/or geotechnical engineering reports. Examples and sources of information are listed in BC Ministry of Energy, Mines and Petroleum Resources (1983), Clague (1987), Grant (1991), Bobrowsky et al (1992), the Canadian Foundation Engineering Manual (1992), Fulton et al (1995) and Resources Inventory Committee (1996a).

Research by the various federal and provincial agencies, and at universities (theses), should not be overlooked. Regional and district offices of the BC Ministries of Energy, Mines and Petroleum Resources; Environment, Lands and Parks; Forests; Municipal Affairs; and Transportation and Highways should be contacted, as should the planning and engineering offices of the appropriate Regional Districts and Municipalities.

- Before beginning a terrain stability mapping project, a thorough review of all relevant mapping and/or studies in the study area and the surrounding region should be carried out.

5.4 4 Slope Map and Drainage Map

As discussed in Section 3.3, slope gradient is the only terrain attribute common to almost all terrain stability maps. It is suggested that at least a simple slope map should be derived from the topographic base as background data to help direct mapping and field checking of potential critical areas.. The slopes can be classified as 'average slopes', or as 'slope classes' consisting of ranges of slopes gradients. Table 5.2 summaries commonly used slope classes.

A drainage network map can also quickly be produced from the topographic base map. Such a map is useful to highlight permanent and ephemeral drainage paths, drainage divides, watershed areas and drainage density.

- Consideration should be given to deriving a slope map and a drainage network map from the topographic base map to provide useful background data.

5.4.5 Air Photos

Interpretation of vertical air photos is an integral part of a terrain stability mapping project, and therefore the selection of appropriate air photos is most important. Air photos are available from federal and provincial agencies, some regional districts and municipalities, private photogrammetry companies and some private resource companies. Important characteristics of the air photos to consider include: scale, focal length of camera, flying height, year of photography, time of year of

The procedures for terrain mapping and additional procedures that are specific to terrain stability mapping are discussed below. Where applicable, the procedures for terrain mapping (Resources Inventory Committee 1996a and 1996b) have been adopted directly. The reader is referred to those documents for details.

- Because terrain stability mapping is often an extension of another form of mapping, the accepted procedures developed for those other types of mapping should be followed, or modified as required.
- The "Guidelines and Standards for Terrain Mapping in British Columbia" (Resources Inventory Committee 1996a) and the "Terrain Database Manual" (Resources Inventory Committee 1996b) summarize the procedures for terrain mapping and, if appropriate to the terrain stability mapping project, should be followed.

5.4.1 Map Scale and Mapping Intensity

Section 3.4 reviewed four general scales of map presentation. As discussed, the scale of presentation of the terrain stability map is important to communicate the appropriate level of detail for the intended use. The presentation scale should be dependent upon the actual scale of mapping, and methods and intensity of field checking.

The suggested mapping intensity levels, and map scales for terrain stability, are adopted from the 'terrain survey intensity levels' (TSILs) for terrain mapping (Resources Inventory Committee 1996a) and presented as Table 5.1. Refer to that document for further details. The map scales in Table 5.1 are minimums and larger scales are encouraged.

- The terrain survey intensity levels (TSILs) and map scales recommended for terrain mapping (Resources Inventory Committee, 1996) should be followed for terrain stability mapping.

5.4.2 Base Map

The best topographic map available, at the appropriate scale, should be used as the base map. For 1:250,000 or 1:50,000 scales, the National Topographic System (NTS) is recommended. For 1:100,000 scale, British Columbia topographic mapping is recommended. For 1:20,000 scale, the provincial topographic Terrain Resource Inventory Mapping (TRIM) is recommended. TRIM mapping also exists for portions of the province at 1:10,000 and 1:5,000 scales. It should be noted that TRIM maps are produced from small scale air photos, and topographic detail, especially in forested areas, is often lacking. Usually base maps for detailed scales have to be custom produced. Besides topography, the base map should include the latitude and longitude, the main geographic names, the major roads and other cadastral detail.

- The best topographic map available, at the appropriate scale, should be used as the base map for a terrain stability mapping project.

5. SUGGESTED METHODS OF TERRAIN STABILITY MAPPING -- GENERAL ASPECTS

This Chapter summarizes the general aspects of terrain stability mapping and provides a series of suggested methods, that are highlighted in a series of boxes. There is no one method of producing a terrain stability map, and the suggested methods are intended to aid the work of the mapper, not stifle it by the imposition of rigid procedures. Suggested methods for specific uses of terrain stability mapping are presented in Chapter 6.

5.1 Starting a Project

When starting a mapping project, the ultimate purpose of the project and map should be clearly defined, and the time and resources that are available to produce such a map should be determined. Once these factors are well defined and understood by both the client and the mapper, the appropriate type of terrain stability map (Section 5.2) and the appropriate method of mapping (Sections 5.3) can be selected. In many cases, the use, the available time and resources, the type, and the method of mapping will direct the mapping procedure (Section 5.4). Section 5.5 describes the professional responsibility of the mapper.

Frequently the time and resources available for a mapping project are defined by the client's budget, however, they should be defined by the purpose of mapping. If the final product is not achievable with the time and/or resources available, either the desired final product should be modified, the project area should be modified, or additional time and/or resources should be allocated to the project.

- Before starting a terrain stability mapping project, the intended purpose of the project and map should be well defined, and the time and resources should be appropriate and available.

5.2 Type of Map

Seven types of terrain stability maps were reviewed in Section 3.2. The first five types (geology maps, terrain maps, engineering geology maps, terrain attribute maps and process inventory maps) must be interpreted or combined with other information to be used as either a landslide hazard or risk map. The latter two types are produced specifically for landslide hazards and risks.

- Early in a project, the type of map that is required for the project, either a landslide hazard map or a landslide risk map, should be determined.

5.3 Method of Mapping

The method of mapping should be selected based on intended use, time and/or resources available, type of map required, nature of the terrain, regional experience, and experience of the mapper. Before the method is selected, consideration should be given to whether the mapping should be qualitative or quantitative (refer to Section 2.3.4), and whether it should be directed toward the initiation zone or the runout zone (refer to Sections 4.1 and 4.2).

Terrain stability mapping in the initiation zone should have three components:

- an identification of potential type or types of landslides (see Table 2.1) and/or description of the typical behavioural characteristics of the landslide;
- an estimation of a magnitude, or range of magnitudes, expressed in terms of volumes or geographic areas potentially affected by each type of landslide; and
- an estimation of probability of occurrence in temporal terms such as events per year or events per specified time period (such as 50 years, or 5 - 10 years after logging), and/or spatial terms such as events per square kilometre, events per linear kilometre, or hectares of potentially unstable ground per km^2.

In many circumstances, these components should consider the landslide hazards and risks after a particular activity, such as road construction or timber harvesting, is carried out within the map unit.

An ideal approach would be to produce a series of terrain stability/landslide hazard classes based on predicted magnitude-probability of occurrence relationships for each landslide type for each map unit (refer to Section 2.3.1 and Figure 2.1). This is rarely practical, and therefore the terrain stability classes are usually simplified depending on the purpose of mapping.

Terrain stability mapping in the runout zone should also have three components:

- an estimation of the magnitude-probability of occurrence relationship for each type of landslide in the initiation zone that could enter the runout zone;
- a runout analysis for each type and magnitude of landslide including an estimation of the characteristics of the landslide movement and debris, such as velocity and thickness; and
- a summary of all elements at risk including the land, resources, buildings, economic activities and people, and their vulnerability

Ideally, each map unit in the runout zone should be assigned a terrain stability/landslide risk class based on a consequence-probability of occurrence relationship (refer to Section 2.3.3 and Figure 2.2). Again, such determinations are exceedingly complex and usually a great deal of simplification is required. Often an assumption is made that the probability of occurrence of a given consequence is the same as the probability of occurrence of the landslide. In other words, the reduction of the probability of occurrence of the landslide, from its initiation to it reaching the runout zone, is not taken into account.

The following provides some other general criteria for selecting and using a particular method of terrain stability mapping:

- the method should be backed by an appropriate amount of reliable data;
- the method should be appropriate to the terrain conditions;
- preference should be given to a method that has been regionally tested;
- if possible, the method should be calibrated by research or experience;
- the method should be compatible with the experience of the mapper; and
- the use of a combination of two or more methods is encouraged.

- The terrain stability mapping method should be selected based on intended use, time and/or resources available, type of map required, availability and reliability of data, nature of the terrain, regional experience, previous calibration, and experience of the mapper.
- The decision to use a qualitative or quantitative approach to terrain stability mapping should be based on the intended use of the project and map, the amount and reliability of the available data, and the capability to appropriately analyze the data.
- Terrain stability mapping in the initiation zone should consider potential type or types of landslides, magnitude or range of magnitudes of each landslide type, and an estimation of probability of occurrence in temporal and/or spatial terms.
- Terrain stability mapping in the runout zone should consider the magnitude-probability of occurrence relationship for each type of landslide in the initiation zone, a runout analysis including the characterization of the landslide movement and debris, and a determination of the elements at risk and their vulnerability.

5.4 Mapping Procedures

Once the above topics have been addressed, the procedures to successfully complete the terrain stability mapping can be established. If the terrain stability mapping is an extension of another form of mapping, such as geology mapping, terrain mapping, engineering geology mapping, terrain attribute mapping and/or process inventory mapping, the accepted procedures developed for those other types of mapping should be followed, or modified as required.

The recently published "Guidelines and Standards for Terrain Mapping in British Columbia" (Resources Inventory Committee 1996a) is a most useful summary for terrain mapping and mapping in general. Of particular interest to terrain stability mapping are sections that refer to selection of map scale, review of previous work including previous mapping, selection of air photos, air photo interpretation, field work, compiling the terrain map and reporting, and reliability of terrain maps The document also briefly discusses derivative maps and uses several terrain stability maps as examples.

The "Terrain Database Manual" (Resources Inventory Committee 1996b) summarizes the standards for collecting terrain information in a data base format and the GIS specifications for map analyses and presentation. It supersedes Kenk et al (1987).