SLOPE STABILITY PREDICTION TECHNIQUES FOR FOREST MANAGEMENT PURPOSES - A CASE STUDY FROM THE QUEEN CHARLOTTE ISLANDS, BRITISH COLUMBIA

by

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ABSTRACT

This study examines the predictive ability of three slope stability assessment techniques used in British Columbia. Two of the methods, environmentally sensitive area mapping (ESA) and slope hazard ratings generated from terrain mapping (SRS), are routinely applied in forest management; the third, still under development and so far utilized for research purposes only, develops a failure probability rating from terrain mapping and clearcut slope failure frequencies (SGA). The specific objectives are to (1) appraise the predictive ability of these stability prediction methods in logged and natural terrain, (2) appraise the comparative performance of the methods, and (3) determine the method most useful to British Columbia land managers.

This study focuses on testing/comparing each method's predictions. To be successful, a stability assessment method must predict where the greatest increase in failures will occur if the hillslopes are logged. Similarly, a method is considered successful if, regardless of treatment, the stability class failure frequencies are ranked in tandem with the predicted likelihood of failure (*i.e.*, the least stable class will have the largest failure frequency).

Two study regions on the Queen Charlotte Islands were subjected to each prediction method using 1:20,000 scale pre-logging (1977) aerial photographs and failure inventories completed in each region. Failure frequencies by stability rating (as determined for each approach), for both logged and natural terrain, were determined from the recent (1988) airphotos. Failure frequency per unit area was the analytical unit utilized for statistical comparisons of predictive success. Two non-parametric statistical techniques, Mann-Whitney *U* Test and Spearman's Rank Correlation were employed in the analysis.

Both regions had the majority of new failures happen in logged terrain. The overall failure frequency was 1.9 per km^2. McClinton Bay's unlogged and logged area failure frequencies were 1.4 and 3.1 per km^2, respectively. Louise Island's unlogged and logged area failure frequencies were 0.9 and 4.8 per km^2. SRS successfully predicted 94% of all failures (52% of land designated medium-high hazard), ESA predicted 73% of all failures (23% of land medium-high hazard), and SGA predicted 52% of all failures (21% of land medium-high hazard).

Which method is better? If economics are not considered then SRS is without qualification the most accurate. ESA is the most cost-effective. As typical with many applied geomorphology questions, the final analysis displays the tension between scientific understanding and hands-on management. In seeking to bring the greatest understanding of the complex factors influencing surficial terrain failure the scientist is often at odds with the land manager who wishes to avoid complex classification. Thus, if understanding is the prime consideration then the SRS method is recommended; otherwise, from an economic and management stance, the ESA method appears to hold the greatest promise.

The importance of this applied geomorphology thesis lies in the development of a methodological approach to critically assess slope stability prediction methods, the failure inventory, the use of non-parametric statistics, the discussion of tension between 'science and management,' and, of course, the results.

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CHAPTER 1. INTRODUCTION

The decision to log or not to log a slope depends, in part, on the assessment of its natural instability. Slope instability can be defined as the tendency of the terrain toward mass wasting occurrence. Determination of stability at a site is a scientific problem, but assessment of an entire hillslope is more art than science. Yet such assessments comprise one aspect of the management of logged forest lands on steep, perhumid terrain.

Slope failures, both naturally occurring and logging-accelerated, cause productive forest site loss, increased industrial operating costs (to replace roads and bridges), interference with fisheries (by changing or damaging habitat if sediment impinges on a watercourse), and encourage environmentalists' negative image of the logging industry. A number of approaches to this problem have attempted to identify terrain with high risk of slope failure. These prediction techniques carry the implicit assumption that if high risk terrain can be adequately identified then appropriate management will minimize slope failure occurrences attributable to human activity.

A number of preventive planning techniques for coastal British Columbia have been used for the last 10 to 12 years. In the late 1970s, in response to accelerated mass wasting on steeper, logged slopes, industry and government began using slope stability rating systems in operation planning (Sauder and Wellburn 1989). They also changed road-building techniques from crawler tractor (bulldozer) to the lower impact backhoe. However, the results of these innovations have not previously been subject to formal critical and comparative appraisal.

There are several reasons to concentrate such an appraisal on the west coast, specifically on the Queen Charlotte Islands (Fig. 1). This island archipelago, about 275 km in length, is located 80 km off the northwest coast of British Columbia.

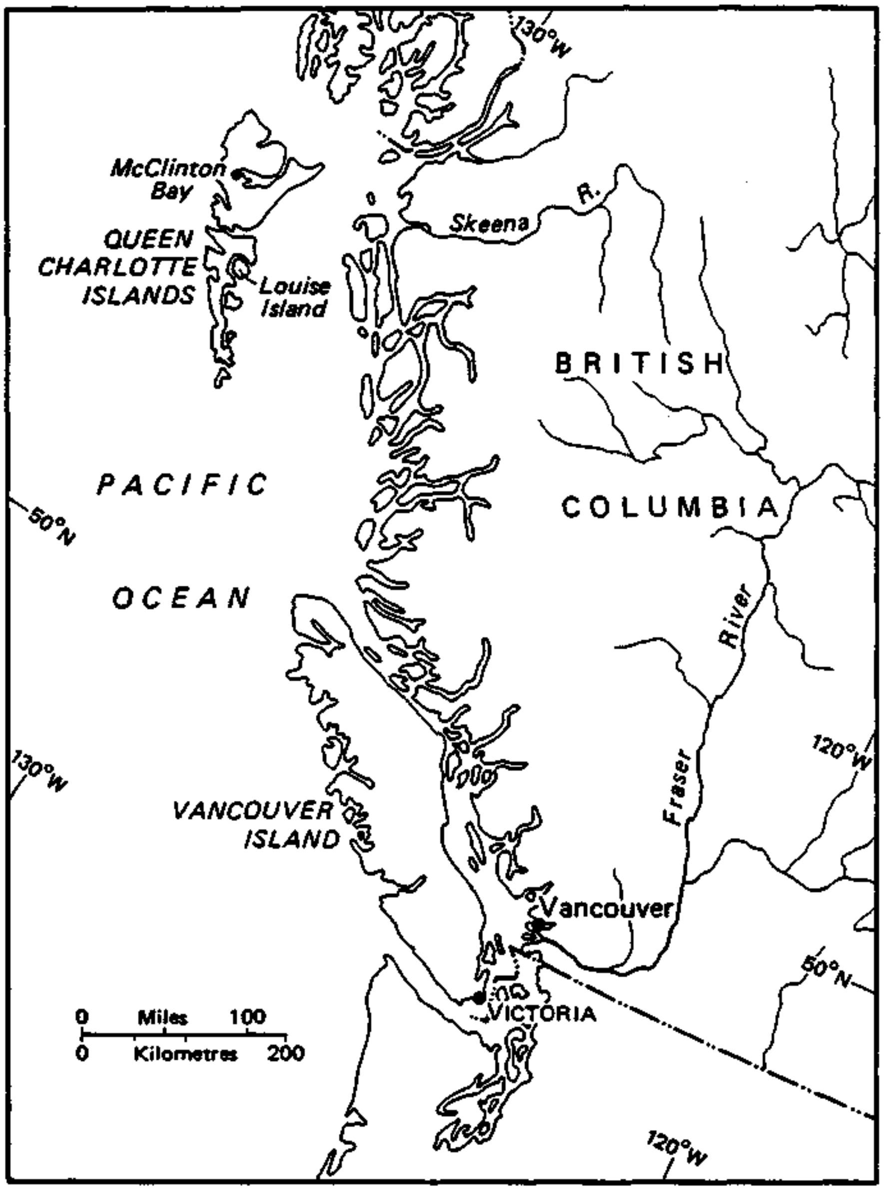

Figure 1: Location of Queen Charlotte Islands on the West Coast of British Columbia

The glaciated terrain varies from rugged mountains in the west and south to lowlands in the northeast (Holland 1964; Chatwin and Smith 1992). The Islands are glacially oversteepened, experience some of the highest recorded winds in Canada, and are very wet (Fig. 2). With a temperate climate, they also have many highly productive and rapidly regenerating timber sites. West Vancouver Island is similarly well suited for tree production without being quite as wet, as steep, or as windy as the Queen Charlotte Islands.

1.1. Physical Environment

The surficial geology of the Islands varies greatly but includes basalt, breccias, gabbro, and volcanic-rich sediments (Sutherland Brown 1968). Soils are young (less than 10,000 years), shallow, coarse-textured, and permeable. The boundary between the soil and underlying compacted glacial till is often abrupt (Gimbarzevsky 1988). Observations by Swanston (1978) and Rood (1984, 1990) indicate that bedrock type itself has no direct effect on failure occurrence in this region. Failures are mainly debris slides with the failure plane most often located at the till/soil interface.

Three secondary physiographic subdivisions, the Queen Charlotte Ranges, the Skidegate Plateau, and the Queen Charlotte Lowlands exist in the Queen Charlotte Islands (Fig. 3). High peaks, steep slopes, and rugged topography are characteristic of the Queen Charlotte Ranges. Elevations range from sea level to greater than 1250 m. In the Skidegate Plateau elevations range from sea level to greater than 700 m. Many of the landforms are shaped by stream erosion and glaciation resulting in rounded to flat-topped ridges and deep, somewhat U-shaped valleys. The Lowlands are low-lying and gently sloping. The region, extending from the eastern shoreline to the Skidegate Plateau, has been extensively glaciated (Dunkley 1986).

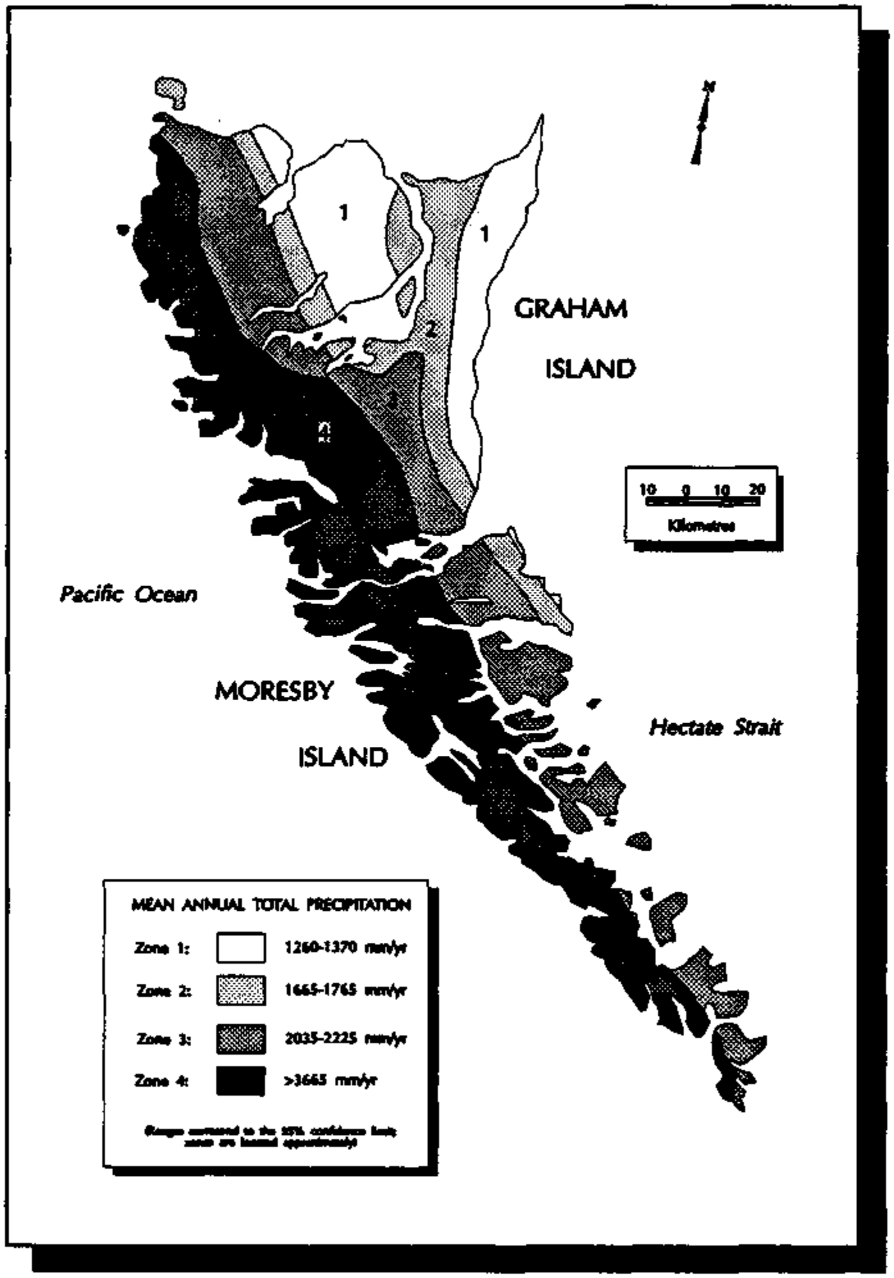

Figure 2: Spatial Variation of Precipitation in the Queen Charlotte Islands (after Hogan and Schwab 1990)

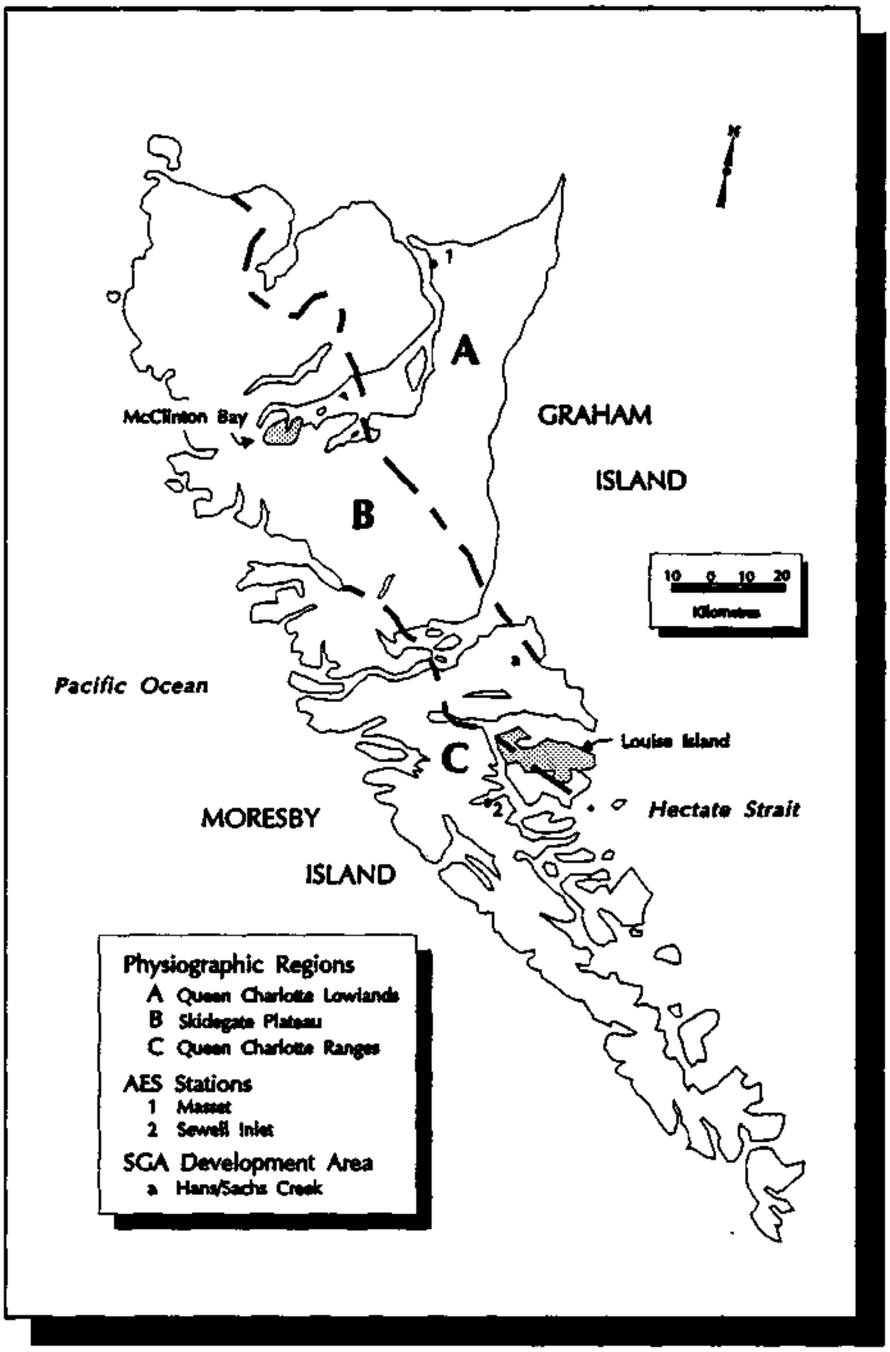

Figure 3: Queen Charlotte Islands Physiographic Regions and Study Site Locations

Four biogeoclimatic zones (Krajina 1969) are found in this essentially maritime, mountainous, forested area (Banner *et al.* 1984). The Coastal Western Hemlock zone, divided into two variants, is dominant. Wet humid conditions make this the most productive forest zone in British Columbia (Jones and Annas 1978). Western hemlock (*Tsuga heterophylla*) is usually found at mid to low elevations along with western red cedar (*Thuja plicata*) and sitka spruce (*Picea sitchensis*). The other three biogeoclimatic zones are the Mountain Hemlock, Coastal Cedar-Pine-Hemlock, and Alpine Tundra (Lewis 1982). The term "zone" as used here mostly represents "islands" of distinctive vegetation not necessarily broad contiguous bands of vegetation. Mountain hemlock (*Tsuga mertensiana*) and cypress (*Chamaecyparis nootkatensis*), characteristic of the Mountain Hemlock zone, are common at middle to high elevations. The Coastal Cedar-Pine-Hemlock zone contains red cedar, cypress, western and mountain hemlock, and lodgepole (shore) pine (*Pinus contorta*). This zone extends from sea level to the alpine along the west coast of the Islands. Alpine Tundra species, mountain hemlock, cypress, and lodgepole pine, the range of which depends on elevation, wind exposure, and aspect, are usually stunted and slow growing (Dunkley 1986). Red alder (*Alnus rubra*) is an important colonizer of disturbed terrain (Chatwin and Smith 1992).

The Islands have a land area of approximately 10,000 km^2 (Gimbarzevsky 1988). Annual precipitation varies from 1150 mm on the north and east coast to over 4500 mm in the mountains on the west coast (Hogan and Schwab 1990) . The high rainfall, strong winds, glacially over-steepened slopes and frequent seismic activity contribute to the Islands' dominant geomorphic process, mass wasting (Alley and Thomson 1978; Wilford and Schwab 1982; Church 1983; Rood 1984). Mass wasting occurs primarily in the forms of rock and debris slides, debris avalanches, debris flows, debris torrents and slump-earth flows (Gimbarzevsky 1988). Failure events involve the initial destruction of most vegetation, a truncated solum, increased bedrock exposure and establishment of conditions conducive to surface erosion. Smith, Commandeur and Ryan (1984) demonstrate that the degree of recovery is a function of age and slope position, though type of bedrock also has an influence on the rate of increase of vegetative and humus cover (and species composition). Because of the lower growth rates caused by relatively poor soil conditions and competition by red alder, production of merchantable timber on slides after 60 years is estimated at only 30% of that produced on logged but undisturbed slopes of similar age.

Natural rates of episodic debris slides and channelized debris flows on the Queen Charlotte Islands exceed those observed elsewhere in the Pacific Northwest (Schwab 1983; Rood 1984). Studies in many areas of the world have related both seasonal rainfall and individual storms to shallow, rapid landslides (Selby 1976; Sidle *et al.* 1985; Keefer *et al.* 1987; and others). The most frequently cited triggering mechanism is moderate to intense rainstorms (Schwab 1983; Eisbacher 1982; Crozier 1969). Heaviest precipitation on the Queen Charlotte Islands usually occurs in late autumn and early winter. Hogan and Schwab (1991), using dendrochronological methods to date every landslide in two large watersheds, indicate that four storms in 1891, 1917, 1935, and 1978 were responsible for more than 85% of all landslides that have occurred on the Islands in the last century. Schwab (1983) reports that 120 to 150 mm of rain in a 12 to 24 hour period is sufficient to trigger mass movement and that return periods for storms of this magnitude are in the order of 5 to 10 years.

Debris mass movements are a natural, if episodic, erosional process of mountainous environments. However, removal of the forest cover enhances and increases these erosional processes. Rood's (1984) regional inventory on the Queen Charlotte Islands suggests a 10-30 fold increase in the incidence of slope failure in logged terrain in comparison with undisturbed terrain. Schwab (1983) estimates an 18-fold increase in failure for logged terrain in the Rennell Sound area of Graham Island. Yet, maintaining the soil mantle on steep clearcuts is essential for the return of forest growth. The prudence of minimizing logging-induced instability is clearly evident.

1.2. Thesis Statement

This study proposes to examine the predictive ability to delineate stability-sensitive slopes of a group of slope stability mapping and assessment methods used in western British Columbia. Two of the methods, environmentally sensitive area mapping and slope hazard ratings generated from terrain mapping, are routinely applied in forest management; the third, still under development and so far utilized for research purposes only, develops a failure probability rating from terrain mapping and clearcut slope failure frequencies. On the basis of predictive success combined with the information requirements for each method, the most cost-effective one will be suggested for operational use or for more intensive development.

1.2.1. Objectives

The specific objectives are to (1) appraise the predictive ability of three slope stability assessment methods in logged and natural terrain, (2) appraise the comparative performance of the methods, and (3) determine the method most useful to British Columbian land managers.

To achieve these objective the following steps must be completed:

1. Determine the gross failure frequency of selected treated (logged) areas in comparison with the failure frequency of paired untreated (natural) areas over similar areal extent and time;

2. Estimate the probable failure frequencies within individual slope stability classes (as defined by each method) in each test area from pre-logging aerial photographs;

3. Within each method compare the actual failure frequencies with the predicted failure likelihood for accuracy, consistency and transferability between test sites;

4. Compare the predictive success of each method with the success of the others.

5. Review the information requirements and expertise necessary to implement each method.

To be successful, a stability assessment method must predict where the greatest increase in mass wasting events will occur if the hillslopes are logged. Similarly, a method will be considered successful if, regardless of treatment, the stability class failure frequencies can be ranked in tandem with the predicted likelihood of failure (*i.e.* the least stable class will have the largest failure frequency). By comparing hillslopes with similar terrain units, stability classes and subject to similar meteorological events but differing in their management treatment, some conclusions can be offered about the sensitivity and usefulness of each method.

1.3. Slope Stability Prediction in British Columbia

Logging of the steeper coastal mountain slopes began in the late 1960's and early 1970's (Slaymaker 1988). Treated areas quickly began to experience road-building related and open-slope failures. In October 1978 the Queen Charlotte Islands experienced intense precipitation triggering over 500 landslides in one three day storm (Chatwin and Smith 1992). These failures occurred all over the Islands but most were concentrated on previously-logged slopes on the west side of Graham Island. After this, concern about the various effects of logging became widespread and slope stability mapping a necessary management planning tool.

Recognizing that in almost all situations the knowledge of boundary conditions is incomplete and the requisite detailed precipitation, slope hydrology and other physical data may be limited, non-existent, or of highly variable quality (Rollerson *et al.* 1986), land managers in British Columbia have opted for essentially "index" stability assessment methods. Table 1 lists these prediction techniques by status, skill required to apply the method, where and by whom it is employed.

Since the mid-1970's, most operational slope stability management for forestry purposes in Tree Farm License[1] (TFL) areas begins with terrain mapping by terrain specialists using the British Columbia Terrain Classification System (ELUC 1976; Ryder and Howes 1984). Using current scientific knowledge and personal experience these specialists then create a map of subjectively-defined (and often poorly documented) slope stability ratings from the terrain maps and airphoto analysis.

More recently, the British Columbia Forest Service began its Environmentally Sensitive Area (ESA) mapping at 1:20,000 scale in certain Timber Supply Areas [2] (TSA). The technique aims to give an accurate picture of lands truly available for inclusion in Annual Allowable Cut (AAC) computations. With a minimum of detailed analyses, this method provides a low cost guide to areas requiring more intensive field assessment. The technique is also considered quite successful as a predictive tool for identifying potentially unstable terrain (Lewis 1989).

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[1]Tree Farm Licenses are Crown Lands on long term lease or tenure to private industry. TFL planning is done by the licensee with ministry consultation and technical review and Chief Forester approval (Ministry of Forests 1983).

[2]Timber Supply Areas are those Crown Lands designated by the Ministry of Forests as land available for logging. Small contractors may make application to log in a TSA. TSA planning is done through TSA committees having both Ministry of Forests and licensee representation (Ministry of Forests 1983).

Within the last decade a more quantitative, analytical method of defining slope stability classes based on terrain polygon stability performance was proposed (Howes 1982, 1987; Rollerson 1984; Sondheim and Rollerson 1985; Rollerson and Sondheim 1985; Howes and Sondheim 1989). This 'statistical-geographic' method differs significantly from other techniques by beginning with an analysis of clearcut (treated) terrain and landslide inventory rather than beginning with an evaluation of natural (untreated) terrain.

Table 1: Stability Prediction Methods Used in British Columbia

Status	Subjectivity	Method	Where Used/By Whom
Operational	high+	Environmentally Sensitive Area (ESA)	Timber Supply Areas / Government
	high*	Slope Stability / Slope Hazard Mapping (SRS)	Tree Farm Licenses / All large forestry companies (differing versions)
Experimental	medium*	Statistical-Geographic Approach (SGA)	Queen Charlotte Islands and Vancouver Island
	low+	Rood (1990) Parametric Equations	------

+any reasonably skilled technician can apply the method
*relies heavily on the skill and knowledge of the terrain specialist

Rood (1990) reports that, at a regional scale, factors known to influence landsliding (*i.e.* bedrock type, aspect) are statistically unimportant in the Queen Charlotte Islands. Slope angle and slope shape appear to be the most useful variables for prediction of debris slides. These variables can be used for parametric estimation of failure incidence using air photo and map measurements. Although offering an estimate of sediment yield to streams at the basin scale, there is no equation for predicting a site specific incidence of failure.

Three of the four methods are generally considered useful in reducing logging and road-related failures through the identification of sensitive terrain (Lewis 1989; Rollerson 1990). All techniques vary in their data requirements, subjectivity, and the skill required to complete the stability analysis. Until now, these techniques have not been subjected to a formal critical and comparative analysis. The purpose of this thesis is to initiate such critical analysis, with particular attention given to the methodology and analytical techniques.

CHAPTER 2. SLOPE STABILITY ASSESSMENT

2.1. Physical Processes

Before embarking on a critical test of slope prediction methods it is necessary to have an understanding of the physical processes governing steepland slope stability. The important factors include pore water pressures, the soil strength parameters, slope steepness, and depth to the potential failure plane (Gray and Megahan 1981; Sidle *et al.* 1985; Sauder *et al.* 1987). Many of the natural factors influencing the stability of slopes may act synergistically to initiate or accelerate soil mass movement. Management practices of road-building and clearcut logging may modify natural conditions such that marginally-stable slopes become prone to failure.

In its simplest terms, a slope is stable when the shear strength of the soil mass is greater than the shear stress. A slope is destabilized when the shear stress becomes equivalent to or greater than the shear strength. Figure 4 illustrates the simplified soil mechanics for a planar failure. Table 2 lists the main conclusions of several studies investigating the relative influence of various soil, slope and hydrological variable changes on slope stability. Both Sidle *et al.* (1985) and Sauder *et al.* (1987) provide useful discussion and more detailed descriptions of the factors affecting shear stress and shear strength with particular attention to the influence of natural and land management factors on slope stability.

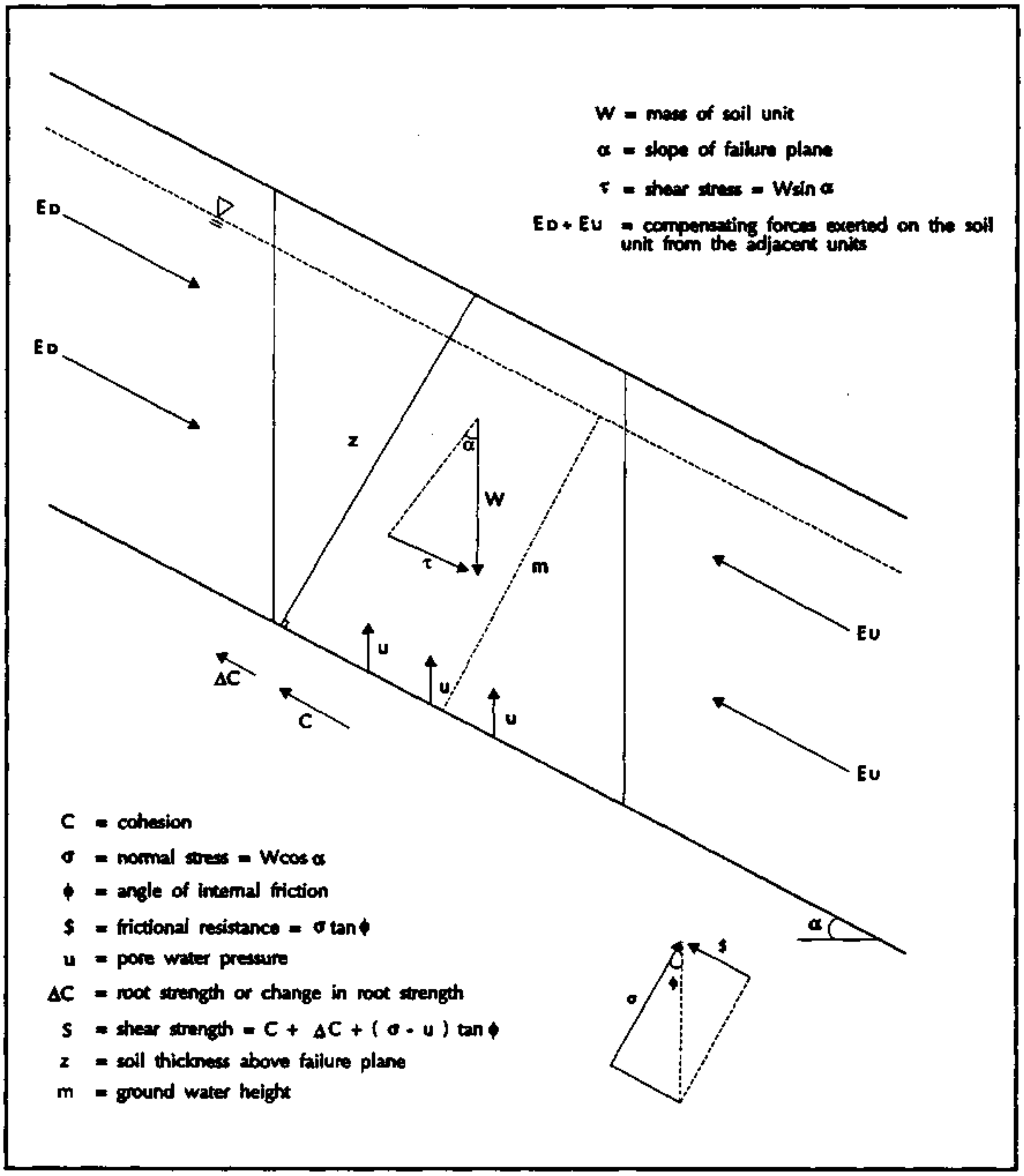

Figure 4: Simplified Soil Mechanics for a Planar Failure (Sauder *et al.* 1987)

Table 2 : Summary Findings of Recent Studies Investigating the Relative Influence of Soil, Slope and Hydrological Variable Changes on Slope Stability in Forested Sites

Study	Importance to Stability		
	High	Medium	Low
Swanston (1974)	• removal of soil mass downslope ↓	• dynamic loading from wind stress on trees transfered through root system to soil ↓	• tree modificaiton to soil moisture via interception, evaporation and transpiration, minimal
Brown & Sheu (1975)	• timber removal (reduce soil weight, and wind loading), short-term ↑ • with time root systems die, strength decreases ↓ • timber removal leads to lower evapotranspiration with rise in water table ↓		
Wu *et al.* (1979)	• roots ↑		• effects of wind ↓
Gray & Megahan (1981)	• changes in root systems • changes in effective soil cohesion • changes in soil thickness above failure plane • slope angle	• changes in the relative ground water height • changes in the angle of internal friction of the soil	• changes in soil unit weight
Swanson (1981)		• trees modify soil moisture distribution and soil pore water pressures through interception, evaporation and transpiration ↑	

↓ indicates decreased stability

↑ indicates increased stability

Table 2 : Continued

Study	Importance to Stability		
	High	Medium	Low
LaHusen (1984)	• slopes ≥ 30° ↓ • major convex break in slope ↓ • poorly drained soils ↓		
Ohta & Tsukamoto (1984)	• "piping" ↓ • antecedent ground moisture conditions		
O'Loughlin (1984)		• new root development 5-10 years after tree felling ↑	• tree modificaiton to soil moisture via interception, evaporation and transpiration, minimal

Sauder (1984)	• location is important
	  • gully headwalls ↓
	  • uniform or convex slopes steeper than 70% ↓
	  • slope depressions ↓
	  • major breaks in concave or convex slopes ↓
		• yarding disturbance ↓	

Schroeder & Brown (1984)	• water input more important than root decay		
Sidle (1984)	• reduction of root strength ↓		• trees removed, effect on soil moisture regime
Ziemer (1984)	• seasonal and annual precipitation		
Church & Miles (1987)	• antecedent ground moisture conditions		

↓ indicates decreased stability

↑ indicates increased stability

Table 2 : Continued

Study	Importance to Stability		
	High	Medium	Low
Reneau & Dietrich (1987)	• root strength along margins of potential failure, limits size • hollows main source of failure initiation		
Sauder *et al*. (1987)	• blockage of soil macropores ↓ • slope angle • rising pore water pressure, near saturation ↓		
Swanston *et al*. (1987)			• No significant correlation of displacement or rate with seasonal or annual precipitation
Wilson & Dietrich (1987)	• exfiltration along hollows prevents pore water buildup ↑ • local upwellings of bedrock storm flow ↓		

↓ indicates decreased stability

↑ indicates increased stability

2.1.1. Triggering Events

Sometimes held in tenuous equilibrium, soil mechanics can be altered when impacted by extremely intense or prolonged rainfall events (Caine 1980; Eisbacher 1982), seismic events (Ouchi 1987; Hara and Yazawa 1987; Anma and Maikuma 1987) and changes in rooting strength (Ziemer 1981; O'Loughlin 1972, 1984; Gray and Megahan 1981).

The most common type of meteorological situation to trigger debris movement is the "repeated or sustained regional rainstorm" where more than 300 mm of rain falls in a 48 hour period (Eisbacher 1982). This storm type has been blamed for failures on the Queen Charlotte Islands (Schwab 1983), in New Zealand (Crozier 1969), Nagasaki, Japan (Iseda and Tanabashi 1986), and Southern California (Rice and Foggin 1971). These morphogenetically-effective meteorological events are usually characterized and analyzed by their intensity and frequency. Other antecedent conditions including snowmelt and rain-on-snow, and the antecedent ground moisture conditions have been identified as important variables in triggering slope and channel debris failure (Church and Miles 1987).

Chatwin (1991) suggests that avoiding logging activities during particularly intense single storms will reduce landslide hazard. For the Pacific Northwest if the rainfall intensity values exceed the values shown in Figure 5 at any time during the storm, there is a high probability of failure. These values are the minimum intensities needed to trigger debris slides, assuming previously saturated soils and vegetated slopes. Less intense storms may trigger failures within clearcuts or along roads.

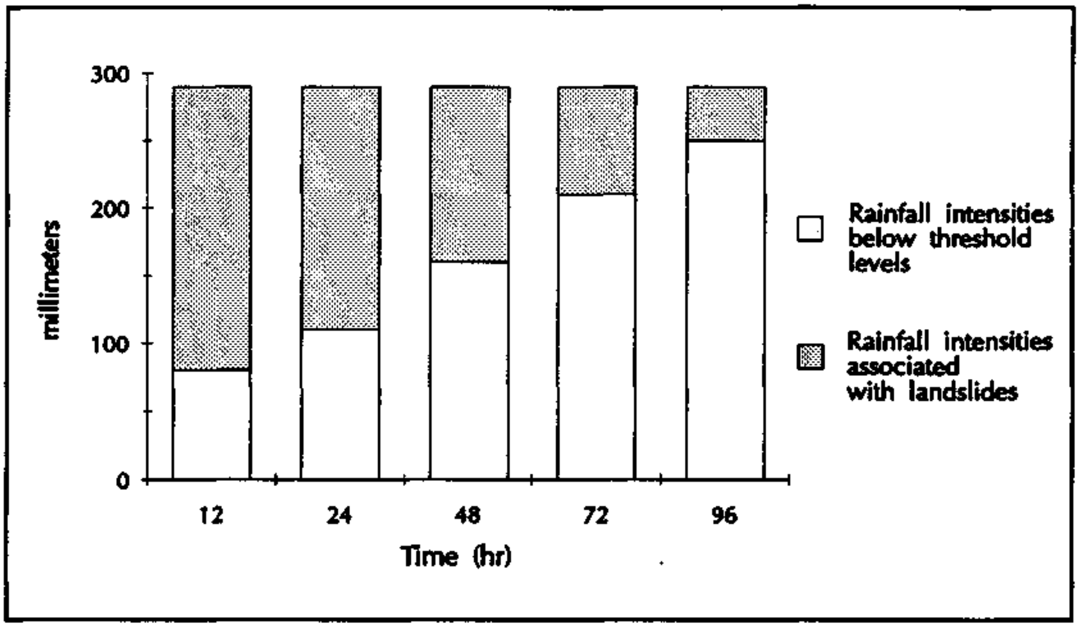

Figure 5: Rainfall Intensities (Assuming Near-Saturated Antecedent Conditions) Commonly Associated with Landslide Activities in the Pacific Northwest (Chatwin 1991)

A number of other papers relate rainfall recurrence intervals with initiation of debris and landsliding events. Lehre (1981) determines that sediment is removed from storage in his study basin by storms with recurrence intervals greater than 10 years. Coats and Collins (1984) describe the effects of a rainstorm with a recurrence interval of up to 150 years which caused extensive debris avalanches, flooding and stream channel changes in San Lorenzo River Basin, California. Schroeder and Brown (1984) report at least 221 new landslides observed after a 5- to 7-year storm event in the central Oregon Coast Range. Characteristically, forest soils on slopes in excess of 35° usually do not exceed 2.0 metres in thickness (Krag *et al.* 1986). Consequently, rapid accumulation of subsurface water along the basal surface can occur during major storm events.

Wieczorek (1987) estimates the geomorphic work performed by landsliding from an inventory of 277 active landslides compiled over a 12 year period (1974-1986). Landslides were categorized according to dominant type of movement to allow comparison of erosion caused by different slope processes and triggering events. Small debris flows were the most frequent type but the majority of geomorphic work was done by a relatively few large slumps, block slides, and earth flows. High, seasonal rainfall affected the geomorphic work more than individual intense storms. Figure 6 shows the relationships between seasonal rainfall and landslide volume. Seismically-induced failure volumes account for only 6% of that from climatically-induced landslides during the same period.

Although seismic events were known for many years to be an external trigger of mass movement events, published reports on seismically-induced landslides did not appear until Ouchi (1987), Hara and Yazawa (1987) and Anma and Maikuma (1987). All three papers report on earthquake-induced mass movement and sedimentation events in Japan. Wieczorek (1987) briefly mentions two seismically-induced landslides in the Pacific northwest. Sidle *et al.* (1985) conclude that of the natural factors affecting soil mass movement, seismicity is the least investigated and the least well understood.

Root systems of plants can increase stability of forested slopes by anchoring through the soil mass into fractures in the bedrock, by crossing zones of weakness to more stable soil, and by providing interlocking long fibrous binders within a weak soil mass. The vertical anchoring effect of roots becomes negligible in deep soils while the other two conditions dominate. O'Loughlin (1972) calculated that the root network accounted for 71% of shear strength at saturation of the till soils on slopes of 35°. After tree removal by harvest or natural events, the root system decays and the soil weakens progressively until the deforested areas revegetate and become progressively reinforced as new roots occupy

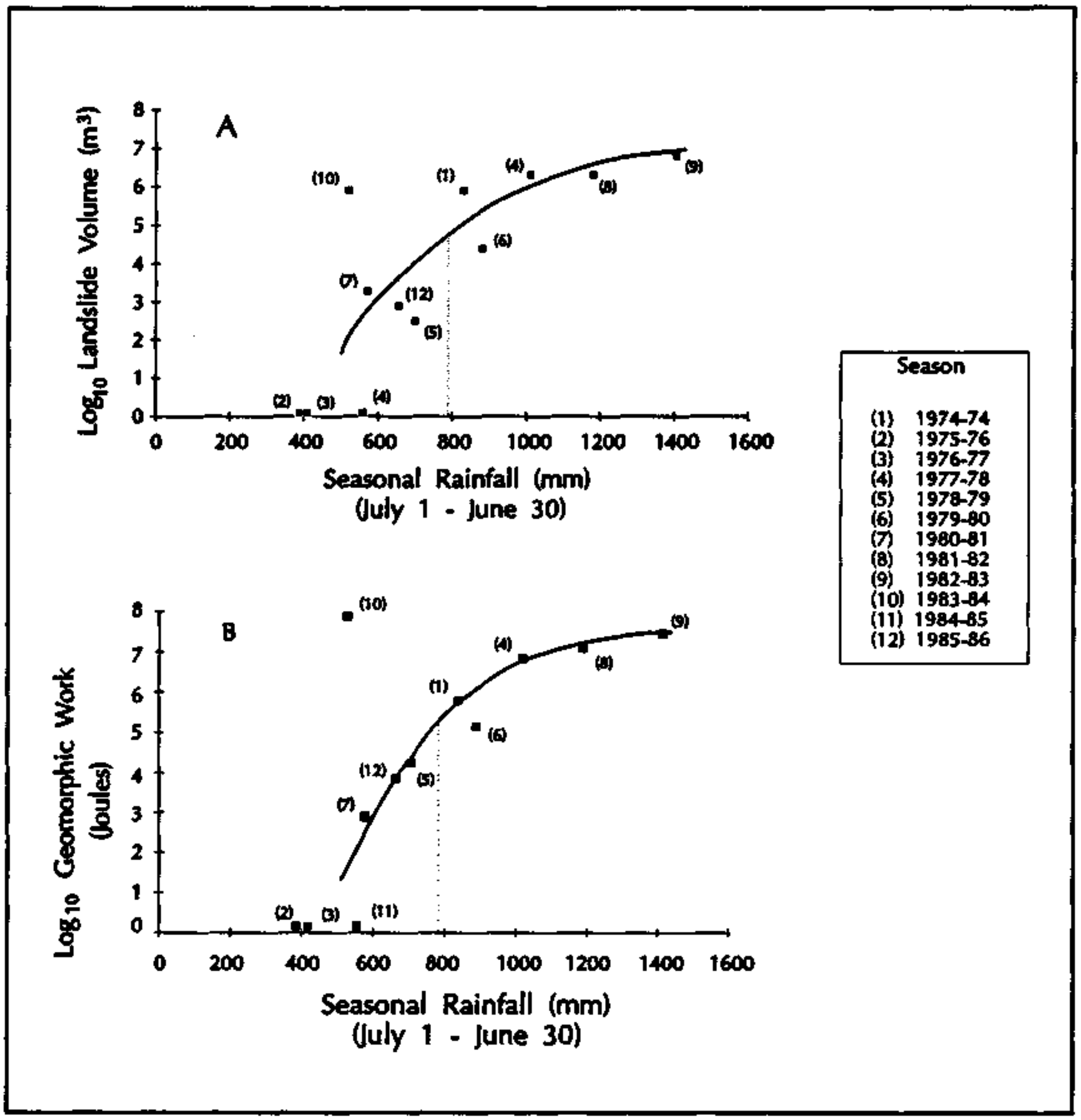

Figure 6: Relationship Between Seasonal Rainfall and Landslide Volume (A) and Geomorphic Work Performed by Landslides (B) (Wieczorek 1987). [Numbers in parentheses refer to individual seasons. Average seasonal rainfall indicated by dashed vertical lines. Values from 1983-84 season represent a single seismically-induced landslide. Curved lines show approximate relation between seasonal rainfall and landslide volume and geomorphic work for climatically-induced landslides.]

the soil (Ziemer 1981). Figure 7 graphically represents the relative reinforcement of soils by live roots as determined by *in situ* shear testing. The reinforcement by live roots generally increased while that by dead roots rapidly decreased with increasing time after clear-felling. The total reinforcement by live and dead roots dropped to a low point about 7 years after logging. O'Loughlin (1984) indicates that the tree root development enables young introduced conifer forests to begin substantially increasing slope resistance to shallow failures between 5 and 10 years after establishment.

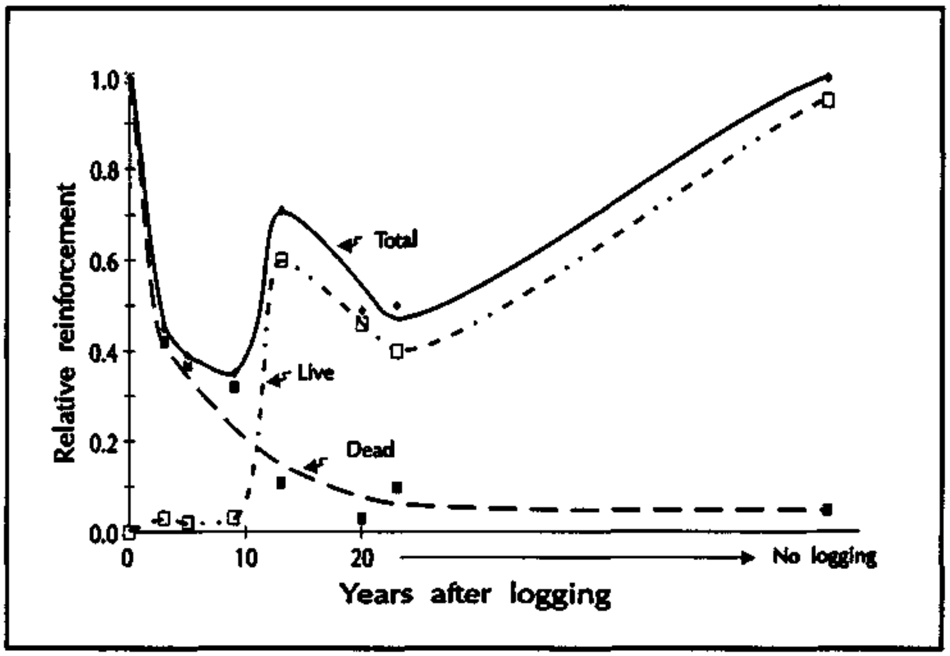

Figure 7: The Relative Reinforcement of Soils by Live Roots (Ziemer 1981)

In cohesionless soils where precipitation commonly provides sufficient water to induce slides in steep, timbered areas, slides can and do occur even without root decay (Schroeder and Brown 1984).

2.2. Types of Assessment

A number of methods for assessing slope stability and landslide hazard have been proposed by scientists working in Pacific Rim steeplands (Table 3). The prediction methods can be classed into three primary categories: deterministic (mathematical modelling), deterministic with a probabilistic term (stochastic[3] modelling), and terrain evaluations/failure inventories (history). Deterministic types of analysis imply soil and hydrologic consideration are known with precision. Natural variabilities in factors influencing stability lead to considerable uncertainty in estimating the factor of safety. To account for this uncertainty some assessment methods use a probabilistic term in the calculation for likelihood of failure. However, predicting the occurrence of failure at a particular site is not feasible when mass movements are frequent and widespread; predicting the general occurrence is most useful (Sidle *et al.* 1985).

Many studies have applied infinite slope analysis to determine natural slope stability in different regions (O'Loughlin 1972; Swanston 1974; Wu and Swanston 1980). Shasko (1989) provides a comprehensive review of the many deterministic modelling techniques. He examines the equations and implementation of twenty selected models. The models are then evaluated in terms of their potential to assess slope failure utilizing a geographic information system.

The infinite slope method assumes that the failure plane is infinite in length, making the use of a length parameter in the equation unnecessary. In effect, it assumes the length of the slope is much greater than the width of the potential failure plane and that edge- and end- effects are negligible. Water flow or seepage through the soil block is assumed to be

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[3] The word "stochastic" was originally used to describe a process which displays random fluctuations over time. Subsequently, a randomness over space has been interpreted as a "stochastic process".

uniform. All assumptions are fairly reasonable given actual failure characteristics in the Pacific Northwest.

Table 3 : Proposed Methods for Assessing Slope Stability in Pacific Rim Steeplands

Author	Type of Model	Area of Development
Brown and Sheu 1975	complex infinite slope	----
O'Loughlin & Pearce 1976	quantitative deterministic	SW New Zealand
Nielsen & Brabb 1977	factor overlays	California
Gage & Black 1979	landslide inventory & multiple-factor surveys	New Zealand
Crozier & Eyles 1980; Crozier 1982	predictive stochastic	New Zealand
Hicks & Smith 1981	multiple-factor assessment	Oregon
Ward *et al.* 1981	infinite slope	----
Rice & Pillsbury 1982	multiple-factor assessment	California
Sidle & Swanston 1982	multiple-factor assessment	Coastal Alaska
Burroughs 1984	deterministic	Oregon Coast Ranges
Rice, Thomas & Furbish 1984	stochastic - linear discriminant	California
Thomas & Trustrum 1984	historical - mechanical	New Zealand
Ziemer 1984	stochastic - Antecedent Precipitation Index	Alaska
Rollerson, Howes & Sondheim 1986	land unit interpretation & landslide inventory	Queen Charlotte Islands, Vancouver Island, SW coast of British Columbia mainland
Kobashi & Suzuki 1987	stochastic - antecedent rainfall	Japan
Rood 1990	regional parametric	Queen Charlotte Islands

Although instability in shallow soils is often treated as a one-dimensional problem, several authors have modified the basic equation to incorporate other physical considerations; particularly the strength provided by roots along the margins of a potential failure (Ward *et al.* 1981; Burroughs 1984; Tsukamoto and Kusakabe 1984; Reneau and Dietrich 1987). Selby (1982) provides modifications to account for non-uniform seepage directed out of the soil block (artesian). His model takes into account variations in the weight and height of the water and the soil weight. Similar equations for non-artesian and artesian conditions are presented by Sidle (1984). These models also consider vegetation weight and root cohesion. Gray and Megahan (1981) incorporate additional variables to account for root reinforcement, variable soil density, and the weight of the vegetation on granitic slopes. Wu *et al.* (1979) included contributions to shear stress caused by wind and to shear resistance due to root strength.

While several authors find that despite some uncertainties, analysis using the infinite slope model provide results in reasonable accord with the bulk of available field data (Blong 1981; Sidle *et al.* 1985), others question whether or not it is feasible to mount massive data collection programs to characterize the frequency distributions of soil properties for each management region or smaller unit (Dunne 1984; Ziemer 1984).

An empirical terrain evaluation method for predicting land susceptible to slope failure provides an alternative to classical engineering inquiry. In general, strictly deterministic techniques for estimating slope stability are not viable in an operational planning context. In almost all situations the knowledge of boundary conditions is incomplete and the requisite detailed precipitation, slope hydrology and other physical data may be limited, non-existent, or of highly variable quality (Rollerson *et al.* 1986).

One of the simplest and most widely-used methods of determining potentially unstable sites is through inventory and identification of the causes and sites of existing logging-related slope movements (Swanson *et al.* 1981; LaHusen 1984; Sauder 1984; Reneau and Dietrich 1987; Rood 1990). Terrain evaluations are often not simply aimed at the single issue of predicting future failure locations or triggering conditions. They vary from single-factor inventory (*i.e.* existing failures) through multi-factor mapping (slope, geology, present erosion *etc.*) to combinations of factors mapping with historical data (Sidle *et al.* 1985). Although there are limitations on the interpretation of such inventory data (Swanson *et al.* 1981), the principal advantages are the low cost, the ease in application, and the lesser requirements for skilled labour. This is a significant advantage where mass movements are frequent and where technology transfer to land management practitioners is inadequate (Sidle *et al.* 1985).

2.3. Science and Management

One could claim that the difference between stability assessment and stability prediction is the difference between site specific knowledge and broad regional understanding. Further, assessment could be seen as the science and prediction the art of steepland management. Frequently the desire "to know", characteristic of scientists, is at odds with the aims of the practical land manager. Increasingly complex models are employed in scientific investigation to simulate better the physical world. However, the controlling conditions are so complex (and often unknowable) that we fall back on associations of easily observable characteristics. So long as it remains accurate, the simpler the better can be seen as the manager's axiom.

Dunne (1984) reviews the limitations and potential of current methods of erosion prediction. He warns that progress in steeplands management can only derive from improved models of the physical process. He emphasizes the importance of physical understanding. Dunne's comments are quite appropriate for site specific situations but not for regional forest management. The models advance understanding at a site but do not necessarily increase the predictive ability for management. Most multi-factor prediction methods have large data requirements, are somewhat area specific, require high uniformity and quality of data, and, even at moderate scales, the labour requirements are intense (Sidle *et al.* 1985). Understandably, land managers are most interested in the difficulty in applying or interpreting a stability prediction method under normal management constraints of limited time, finances and technical expertise.

In light of this tension between science and management, the results of the analysis accomplished in this thesis may be of interest. The three slope stability methods under investigation are models based on (1) morphologic-genetic materials (SRS), (2) morphologic-genetic-performance (SGA), and (3) direct evidence of failure (ESA). They range in complexity from the simple (ESA) to the complex (SRS) to the highly complex (SGA).

2.4. Assessment Techniques Used in British Columbia

As described in the introduction (Table 1), there are two methods used operationally in British Columbia, Environmentally Sensitive Area (ESA) mapping and Slope Hazard Mapping (SRS). Two experimental methods, the Statistical-Geographic Approach (SGA) and Rood's parametric equations, are suggested. Additional to these specific techniques (discussed in the following sections), Howes and Swanston (1991) suggest a general procedure for recognizing unstable terrain and identifying areas affected by landslides. This procedure is quite similar to, albeit more elaborate than, the ESA approach. The steps for identifying potential and existing landslide areas and the hazard assessment they propose was not available until late in this study; its ability to predict slope stability was not investigated (see Appendix 1).

2.4.1. Environmentally Sensitive Area (ESA) Mapping

The objectives of the British Columbia ESA classification system include the following:

A. To identify areas that are environmentally sensitive or have values for other resources, including:

   (Es) Areas having actual or potential, fragile or unstable soils that may deteriorate unacceptably after timber harvest;

B. To identify the importance of streams, or stream reaches, to fish and the sensitivity of streams to forest harvesting;

C. To provide site-specific data on environmental sensitivity and on other resource values for consideration by forest planners and managers in the determination of the rate, location and timing of timber harvesting (Inventory Manual 1984 p 11).

ESAs are normally identified through photo interpretation, ground investigation, low-level helicopter flights, and data provided by other resource agencies and public interest groups. In each ESA category two ESA classes are recognized: high hazard (subscript 1) and moderate hazard (subscript 2). This implied three class system is used primarily to "flag" potential problem areas for further analysis before making the Annual Allowable Cut (AAC) netdown calculations. Forest land not having an ESA designation is subject only to operational constraints consistent with the policies of the forest regional district office.

The highest ESA class is applied to highly-sensitive forested terrain and/or to areas highly valuable for other resources. Es_1 is defined as "areas having extremely fragile or unstable soils" (Inventory Manual 1984 p 14). An Es_1 designation may reduce the timber cut in that polygon by approximately 90% (Laird 1990).

ESA Es_2 class is considered available for sustained timber production only under special management. Es_2 is defined as "areas having significantly fragile or unstable soils but less than those for Es_1" (Inventory Manual 1984 p 14). An Es_2 designation may reduce the timber cut in that polygon by approximately 50% (Laird 1990).

The Inventory Manual (1984) specifies that Es areas include sites of actual and potential excessive wind or water erosion and/or mass movement. The mapper is to consider only sites where forest harvesting could lead to "unacceptable site deterioration" for Es areas. Unacceptable site deterioration includes severe lowering of site productivity owing to the removal of soil necessary for plant growth, extreme delay in the re-establishment of protective vegetation and forest cover, long-term loss of the productive land base, and severe lowering of the quality of downstream water and degradation of fisheries habitats. The manual cautions that the "critical slope angles and susceptible terrain are listed with the understanding that surface erosion and mass movement can occur in almost any terrain if the conditions are right" (p 21).

Appendix 2 Tables A2.1 and A2.2 reproduces the technical guidelines for identification of areas for consideration as Es_1 and Es_2. Note that this system is almost completely process-based; evidence of previous failure is the primary criterion.

2.4.1.1. Implications for This Study

For this study, Es areas are identified through airphoto interpretation and use of the terrain classification maps at a working scale varying between 1:15,000 and 1:20,000. This differs from the usual Es application at the primary planning scale of 1:100,000.

With the usual application, some of these flagged potential-hazard sites are then field checked. Here, no ground-truthing was carried out after the areas were delineated.

2.4.2. Slope Stability Mapping

Slope stability mapping for the Queen Charlotte Islands was initiated by MacMillan Bloedel Ltd. in the early 1970's (Bourgeois 1974). Although the extent of areal coverage is dictated by the end user's needs, most British Columbia forest companies have embarked on an extensive program of slope stability mapping for forestry purposes (Rollerson and Sondheim 1985). Figure 8 contains suggested stability rating equivalents between mapping systems used by different groups while Appendix 3 Tables A3.1, A3.3 and A3.4 contain the details of each system's class ratings (*i.e.*the expected response of the terrain unit to forest harvesting and road development).

The mapping procedure begins with the production of a surficial geology map at an intermediate scale (1:15,000 to 1:25,000). Over the years the classification system has evolved from the original Geological Survey of Canada system to the British Columbia Ministry of the Environment 'Terrain Classification System' (ELUC 1976; Ryder and Howes 1984). This descriptive classification scheme is used to delineate terrain polygons homogeneous with respect to materials (genetic origin, texture), surface expression (including slope angle, slope form and material thickness) and geomorphic modifying processes. The terrain polygons are determined from airphoto interpretation and some field checking (typically, approximately 25% of an area is inspected).

Each terrain polygon is then subjectively assessed according to its failure potential following logging. Different agents have variously used three, four and five class stability ratings. These stability maps are highly interpretive with the class assignment methodology being subjective and often poorly documented. Map quality is considered to be highly dependent on the local knowledge of the mapper (Rollerson and Sondheim 1985).

The stability maps are subsequently used to guide road placements and yarding methods in the different terrain units. Although the format is decided by the individual company, stability maps must be used in conjunction with other data to formulate the long-term resource management plans which are required by the British Columbia Ministry of Forests before cutting permits can be issued.

2.4.2.1. Implications for This Study

Valid results are a function of the experience and expertise of the terrain analysts. With this in mind, I did not attempt to apply this method personally. One of the main criteria for selection of test sites to be used in this study was that terrain and slope stability mapping already existed and completed previous to logging the area. In subsequent discussion this assessment approach is referred to as the Stability Rating System (SRS).

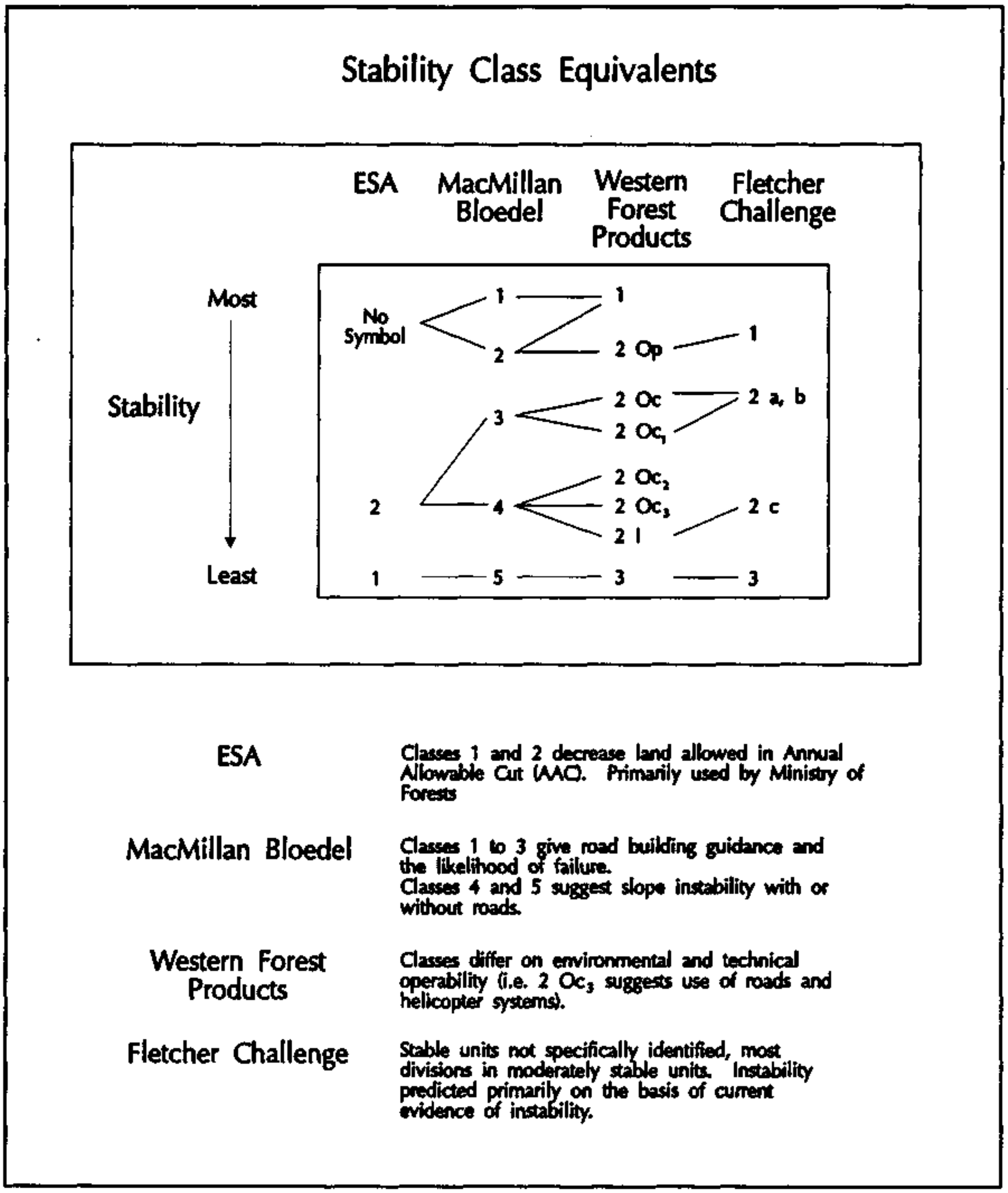

Figure 8: Suggested Stability Rating Equivalents Between Different Mapping Programs

2.4.3. A Statistical-Geographic Approach

This approach (SGA) evolved through the mid-1980's with contributions from many earth scientists in British Columbia. Methodological details and discussions of various aspects of the approach are found in papers by Howes (1982, 1987), Rollerson (1984), Sondheim and Rollerson (1985), Rollerson and Sondheim (1985), and Howes and Sondheim (1989). It is an empirical method for developing probabilities for post-logging landslide frequencies within varying terrain units. Terrain stability statistics are derived from detailed clearcut terrain inventories. The approach depends on statistical inference based on frequencies estimated over large geographical areas. The procedure involves five main steps:

1. The collection of terrain mapping and failure inventory data in a series of logged sites viewed as being typical for the larger region. The surficial geology is mapped using the British Columbia Terrain Classification System to define homogeneous areas with respect to material, texture, surface expression and process;

2. The definition of a new set of terrain classes such that each terrain polygon can be assigned to one and only one class;

3. The calculation of several stability statistics for each new terrain class, including the probability of post-logging failure;

4. Grouping of the terrain classes into a smaller number of consecutively numbered stability classes;

5. Generation of a failure probability map for unlogged terrain that is geomorphically and climatically similar.

Dominant surficial material, whether or not the hillslope is benchy or irregular, presence or absence of gullies, presence or absence of natural failures, average slope angle in degrees, average aspect in degrees, polygon area, and the number of presumed logging induced clearcut failures are the variables manipulated to produce a new classification.

Certain assumptions were made in choosing variables (i) to (vi). "Certain materials, such as till on steep slopes, are assumed to be comparatively more prone to failure. The presence of gullies or of natural failures suggests a potentially greater sensitivity to disturbances. Benchy or irregular slopes, or slopes with a significant proportion of bedrock outcropping are assumed to be more stable. Steeper slopes generally are less stable. If significant local rainshadow effects exist, east facing slopes in the study area may be less failure prone" (Sondheim and Rollerson 1985). Rollerson (1984) and Rood (1984), among others, have shown these variables to have a statistically significant relation specific to either road or clearcut failure frequencies.

The SGA is based on the terrain unit failure history. Designed to eliminate some of the subjectivity inherent in the stability rating systems most often used, it was developed as an extension of a more general project investigating landslide characteristics and the attributes of landscape units subject to post-logging landslide activity (Rollerson 1984). The approach has been explored in three areas: Norrish-Cascade Lower Mainland Vancouver (Rollerson *et al.* 1986; Howes 1987; Howes and Sondheim 1989); West Vancouver Island (Sondheim and Rollerson 1985; Rollerson and Sondheim 1985; Rollerson *et al.* 1986); and, the Queen Charlotte Islands (North Moresby) (Rollerson *et al.* 1986). Neither magnitude nor routing are taken into account; this method concentrates solely on debris slide occurrence and frequency.

Sondheim and Rollerson (1985) use the West Vancouver Island database to generate three terrain classifications using data taken from clearcut areas. The terrain was first inventoried at the scale of 1:20 000. Each polygon was then visited in the field and a set of data describing its geomorphic and geometric attributes recorded. The data recorded included surficial material present (including bedrock, in order of dominance), the presence or absence of natural failures, slope morphology including the presence or absence of gullies, soil type, elevation, slope angle, slope aspect, and slope position. Only areas with slopes greater than 20° were investigated. After all the data have been collected, Sondheim and Rollerson manipulate the variables using different assumptions to develop different terrain classifications. Their paper is mostly concerned with comparing the three classifications to see if they vary significantly in their stability implications. The authors include a detailed description of the study area and data collection; the development of the terrain class stability statistics, and the statistics used to compare the classifications.

A classification may emphasize topography, or materials, or processes or some combination of all these factors. Since the evaluation of any particular polygon or area depends upon the terrain class into which it falls, the question of validity of the classification used is raised. The three classifications developed in Sondheim and Rollerson (1985) can be described, respectively, as "remote sensing" (all factors can be determined from aerial photographs and topographic maps), "geomorphic" (ignores aspect but accounts for different types of surficial material), and "geomorphic plus aspect" (combination of the previous two). The comparisons do not clearly indicate which terrain classification is preferable although they do conclude that the terrain classification "geomorphic plus aspect" seems to perform best at identifying sensitive areas. It also has the greatest degree of discrimination of the three. However, they also suggest that the "remote sensing" classification would be the cheapest to apply and could provide quick results for large areas for general planning and assessment purposes.

The Rollerson, Howes and Sondheim (1986) paper succinctly describes the statistical-geographic approach, the development of the terrain classifications and stability statistics, and offers examples from the three different coast areas. For the West Vancouver Island data only the "geomorphic" classification (*cf.* Sondheim and Rollerson 1985; Rollerson and Sondheim 1985) is presented. They consider the Queen Charlotte Island example to be only a preliminary terrain classification as the data set is "quite small."

This methodology requires a much larger, more quantitative database than the Environmentally Sensitive Area mapping or the Slope Rating Systems. However, in many cases the information is easier to obtain since the forest does not obscure the landforms. Other than for test sites, this method has not yet been used operationally. In all the above-mentioned papers the authors state "... the real value of the exercise would come from applying the knowledge gained on the study areas to geomorphically-similar, unlogged areas." However, until now, only Howes (1987) attempts to extend the stability classification to adjacent unlogged terrain.

2.4.3.1. Implications for This Study

The first four steps are not attempted on the clearcut study areas of this project. Instead, the Queen Charlotte Island study sites are assumed to be geomorphically and climatically similar to the sites used to develop the Queen Charlotte Islands terrain classes reported in Rollerson *et al.* (1986). See Appendix 4 Table A4.1 for the terrain classifications used in this study. This Queen Charlotte Islands terrain classification is considered only a preliminary classification which may effect prediction accuracy. That the terrain stability statistics generated can be considered valid only within the local climatic region inventoried has implications related to the transfer of the classification from the calibration area to the operational areas. However, the two study sites chosen are in the same physiographic region and receive generally similar yearly precipitation totals as the calibration sites (see Figs. 2 and 3).

2.4.4. Parametric Stability Estimation

Failure inventory (Rood 1984) and statistical analysis (Rood 1990) suggests that, at the regional scale, factors known to influence landsliding (*i.e.* geology, aspect, physiographic region) are unimportant on the Queen Charlotte Islands (a position not necessarily accepted by all). From empirical data, Rood (1990) developed multiple regression equations to predict sediment yield to streams (YS) in $m^3\ ha^{-1}$. Using physiographic variables as measured on 1:50 000 maps:

$$YS = -2.46 + 0.11AS + 0.006PS\ (R^2=0.31;\ SE=0.78)$$

where AS is the average steepland slope (in degrees) and PS is the proportion of steeplands (%). For use with large scale aerial photographs, the following equations were developed:

$$YS = 9.0SF - 0.07\ (N=12;\ R^2=0.58;\ SE=0.69)\ \text{No footslopes}$$

$$YS = 1.9SF + 0.2\ (N=11;\ R^2=0.09;\ SE=0.36)\ \text{Footslopes}$$

where, SF is the total debris slide frequency (both gully and open slope slides). The equation for stream yield from basins with footslopes is not significant.

Rood finds that slope and slope shape are the most important site predictors of failure. These two variables could be used for parametric estimation of failure incidence using airphoto and map measurements. However, no regression equations were developed. If developed and proven useful, this could becomes the least subjective and most cost-effective method available. When complete, the British Columbian Terrain Resource Information Management (TRIM) data will facilitate attempts at parametric estimation of failure probabilities using non-interpretive digital elevation data analysis. Niemann and Howes (1991) investigate the potential use of Digital Terrain Models (DTM) for slope stability mapping.

2.4.4.1. Implications for This Study

Currently these equations offer a sediment yield to stream estimate valid only at the basin scale. In effect these equations integrate site instability over the entire basin. As a simple parametric method of estimating failure potential, the form of these equations fails to provide operationally useful predictions. Thus, for the purposes of this study these parametric equations are not useful for comparison with the three other methods.

CHAPTER 3. METHODOLOGY

Although there are numerous questions to be asked of the methods themselves, this study focuses on testing and comparing each method's predictions. To conduct a proper test of each method's predictive ability and to compare across the methods a study site must be subjected to analysis by all three methods. Aerial photographs flown before logging began are required. Slope failure frequencies by stability rating (as determined for each approach) for both treated (logged) and untreated (unlogged) areas then can be determined from recent aerial photographs. The methodology can be resolved into three main sections: (1) study site selection; (2) mapping and assessment; and, (3) statistical comparison of predictive success.

3.1. Study Site Selection

After determining the slope stability prediction methods to test: the MacMillan Bloedel Slope Rating System (SRS), the Rollerson, Howes and Sondheim Statistical-Geographic Approach (SGA) and the Ministry of Forest's Environmentally Sensitive Area (ESA) method; the next most important consideration was finding suitable study regions where all three methods could be applied. The primary criteria for selection included availability of pre- and post-logging aerial photographs at a suitable scale (1:15 000 to 1:20 000) and the existence of terrain and slope hazard rating maps of consistent quality, completed prior to logging.

Since terrain mapping had not reached its present reasonably standardized form until about 15 years ago, the mapping desirably should have been completed between 1975 and 1980. As the quality of mapping directly impacts the accuracy of prediction, the area must have been mapped (terrain and slope hazard) by an acknowledged[4] expert. Studies investigating the effects of root deterioration clearly demonstrate a slope failure acceleration window of 3 to 10 years following logging (see Figure 9). Therefore, the potential study site had to have been partially logged at least three years prior to 1989 (and desirably earlier) so that slope failure might be reasonably associated with that land use. The search for suitable study sites was limited to the most westerly parts of British Columbia since these areas have the longest history of application of these methods.

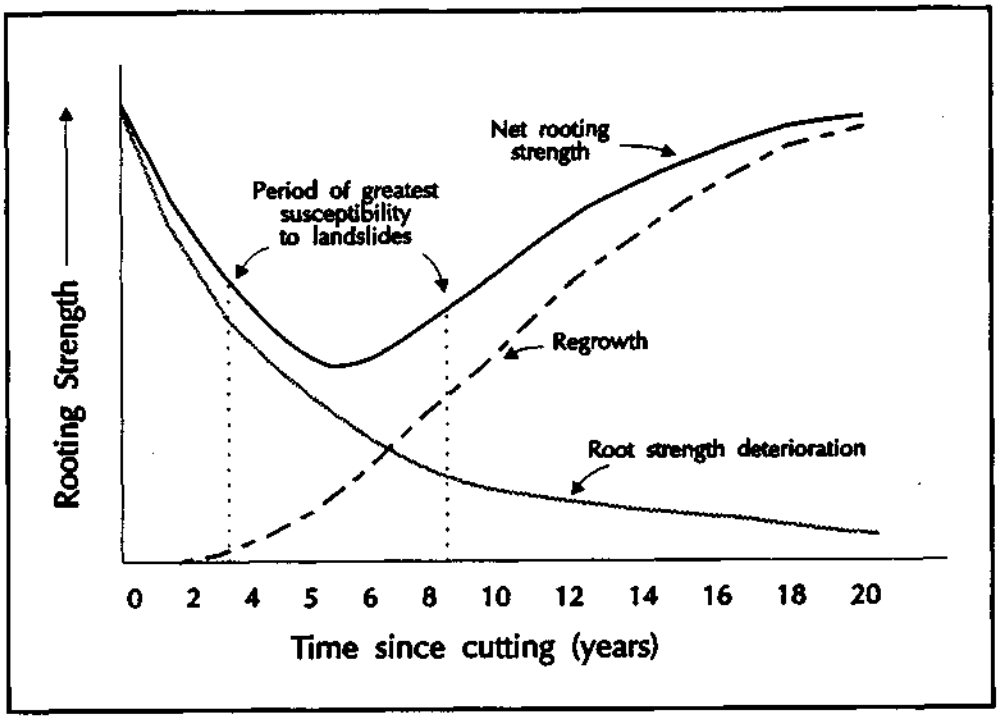

Figure 9: Hypothetical Curves Depicting Root Strength Conditions Through Time (Sidle 1985)

Seven potential sites were identified, six on the Queen Charlotte Islands and one on Vancouver Island. Primarily due to the time and labour involved in applying the

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[4]everal local authorities were consulted on who they considered consistent, high-quality mappers.

methods (see Table 5), final site selection limited analysis to two areas -- McClinton Bay and Louise Island . Although both study sites are TFL areas managed by MacMillan Bloedel, this forestry company was not singled out for any reason other than availability of all pertinent information.

3.1.1. Field Investigation

Each region was visited in August 1989. Both McClinton Bay area and Louise Island were reached by boat. Field work primarily consisted of driving all four-wheel-drive vehicle accessible roads to become familiar with the geomorphology in each area and to check slope failure visibility on available airphotos. Failures more recent than those visible on the photos were measured and marked on a map. Equipment included an abney level, range finder, and tape measure. Standard field data cards developed by MacMillan Bloedel were used to ensure consistency between site to site observations. This initial site investigation provided invaluable experience enhancing my ability to recognize the variety of slope failure types in the field (and on airphotos) and to determine slope angles and details of slope morphology.

3.2. Mapping and Assessment

All data used in this analysis were derived from aerial photographs, terrain classification maps, terrain stability maps and forest cover maps (Table 4). All pre-logging (herein referred to as "old") airphotos were flown by the Province of British Columbia and all post-logging (herein referred to as "new") airphotos were flown by MacMillan Bloedel and were available only with permission. MacMillan Bloedel generously provided all maps.

Table 4 : Data Sources

	Nominal Scale	McClinton Bay		Louise Island	
Aerial Photographs - old (Black and White)	1:20,000	BC77062	#202-205 #244-249	BC77062 BC77063 BC77064	#298-302 #13-23 #157-167 #192-198 #84-88
Aerial Photographs - new (Colour)	1:15,000	MB88006	#141-146 #165-170 #234-238	MB89005 MB88010	#152-160 #168-174 #282-290 #299-305 #370-381 #385-400 #433-448
Forest Cover Map (1985)	1:20,000	103F.067 / 103F.068		103B.091 / 103B.092 103G.001 / 103G.002	
Terrain Classification and Stability Maps - (1980)	1:20,000			103B.092	
Terrain Classification and Stability Maps - (1977)	1:20,000			103 B/13-7 103 B/13-8+ 103 B/13-9+ 103 G/4-2 103 G/4-3+	
Terrain Classification (1980)	1:20,000	103F.067 / 103F.068			
Terrain Stability (1977)	1:20,000	no identification			

The forest cover maps provided the date each cutblock was logged. The terrain stability maps gave the SRS stability ratings. The terrain classification maps describe the surficial material, material texture, surface expression, ongoing geomorphic process, slope angle, and soil moisture regime. These maps were used to enhance the photo interpretation required to complete ESA and SGA. Although MacMillan Bloedel has updated its terrain stability maps for the McClinton Bay area (Dunkley 1986), an older map (probably completed in 1977) was used in this analysis to preserve the aspect of "prior-to-logging" criteria.

3.2.1. Data Collection

The following section describes the data collected, how it was defined and the collection procedures.

The data required to answer the central question of this study are fairly basic. We need to know about the failure events (how many, where, what type) and the stability classes (areal extent in logged and unlogged terrain). This information was initially recorded on worksheets (see Appendix 5) and later summarized into the data tables in Appendix 2 (A2.3 and A2.4), Appendix 3 (A3.5 and A3.6), and Appendix 4 (A4.3 and A4.4). Additionally, each failure was identified as either a single event or as part of a complex. In some instances a broad zone of instability focuses into one distinct transportation zone. This zone of instability was delineated on the airphotos as one unit (*i.e.* given one identification number) but was recorded on the worksheet as the appropriate number of failure events.

Following Rood (1984) and Rollerson (1984) debris failures were recorded only if larger than 200 m^2 with visible initiation zones. The visibility requirement means that revegetation has not obscured the ground and that the feature is clearly visible on a pair of overlapping aerial photographs. Small debris slides can become obscured by vegetation in forested terrain whereas, in clearcut terrain, very small failures are easily identified. Imposing a 200 m^2 size limit avoids bias in distinguishing between logged and unlogged failure rates. Additionally, both Rollerson (1984) and Chatwin and Rollerson (1984) reveal that although smaller failures are common, they contribute only marginally to the total area of the land base disturbed by debris slides. Very old failures were not inventoried. Gully headwall complexes were grouped and counted as one failure.

For the purposes of this thesis, only a simple "type of failure" classification can be used as more subtle differences are often ambiguous on air photographs. Debris failure initiation zones are identified as either open slope, gully headwall, gully sidewall, active wall, or road-related. Gully headwalls are seen as the distinct facet upslope of an incised gully. Failures initiated on the wall of the incised gully are classed as gully sidewall failures. Active wall failures include features where the scar may represent a debris slide, an exposure of bedrock, or a laterally-extensive portion of a ravelling gully wall (Rood 1984). Active wall features do not have a classic landslip scar but still exhibit a zone of instability. Failures occurring just above or just below a road-bed are distinguished as being road-related. Failure events occurring just above a gully sidewall were listed as open slope with a comment indicating its relationship to a gully.

The data collection procedure is outlined by the flow diagram in Figure 10 and detailed, step by step, in the following paragraphs.

Step 1: Photo Preparation

On both old and new photographs the limits of the study area were delineated. Areal extent of the study area was defined by mapped coverage. When the scale differs between the airphoto and the map they cannot be simply overlain on a light table. Using a Saltzman Projector to overlay the two sources, the scales are matched by adjusting the projection height.

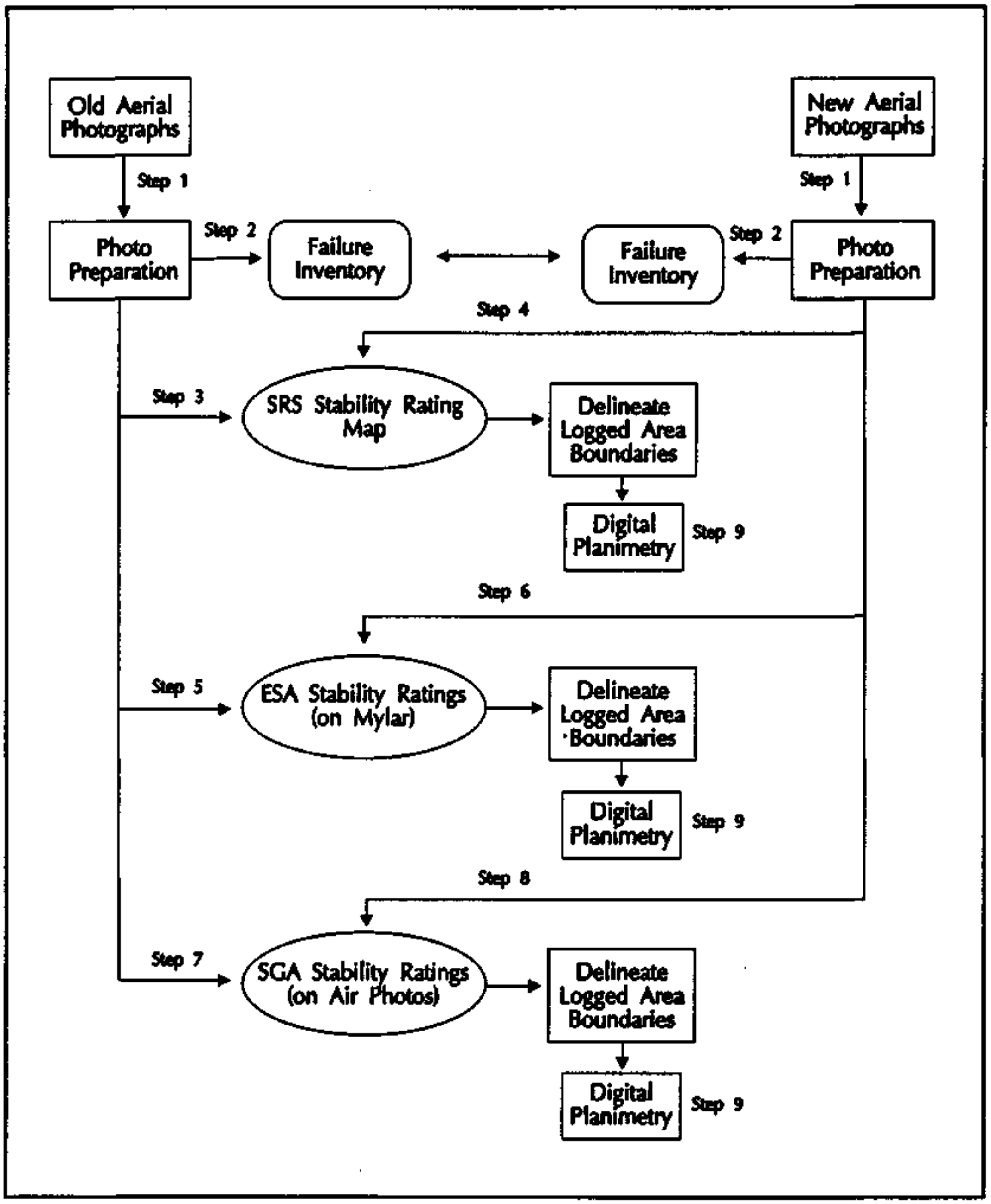


Figure 10: Flow Diagram of Study Mapping and Assessment Procedure

As a portion of land may be depicted on several photographs due to overlapping flight lines, one must ensure that a failure event is recorded only once, a terrain polygon depicted only once, and, the entire study region is represented without missing portions. Consequently, using a mirror stereoscope, one photo of a photo pair was assigned an area inside which the terrain stability units were mapped and the individual failures recorded. Effort was made to minimize the effects of distortion by choosing the photograph with that part of the study region close to the nadir. In other words, the entire study area was depicted in discrete, non-overlapping portions such that a land unit was inventoried and mapped on one photo only.

Step 2: Failure Inventory

Using standard airphoto interpretation techniques, all slope failure events greater than 200 m^2 were identified and delineated on the photo (within each unique area). Each failure was then given a number and recorded on a worksheet. Then, using the Saltzman projector to match the old and new photos, the old failures were cross-referenced so as to identify failure events new since 1977.

Step 3: Assess Failure Rating - SRS old

Old airphotos were superimposed on the paper SRS map and the stability rating for each failure event recorded. In some cases simple overlay techniques on a light table were used since the nominal scale of both the old airphotos and the SRS map was 1:20,000. However, topographic distortion often made it necessary to use the projector to achieve a better local area fit.

Step 4: Assess Failure Rating - SRS new

New airphotos were superimposed with the paper SRS map using the Saltzman projector and the stability rating for each failure event recorded. Then, on the map, the superimposed cutblock boundaries were delineated so that the polygons could be measured to obtain areal extent of both logged and unlogged terrain by stability class (Step 9).

Step 5: Map Es Ratings onto Old Airphotos

By airphoto interpretation, using a mirror stereoscope, the Es_1 and Es_2 polygons were delineated on mylar overlays. See Appendix 2 for technical guidelines for identification of Es areas.

Step 6: Assess Failure Ratings - ESA Approach

The new photographs were projected onto the old photographs with Es stability ratings and the stability rating for each failure recorded. By Es definition, all previous failures appear within an Es_1 polygon. Then, on the mylar, the superimposed cutblock boundaries were delineated so that the polygons could be measured to obtain the areal extent of both logged and unlogged terrain by stability class (Step 9).

Step 7: Map SGA Terrain Ratings onto Old Airphotos

By airphoto interpretation, using a mirror stereoscope, the eight SGA terrain polygons were delineated on the airphoto using washable ink. The polygons were identified in order of these four primary characteristics:

(1) failures present; (2) gullied terrain (2 classes based on slope angle); (3) slope angle (3 classes); and, (4) moisture content (2 classes). See Appendix 4 Tables A4.1 and A4.2 for the QCI - SGA terrain classification definitions and associated stability ratings. An additional class 0 (none of the above) was also mapped. A gully headwall failure had its initiation zone delineated as terrain class 1 and the rest of the gully as a gully feature (class dependent on slope angle).

Step 8: Assess Failure Ratings - SGA

The new photographs were projected onto the old photographs with the SGA terrain polygons and the stability rating for each failure event recorded. By definition all previous failures are contained within terrain class 1 (stability class 5). Then, on the old airphotos, the superimposed cutblock boundaries were delineated so that the polygons could be measured to obtain the areal extent of both logged and unlogged terrain by stability class (Step 9).

Step 9: Digital Planimetry

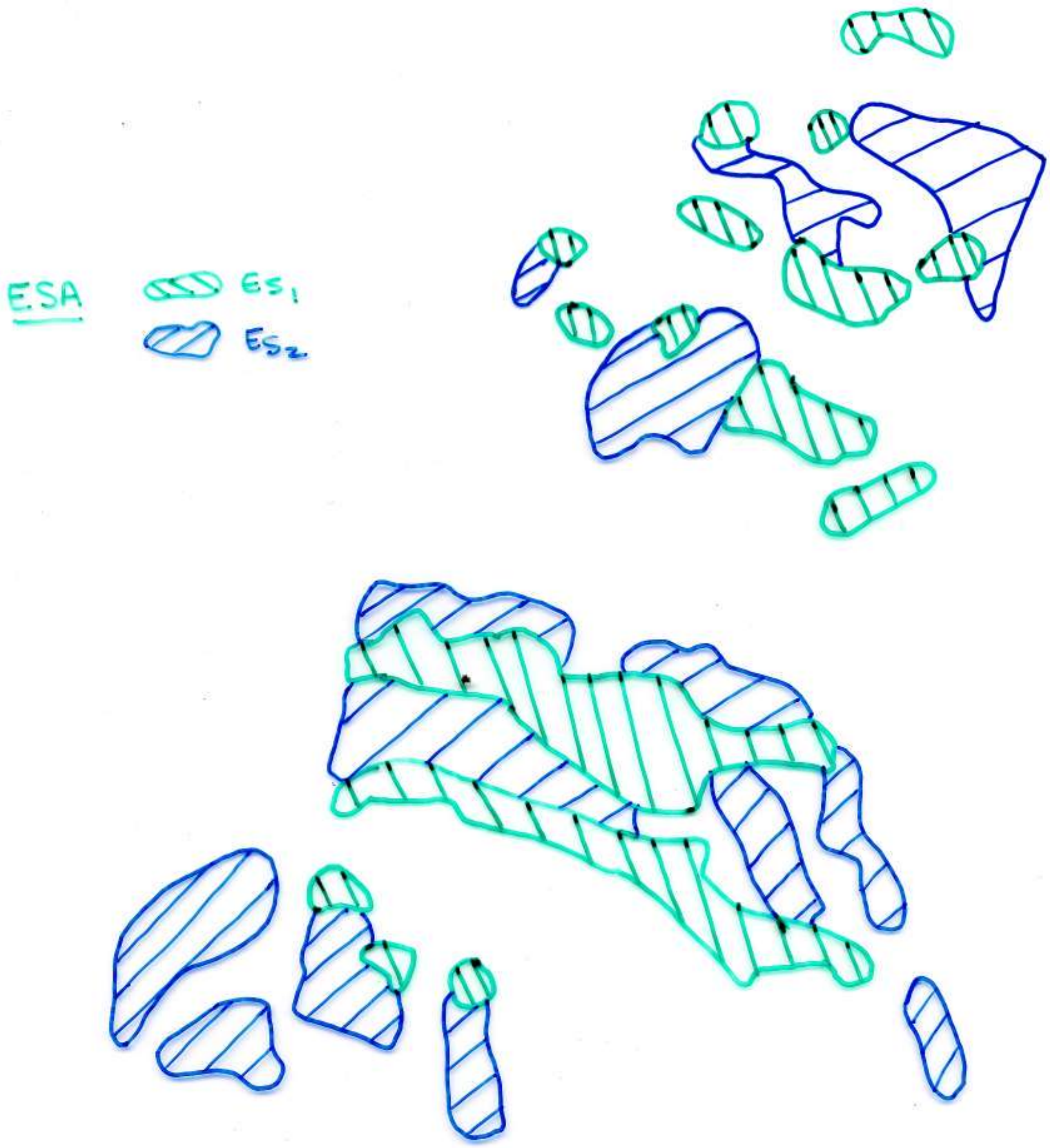
The areal extent of each stability class was measured after each of Steps 4, 6 and 8. Before digital planimetry began each polygon was given a number and colour-coded for ease in distinguishing between logged and unlogged polygons. Since digital planimetry is very sensitive to the smallest deviation from the polygon outline, each polygon was traced three times and the average recorded. This step was extremely time consuming in light of the large number of polygons generated by each method (Table 5).

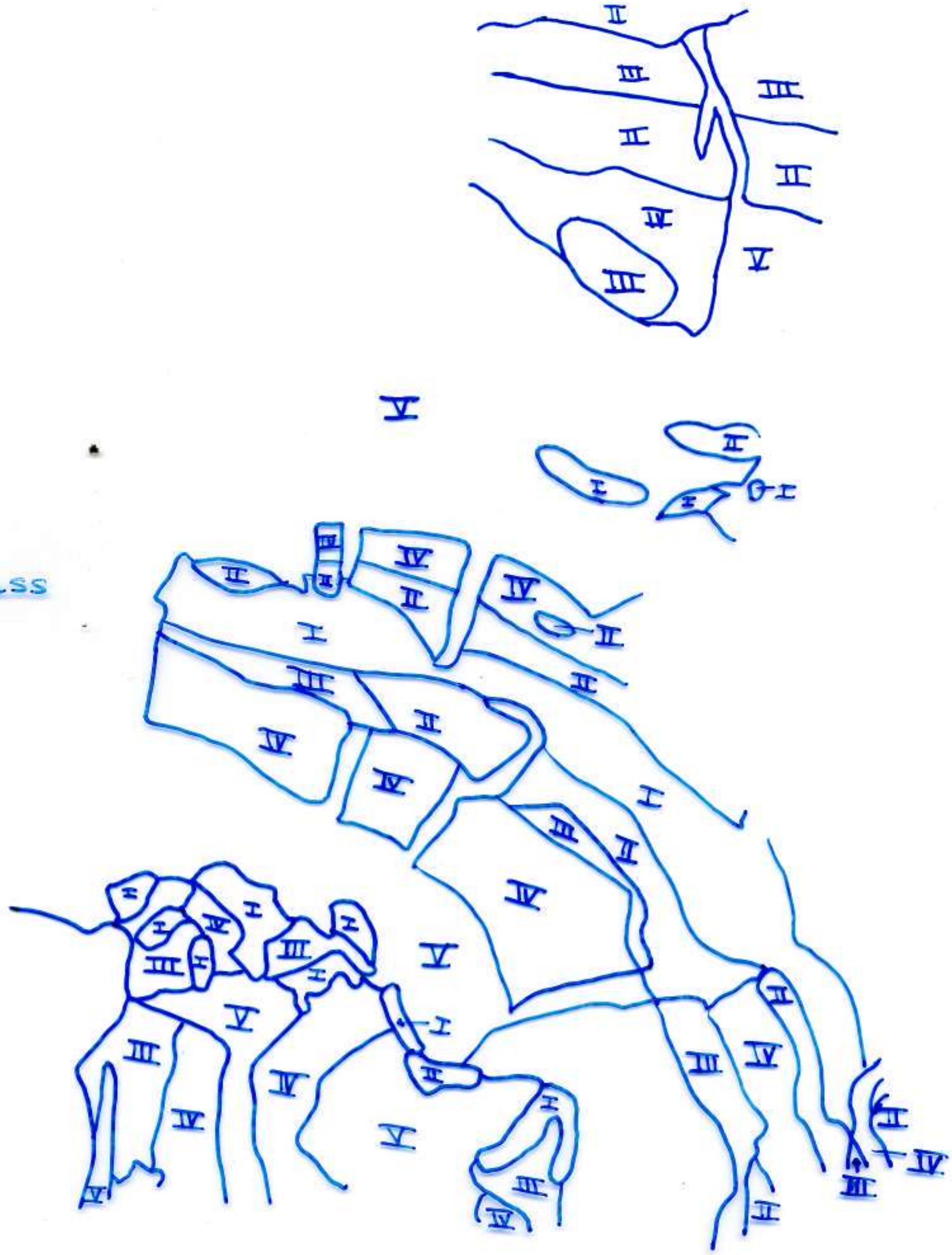
Figure 11 depicts an area on Louise Island with SGA units mapped directly onto the airphoto with ESA and SRS overlays.

Table 5: Number of Stability Polygons Generated by Each Method.

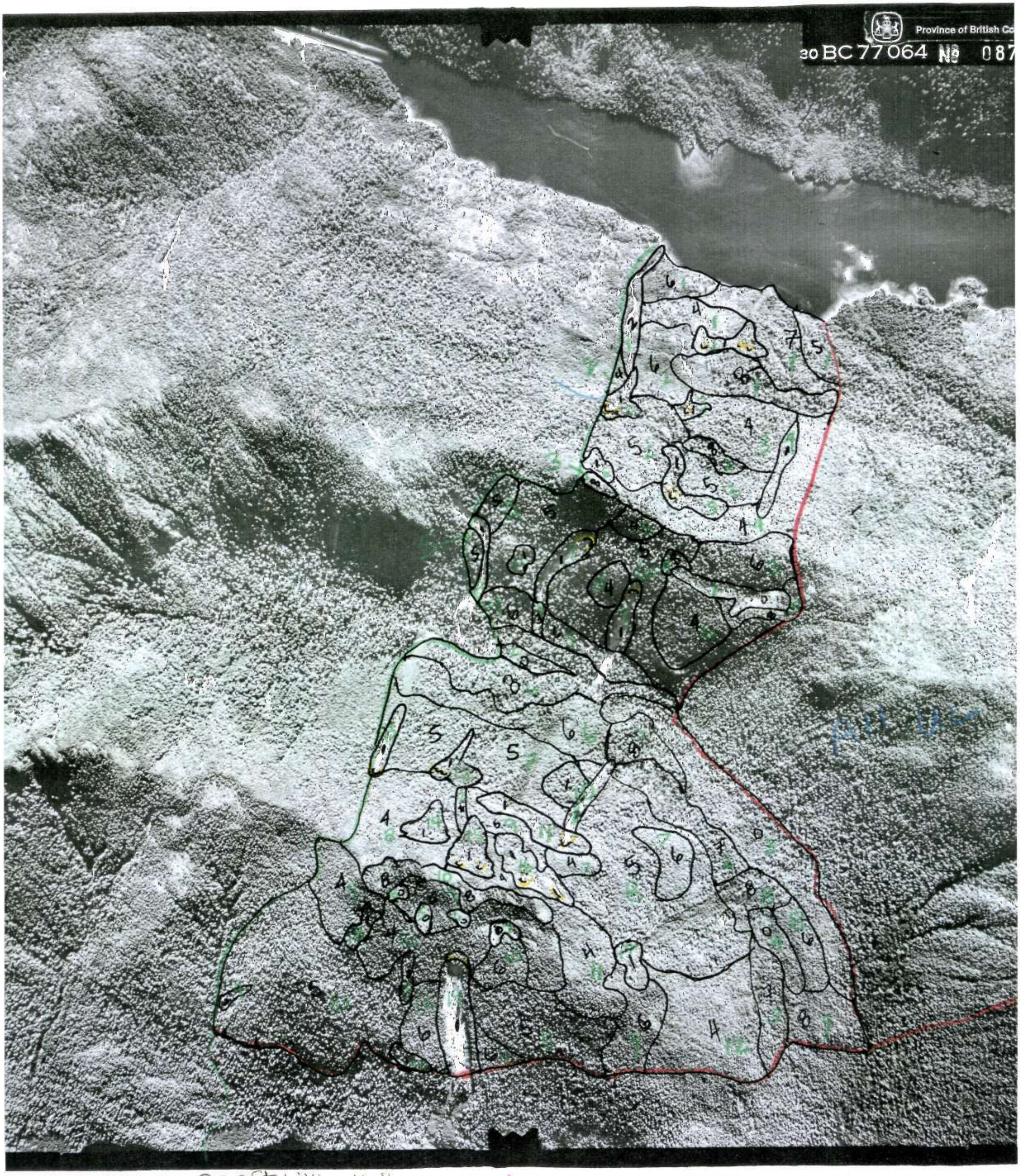
Method	Stability Class	McClinton Bay Unlogged	McClinton Bay Logged	Louise Island Unlogged	Louise Island Logged
SRS	1	15	17	107	62
	2	32	20	174	97
	3	31	16	155	86
	4	21	21	174	83
	5	19	26	110	72
	Totals	118	100	720	400
SGA	1	86	45	448	229
	2	53	27	272	147
	3	2	2	21	16
	4	49	17	346	142
	5	48	10	165	52
	Total	238	101	1252	586
ESA	2	23	9	117	78
	1	32	9	160	73
	Total	55	18	277	151

Figure 11: Airphoto of Louise Island with SGA Mapping And ESA and SRS Overlays


ESA
Es1
Es2



SRS - 5 Class



SGA Stability Units

↑ measure -

3.2.2. Commentary on Potential Sources of Error

Air Photo Interpretation

Debris failure events had to be visible to be recorded. Overall the aerial photographs were very clear and cloudless but some failures could have been missed in shadowed areas. The small number of features that could not be positively identified as debris failures were left undelineated. In forested terrain, a failure was given an open slope classification unless a gully channel was clearly visible below the failure. This could be a potential problem since some features may be actually gully headwalls but we cannot know this until that area is logged or field surveyed. Very small slides might have been missed under the forest canopy.

In cases where an old failure became engulfed by a newer failure (that had a different initiation point), the newer failure is counted as entirely different. Similarly, an old headscarp showing more recent failure on the new airphoto was considered a new failure.

Saltzman Projector

One of the most frustrating aspects of this research was "fitting" the new airphoto to the old airphoto and the maps. The scale differed as did the perspective. Therefore, visual angle changes influenced the photo/photo and photo/map matching. Additionally, due to topographic distortion, local area fitting was required where the photo/map might fit well in one spot but then need to be moved or have the projector readjusted for another area on the same photo. The need to "fudge" the location of the map/photo match was largely dependent on the slope of the terrain. Obviously this could influence a failure event's stability rating allocation. Water lines and ridge heights drawn on stability maps were employed to help match the evidence on the airphoto.

Digital Planimetry

Planimetric area measurements are made by tracing the perimeter of an area. The digital planimeter used is estimated to be accurate to within 5% of the true area, however, slips while tracing the hundreds of different-size polygons can be expected. This type of error was minimized by recording the average area after measuring each polygon three times.

As always, when recording three dimensional data on a two dimension surface, the area depicted is a "projected" area not the "true" area. The difference between the projected and true area is influenced by topographic distortion and photographic displacement. The areas measured from paper maps are considered most accurate since photogrammetric distortion was removed during map creation. Although each study region's size should match, whether determined by tracing the area from a map or from the airphotos, they do not. The differences (or sources of error) range from: (1) inaccurate placement of the outer boundary on the airphotos; (2) use of the "nominal" scale when scale varies substantially across an airphoto especially in high relief terrain; and, (3) unknown complex interaction between topography and off-nadir distortion. Off-nadir error was minimized by mapping polygons close to the nadir. The SGA terrain polygon areas were "corrected" by multiplying each area total by

$$\Sigma A_m / \Sigma A_{SGA}$$

where A_m is the total area delineated on the paper maps and A_{SGA} is the total area determined from the airphotos (see Table A4.5). This assumes the errors apply over all areas and the mapped area is correct in absence of any other linear magnification error. As the ESA areas are partially derived from SRS measurements, they were left uncorrected.

Method of Mapping

At the time they were compiled, the SRS stability polygons were checked in the field to correct or confirm any units the mapper considered doubtful. Accuracy of stability interpretation for both SGA and ESA approaches would be improved with ground-truthing. Time and monetary considerations did not permit this undertaking. This probably introduces some error, especially in polygon boundary placement which could cause a failure to be rated inappropriately.

Although the determination of slope angle using a parallax bar is straightforward, when mapping large areas making precise slope angle measurements is not practical. Interpretation and judgment were used in mapping the stability polygons defined by slope angle. Misjudgment would influence the perceived prediction accuracy of these methods.

3.3. Statistical Comparisons of Predictive Success

The size of each study region was determined by the area mapped with stability ratings. Each study region differs in size, in proportion of the land area logged, and in the number of debris failures experienced. Similarly, each prediction method classifies a differing portion of land into each of its stability classes. The only suitable means of comparison is proportional (percentages) and dimensionless data (*i.e.* number of failures per unit area). Failure frequencies per unit area are the analytical unit utilized for statistical comparisons of predictive success.

Distribution-free or nonparametric tests are generally less powerful than their parametric counterparts. However, they are most useful in situations where parametric procedures are not appropriate: when the data are nominal or ordinal, or when interval data are drawn from markedly non-normal distributions. Two nonparametric statistical techniques, the Mann-Whitney *U* Test and Spearman's Rank Correlation are employed in the analysis.

3.3.1. Mann-Whitney *U* test

The Mann-Whitney test, also known as the Wilcoxon test, does not require assumptions about the shape of the underlying distributions. This is the nonparametric alternative to the Student's-*t* test for difference between two independent means. It tests the hypothesis that two independent samples come from populations having the same distribution. The form of the distribution need not be specified. The test does not require that the variable be measured on an interval scale; an ordinal scale is sufficient. The principal requirement is the need for two independent random samples and continuous random variables. For our purposes this test is used to determine if the two regions are responding similarly to the methods. Johnson (1984) puts the *U* test efficiency at 0.95 that of the Student's-*t* test.

To compute the test, the observations from both samples are first combined and ranked from smallest to largest. If two observations have the same value then the data would be arbitrarily assigned the rank that is an average of the two ranks the data would have been (*i.e.* identical observations that would rank 3 and 4 would be assigned rank 3.5). The statistic for testing the hypothesis that the two distributions are equal is the *sum of the ranks* (R) for each of the two groups (a and b). If the groups have the same distribution, their sample distributions of ranks should be similar. If one of the groups has more than its share of small or large ranks, there is reason to suspect the two underlying distributions are different. Then using the sum of ranks, calculate the *U* score for each sample. The smaller *U* score is the test statistic.

$$U_a = [n_a * n_b] + [\ (n_b)\ (n_b + 1) / 2\ ] - R_b$$
$$U_b = [n_a * n_b] + [\ (n_a)\ (n_a + 1) / 2\ ] - R_a$$

3.3.2. Spearman's Rank Correlation

The Spearman's rank correlation coefficient, r_s, is the non-parametric alternative to the linear correlation coefficient. Only rankings are used in the calculation of this coefficient:

$$r_s = [1 - 6\Sigma(d_i)^2] / [n(n^2 - 1)]$$

where d_i is the difference in the rankings and n is the number of pairs of data. r_s ranges from -1 to +1. The null hypothesis is that there is no correlation between the two rankings. We fail to reject H_0 when r_s is close to 0 and reject H_0 when r_s is close to either -1 or +1. Johnson (1984) puts the r_s test efficiency at 0.91 that of Pearson's linear regression "r" statistic.

3.3.3. Cross Tabulation

Each failure was categorized into a stability class as defined by each method. The results can be compared to ascertain the degree of failure rating correspondence between the classifications. Sondheim and Rollerson (1985) and Howes and Sondheim (1989) also take this approach to compare different terrain classification results. The tabular comparisons present the stability ratings based on one prediction method in comparison with the other two methods. The method with the greatest degree of predictive accuracy will be regarded as the "true" value for the polygon such that this will be considered the independent variable.

The sum of the main diagonal element of the matrix divided by the total number of observations defines the statistic p; p indicates the proportion of the observations which are classed the same for both classifications. When two classifications are completely equivalent, p equals one (or 100%) and all values not on the diagonal are zero. Two other concepts, the "user accuracy" and the "producer accuracy" (Storey and Congalton 1986) are of interest (*cf.* Howes and Sondheim 1989). The "user accuracy" can be considered as the percentage of the failures classed by the dependent classification that concurs with the "true" classification. For example, if the row total for stability class 1 is 27 and the number of failures that fall within column one (also stability class one) is 8 then the user accuracy is 30%. Similarly, if the column one total is 45 (this is the number that should be rated as class 1) then only 8 failures or 18%, are rated "correctly." Producer accuracy is of most interest to the mapper.

CHAPTER 4. CONTEXT AND DATA ANALYSIS

4.1. Data Organization

All data are tabulated by region, by prediction method, by occurrence in logged or unlogged terrain, and in order of lowest to highest predicted stability risk. As discussed previously, the Stability Rating System (SRS) is a 5 Class system, the Statistical-Geographic Approach (SGA) used here is an implied[5] 6 Class system, and the Environmentally Sensitive Area (ESA) method is an implied 3 Class system. In order to compare the methods the more detailed approaches were reduced to 3 classes as illustrated in Table 6. The new class groupings are reasonably consistent with the definitions in the original classifications.

Table 6: Stability Ratings for Each Prediction Method

SGA			SRS		ESA
6 Classes	5 Classes	3 Classes	5 Classes	3 Classes	3 Classes
0					
1	1	1	1	1	0
2	2		2		
3	3	2	3	2	2
4	4		4		
5	5	3	5	3	1

The raw data consist of the number of failures, the areal extent of each stability class, and the type of each failure. Grouped by method, the raw data are found in Appendix 2 Tables A2.3 (McClinton) and A2.4 (Louise), Appendix 3 Tables A3.5

[5]implied" means that a specific number of categories are specified and what is left over (in both these cases always the lesser sloping areas) comprises the nth category.

(McClinton) and A3.6 (Louise), and Appendix 4 Tables A4.3 (McClinton) and A4.4 (Louise). Since the two regions are not of comparable size, only proportional data and the failure frequencies may be used for true comparison between the regions.

As noted in Section 3.2.1 area measurements were made by digital planimetry. SRS measurements were all made from paper maps. Both SGA and ESA terrain polygons were measured from air photographs. SGA areas were rectified to "truer" areal coverage by multiplying each terrain class area total by an error correction (See Table A4.5 for details). This explains the difference (< 5%) between the size of each study region as determined by each method.

4.2. The Two Study Regions

Although the actual number of failures and areal extent differ between McClinton Bay and Louise Island, proportionally, several characteristics are similar. For example, both regions have (1) less land logged than unlogged (Fig. 12); (2) more failures in logged than unlogged terrain (Fig. 13); (3) a larger logged-area failure frequency than an unlogged-failure frequency (Fig. 14); and, (4) a similar distribution of type of failures (Fig. 15). The two regions experience a similar mean annual total precipitation of approximately 2035-2225 mm/yr (Hogan 1985; Hogan and Schwab 1990). Table 7 lists points of comparison unrelated to stability prediction method between the two regions.

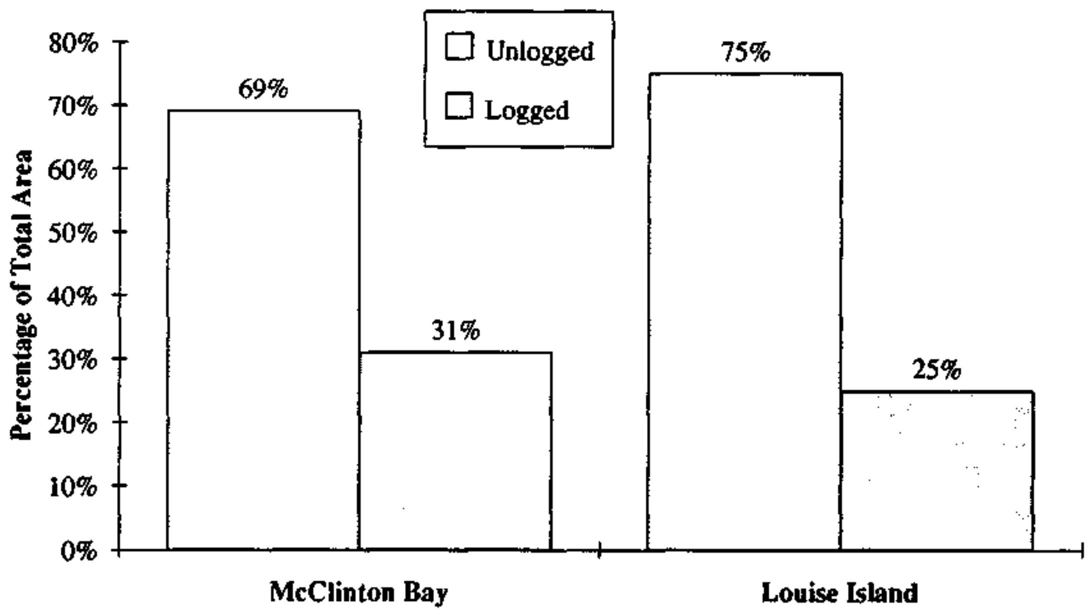


Figure 12: Percentage of Logged and Unlogged Terrain

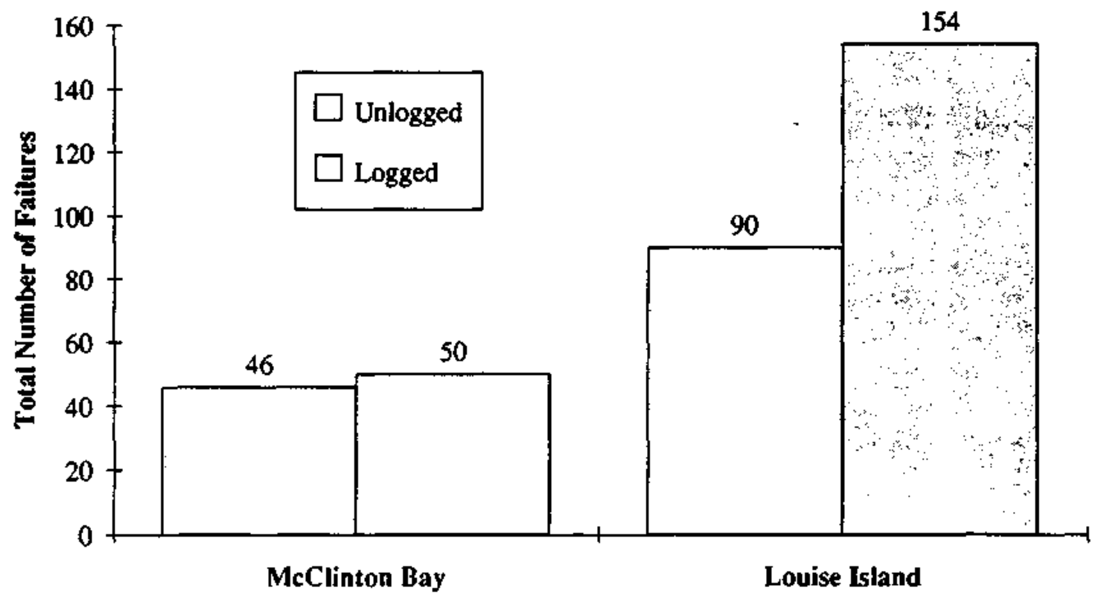


Figure 13: Absolute Number of Failure Events

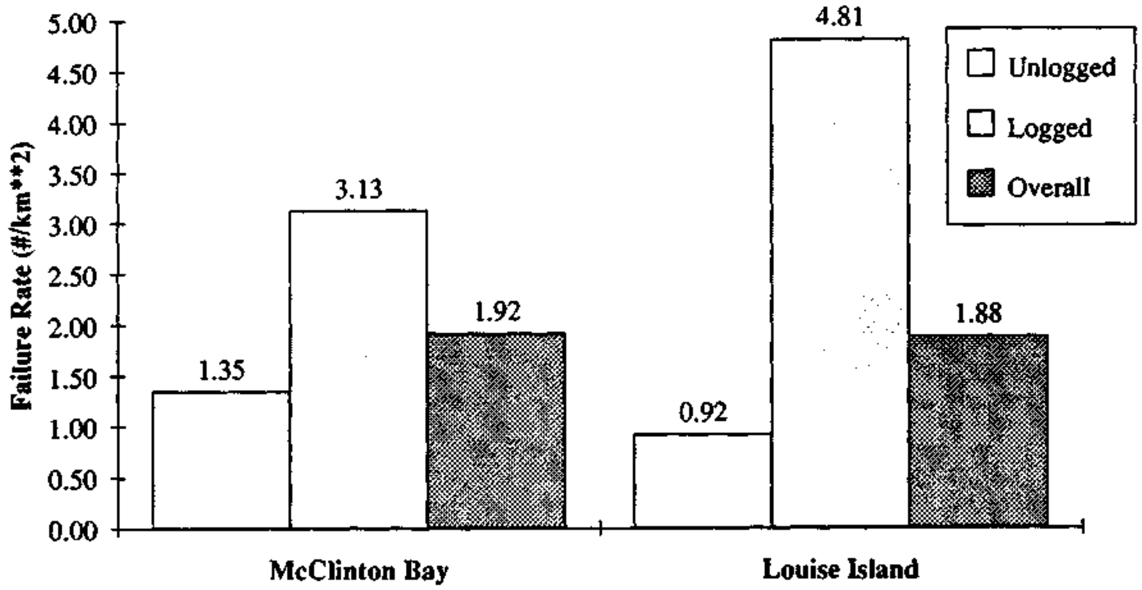


Figure 14: Failure Frequency Per 100 Hectares

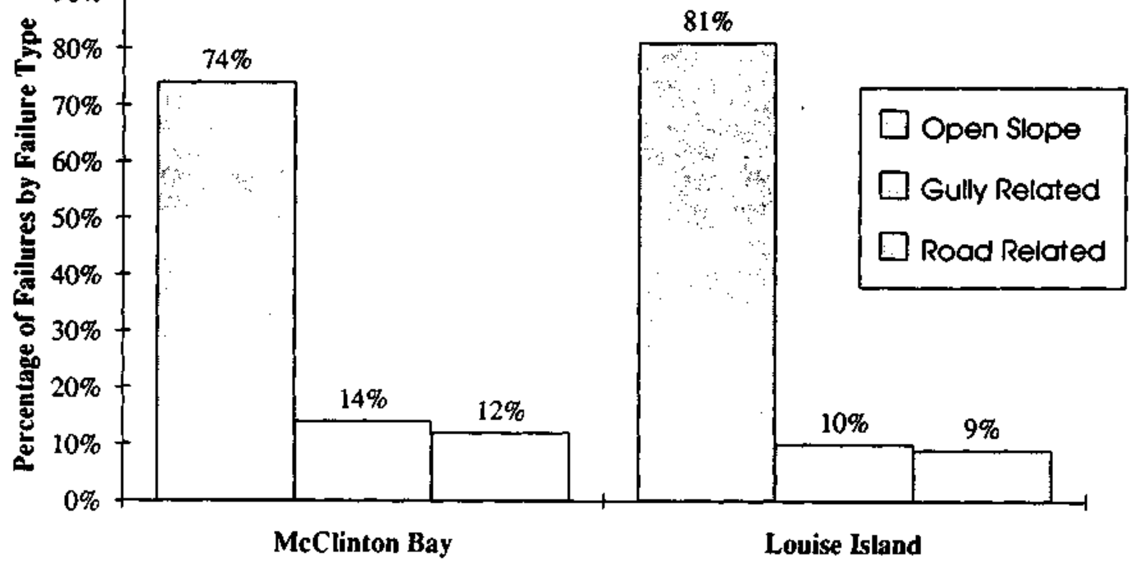


Figure 15: Failure Types as a Percentage of Total Events

Table 7 : Comparisons Between McClinton Bay and Louise Island

			McClinton Bay	Louise Island
Area (km^2)		Total	50	130
		uL	34	98
		L	16	32
Number of Failure Events		Total	96	244
		uL	46	90
		L	50	154
Failures / km^2		Overall	1.92	1.88
		uL	1.35	0.92
		L	3.13	4.81
Type of Failure (Number of Events)	Open Slope	uL	45	81
		L	26	118
	Gully-Related	uL	1	8
		L	13	15
	Road-Related	uL	-	1
		L	11	21

uL = Unlogged Terrain
L = Logged Terrain

At McClinton Bay the majority of failures (52%) occurs on the 32% of the land that is logged. Similarly, Louise Island has 63% of failures on the logged 25% of the land base. Their overall failure frequencies (#failures/total area) are very similar, differing by only 0.04 failures per km^2. However, the difference between the unlogged and logged area failure frequencies varies substantially between the regions. McClinton Bay's logged-area failure frequency is only 2.3 times that of the unlogged-failure frequency. In contrast, Louise Island's logged-area failure occurrence is 5.2 times that of the unlogged rate.

Open slope failures substantially dominate over gully-related and road-related failures (as a percentage of the total), with a ratio of 6.2 open slope to 1.2 gully-related to 1 road-related failures for McClinton Bay and a ratio of (9):(1.1):(1) for Louise Island.

Unsurprisingly, all but one road-related failure event happened in logged terrain. Table 8 lists the frequency of failure for different event types and the rate of increase related to logging. We find that the logged-area open slope rate of increase varied from 1.2 to 4.5 times, the gully-related accelerated failure frequency ranged from 6.1 to 24 times, and the road-related increase went from 0 to 60 times. The high magnification factors for gully- and road-related failures result from the nearly zero occurrence prior to logging. In both cases, the absolute rate remains lower than on open slopes.

Table 8: The Number and Frequency of Failure Events by Failure Location Logged and Unlogged Terrain

	McClinton Bay						
	Unlogged			Logged			Rate relative to
	No.	No./km2	No./km^2/yr	No.	No./km^2	No./km^2/yr	unlogged areas
Open Slope	45	1.32	0.12	26	1.63	0.147	x 1.2
Gully-related	1	0.03	0.003	13	0.81	0.073	x 24
Road-related	-	-	-	11	0.69	0.063	-
Total	46	1.35	0.12	50	3.13	0.28	x 2.3
	Louise Island						
Open slope	81	0.83	0.075	118	3.69	0.335	x 4.5
Gully-related	8	0.08	0.007	15	0.47	0.043	x 6.1
Road-related	1	0.01	0.001	21	0.66	0.060	x 60
Total	90	0.92	0.083	154	4.81	0.438	x 5.2

Note: assumes an 11 year record

Interestingly, when looking at absolute differences between McClinton Bay and Louise Island individual stability class failure frequencies (separated into logged and unlogged failure frequencies) (Table 9), we find reasonably small differences for the lower stability class (1-4) and large differences for stability class 5. The SRS data do not exhibit a great difference in overall failure frequency. The SGA results present a slightly different pattern in that the average difference between McClinton and Louise is very small in unlogged terrain but quite large for logged terrain. ESA results also differ between McClinton and Louise logged and unlogged terrain.

Table 9: Individual Stability Class Logged and Unlogged Failure Frequencies

Stability Rating	SRS Failure per km^2						SGA Failures per km^2						ESA Failures per km^2					
	McClinton Bay			Louise Island			McClinton Bay			Louise Island			McClinton Bay			Louise Island		
5 Class	uL	L	Total	uL	L	Total	uL	L	Total	uL	L	Total	uL	L	Total	uL	L	Total
1	0	0	0	0	0.27	0.05	0	1.83	0.56	0.16	0.99	0.35						
2	0	0.72	0.21	0.16	1.86	0.80	3.03	3.49	3.20	1.30	4.53	2.27						
3	0.25	2.11	1.03	1.30	4.35	2.40	0	0	0	0	0	0						
4	0.79	13.38	3.10	1.09	11.73	3.31	0.99	8.56	3.39	2.03	13.00	4.83						
5	11.02	22.73	12.86	3.32	14.96	5.16	6.19	6.67	6.23	3.56	25.35	6.38						
Overall	1.35	3.13	1.92	0.92	4.81	1.88	1.34	3.20	1.93	0.93	4.77	1.88	1.35	3.13	1.92	0.92	4.81	1.88
3 Class																		
1/0	0	0.51	0.17	0.04	1.07	0.29	0.82	2.40	1.34	0.52	2.41	0.94	0.22	1.25	1.34	0.27	2.69	0.79
2	0.49	4.35	1.77	1.19	6.78	2.82	0.99	8.12	3.32	1.98	12.10	4.66	1.21	10.45	3.32	2.17	5.26	3.41
3/1	11.14	22.73	12.88	3.32	14.96	5.16	6.19	6.67	6.23	3.56	25.35	6.38	7.29	24.98	6.23	4.53	24.19	8.25

MB = McClinton Bay

LI = Louise Island

4.3. Comparisons

The question "how well do these prediction methods work" can be satisfied by answering four questions:

1. Are the methods accurate? (*i.e.* individual stability class failure frequencies rank in the same order as the stability classes)
2. Are the methods consistent with differing land management treatment?
3. Are the methods transferable from one region to another?
4. What is the prediction success rate?

The primary unit of comparison is the failure frequency found in each method's stability rating classes (Table 9).

Additional questions of interest include:

5. Whether these methods have any apparent ability to predict if a particular type of failure will occur in a particular stability rating?
6. The question of temporal representativeness (*i.e.*, is this decade's failure record typical?) is considered with the aid of available climate records (AES 1991) and comparison between the pre-1977 failure frequency and failure type distributions with the 1988 compilation.
7. In both regions, SGA stability class 3 areas are so small they constitute a negligible proportion of the total area. Additionally, no failure events were recorded in this class. This minimal contribution from class 3 effects the statistical performance of SGA when using nonparametric statistics. Thus, in addition to the statistics generated

for each 5- and 3-Class system, a statistic for a 4-Class system will be generated also for each test. Stability class 3 will be ignored and the rankings assigned accordingly. How will this affect the statistical performance of SGA?

4.3.1. Accuracy within One Region

How accurately did each method predict failure occurrence within each region? For the method to be considered accurate, the ranking of the *actual* individual stability class failure frequencies should correlate with the order of the (increasingly stability-sensitive) stability classes (the *expected* ranking). Spearman's Rank Correlation "r_s" statistic, the nonparametric alternative to the linear correlation coefficient, is used here to evaluate the correlation between the expected rank ordering and the actual failure frequency ranked results[6]. Table 10 shows the r_s values from this comparison. Spearman's r_s values equal to or exceeding the critical value lead us to reject the null hypothesis (no correlation) and accept the alternative hypothesis (correlation). Where the number of classes are small (n=5), α=0.05 (one-tailed test), the critical r_s = 0.9 (Johnson 1984). Where there is fewer than 5 classes perfect correlation (r_s = 1.0) is necessary to reject the null hypothesis.

In both regions SRS and ESA actual failure frequencies ranking statistically matched the expected ranking. SGA 5-Class did not correspond to the expected rankings. No failures (in either region) occurred in SGA stability class 3 so the rate of failure is considered zero. Thus, in calculating the correlation to the "expected" rank order in the five class system there is no way that this method could do as expected. Ignoring stability

[6]Failure frequencies are ranked in order of smallest to largest to correspond with normal stability class increasing-sensitivity rank ordering.

class 3, for the 4- and 3-Class systems, the overall failure frequency distribution corresponded appropriately for both regions. However, SGA 4-Class logged and unlogged r_S values force acceptance of the null hypothesis (no correlation). Both SRS and ESA accurately identify areas of instability in order of likelihood while SGA does not appear to do so consistently.

Table 10: Spearman's Rank Correlation r_S Statistic from Comparing Individual Stability Class Failure Frequency "Expected" Ranking to "Actual" Failure Frequency Ranking

	McClinton Bay			Louise Island		
	Overall	Logged	Unlogged	Overall	Logged	Unlogged
5 Class*						
SRS	1.0	1.0	*0.975*	1.0	1.0	0.9
SGA	*0.7*	*0.7*	*0.625*	*0.7*	*0.7*	*0.7*
4 Class+						
SGA	1.0	*0.80*	*0.80*	1.0	1.0	1.0
3 Class						
SRS	1.0	1.0	1.0	1.0	1.0	1.0
SGA	1.0	*0.5*	1.0	1.0	1.0	1.0
ESA	1.0	1.0	1.0	1.0	1.0	1.0

*where n=5, $\alpha = 0.05$ critical $r_S = 0.9$, one-tailed test

+where n<5, $\alpha = 0.05$ critical $r_S = 1.0$, one-tailed test

4.3.2. Consistency Between Management Treatments

By comparing the individual stability class *logged-area* failure frequencies to the individual stability class *unlogged-area* failure frequencies within each region, we investigate a method's *consistency* with respect to management treatment. When the results between logged and unlogged terrain correlate within a method we can conclude that the method predicts consistently even when the land receives different treatment. We find (Table 11) that in both regions SRS and ESA yield statistically-consistent predictions.

SGA McClinton Bay does not predict consistently by management treatment. In contrast, although SGA Louise Island did not predict failure frequencies in the expected order (see Table 10), it did predict consistently between logged and unlogged terrain. Thus, while SRS and ESA seem to predict equally well no matter what the land management treatment, SGA results are less consistent.

Table 11 : Spearman's Rank Correlation r_S Statistic from Comparing Individual Stability Class Logged and Unlogged Failure Frequency Rankings Within a Region

	McClinton Bay			Louise Island		
	5 Class*	4 Class+	3 Class+	5 Class*	4 Class+	3 Class+
SRS	0.975	-	1.0	0.9	-	1.0
SGA	*0.875*	*0.8*	*0.5*	1.0	1.0	1.0
ESA	-	-	1.0	-	-	1.0

*where n=5, $\alpha = 0.05$ critical $r_S = 0.9$, one-tailed test
+where n<5, $\alpha = 0.05$ critical $r_S = 1.0$, one-tailed test

4.3.3. Transferability Between Regions

The Mann-Whitney U test, the nonparametric alternative to Student's-t test for the difference between two independent means, was used to investigate whether these two independent samples (study regions) are from the same "population." Can we consider the results (the individual stability class failure frequencies) of these methods in each of the study regions to be statistically similar? The null hypothesis is that the two areas will have a similar response to these treatments (methods) such that the results will have the same distribution (*i.e.* McClinton Bay's individual stability class logged-area failure frequencies will have the same distribution as Louise Island's individual stability class logged-area failure frequencies). With nonparametric tests the form of the distribution need not be specified. The actual failure frequency of each class, for each region, were listed together in order of smallest to largest and the Mann-Whitney U value calculated. Table 12 lists these values.

Table 12: Individual Stability Class Failure Frequency Comparisons Between McClinton Bay and Louise Island: Mann-Whitney U Values

	5 Class*		4 Class⁻		3 Class⁺	
	Logged	Unlogged	Logged	Unlogged	Logged	Unlogged
SRS	12	10	-	-	4	4
SGA	7.5	12	6	8	2	4
ESA	-	-	-	-	4	4

*where n=5, α = 0.05 critical U = 4, one-tailed test
⁻where n=4, α = 0.05 critical U = 1, one-tailed test
⁺where n=3, α = 0.05 critical U = 0, one-tailed test

The null hypothesis is accepted in all cases; indicating each sample belongs to the same population. All three methods give a similar distribution of results (individual stability class failure frequencies) between different regions. Accepting that each regions results belong to the same statistical population gives confidence to the validity of comparing results between the regions.

If the methods are transferable between regions we would expect each method's ranked distribution of individual stability class failure frequencies to correspond between the two regions. Again, Spearman's Rank Correlation r_S statistic is used to determine whether the ranking of the failure frequencies follows the same pattern in each region (Table 13). The null hypothesis is that no correlation exists between the regions.

Table 13 : Spearman's Rank Correlation r_S Statistic for Individual Stability Class Failure Frequency Comparisons Between McClinton Bay and Louise Island

	5 Class*			4 Class+			3 Class+		
	Overall	L	uL	Overall	L	uL	Overall	L	uL
SRS	1.0	1.0	*0.875*	---	---	---	1.0	1.0	1.0
SGA	1.0	0.9	*0.875*	1.0	*0.8*	*0.8*	1.0	*0.5*	1.0
ESA	---	---	---	---	---	---	1.0	1.0	1.0

*where n=5, $\alpha = 0.05$ critical $r_S = 0.9$, one-tailed test
+where n<5, $\alpha = 0.05$ critical $r_S = 1.0$, one-tailed test

Comparison of the overall (logged and unlogged together) failure frequencies shows perfect correlation between the regions for all methods. However, when the failure frequencies are divided into the logged and unlogged components and compared, a mixed result is seen. Both SRS and SGA (5- and 4-Class) logged-area results correlate, but neither method correlates in the unlogged terrain. Almost the opposite is found after the classes have been collapsed into 3 categories. Now the results correspond in the unlogged terrain for all three methods, but only ESA and SRS also show a correlation between the two regions in logged terrain. A closer look at Table 9 shows the SRS 5-Class correlation was thrown off by Louise Island's unlogged-area class 4 having a failure frequency 0.2 larger than class 3 causing a skew in the rank ordering. This slight difference was easily absorbed when the 5 classes were collapsed into 3 classes. Thus I will still conclude that the SRS is as transferable as the ESA. And, although the SGA correlates when using the overall failure frequency, SGA's transferability is more questionable because of its inconsistencies.

4.3.4. Distribution of Failures

Although the failure types distribution varies more widely in logged terrain than in unlogged terrain, open slope failures clearly dominate in both regions (Table 14). The majority of road-related failures occur in logged terrain and account for approximately 10% of all failures in each region.

Table 14: Failure Type as a Proportion of All Failures

Failure Type	McClinton		Louise Island	
	Logged	UnLogged	Logged	UnLogged
Open Slope	27%	47%	48%	33%
Gully Headwall	10%	1%	3%	1%
Gully Sidewall	3%	-	3%	3%
Road Related	12%	-	9%	1%

Comparison of the distribution of failures by rating as a percent of the total number of failures offers no significant correlations, especially for McClinton Bay. Table 15 shows the rank ordering of proportion of failures occurring in each class (where 1=highest proportion). Louise Island is consistent across the methods (3-Class) with stability class 2 always having the highest proportion of failures and with SRS and ESA having a similar rank order pattern.

Table 16 show the type of failure that dominates in each of the stability classes (3-Class only). In all six cases, the majority of failures occurring in the highest instability class are open slope failures. Except for Louise ESA, in five out of the six cases, the majority of open slope failures are in unlogged terrain (see Tables A2.3, A2.4, A3.5, A3.6, A4.3, A4.4). For the middle stability class, five of six cases show that the majority of failures will be open slope in logged terrain. If there are failures in the most stable class, three of six cases show open slope failures in logged terrain as dominant and two of six have road-related in logged terrain as predominant. Louise Island is clearly dominated by open slope failures with six of nine cases occurring in logged terrain and the other three in unlogged terrain.

Table 15: Rank Ordering of Proportions of Failures (All Types Combined)

	McClinton Bay			Louise Island		
	SRS	SGA	ESA	SRS	SGA	ESA
5 Class						
1	-	4	-	4	4	-
2	4	1	-	2	2	-
3	3	-	-	-	-	-
4	2	3	-	1	1	-
5	1	2	-	3	3	-
3 Class						
1/0	3	1	2	3	2	3
2/2	2	3	3	1	1	1
3/1	1	2	1	2	3	2

1 = highest proportion

Table 16: Dominant Type of Failure In Each Stability Class

	McClinton Bay			Louise Island		
Class	SRS	SGA	ESA	SRS	SGA	ESA
1/0	rr - L	os - uL	rr - L	os - L	os - L	os - L
2/2	os - L	os - L	gh - L	os - L	os - L	os - L
3/1	os - uL	os - uL	os - uL	os - uL	os- uL	os - uL

There is really no logical reason for the methods to produce consistent results with respect to predicting what types of failure will occur in a particular class, nor does such a pattern exist. However, it is interesting that at McClinton Bay, road-related failures in logged terrain dominate the most stable class for two of three methods.

4.3.5. Temporal

The failures tabulated in this study occurred at a snapshot of time. The representativeness of the failure frequency can be questioned since it is not known if this rate of failure is abnormally high/low or average. The inventory of failures compiled from the 1977 airphotos provide a means of comparing previous rates of failure with the new failure rates. Remember, the purpose of this thesis involves testing the performance of the stability classes, a higher or lower frequency of failure for the 1977-1988 time period will not affect the analysis of performance. Only the SRS 1977 data can be compared with the 1988 SRS data distribution as the other methods would place all the failures on the 1977 airphotos in the highest instability class.

Comparison between the failure distributions (Table 17) and the failure frequency distributions (Table 18) shows a perfect rank correlation between the time periods for both regions. Three failure frequency distributions are provided from the 1988 inventory. The "1988" data is the failure frequency from the complete inventory, whereas, the "1977-1988" data is the number of failures (undivided by land management treatment) that newly occurred between 1977 and 1988. "1977-1988 uL" is the distribution of failures occurring between 1977 and 1988 on the unlogged terrain.

The McClinton Bay 1988 failure inventory has a greater number of failures (1.4 times) than 1977 inventory. However, the 1977 total is 1.2 times larger than the 1977-1988 total. On Louise a greater number of failures happened in the both the 1988 inventory and 1977-1988 period than were recorded in 1977 (1.6 and 1.4 times as many, respectively). The primary difference appears to be that there is a slightly broader distribution across the stability ratings for the 1988 data, most likely as a result of the influence of clearcut logging (*i.e.* more failure events in lower risk classes and fewer failure rates in the higher risk classes).

Table 17: Number of Failures Pre- and Post-1977 by SRS Stability Class

Stability Rating	McClinton Bay 1977		1988		1977-1988		Louise Island 1977		1988		1977-1988	
	#	%	#	%	#	%	#	%	#	%	#	%
1	0	-	0	-	0	-	0	-	3	1	2	1
2	0	-	4	2	4	4	3	2	16	6	16	6
3	12	11	22	14	14	15	26	15	69	25	66	27
4	25	22	37	24	24	25	53	30	89	32	77	32
5	77	67	93	60	54	56	92	53	101	36	83	34
Total	114	100	156	100	96	100	174	100	278	100	244	100

Table 18: Failures per 100 ha Pre- and Post-1977 by SRS Stability Class

Stability Rating	McClinton Bay 1977	1988	1977-1988	1977-1988 uL	Louise Island 1977	1988	1977-1988	1977-1988 uL
1	0	0	0	0	0	0.07	0.05	0
2	0	0.21	0.21	0	0.15	0.80	0.80	0.16
3	0.88	1.61	1.03	0.25	0.95	2.50	2.40	1.30
4	3.23	4.77	3.10	0.79	2.28	3.83	3.31	1.09
5	18.33	22.14	12.86	11.02	5.72	6.28	5.16	3.32
Overall	2.29	3.14	1.93	1.34	1.34	2.14	1.88	0.92

uL = Unlogged Terrain

Assuming the rate of failure disappearance and occurrence is the same through time, then the two overall failure inventories incorporating all failure events are the most suitable terms for comparison. The "1988" failure frequencies is 1.4 to 1.6 times greater than that recorded for 1977. The new rate of failure "1977-1988" is both lower (McClinton) and higher (Louise) than the 1977 inventory. The influence of logging on failure initiation is obvious when comparing Louise Island's failure frequency over time. Although the 1988 failure occurrence is greater than 1977's, when considering only untreated terrain the 1988 failure frequency is about two-thirds that of the past. Similarly, McClinton's undisturbed terrain had new failure occurrences at a lower frequency than the 1977 frequency (about 70% less). Of course the failures inventoried on the 1977 airphotos probably occurred over a longer time period than those inventoried on the 1988 airphotos. Therefore, the two failure densities can be considered only relatively, not completely, comparable.

The next obvious question is to ask if the climatological influences were "normal" for the observed time period. Table 19 shows the Canadian Atmospheric Environment Service (AES) 1951 to 1980 30-year climate normals and the climate data averaged over the years 1983-85[7] (Masset) and 1983-88 (Sewell Inlet). All data except the mean temperature are yearly mean totals. Refer to Figure 3 for AES station locations. Caution must be used in extrapolating the information about these stations to the study regions as neither station is located within the same mean annual precipitation zone (Fig. 2) as the study areas.

The climate data for these two stations indicates an increase in total yearly precipitation, an increased number of days experiencing precipitation, a decrease in snowfall, and smaller greatest 24 hour rainfall totals for the smaller time period. If we assume that the two study regions similarly experienced an increased yearly total of precipitation it does not appear to have unduly influenced the incidence of failure. Since we do not know the time horizon of the earlier period (<1977) nor the "loss" rate of identifiable failure events the comparison is most usefully made employing the 1988

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[7] AES Masset data ended midway through 1986

inventory and the inventory of new failures in logged terrain. Thus, although we do see an overall increase in the number of visible failures from the 1988 inventory, there appears to be no evidence in the undisturbed terrain of an increased spatial failure frequency (Table 18). Even though one common trigger of failure events has increased (total precipitation), smaller 24 hour rainfall totals than average were recorded. The incidence of intense rainfall apparently did not often cross the critical threshold. However, even with these climatic averages and change in averages the local rainfall intensities are not documented and, probably, unknowable in rugged terrain.

Table 19: Climatological Data

	Masset		Sewell Inlet	
	30 year normal 1951-1980	1983-1985 (3 year avg.)	30 year normal 1951-1980	1983-1988 (6 year avg.)
Mean Rainfall (mm)	1353	1654	4028.9	4253.7
Mean Snowfall (mm)	87.7	66.8	143.9	38.9
Total Precipitation (mm)	1433.9	1718.5	4168.5	4259.2
No. Days of Rain	200	258	209	255
No. Days with Precipitation	211	266	222	259
Greatest 24hr Rainfall (mm)	76.2	39.6	203	187.2
Mean Daily Temperature (°C)	7.6	7.2	7.6	8.4

It seems that the pre-1977 and 1977-1988 data distributions or failure frequencies do not vary so significantly to conclude the 1977-1988 decade was abnormal despite an apparent increase in rainfall. Based on this limited testing, the data appears representative (at least for failure rates in the later 20th century) on a temporal basis.

4.3.6. Predictive Success

If we make the tenable assumption that all failures should happen in the least stable classes (*i.e.* in the three class system these are SRS/SGA classes 2 and 3, and ESA class 2 and 1), we can ask what percentage of failures did each method accurately predict? Table 20 lists the proportion of land and the proportion of failure occurrence in each stability class. SRS has the best record, accurately predicting the location of 96% of McClinton Bay's (MB) and 92% of Louise Island's (LI) failures. ESA has the second best record, accurately predicting 76% (MB) and 70% (LI) of all failures. SGA predicted only 44% (MB) and 59% (LI) of the failure events. SGA left approximately 78-81% of the land area classified as very low risk but had 41-56% of the failures occur there. In contrast, ESA identified 82-73% of the land as being low risk and had 24-30% of the failures occur there. SRS identified 48-49% of the land as low risk and failed to predict only 4-8% of the failures recorded

Another way to evaluate the predictive success is to calculate an artificial "failure events per unit of land" magnification factor. For example if we have 100 ha, 18% of which is high hazard, and 50 failures, then 38 (76%) will occur on the high hazard land, for rate of 2.11 failures per unit of land. The index (Table 21) is a "magnification factor" such that if you have 100 ha and 50 failures, equally distributed (0.5/ha), then in high hazard terrain, the ESA predicted failure frequency would be (0.5 x 4.22) or 2.11/ha. Similarly, for low hazard zones we could expect failure rate of 0.15/ha. This could be seen as land cost-effective in that the method that classifies the least amount of land as high hazard but has a large portion of the failure events happen in that classification yields a higher magnification factor. The meaning of the low hazard land magnification factor is reversed in that a large value indicate a lower effectiveness. Following this argument then, ESA is very land cost-efficient in high hazard lands but less cost-effective in low hazard lands. SRS is very land cost-effective in low hazard lands but has the lowest magnification factor for high hazard lands.

Table 20: Proportion Of Land And Failure Events In Each Stability Class

Method	5 Class	McClinton Bay Land Area (% of total)	McClinton Bay Failures (% of total)	Louise Island Land Area (% of total)	Louise Island Failures (% of total)
SRS	1	10	-	33	1
	2	38	4	16	7
	3	28	14	21	27
	4	16	25	18	31
	5	8	57	12	34
SGA	1	55	16	50	9
	2	25	40	27	32
	3	-	-	1	-
	4	13	21	18	45
	5	7	23	4	14
	3 Class				
SRS	1	48	4	49	8
	2	44	39	39	58
	3	8	57	12	34
SGA	1	81	56	78	41
	2	12	21	18	45
	3	7	23	4	14
ESA	0	82	24	73	30
	2	5	14	20	36
	1	13	62	7	34

Note: rounding errors may cause some difference between Class percentage totals

Table 21: 'Failure Events per Unit of Land' Magnification Factor

Risk	Method	McClinton	Louise
Low	SRS	0.08	0.16
Hazard	SGA	0.69	0.52
	ESA	0.29	0.41
High	SRS	1.85	1.80
Hazard	SGA	2.32	2.68
	ESA	4.22	2.59

4.3.7. Tabular Comparisons of the Failure Classifications

Each failure was categorized into a stability class as defined by each method. The results can be compared to ascertain the degree of failure rating correspondence between the classifications. Since SRS has proven to have the most predictive success, its stability designations can be taken as "true" and the other two methods are compared with SRS to check if they "correctly" identified each failure. The cross tabulations appear in Appendix 5, Tables A5.3 and A5.4, with SRS and SGA being compared initially with 5 classes and then collapsed to 3 classes. ESA and SGA are also compared, with ESA considered as "true."

For SGA 5-Class, the percentage of polygons identified as belonging to the same stability class as SRS assignments is 30% (MB) and 27% (LI). When the 5-Class data are generalized to 3-Class, SGA yields a 38% (MB) and 36% (LI) correspondence with SRS. ESA corresponds 50% (MB) and 45% (LI) with SRS assignments. SGA and ESA failures correspond 40% (MB) and 43% (LI). None of the three comparisons has a high degree of correspondence. SRS and ESA have the best correspondence in both regions.

Comparing SGA and ESA with SRS classes as true, the "user accuracy" seems to improve slightly as one moves from most stable to least stable classes. This could be interpreted to mean that the polygons rated the most unstable are likely to be well mapped using the other two methods. The "producer accuracy" shows the opposite trend where the more stable classes are correctly identified but the more unstable classes have a lower correspondence. Comparing SGA, with ESA classes as true, produces similar trends.

4.4. SUMMARY

The overall frequency of failures differs only slightly between the two regions with McClinton Bay having the larger failure occurrence at 1.92 failures per 100 hectares. However, Louise Island's unlogged-area failure frequency (0.92 per km^2) is 69% of McClinton Bay's frequency (1.34 per km^2) and its logged-area failure frequency (4.81 per km^2) is 154% of McClinton's (3.13 per km^2). The failure frequency occurring in the study time frame (1977-1988) appears to be fairly representative of the "usual" mid-20th century failure occurrence.

Both areas exhibit a similar distribution of failure types with 74% to 81% of failures classified as open slope failures. No method displays an overall association between a particular type of failure and any one stability class. However, all three methods had unlogged open slope failures as the dominant failure type for the highest risk class.

SRS and ESA methods were shown to be statistically *accurate* in the sense that failure frequencies occurred in rank proportion, *consistent* in the sense that they had similar failure rate rank distributions regardless of land management treatment, and *transferable* in that they performed similarly in both regions. The SGA as applied here was accurate only in one region and only for 4- and 3-Class structure, could not be extrapolated with confidence, and had mixed results as to consistency within a region.

Assuming the hallmark of a successful failure prediction model is its ability to predict accurately the location of subsequent failures, then SRS was the best method, successfully predicting between 92% and 96% of the failure events. Although McClinton Bay's unpredicted 4% of failures were all road-related, 83% of the unpredicted failures occurring on Louise Island were open slope. ESA accurately predicted between 70% and 76% of the failures and SGA predicted between 44% and 59%.

CHAPTER 5. DISCUSSION

"Identifying sensitive forest sites and preparing good logging plans are essential if logging-accelerated mass wasting is to be reduced" (Sauder and Wellburn 1989 p 1). Slope stability hazard rating methods are an essential component of this task. The Queen Charlotte Islands' Forest District was the first area in British Columbia to use operability plans integrating long-term logging development plans with terrain-stability mapping. The purpose of this thesis was to examine and compare the stability prediction methods used in British Columbia asking if they (1) accurately predict likely sites of failure; (2) reduce the incidence of failure related to clearcut logging and road development; and, (3) each predict equally well. In the following section I discuss the answers to these questions and comment on each methods' successes and limitations.

5.1. Predictive Success

Assuming that all failures are most likely to occur in the medium to high risk terrain then the SRS method is the best predictor. In the test areas, it accurately predicted the location of 94% of the failures[8]. ESA accurately predicted 73% of all failures and SGA predicted 52% of all failures. To achieve this success, SRS identified 52% of the land base as medium to high risk, whereas ESA and SGA identified 23% and 21%, respectively, as such.

Road-building and tree-felling decisions in difficult terrain are made on-site, guided by, but not limited by, information developed by one of the above methods. The possibility of judging predictive success of the methods may thus appear biased by the fact that only areas deemed workable will have been cut. From the perspective of improved

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[8]This and the following numbers are the average value between the two regions.

productivity, however, it is success in predicting performance in medium risk terrain, and the effort required to achieve those predictions, that is of key importance. Field judgments will be made in such terrain no matter what the pretyping method, thus we expect that this will not introduce special bias. Based on this, SRS had 49% of the failures happen on the 42% of the land identified as medium risk. SGA has 33% of the failures happen on 15% of the land so identified and ESA had 25% of failures happen on the 13% of medium risk terrain.

While SRS has the best overall prediction rate, it is necessary to consider whether identifying 42% of the entire land area as medium risk means SRS is too conservative; potentially decreasing its usefulness as a management tool. Although less conservative (identifying much less of the land base as hazardous), ESA remains relatively accurate. For these study areas at least, ESA classification appears to isolate sensitive areas best. ESA's accuracy would be increased with field checking and would benefit from on-site evaluations by terrain specialists as potentially difficult areas are discovered in the course of development.

Rollerson and Sondheim (1985) briefly discuss the philosophy of hazard classifications and suggest that complex classification should be avoided. If most of an area falls into classes rated as at moderate risk, a manager will probably feel that the classification does not serve adequately as a management tool. "Thus when creating a classification, the combinations of factors and cutoff values (*e.g.*, slope breaks) should be sought which best demarcate both those areas most subject to failure and those most likely to be stable. If this is done well, the number of hectares in the intermediate classes with moderate ratings should be reduced" (p 4).

Each failure was categorized into a stability class as defined by each method. The results can be compared to ascertain the degree of failure rating correspondence between the classifications. Since SRS has proven to be the most accurate, its stability designations can be taken as "true." For SGA 5-Class, the percentage of polygons identified as belonging to the same stability class as SRS assignments is 30% (MB) and 27% (LI) (see Tables A5.3 and A5.4). When the 5-Class data are generalized to 3 classes, SGA yields a 38% (MB) and 36% (LI) correspondence with SRS. ESA corresponds 50% (MB) and 45% (LI). Similarly, SGA and ESA failures correspond 40% (MB) and 43% (LI). Although none of the three classifications have a high degree of correspondence, the higher stability-sensitive classes have a higher correspondence than for the lower sensitivity classes. SRS and ESA have the best correspondence as befits the two best prediction methods.

5.2. Decreased Incidence of Failure?

Using a slope stability hazard map to guide road placement and logging technique should help to moderate the incidence of mass wasting characteristic of slopes after clear-cutting. Comparison with other failure inventories from the Queen Charlotte Islands supports this idea (Table 22). Rood's (1984) inventory of over 1500 failures in a 350 km^2 area found that logging increased the frequency of debris slides by a factor of 34. His logged areas had been logged between 1 and 16 years prior to the inventory for an average age of 7.3 years since felling. Schwab's (1983) study of the 1978 Hallowe'en storm found an increase of 15 times following the storm event. He also found the majority of the storm-induced failures occurred on lands logged 4 to 11 years previously (86%). In comparison, the failure rate increase in logged terrain of 2.4 and 5.2 times over an 11 year period found in this study seems remarkably low. Even the overall failure frequency of 1.9 per km^2 is lower than the 2.6 per km^2 reported by Gimbarzevsky (1988). Perhaps most tellingly, Gimbarzevsky's land base was 2500 km^2 and included

Table 22: Comparison of Failure Frequencies Reported in Queen Charlotte Island Failure Inventories

Source	Failure Density No./km^2			Failure Frequency No./km^2/year			Failure Rate Relative to Unlogged
	Overall	Unlogged	Logged	Overall	Unlogged	Logged	
Rood (1984)	4.5	4.80	29.70	0.12	0.12	4.10	x 34
min	-	-	-	-	0.02	0.59	-
max	-	-	-	-	0.30	11.1	-
Gimbarzevsky (1988)	2.6	-	-	-	-	-	-
Schwab (1983)	-	0.80	11.60	-	-	-	x 15
McClinton Bay	1.92	1.35	3.21	0.17	0.12	0.29	x 2.4
Louise Island	1.88	0.92	4.78	0.17	0.08	0.43	x 5.2

only 1-km^2 blocks of terrain where failures were observed. "His regional data were extracted from 1:50,000 scale photography and the minimum detectable size was much larger than in this study" (Rood 1984 p 24). Rood wrote this to rationalize why his failure frequency was 70% greater than Gimbarzevsky's findings even though Gimbarzevsky's approach probably inflates the failure frequency since land without failures was not included in the area term. Here, I use the fact that the 2.6 per km^2 is 37% larger than the overall frequency found in this study as evidence that MacMillan Bloedel's use of the SRS method in logging planning for the study regions helped reduce the logging related incidence of mass wasting.

However, in addition to the use of the methods as an aid to reduce acceleration of debris failures, this reduced failure frequency could also be explained by a dearth of storms of sufficient intensity to trigger failure. The rate of mass wasting is sensitive to the age distribution of the clearcut areas and on whether a major storm capable of initiating mass wasting has occurred since logging. Further, even if there were a major storm(s), terrain sensitivity to failure is related to when in the sequence of clearcut, root deterioration and establishment of second growth the storm occurs (Rood 1984). As a rule of thumb though, Schwab (1983) found that a storm of sufficient intensity to trigger debris failures has approximately a 5 year recurrence interval. However, ten years has passed (until the 1988 photos) since the 1978 storm and we might make the assumption that such a storm has occurred at least once since.

Also of note is the differences in distribution of failure type. The findings of this failure inventory shows that road-related failures, at 11% (logged area), accounted for a smaller percentage of the total than previous studies. Wilford and Schwab (1982) report road-related failures as 39% of the total; Chatwin and Rollerson (1983) found 17% road-related and Rood (1984) found 19%. Schwab's (1983) report of a road-related failure frequency of 20.8 per km^2 is probably misleading since only a small, concentrated section of road actually failed. He also found a low frequency of failures on road constructed since 1976 probably reflecting the shift from crawler tractors to backhoes for subgrade construction. Additionally, companies now recognize the need to rehabilitate roads and landings after use and much greater attention is paid to providing adequate road drainage (Sauder and Wellburn 1989). The lower percentage of road-related failures found in this study presumably reflect these changes.

This study has made no attempt to identify the influence of specific logging technique on stability predictions. Changing the method of logging in an effort to decrease the adverse impact in medium to high risk terrain may substantially decrease the mass wasting acceleration due to clearcutting. Operational sensitivity may have been influential in the overall lower failure frequency found by this study.

5.3. Comparative Usefulness of the Methods

Table 23 summarizes the results from the statistical data analysis questioning "how well do these prediction methods work?" as discussed in Chapter 4. ESA is the only method to have passed all tests with 100% correlation. SRS method also achieved statistically acceptable correlations in all tests but did have a few mismatches. SGA was inaccuracte in the 5- and 4-Class but accurate in the 3-Class. It was consistent within the method for Louise Island data but appears doubtful as to transferability between regions.

Well established in its use, at least on the Queen Charlotte Islands, the SRS methodology is labour-intensive, complex and expensive. Quality and scale of photography and expertise of the mapper strongly influence the reliability of data. An experienced mapper and good quality photographs result in an accurate map (Howes and

Swanston 1991). As shown by this study, SRS is conservative (more likely to give a terrain unit a rating indicating higher instability) and accurate.

Table 23: Summary of Data Analysis

Method		Accurate	Consistent	Transferable	Predictions
SRS	5 Class	Yes	Yes	Yes	
	3 Class	Yes	Yes	Yes	92% and 96%
SGA	5 Class	No	in one region	Doubtful	
	4 Class	in one region	in one region	Doubtful	
	3 Class	Yes	in one region	Doubtful	44% and 56%
ESA	3 Class	Yes	Yes	Yes	70% and 76%

The ESA method is very rapid; both regions were mapped in a morning's work while the SGA delineations took several days each. As shown here, ESA is less conservative and accurate than SRS, but the accuracy would improve with ground-truthing. The method is heavily process-based but several studies have shown past instability to be a good predictor of future instability. This is borne out with the results of this study. After comparing the results of different classifications, Howes and Sondheim (1987) suggest that the simpler classifications may be as useful as the very detailed work suggested by the SGA method and that "the use of natural failure as an indication of susceptibility of clearcut-induced failure seems valid" (p 180). With reference to Table 5 the ESA method produced a total of 501 polygons, SRS produced 1338 and SGA 2177[9] for a ratio of 1 ESA polygon to 2.7 SRS to 4.3 SGA. One could speculate that the greater the number of classifications requiring accurate identification the greater the potential for producer error (but also, the greater the potential sensitivity).

[9] Actually SGA produced many more polygons than cited here since the terrain units were first identified using 8 terrain classes.

The statistical-geographic approach produced mixed results. This method is very labour-intensive and complex. It requires a high level of interpretive expertise to evaluate the composite information base. Without even completing steps 1 through 4 of the methodology (see section 2.4.3) this approach required the greatest amount of time and effort in mapping the many terrain categories. Although Howes and Sondheim's (1989) suggestion that a classification derived in one area may be applied with reasonable results to another geomorphically similar area, this is the first time a SGA terrain classification derived in one area was applied in "similar" areas without first actually developing the classifications. As applied in this study, SGA appears to be both insensitive and inaccurate. Perhaps the two regions were insufficiently similar to the area (north Moresby Island, Hans/Sachs Creek area) where the terrain classes were developed. Additionally, the QCI terrain classification was clearly presented by Rollerson *et al.* (1986) as preliminary. However, although the study regions are in the same physiographic region as the classification development area, I feel the terrain classes were adequate but the assigned stability ratings were incorrect. A stability rating of 2 was insufficient for terrain classes 4 and 7. The data support this in that 40% of McClinton Bay failures (highest by proportion of failures) and 32% of Louise Islands failures (second) happen in this class. If these terrain classes had been assigned even a medium risk stability class then SGA's prediction record would have improved substantially.

Based on the results of this study, SRS and ESA can be considered useful prediction methods. SRS can be considered both sensitive and accurate while ESA is relatively insensitive but accurate. However, SRS conservatively "isolated" 52% of the land as stability-sensitive to achieve this accuracy while ESA "isolated" only 23%. From a scientific viewpoint the greater understanding contained within the SRS is preferable. Operationally, ESA may be the better method.

5.4. ECONOMIC AND INSTITUTIONAL CONSIDERATIONS

All methods are relatively costly in that they all use aerial photography acquisition and analysis. However, airphotos are a necessary and somewhat unquestioned aspect of the land management planning process. Ground-truthing is another necessary cost. Sauder and Wellburn (1989) in their case study of logging planning on the Queen Charlotte Islands confirmed the importance of thorough field reconnaissance when they found extensive areas of potential instability within areas previously defined as "stable" units and areas of stable ground in "unstable" units. They suggest the cost of terrain stability mapping (SRS) depends "on the access available for field verification of photograph typing, the number of field plots required, and the experience of the terrain specialist. On the Queen Charlottes, terrain stability mapping costs ranged between $1.11 and $4.30 per hectare" (p 13). Additionally Howes and Swanston (1991) state that no matter how detailed a photo interpretation may be, areas mapped strictly from airphotos are less reliable than those that have been field checked. Based on this estimate, McClinton Bay would cost $5,513 to $21,359 and Louise Island $14,401 to $55,788 to map.

The SRS mapping is carried out at 1:20,000 and 1:50,000, generally using airphoto interpretation with reconnaissance level ground-truthing. Sondheim and Rollerson (1985) estimate that one day of field checking may suffice for every 800 ha mapped at a scale of 1:20,000 or every 5,000 ha at 1:50,000 . Based on this estimate McClinton Bay would require 6 days of field work and Louise Island would need 16 days.

Until this study, all application of the SGA method has involved acquiring the data from the clearcut lands, developing the terrain classifications and associated stability rating but not applying these classifications (expect for Howes 1987) to other similar areas.

Howes (1987) reported the first large scale project (150 km^2) where the terrain evaluation method was completed and then applied to forested as well as logged landscapes. SGA is even more labour and data intensive than SRS.

ESA has the lowest labour, formal expertise and data requirements. Local knowledge is, of course, very valuable. As applied in this study, it left 27% of the failures unpredicted. Having nearly 30% of failures happen where they "shouldn't" can be a very costly mistake. However, field checking would improve the prediction success of this method; and, with its smaller initial cost and greater ability to isolate stability sensitive land, ESA has the potential to be much more cost effective than SRS.

Sauder and Wellburn (1989) discuss the current timber harvest planning process (and some limitations) on the Queen Charlotte Islands. Table 24 shows the five levels of planning for TSA's and the four levels for TFL's undertaken in British Columbia. Planning begins at a broad level and progresses through to detailed layouts for specific cutting areas. Shasko (1989) suggests that the two levels best suited to any type of slope stability analysis is at the Management and Working Plans planning level (1:100,000 scale) and the Operability planning stage (1:20,000 scale).

Table 24: Levels of Planning on the Queen Charlotte Islands (after Sauder and Wellburn 1989)

Tenure		Plan (Scale)	Purposes	Prepared By:	Time Frame	Area of Concern
TSA only	1.	Timber Supply Area (TSA)	Overall goals, strategies, and policies	MOF Regional and District Offices*	Long-term	Entire TSA
TFL and TSA	2.	Management and Working Plans (1:100 000)	Explains how the TFL and TSA objectives wil be addressed	Forest company staff	Long-term	The area of land a forest operator manages.
	3.	Operability (1:50 000 and 1: 20,000)	Long-term operational development combined with terrain stability analysis	TFL's: Forest company staff. TSA: Forest company staff plus MOF.	10-20 years	The overall area of forest land an operator expects to log within the 10- to 20- year period
	4.	Development Plan (5-Year Plan) (1:20 000)	Operational measures to develop and log the next 5 years of timber	Forest company staff	5 years	Specific areas to be logged within the next 5 years
	5.	Cutting Permits (1:5 000)	Detailed operational specifications	Forest Company staff	1-2 years	Specific logging areas

*Quota holders on the Queen Charlotte TSA reveiw the proposed plan, whereas in other coastal areas quota holders actively participate in the preparation of plans. A quota holder is a company or individual having the right to harvest timber from the TSA.

5.5. Summary and Conclusions

This study is the first attempt to examine the accuracy and predictive ability of three slope stability prediction techniques utilized in coastal British Columbia. These techniques have been used consistently only for the last 10 to 15 years. Studies investigating the effects of root deterioration clearly demonstrate a slope failure acceleration window of 3 to 10 years following logging. Analysis of the predictive ability of these models could not have been undertaken much earlier than now. By comparing hillslopes having similar terrain units, stability classes and subject to similar meteorological events but differing in their management treatments, we can offer some conclusions about the effectiveness of these forms of stability prediction.

While geoscientists develop complex, often site-specific, models to better understand the physical processes governing hillslope stability, land managers are more interested in the difficulty of applying or interpreting a stability prediction method[10] under normal management constraints of limited time, finances and technical expertise. Examination of the effectiveness of the British Columbian slope stability prediction methods is interesting both academically and operationally. The process of producing a rigorous critical test of these physically-based probabilistic methods provides an analytical framework for future model-testing. And, comparative analysis of stability prediction methods in use industrially provides land managers with additional information about potential accuracy and technical requirements.

Some form of a slope stability rating system (SRS), which begins with terrain mapping using the British Columbia Terrain Classification System, is used by all major

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[10] assuming all prediction mthods are accurate.

forestry companies. The British Columbia Ministry of Forests uses a slope stability prediction system within its Environmentally Sensitive Area (ESA) designations. The "statistical-geographic" terrain evaluation method (SGA) was proposed by Rollerson, Howes, and Sondheim in various papers presented through the 1980s. All prediction techniques are generally considered useful in reducing logging and road-related failures but, until this study, this hypothesis has never been tested.

To conduct a proper test of each method's predictive ability and to compare methods, a study site must be subjected to analysis by all three methods before logging began. This was achieved in this study by using pre-logging airphotos. Slope failure frequencies by failure rating for both logged and unlogged terrain can be determined from recent aerial photographs of comparable scale. The methodology is resolved into three main sections, study site selection, mapping and assessment, and statistical comparison of predictive success.

Two Queen Charlotte Islands study regions are used, McClinton Bay and Louise Island, both TFL's managed by MacMillan Bloedel. All data are tabulated by region, by prediction method, by occurrence in logged or unlogged terrain, and in order of lowest to highest predicted stability risk. The data consist of the number of failures, the areal extent of each stability class, and the type of initiation zone. Since the two regions are not of comparable size, only proportional data and failure frequencies may be used for true comparison between the regions.

Both regions had a majority of failures happen in logged terrain. The overall failure frequency is 1.9 per km^2. The difference between the unlogged and logged area failure frequencies varies substantially between the regions. McClinton Bay's logged area failure occurrence is 2.4 times greater than its unlogged failure frequency while Louise Island's logged area failure frequency is 5.2 times greater than its unlogged failure occurrence. Open slope failures (74-82%) dominate over gully-related (15-10%) and road-related failures (10-12%).

The general thesis question asking "how well do these prediction methods work" can be satisfied by answering four questions: (1) are the methods accurate? (2) are they consistent with differing land management treatment? (3) are they transferable from one region to another? and (4) what was the prediction success rate?

SRS and ESA methods are statistically shown to be accurate (in the sense that failure frequencies occurred in rank proportion), consistent (in the sense that they had similar failure frequency rank distributions regardless of land management treatment) and transferable (similar results in both regions). SGA, as applied in this study, did not exhibit accuracy, allow confidence in transferability and had mixed results as to consistency within a region.

SRS successfully predicted 94% of all failures, ESA predicted 73% and SGA predicted 52% of all failures. SRS designated 52% of the land base as medium to high risk while ESA and SGA isolated 23% and 21%, respectively.

In conclusion, both SRS and ESA are considered to have had predictive success. All methods appear to have lessened the incidence of failure overall and decreased the mass wasting acceleration due to logging in particular. Based on the findings of this study, SGA appears to be the least useful method as it is both insensitive and inaccurate. Both SRS and ESA are useful, with SRS being both sensitive and accurate and ESA being less sensitive but also accurate. Which method is better? If economics are not considered then SRS is without qualification the most accurate. ESA can be considered the most cost-effective method. ESA is rapid, passed all the statistical tests, best isolated stability sensitive land, and, with field checking could likely improve its prediction success at minimal additional cost.

It must be noted that SGA was applied here with classifications considered preliminary. Statistically significant correlations were hindered by an absence of failure in stability class 3 and what the author considers inappropriate evaluation of terrain classes 4 and 7 as low risk classes. The results are not sufficient to conclude that SGA does not have merit.

On the basis of predictive success coupled with informational requirements and cost-efficiency ESA appears to be "the best" for operational use. Additional development is not required for SRS; it is a successful method. ESA terrain units were airphoto interpreted with the assistance of terrain classification maps (produced in conjunction with the SRS stability classes). Completing ESA analysis without this assistance may or may not decrease the accuracy.

As typical with many applied geography questions the final analysis displays the tension between scientific understanding and hands-on management. In seeking to comprehend the manifold factors influencing surficial terrain failure the scientist is often at odds with the manager who wishes to avoid complex classifications. Thus, if understanding is the prime consideration, then the SRS method is recommended; otherwise, from an economic and management stance, the ESA method appears to holds the greatest promise.

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APPENDIX 1 HAZARD ASSESSMENT CHARTS

These slope hazard assessment charts were developed by Howes and Swanston (1991) and presented with their general approach to the identification of landslide prone terrain.

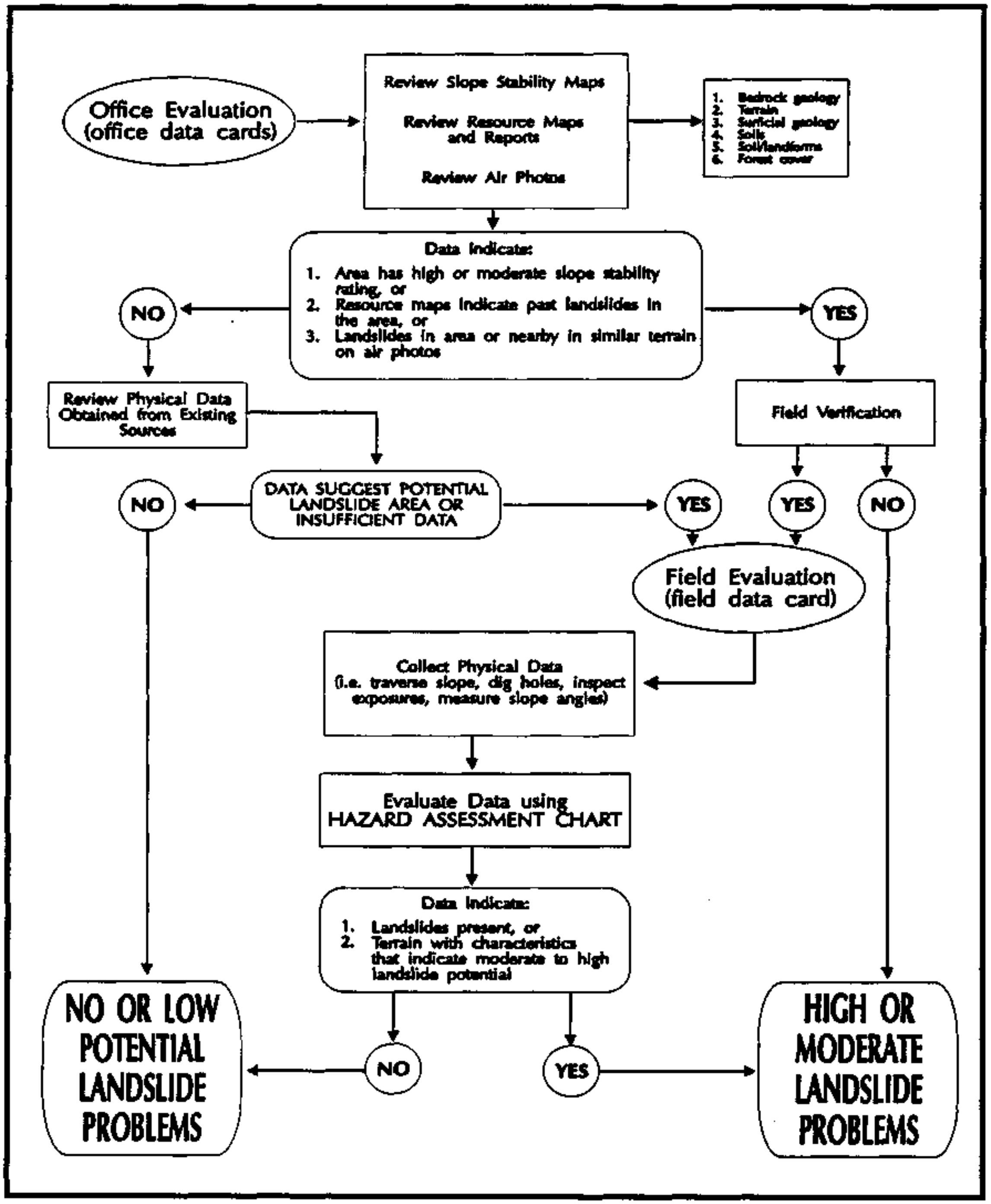
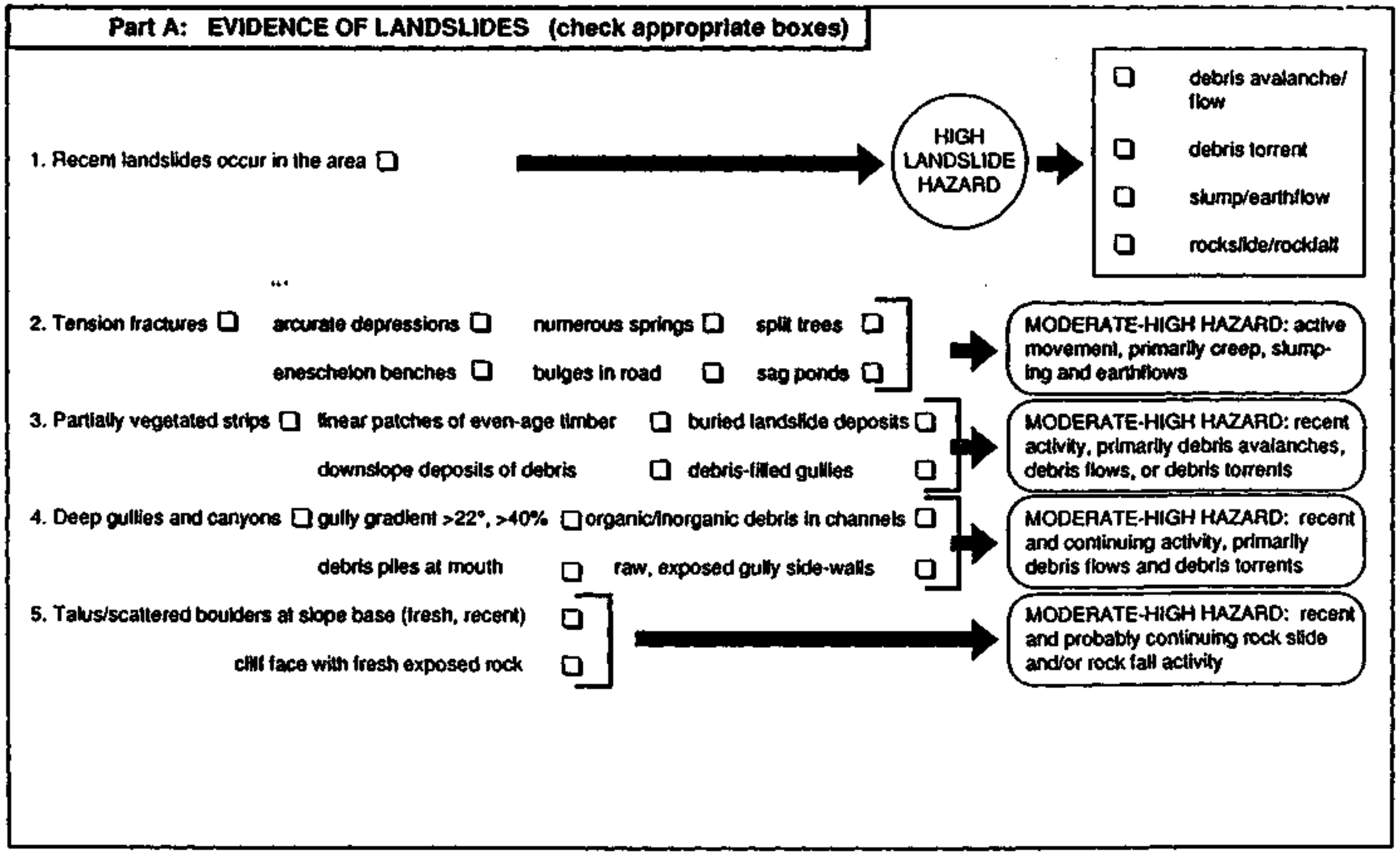
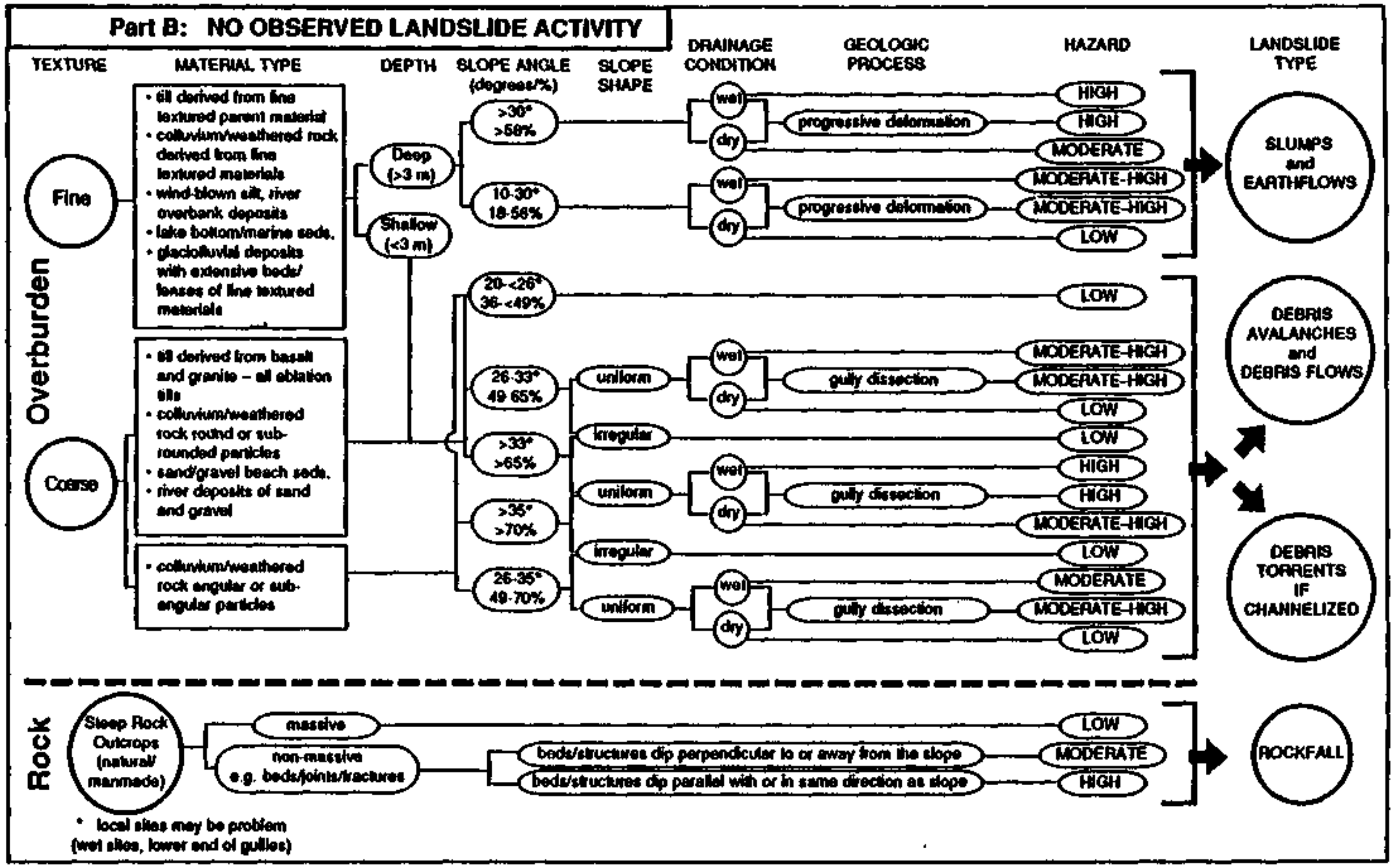


Figure A1.1 : Flow Diagram of Procedures for Recognizing Unstable Terrain (After Howes and Swanston 1991)

Figure A1.2 : Slope Hazard Assessment Charts (Howes and Swanston 1991)





Part B: NO OBSERVED LANDSLIDE ACTIVITY
TEXTURE
MATERIAL TYPE
DEPTH
SLOPE ANGLE (degrees/%)
SLOPE SHAPE
DRAINAGE CONDITION
GEOLOGIC PROCESS
HAZARD
LANDSLIDE TYPE
Overburden
Fine
• till derived from fine textured parent material
• colluvium/weathered rock derived from fine textured materials
• wind-blown silt, river overbank deposits
• lake bottom/marine seds.
• glaciofluvial deposits with extensive beds/ lenses of fine textured materials
Deep (>3 m)
Shallow (<3 m)
>30° >58%
10-30° 18-58%
wet
dry
progressive deformation
HIGH
HIGH
MODERATE
MODERATE-HIGH
MODERATE-HIGH
LOW
SLUMPS and EARTHFLOWS
Coarse
• till derived from basalt and granite – all ablation tills
• colluvium/weathered rock round or sub-rounded particles
• sand/gravel beach seds.
• river deposits of sand and gravel
• colluvium/weathered rock angular or sub-angular particles
20-<26° 36-<49%
26-33° 49-65%
>33° >65%
>35° >70%
26-35° 49-70%
uniform
irregular
gully dissection
LOW
LOW
LOW
DEBRIS AVALANCHES and DEBRIS FLOWS
DEBRIS TORRENTS IF CHANNELIZED
Rock
Steep Rock Outcrops (natural/ manmade)
massive
non-massive e.g. beds/joints/fractures
beds/structures dip perpendicular to or away from the slope
beds/structures dip parallel with or in same direction as slope
ROCKFALL
* local sites may be problem (wet sites, lower end of gullies)

APPENDIX 2 ENVIRONMENTALLY SENSITIVE AREAS - SLOPE HAZARD

To designate Es_1 areas an analyst must identify areas of actual and potential excessive wind or water erosion and/or mass movement. They are to consider only sites where forest harvesting could lead to unacceptable site deterioration. Unacceptable site deterioration includes: severe lowering of site productivity owing to the removal of soil necessary for plant growth; extreme delay in the re-establishment of protective vegetation and forest cover; long-term loss of the productive land base; and, severe lowering of the quality of downstream water and degradation of fisheries habitats (Inventory Manual 1984).

Sites designated as Es_2 should have significant potential for wind or water erosion and/or mass movement where conditions on harvesting (road construction, logging method, logging season) are required to prevent unacceptable site deterioration.

Table A2.1 : Areas for Consideration as Es_1 (Inventory Manual 1984)

Wind and Water Erosion

1. Sites with visible evidence of significant wind erosion, sheet erosion, channel erosion (rilling and gullying), karst processes or piping.
2. Sites with extreme potential for erosion. Include sites with geological characteristics (slope gradient, slope form, surficial materials, texture, drainage, bedrock) that are very similar to those having visible evidence of erosion in the same area.
   - eolian deposits
   - sites with dry, shallow soils (<30 cm) with frequent bedrock exposure (50%+)
   - sites on steep topography (70% +, 35 degrees +) with very thin soils
   - colluvial or fluvial fans

Mass Movement

1. Sites with visible evidence of mass movement (active or historic)
   - Slopes showing soil creep, which is indicated by small scarps and tension cracks across a slope and by tilted or bowed trees and displaced human structures
   - Areas having tension cracks and lateral spreads
   - Areas with slumps or flows. Delineate the complete terrain unit associated with deep-seated slumps and flows as Es_1
   - Areas with debris slides, debris avalanches, debris flows (characterized by visible scars). Designate the terrain associated with the initial failure zone as Es_1
   - Steep, gullied terrain associated with distinct fan deposits (debris torrents)
2. Sites with extreme potential for mass movements. Include sites with geological characteristics (slope gradient, slope form, surficial materials, texture, drainage, bedrock) that are similar to those having visible evidence of mass movement in the same area. Also, include sites having a history of severe deterioration after forest harvesting. Examples of sites with extreme potential for mass movement are:
   - Steep, colluvial slopes (≥35°) having continuous movement of surficial material such as dry ravel, dry creep and sliding. All these involve downslope movement of single particles and/or thin sheets of coarse materials which lacks cohesion on sparsely vegetated slopes. The more extreme problems with steep, colluvial slopes occur on south to southwest exposures.
   - Steep slopes (70% or ≥35°) having a thin blanket of loose till over an impermeable layer of compacted till or bedrock with a smooth sliding lane parallel to the surface.
   - Faces of outwash and kame terraces
   - Steep stream banks consisting of lacustrine deposits (silts, clays)
   - Steep stream edges and gullies associated with unconsolidated material (till, colluvium)
   - Marine deposits (sensitive clays)

Table A2.2 : Areas to Consider as Es_2 (Inventory Manual 1984)

• Sites adjacent to actual or potential Es1 areas having the potential to start active mass movement or erosion
• Downslope positions of sites with extreme potential (Es_1 areas) for mass movement. Landslides may traverse Es_2 areas but should not originate within them.
• Uniform, moderately steep, colluvial slopes (60% to 70%, 31° to 35°) These slopes are usually in the upper landscapes
• Uniform, moderate to steep slops (40% to 70%, 22° to 35°) on medium and fine-textured morainal and highly weathered bedrock deposits. These slopes are usually in the middle to upper landscapes.
• Areas with numerous pockets of wet soils or seepage areas and/or areas with common inclusions of steep topography, V-shaped gullies or exposed bedrock where some harvesting will be permitted. The problems of instability on these areas are not severe enough to warrant an Es1 designation.
• Sites with non-cohesive materials on moderately steep slopes close to watercourses.
• Areas with significant potential for collapse and subsidence of the ground surface owing to underground erosion. Include areas of carbonate or other water-soluble rocks (karst processes) and fine-textured lacustrine materials (piping).

Table A2.3 : ESA Data for McClinton Bay

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
0	6	6	17	18	2720	55	1358	27	6	7	-	1	-	1	-	8
2	2	2	12	12	166	3	117	2	2	3	-	7	-	1	-	1
1	38	40	21	22	522	11	84	2	37	16	1	2	-	1	-	2
Totals	#	%	#	%	#	%	#	%	45	26	1	10	-	3	-	11
	46	48	50	52	3408	69	1559	31								

Table A2.4 : ESA Data for Louise Island

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
0	20	22	54	8	7411	57	2007	16	19	40	-	5	1	-	-	9
2	33	22	54	14	1523	12	1027	8	29	42	-	2	3	6	1	4
1	39	19	46	15	816	6	190	1	33	36	2	-	2	2	-	8
Totals	#	%	#	%	#	%	#	%	81	118	2	7	6	8	1	21
	90	63	154	37	9750	75	3224	25								

APPENDIX 3 SLOPE RATING SYSTEMS

Suggested stability rating equivalents (Fig. 9) links the different rating systems used by three forestry companies on the Queen Charlotte Islands and the ESA method favoured by the Ministry of Forests for TSAs. Each large forest company has developed its own stabiltiy rating system. The following sections describe the expectations for each stability class.

A3.1. MacMillan Bloedel

Table A3.1 lists the terrain class criteria and expected response for the MacMillan Bloedel system as used today. Table A3.2 describes the soil moisture regime classification and definitions mentioned in the class criteria. All information is taken directly from Dunkley (1986). Terrain stability classes are derived from data on surficial material, landform, geomorphic process, slope angle, texture, length of slope, soil moisture regimes, landscape position, vegetation and bedrock properities. Based on the relative importance of each factor, stability classes are assigned. These classes are indicative of the natural terrain stability which can be reduced by disturbances such as road construction and logging.

The soil moiture classification is based on the relative wetness of a soil within a given climatic zone. Within each climatic zone, five soil moisture regimes were estabilished using the driest and wettest soil moisture regimes within the zone as Classes 1 and 5, respectively. The number of days per year that a soil is near or above field capacity is estimated. Separation of soil moisture regime classes is based primarily on the differences in vegetation and soil morphologic characteristics, however, other parameters can also be used, *e.g.*, landscape position, aspect. Complexing of soil moisture regimes within a mapping unit is indicated with the same notation as the unconsolidated materials composite units with the corresponding realtive proportions of each regime.

Table A3.1 : MacMillan Bloedel SRS Classes (after Dunkley 1986)

Terrain Stability Class	Expected Response	Class Criteria
1	• No significant stability problems exist	• Organic and fluvial materials primarily with minor amounts of moraine and bedrock included • Slope are quite level (range from 0° to 10°). Sometimes up to 15°. Within larger terrain units, there may be small areas greater than 20°. • Soil moisture regimes range from 1 to 5; but 3,4, and 5 are dominant types. • No natural failures
2	• No significant stability problems exist • Normal road construction and logging practices will not significantly decrease stability • Periodic maintanence involving ditch cleaning is expected due to sloughing along road cuts on roads constructed through colluvial landforms	• Fluvial, morainal, and colluvial materials primarily with minor amounts of bedrock, marine, or glaciofluvial deposits • Slopes usually between 0° to 20°, but up to 30° in places. The steeper areas are considered small or minor • Soil mositure regime ranges from 1 to 4 • No natural failures are present
3	• Minor stability problems can develop • Clearcutting should not signifiantly reduced terrain stability, but minor slumping and small debris slides are expected, paniculariy wher slopes are greater tnan 35° • Minor slumping expected along road cuts on raods crossing areas with slopes > 30°, especially for 1 to 2 years following construction • Sidecast materail which forms slopes >35° will increase the portential for terrain failures	• Morainal, colluvial, and fluvial deposits with minor bedrock areas • Slopes range from 10° to 35°, with 20° to 30° most common. There may be short steep slopes greater than 30° in places. These are considered insignificant to be classified Class 4 or greater. • Soil moisture regimes range from 1 to 4, but 3 is the norm. • No natural failures are present

Table A3.1: Continued

Terrain Stability Class	Expected Response	Class Criteria
4	• Contains areas where there is a low to moderate likelihood of failure because of road construction. Wet period construction will signifiantly increase the potential for failures. Terrain failures can occur if sidecasting is allowed on units exhibiting significant soil creep. • There is a low to moderate likelihood of failures in clearcuts. • A field instpection of these zones should be made by a soil specialist prior to any proposed development in order to assess the stability of the affected areas.	• Morainal and colluvial materials, plus some areas of bedrock • Slopes range from 20° to 35°, but 30° to 35° is dominant • A few small failures may exits, but generally no natural failures area present • Soil moisture regimes range from 2 to 4, but 3 is dominant • Terrasets, pistol butted trees; soil creep, and small failure scars may be recognized in the field
5	• Contains areas where there is a high likelihood of failure during conventional clearcutting or road construction. • Construction during wet periods will significantly increase the potential for failures • A field inspection of these zones should be made by a soil specialist prior to any proposed development in order to assess in detail the stability of the affected areas. Careful planning and supervision at all levels of development will dcrease, but not completely remove the high potential for terrain failures	• Colluvial, morainal, and steep bedrock areas. • Slopes range from 20° to 35°, generally with slopes <30° dominating. • Failures are almost always present and recongizable on air photos. Occasionally steep slopes <35° with no failures will be included. Morainal slopes between 30° and 35° with high moisture regimes (3 to 4) may also be included. • Generally restricted to the initiation zones of natural slides, or cliffs where rockfalls are in evidence • Soil mositure regimes range from 1 to 4, with 3 to 4 dominating.

Table A3.1: Continued

Terrain Stability Class	Expected Response	Class Criteria
5'	• These units are expected to have a high to very high likelihood of failure following clearcutting or road construction. Construction during wet periods will increase likelihood of failure. • A field inspection of these zones should be made by a soil specialist prior to any proposed development.	• Contains areas of very unstable terrain and exhibits clear evidence of recent and recurrent landslides throughout the unit. Failures occupy a significant portion of the landscape. Easily identified on air photos • Colluvial, morainal, and steep bedrock areas • Found on slopes >30° and usually >35°. Small areas may exist which are < 30°, however, these are considered insignificant. Morainal slopes with high moisture regime may fail on lower slope angles • Soil moisture regime ranges from 1 to 4, with 3 and 4 dominating

Note: Stability Class 5' is a newer class than used on the stability maps utilized in this study. Consider Class 5 as a combination of 5 and 5' for the purposes of the discussion in this paper.

Table A3.2 : Soil Moisture Regimes (SMR) Classification and Definitions (after Dunkley 1986)

Class		Description
SRM 1	Very low	• Water is removed from soil rapidly during heavy rainfall periods. Water source is precipitation. Rock outcrops.
SRM 2	Low	• Water is removed readily in relation to supply. Water source is mainly precipitation with some subsurface flow from upper slope areas. Podzol, Brunsol, Regosol orders.
SRM 3	Medium	• Water is removed slowly enough relative to supply to keep the soil wet for a significant periods (250 to 300 days) of the year. Water source is subsurface flow and to a lesser extent precipitation. Gleyed members.
SRM 4	High	• Water is removed from the soil so slowly in relation to supply that the soil remains wet for a considerable period (> 300 days) of the year. The majority of the water source comes from subsurface flow and/or groundwater with some contribution from precipitation. Gleysols.
SRM 5	Very High	• Water is removed from the soil so slowly that the water table remains at or near the surface throughout most of the year. Groundwater and subsurface flow are the principal water sources. Organics.

A3.2. WESTERN FOREST PRODUCTS LTD.

Table A3.3 : Western Forest Products Stability Class Descriptions

Stability Class		Environmental and Technological Operability
1		• Landscape units predominantly stable; few, scattered and localized failures may occur, moss movement depositional zones may be present
2		• Landscape units showing evidence of scattered mass wasting in undisturbed sited, or sensitive landscape units likely to exhibit mass wasting if clearcut
	Op	• Highlead systems. Operable areas, with no harvesting constraints.
	Oc	• Operable but constrained, harvesting system determined by road constraints.
	Oc_1	• Operable with uphill long yarding maximum lift system.
	Oc_2	• No roads, helicopter systems.
	Oc_3	• Shoreline units suitable for A-frame/ helicopter/ handlogging.
	I	• Technically inoperable identifying physically and economically inaccessible areas.
3		• Landscape units where mass wasting is the dominant geomorphic process, exhibiting clear evidence mass movement is present throughout the unit, or an extensive occurrence of a particularly sensitive landscape unit.

A3.3. FLETCHER-CHALLENGE LTD.

Table A3.4 : Fletcher-Challenge Stability Class Descriptions

Stability Class	Class Description
1	• Not outlined, low mass wasting hazard, no natural instability problems present, no limitations.
2	• Moderate to high mass wasting hazard, scattered evidence of natural failure, road building constraints.
2a	• Shallow surface material (< 1 m), gradient exceeding critical angles of nearby natural slope failures, no or few widely scattered failures.
2b	• Slopes with deep surface materials (> 1 m), gradient exceeding critical angles of nearby natural slope failures, no or few widely scattered failures.
2c	• Shallow or deep soils, gradient exceeding critical angles of nearby natural slope failures, no or few widely scattered failures.
3	• Extreme mass wasting hazard, recent and recurring landsliding the predominant geomorphic process, avoid roads and logging.

Table A3.5 : SRS Data for McClinton Bay

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
5 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	-	-	-	-	263	5	227	5	-	-	-	-	-	-	-	-
2	-	-	4	4	1363	27	554	11	-	-	-	-	-	-	-	4
3	2	2	12	12	795	16	570	12	2	11	-	-	-	-	-	1
4	5	5	19	20	633	13	142	3	5	9	-	5	-	-	-	5
5	39	41	15	16	354	7	66	1	38	6	1	5	-	3	-	1
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	-	-	4	4	1626	32	781	16	-	-	-	-	-	-	-	4
2	7	7	31	32	1428	29	721	15	7	20	-	5	-	-	-	6
3	39	41	15	16	354	7	66	1	38	6	1	5	-	3	-	1
Totals	#	%	#	%	#	%	#	%	45	26	1	10	-	3	-	11
	46	48	50	52	3408	68	1559	32								

Table A3.6 : SRS Data for Louise Island

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
5 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	-	-	2	1	3544	27	745	6	-	2	-	-	-	-	-	-
2	2	1	14	6	1248	10	751	6	2	11	-	-	-	-	-	3
3	23	10	43	17	1764	14	988	7	22	34	-	4	-	-	1	5
4	20	8	57	23	1840	14	486	4	19	42	-	2	1	1	-	12
5	45	18	38	16	1354	10	254	2	38	29	2	1	5	7	-	1
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	2	1	16	7	4792	37	1496	12	2	13	-	-	-	-	-	3
2	43	18	100	40	3604	28	1474	11	41	76	-	6	1	1	1	17
3	45	18	38	16	1354	10	254	2	38	29	2	1	5	7	-	1
Totals	#	%	#	%	#	%	#	%	81	118	2	7	6	8	1	21
	90	37	154	63	9750	75	3224	25								

APPENDIX 4 STATISTICAL-GEOGRAPHIC APPROACH

Table A4.1: SGA Terrain Class Criteria for the Queen Charlotte Islands

Terrain Class	Class Criteria
1	• evidence of natural failures present
2	• gullied, average slope ≥ 21°
3	• gullied, average slope 15° to 20°
4	• Average slopes ≥ 30°, well drained
5	• Average slope ≥ 30°, imperfectly to poorly drained
6	• Average slopes 21° to 29°, well drained
7	• Average slopes 21° to 29°, imperfectly to poorly drained
8	• Average slopes 15° to 20°
0	• None of the others

Table A4.2: SGA QCI Terrain Class and Associated Stability Rating

Stability Class	Terrain Class
1	0, 6, 8
2	4, 7
3	3
4	2, 5
5	1

Table A4.3 : SGA Data for McClinton Bay

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
6 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
0	-	-	2	2	1145	23	258	5	-	-	-	-	-	-	-	2
1	-	-	14	14	819	16	618	12	-	6	-	4	-	1	-	3
2	22	23	16	17	727	16	459	9	21	9	1	2	-	1	-	4
3	-	-	-	-	1	0	10	0	-	-	-	-	-	-	-	-
4	4	4	16	17	403	8	187	4	4	10	-	3	-	1	-	2
5	20	21	2	2	323	6	30	1	20	1	-	1	-	-	-	-
5 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	-	-	16	17	1964	39	876	17	-	6	-	4	-	1	-	5
2	22	23	16	17	727	16	459	9	21	9	1	2	-	1	-	4
3	-	-	-	-	1	0	10	0	-	-	-	-	-	-	-	-
4	4	4	16	17	403	8	187	4	4	10	-	3	-	1	-	2
5	20	21	2	2	323	6	30	1	20	1	-	1	-	-	-	-
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	22	23	32	33	2691	55	1335	26	21	15	1	6	-	2	-	9
2	4	4	16	17	404	8	197	4	4	10	-	3	-	1	-	2
3	20	21	2	2	323	6	30	1	20	1	-	1	-	-	-	-
Totals	#	%	#	%	#	%	#	%	45	26	1	10	-	3	-	11
	46	48	50	52	3418	69	1562	31								

Table A4.4 : SGA Data for Louise Island

	Failures				Area (ha)				Type of Failure							
	Unlogged		Logged		Unlogged		Logged		OS		GH		GS		RR	
6 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
0	-	-	-		2875	22	528	4	-	-	-	-	-	-	-	-
1	8	3	15	6	2273	18	993	8	7	14	-	-	1	-	-	1
2	31	13	46	19	2381	18	1015	8	30	33	-	1	-	-	1	12
3	-	-	-	-	39	0	43	0	-	-	-	-	-	-	-	-
4	34	14	75	31	1678	13	577	4	30	58	1	6	3	3	-	8
5	17	7	18	7	478	4	71	1	14	13	1	-	2	5	-	-
5 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	8	3	15	6	5148	40	1521	12	7	14	-	-	1	-	-	1
2	31	13	46	19	2381	18	1015	8	30	33	-	1	-	-	1	12
3	-	-	-	-	39	0	43	0	-	-	-	-	-	-	-	-
4	34	14	75	31	1678	13	577	4	30	58	1	6	3	3	-	8
5	17	7	18	7	478	4	71	1	14	13	1	-	2	5	-	-
3 Class	#	%	#	%	#	%	#	%	uL	L	uL	L	uL	L	uL	L
1	39	16	61	25	7529	58	2536	20	37	47	-	1	1	-	1	13
2	34	14	75	31	1717	13	620	4	30	58	1	6	3	3	-	8
3	17	7	18	7	478	4	71	1	14	13	1	-	2	5	-	-
Totals	#	%	#	%	#	%	#	%	81	118	2	7	6	8	1	21
	90	37	154	63	9724	75	3227	25								

Table A4.5: SGA QCI Terrain Class Area Adjustment

Terrain Class	Measured Areas (hectares)				Area x Error Correction* (hectares)			
	Louise		McClinton		Louise		McClinton	
	L	uL	L	uL	L	uL	L	uL
0	550	2687	243	1145	528	2875	258	1145
1	74	447	28	323	71	478	30	323
2	163	382	62	136	156	409	66	136
3	45	36	9	1	43	39	10	1
4	468	1538	216	573	449	1646	229	573
5	439	1186	114	267	421	1269	121	267
6	537	1052	193	257	515	1126	205	257
7	590	687	217	154	566	735	230	154
8	498	1072	390	562	478	1147	413	562
ΣA_{SGA}	3364	9087	1472	3418	3227	9724	1562	3418
ΣA_{SRS}	3224	9750	1559	3408	3224	9750	1559	3408
*	0.96	1.07	1.06	1.00				

$* \ \Sigma A_{SRS} / \Sigma A_{SGA}$

APPENDIX 5 FAILURE INVENTORY WORKSHEETS

The first column indicates whether the failure happened in logged (L) or unlogged (uL) terrain. The failure number has three parts; (1) the flight line number, (2) the number of the photo, and (3) the failure number as marked on that airphoto. "N" indicates it is on the new photo's and "O" the old photos. Each failure's type is listed: open slope (os), gully headwall (gh), gully sidewall (gs), active wall (aw), or road-related (rr). The stability class into which the failure falls for each prediction method is listed. If the failure that occurred at or near a cut-boundary is recorded with an "x". The failures are listed in order of SRS rating. Then, within each SRS class, the failures are ordered from lowest to highest SGA class. That the failure is a single event (S) or part of a complex (C) is also noted. The associated old or new photo(s) is shown for cross-referencing. If the failure noted on the new photography is also visible on the old photography it is not listed with the new failures but will appear with the old photographs under the "associated photo" column. In the comments column "zis" means zone of instability and "bis" means break in slope.

Table A5.1: McClinton Bay Data Worksheet

	Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
	LOGGED								
L	88006-143-N1	rr	2	1	0		S	77062-248	
L	88006-143-N2	rr	2	1	0		S	77062-248	
L	88006-143-N3	rr	2	1	0		C	77062-248	
L	88006-143-N4	rr	2	1	0		C	77062-248	
L	88006-234-N7	os	3	1	1		S	77063-068	
L	88006-234-N8	os	3	1	1		S	77063-068	
L	88006-234-N40	os	3	1	1		S	77063-068	
L	88006-234-N4	rr	3	2	0		S	77063-068	
L	88006-169-N9	os	3	2	1		S	77062-248	
L	88006-169-N10	os	3	2	1		S	77062-248	
L	88006-169-N11	os	3	2	1		S	77062-248	
L	88006-234-N11	os	3	2	0		S	77063-068	
L	88006-234-N15	os	3	2	2		S	77063-068	
L	88006-234-N3	os	3	4	1		S	77063-068	
L	88006-234-N5	os	3	4	1		S	77063-068	
L	88006-234-N6	os	3	4	1		S	77063-068	
L	88006-234-N13	os	4	1	0		S	77063-068	
L	88006-234-N14	os	4	1	2		S	77063-068	
L	88006-169-N27	os	4	1	1		S	77062-248	
L	88006-234-N16	gh	4	1	2		S	77063-068	
L	88006-234-N12	gh	4	1	2		S	77063-068	
L	88006-234-N29	rr	4	1	0		S	77063-068	
L	88006-169-N7	os	4	2	2		S	77062-248	
L	88006-169-N26	gh	4	2	2		S	77062-248	
L	88006-169-N18	rr	4	2	0		S	77062-248	
L	88006-234-N21	rr	4	2	0		S	77062-248	
L	88006-169-N25	rr	4	2	2		S	77062-248	
L	88006-169-N6	os	4	4	0		S	77062-248	
L	88006-169-N13	os	4	4	1		S	77062-248	
L	88006-169-N15	os	4	4	1		S	77062-248	
L	88006-169-N16	os	4	4	1		S	77062-248	
L	88006-234-N27	os	4	4	0		S	77063-068	
L	88006-234-N17	gh	4	4	1		S	77063-068	
L	88006-234-N18	gh	4	4	1		S	77063-068	
L	88006-169-N22	rr	4	4	1		C	77062-248	
L	88006-234-N10	gh	5	1	2		S	77063-068	

	Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
L	88006-234-N42	gh	5	1	2		S	77063-068	
L	88006-234-N9	gs	5	1	2		S	77063-068	
L	88006-169-N14	os	5	2	1		S	77062-248	
L	88006-169-N17	os	5	2	0		S	77062-248	
L	88006-169-N24	os	5	2	0		C	77062-248	
L	88006-169-N8	gh	5	2	2		S	77062-248	
L	88006-169-N23	gs	5	2	1		C	77062-248	
L	88006-169-N12	os	5	4	1		S	77062-248	
L	88006-169-N20	os	5	4	0		S	77062-248	
L	88006-234-N41	gh	5	4	2		S	77063-068	
L	88006-169-N21	gs	5	4	0		S	77062-248	
L	88006-169-N29	rr	5	4	1		S	77062-248	
L	88006-234-N20	os	5	5	1		S	77063-068	
L	88006-234-N26	gh	5	5	0		S	77063-068	
uL	88006-145-N52	os	3	2	0		S	77062-246	
uL	88006-145-N53	os	3	2	1		S	77062-246	
uL	88006-145-N20	os	4	2	1		S	77062-246	
uL	88006-145-N21	os	4	2	1		S	77062-246	
uL	88006-145-N30	os	4	2	1		S	77062-246	
uL	88006-145-N31	os	4	2	1		S	77062-246	
uL	88006-167-N5	os	4	5	1		C	77063-070	
uL	88006-167-N12	os	5	2	1		C	77063-070	
uL	88006-167-N13	os	5	2	1		C	77063-070	
uL	88006-234-N30	os	5	2	1		C	77063-068	is now a gully, probably wasn't before
uL	88006-234-N31	os	5	2	1		C	77063-068	
uL	88006-234-N33	os	5	2	1		C	77063-068	very broad headwall
uL	88006-234-N36	os	5	2	1		C	77063-068	
uL	88006-234-N45	os	5	2	1		S	77063-068	
uL	88006-238-N3	os	5	2	0		S	77063-070	
uL	88006-145-N44	os	5	2	0		S	77062-246	
uL	88006-145-N45	os	5	2	0		S	77062-246	
uL	88006-145-N46	os	5	2	1		S	77062-246	
uL	88006-145-N47	os	5	2	1		S	New #145-02	
uL	88006-145-N49	os	5	2	0		S	77062-246	
uL	88006-145-N50	os	5	2	1		S	77062-246	
uL	88006-145-N32	os	5	2	1		S	77062-246-O8	much larger
uL	88006-145-N29	gh	5	2	1		S	77062-246	

	Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
uL	88006-238-N4	os	5	4	1		S	77063-070	
uL	88006-238-N11	os	5	4	1		C	77063-070	
uL	88006-145-N41	os	5	4	2		S	77062-246	
uL	88006-145-N51	os	5	4	1		S	77062-246-O42	much larger
uL	88006-167-N10	os	5	5	1		S	77063-070	
uL	88006-167-N11	os	5	5	1		S	77063-070	
uL	88006-167-N14	os	5	5	1		C	77063-070	
uL	88006-234-N2	os	5	5	1		S	77063-068	bis
uL	88006-234-N35	os	5	5	0		C	77063-068	bis
uL	88006-234-N39	os	5	5	1		C	77063-068	
uL	88006-234-N43	os	5	5	1		S	77063-068	very broad headwall
uL	88006-234-N44	os	5	5	1		S	77063-068	
uL	88006-238-N14	os	5	5	1		S	77063-070	
uL	88006-237-N4	os	5	5	1		S	77062-068	
uL	88006-145-N6	os	5	5	1		S	77062-246	
uL	88006-145-N11	os	5	5	1		S	77062-246	
uL	88006-145-N25	os	5	5	1		C	77062-246	
uL	88006-145-N28	os	5	5	2		C	77062-246	
uL	88006-145-N39	os	5	5	1		S	77062-246	
uL	88006-145-N27	os	5	5	1		C	246-O34,35,11	much larger
uL	88006-145-N38	os	5	5	1		S	77062-246-O5	much larger
uL	88006-167-N4	os	5	5	1		C	77063-068-O1,O12	much larger
uL	88006-234-N34	os	5	5	1		S	77063-068-O10	much larger
	Old Photography								
	77063-070-O8	os	3	5	1		S	88006-238-N15	
	77063-070-O13	os	3	5	1		S	not seen on new	
	77063-070-O17	os	3	5	1		S	88006-167-N16	
	77062-246-O36	os	3	5	1		S	not visible	
	77062-246-O24	os	3	5	1		C	88006-145-N2	
	77062-246-O25	os	3	5	1		C	88006-145-N1	
	77062-246-O44	os	3	5	1		C	88006-145-N42	
	77063-070-O16	gh	3	5	1		C	88006-167-N15	
	77063-070-O16	gh	3	5	1		C	88006-167-N15	
	77063-070-O16	gh	3	5	1		C	88006-167-N15	
	77062-246-O23	gh	3	5	1		S	88006-145-N3	
	77062-246-O29	aw	3	5	1		n/a	88006-145-N40	
	77063-070-O29	os	4	5	1		C	88006-165-N1	
	77063-070-O4	os	4	5	1		S	88006-238-N18	

Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
77063-070-O5	os	4	5	1		S	88006-238-N17	
77063-070-O26	os	4	5	1		S	88006-238-N1	
77062-246-O1	os	4	5	1		S	88006-145-N43	
77062-246-O2	os	4	5	1		S	88006-145-N47	
77062-246-O4	os	4	5	1		S	no new failure	
77062-246-O6	os	4	5	1		S	not visible	
77062-246-O8	os	4	5	1		S	88006-145-N32	
77062-246-O9	os	4	5	1		S	not visible	
77062-246-O10	os	4	5	1		S	mostly overgrown	
77062-246-O22	os	4	5	1		S	not visible	
77062-246-O32	os	4	5	1		S	not visible	
77062-248-O4	os	4	5	1		S	88006-234-N19	
77063-071-O3	os	4	5	1		S	no matches, no new failures	
77063-0111-O3	os	4	5	1		S	strong shadows	bis
77063-068-O11	gh	4	5	1		S	88006-234-N32	
77063-070-O21	gh	4	5	1		S	88006-238-n5 to n8	
77063-070-O25	gh	4	5	1		S	88006-238-N2	
77063-070-O7	aw	4	5	1		S	88006-238-N16	
77063-0111-O1	aw	4	5	1		?	strong shadows	bis
77063-0111-O2	aw	4	5	1		C	strong shadows	bis
77063-0111-O4	aw	4	5	1		?	strong shadows	bis
77063-0111-O5	aw	4	5	1		C	strong shadows	bis
77063-0111-O6	aw	4	5	1		C	strong shadows	bis
77062-246-O13	os	5	5	1		S	88006-145-N2	
77062-246-O30	os	5	5	1		S	88006-145-N37	
77063-068-O1	os	5	5	1		C	88006-167-N4	
77063-068-O3	os	5	5	1		S	88006-237-N2	
77063-068-O4	os	5	5	1		S	88006-237-N3	
77063-068-O5	os	5	5	1		S	88006-234-N1	
77063-068-O6	os	5	5	1		S	88006-234-N38	
77063-068-O7	os	5	5	1		S	gone	
77063-068-O8	os	5	5	1		S	88006-234-N37	
77063-068-O9	os	5	5	1		S	88006-234-N35	
77063-068-O10	os	5	5	1		S	88006-234-N34	
77063-068-O12	os	5	5	1		S	88006-167-N4	
77063-068-O13	os	5	5	1		S	88006-167-N13	
77063-070-O1	os	5	5	1		S	88006-165-N4, N5	
77063-070-O2	os	5	5	1		S	88006-165-N3	

Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
77063-070-O12	os	5	5	1		S	not visible	
77063-070-O22	os	5	5	1		S	88006-238-N12	
77063-070-O27	os	5	5	1		C	88006-165-N2	
77063-070-O28	os	5	5	1		C	88006-165-N2	
77062-246-O5	os	5	5	1		S	88006-145-N38	
77062-246-O7	os	5	5	1		S	88006-145-N35	
77062-246-O11	os	5	5	1		S	88006-145-N27	
77062-246-O12	os	5	5	1		C	88006-145-N26	
77062-246-O17	os	5	5	1		S	not visible	
77062-246-O18	os	5	5	1		S	not visible	
77062-246-O19	os	5	5	1		S	not visible	
77062-246-O20	os	5	5	1		C	88006-145-N5	
77062-246-O21	os	5	5	1		C	88006-145-N4	
77062-246-O33	os	5	5	1		S	not visible	
77062-246-O2	os	5	5	1		S	88006-145-N22	
77062-246-O41	os	5	5	1		S	88006-145-N36	
77062-246-O42	os	5	5	1		S	88006-145-N51	
77062-246-O43	os	5	5	1		C	88006-145-n33,34	
77062-248-O1	os	5	5	1		S	88006-169-N28	
77062-248-O2	os	5	5	1		S	not visible	
77062-248-O3	os	5	5	1		C	not visible	
77062-248-O5	os	5	5	1		C	88006-234-N23	
77062-248-O6	os	5	5	1		C	88006-234-N24	
77062-248-O7	os	5	5	1		S	not visible	
77062-248-O8	os	5	5	1		S	88006-234-N25	
77062-248-O9	os	5	5	1		S	88006-234-N45	
77063-070-O24	os	5	5	1		S	88006-238-N13	
77063-071-O1	os	5	5	1		S	no matches, no new failures	at apex of a peak
77063-071-O2	os	5	5	1		S	no matches, no new failures	
77063-071-O4	os	5	5	1		S	no matches, no new failures	
77063-071-O5	os	5	5	1		S	no matches, no new failures	
77063-071-O6	os	5	5	1		S	no matches, no new failures	
77063-071-O8	os	5	5	1		S	no matches, no new failures	
77063-071-O9	os	5	5	1		S	no matches, no new failures	
77063-071-O10	os	5	5	1		S	no matches, no new failures	
77063-071-O11	os	5	5	1		C	no matches, no new failures	
77063-071-O12	os	5	5	1		C	no matches, no new failures	

Failure Number	Type	SRS	SGA	ESA	Cut Bdy	Event	Associated Photo's	Comments
77062-246-O28	gh	5	5	1		S	88006-145-N18	
77062-246-O16	gh	5	5	1		C	880066-145-n8, n9	
77062-246-O16	gh	5	5	1		C	880066-145-n8, n9	
77062-246-O16	gh	5	5	1		C	880066-145-n8, n9	
77063-068-O2	gh	5	5	1		C	88006-167-n3, n2	
77063-068-O2	gh	5	5	1		C	88006-167-n3, n2	
77063-068-O2	gh	5	5	1		C	88006-167-n3, n2	
77063-070-O9	gh	5	5	1		S	88006-238-N2	
77063-070-O10	gh	5	5	1		S	88006-167-N7	
77063-070-O11	gh	5	5	1		S	88006-167-N6	
77063-070-O18	gh	5	5	1		S	88006-167-N9	
77062-246-O3	gh	5	5	1		S	not visible	
77062-246-O14	gh	5	5	1		C	88006-145-N7	
77062-246-O34	gh	5	5	1		C	88006-145-N27	
77062-246-O35	gh	5	5	1		C	88006-145-N27	
77062-246-O38	gh	5	5	1		C	88006-145-n13,14,15	
77062-246-O38	gh	5	5	1		C	88006-145-n13,14,15	
77063-070-O6		5	5	1	x	C	88006-238-N6 to N9	
77063-070-O19	aw	5	5	1		C	88006-167-N17	
77063-070-O20	aw	5	5	1		C	88006-165-N6	
77062-246-O39	aw	5	5	1		C	88006-145-n16,17,19	
77062-246-O40	aw	5	5	1		C	88006-145-n23,24	
77062-246-O15	aw	5	5	1		C	88006-145-N10	
77062-246-O31	gs	5	5	1		S	not visible	
77063-071-O7	gs	5	5	1		S	no matches, no new failures	

Table A5.2: Louise Island Data Worksheet

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
	NEW FAILURES								
L	88010 - 385- N7	os	1	0	2		S	New - #301	
L	88010 - 385- N1	os	1	0	4		S	New - #301	
L	88010 - 441 - N2	os	2	0	1		S	New - #162	
L	89005 - 157 - N24	rr	2	0	1		S	New - #158	
L	88010 - 443 - N1	os	2	2	1	x	S	New - #18/19	
L	89005 - 154 - N1	os	2	0	2		S	New - #21	
L	88010 - 302 - N6	os	2	0	2		S	New - #166/14	
L	88010 - 378 - N3	rr	2	0	2		S	New - # 15/14	
L	88010 - 391- N6	os	2	2	2		S	New - #19/162	into gully
L	89005 - 155 - N12	os	2	2	2		S	New - #158/159	
L	88010 - 437 - N11	rr	2	2	2		S	New - #197/195	
L	88010 - 434 - N2	os	2	0	4		S	New - #85/86	
L	88010 - 434 - N3	os	2	0	4		S	New - #85/86	
L	88010 - 434 - N4	os	2	0	4		S	New - #85/86	
L	88010 - 434 - N5	os	2	0	4		S	New - #85/86	
L	89005 - 157 - N40	os	2	1	5		S	New - #158	
L	88010 - 441 - N1	os	3	0	1		S	New - #162	
L	88010 - 435 - N16	os	3	0	1		S	New -#86/197/298	
L	88010 - 391- N1	os	3	2	1		S	New - #19/162	into gully
L	88010 - 391- N2	os	3	2	1		S	New - #19/162	into gully
L	88010 - 391- N3	os	3	2	1		S	New - #19/162	into gully
L	88010 - 391- N4	os	3	2	1		S	New - #19/162	into gully
L	88010 - 391- N5	os	3	2	1	x	S	New - #19/162	into gully
L	88010 - 301 - N7	gh	3	0	2		S	New - #14	
L	88010 - 379 - N2	os	3	0	2		S	New - #301/302/14	
L	88010 - 301 - N6	os	3	0	2		S	New - #14	into gully
L	89005 - 157 - N28	os	3	0	2		S	New - #158	
L	89005 - 157 - N29	os	3	0	2		S	New - #158	
L	89005 - 157 - N36	os	3	0	2		S	New - #158	
L	89005 - 157 - N37	os	3	0	2		S	New - #158	
L	89005 - 157 - N37	os	3	0	2		S	New - #158	
L	88010 - 385- N2	rr	3	0	2		S	New - #301	
L	88010 - 385- N3	rr	3	0	2		S	New - #301	
L	88010 - 386- N3	rr	3	1	2		S	New - #300	
L	88010 - 386- N4	rr	3	1	2		S	New - #300	
L	88010 - 377 - N1	os	3	2	2		S	New - #16	
L	88010 - 303 - N1	os	3	2	2		S	New - #166	
L	88010 - 441 - N3	os	3	2	2		S	New - #162	into a gully

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
L	88010 - 442 - N3	os	3	2	2		S	New - #19	
L	89005 - 155 - N10	os	3	2	2		S	New - #158/159	
L	89005 - 155 - N11	os	3	2	2		S	New - #158/159	
L	88010 - 301 - N5	gh	3	0	4		S	New - #14	
L	89005 - 157 - N34	gh	3	0	4		S	New - #158	
L	88010 - 447- N1	os	3	0	4		S	New - #300	
L	88010 - 379 - N1	os	3	0	4		S	New - #301/302/14	
L	88010 - 386- N2	os	3	0	4		S	New - #300	
L	89005 - 159 - N6	os	3	0	4		S	New - #198/197	
L	89005 - 159 - N7	os	3	0	4		S	New - #198/197	
L	89005 - 159 - N8	os	3	0	4		S	New - #198/197	
L	89005 - 157 - N35	os	3	0	4		S	New - #158	
L	89005 - 157 - N33	rr	3	0	4		S	New - #158	
L	88010 - 442 - N2	gh	3	2	4		S	New - #19	
L	89005 - 159 - N2	os	3	2	4		S	New - #198/197	
L	89005 - 159 - N3	os	3	2	4		S	New - #198/197	
L	89005 - 159 - N4	os	3	2	4		S	New - #198/197	
L	89005 - 159 - N5	os	3	2	4		S	New - #198/197	
L	88010 - 391- N7	os	3	2	4		S	New - #19/162	into gully
L	89005 - 158 - N1	os	3	2	5		S	New - #197	
L	89005 - 159 - N1	os	3	2	5		S	New - #198/197	
L	88010 - 447- N3	os	4	0	1		S	New - #300	bis
L	88010 - 301 - N1	os	4	2	1		S	New - #14	
L	88010 - 301 - N4	os	4	0	2		S	New - #14	
L	88010 - 385- N6	os	4	0	2		S	New - #301	
L	89005 - 155 - N6	rr	4	0	2		S	New - #158/159	
L	89005 - 157 - N8	rr	4	0	2		S	New - #158	
L	89005 - 157 - N9	rr	4	0	2		C	New - #158	
L	89005 - 157 - N10	rr	4	0	2		C	New - #158	
L	89005 - 153 - N1	aw	4	1	2		S	New - #21	bis
L	89005 - 155 - N7	os	4	1	2		S	New - #158/159	
L	89005 - 159 - N13	os	4	1	2	x	S	New - #198/197	bis
oL	88010 - 381 - N2	os	4	1	2		S	New - #302	
L	89005 - 157 - N1	rr	4	1	2		C	New - #158	
L	89005 - 157 - N2	rr	4	1	2		C	New - #158	
L	88010 - 435 - N7	os	4	2	2		S	New -#86/197/298	
L	88010 - 435 - N8	os	4	2	2		S	New -#86/197/298	
L	88010 - 435 - N9	os	4	2	2		S	New -#86/197/298	

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
L	88010 - 437 - N10	os	4	2	2		S	New - #197/195	
L	88010 - 435 - N10	os	4	2	2		S	New -#86/197/298	
L	88010 - 435 - N11	os	4	2	2		S	New -#86/197/298	
L	89005 - 153 - N2	gh	4	0	4		S	New - #21	
L	89005 - 157 - N26	gh	4	0	4		C	New - #158	
L:	88010 - 447- N2	os	4	0	4		S	New - #300	
L	88010 - 434 - N6	os	4	0	4	x	S	New - #85/86	
L	89005 - 155 - N8	os	4	0	4	x	S	New - #158/159	
L	88010 - 446 - N1	os	4	1	4		S	New - #298	bis
L	89005 - 155 - N4	os	4	1	4		S	New - #158/159	
L	88010 - 443 - N4	os	4	1	4		S	New - #18/19	
L	88010 - 443 - N5	os	4	1	4		C	New - #18/19	
L	88010 - 443 - N5	os	4	1	4		C	New - #18/19	
L	88010 - 443 - N5	os	4	1	4		C	New - #18/19	
L	88010 - 443 - N6	os	4	1	4		S	New - #18/19	
L	88010 - 443 - N7	os	4	1	4		S	New - #18/19	
L	89005 - 159 - N12	os	4	1	4		S	New - #198/197	
L	89005 - 157 - N30	os	4	1	4		S	New - #158	
oL	88010 - 381 - N4	os	4	1	4		S	New - #302	bis
L	89005 - 157 - N3	rr	4	1	4		C	New - #158	
L	89005 - 157 - N5	rr	4	1	4		C	New - #158	
L	89005 - 157 - N6	rr	4	1	4		C	New - #158	
L	89005 - 157 - N27	rr	4	1	4		S	New - #158	
L	88010 - 435 - N15	gs	4	2	4		S	New -#86/197/298	
L	89005 - 157 - N4	os	4	2	4		S	New - #158	
L	89005 - 158 - N6	os	4	2	4		S	New - #197	
L	89005 - 158 - N7	os	4	2	4		S	New - #197	
L	88010 - 391- N8	os	4	2	4		S	New - #19/162	
L	89005 - 158 - N8	os	4	2	4		S	New - #197	
L	89005 - 158 - N9	os	4	2	4		S	New - #197	into gully
L	89005 - 157 - N13	os	4	2	4		S	New - #158	
L	88010 - 435 - N13	os	4	2	4		S	New -#86/197/298	
L	89005 - 157 - N12	rr	4	2	4		S	New - #158	
oL	89005 - 157 - N22	rr	4	2	4		S	New - #158	
L	89005 - 157 - N25	os	4	0	5		S	New - #158	
L	89005 - 158 - N2	os	4	1	5		S	New - #197	
L	88010 - 385- N5	os	4	1	5		S	New - #301	bis
L	89005 - 155 - N9	os	4	1	5		S	New - #158/159	

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
L	88010 - 443 - N10	os	4	1	5		S	New - #18/19	
L	89005 - 159 - N14	os	4	1	5	x	S	New - #198/197	bis
L	89005 - 159 - N15	os	4	1	5	x	S	New - #198/197	bis
L	88010 - 442 - N1	os	5	0	1		S	New - #19	
L	88010 - 379 - N3	os	5	0	1	x	S	New - #301/302/14	
L	89005 - 158 - N4	os	5	2	1		S	New - #197	
L	89005 - 157 - N7	os	5	0	2		S	New - #158	
L	88010 - 301 - N8	os	5	0	2		S	New - #14	
L	88010 - 442 - N5	os	5	1	2		S	New - #19	
L	88010 - 443 - N16	os	5	1	2		S	New - #18/19	
L	88010 - 434 - N1	os	5	0	4		S	New - #85/86	
L	89005 - 157 - N15	os	5	0	4		S	New - #158	
L	89005 - 157 - N31	os	5	0	4		S	New - #158	
oL	89005 - 157 - N23	os	5	0	4		S	New - #158	
L	88010 - 443 - N8	gs	5	1	4		S	New - #18/19	
L	88010 - 446 - N2	os	5	1	4		S	New - #298	bis
L	88010 - 446 - N3	os	5	1	4		S	New - #298	bis
L	88010 - 302 - N4	os	5	1	4	x	S	New - #166/14	
L	89005 - 159 - N9	os	5	1	4		S	New - #198/197	
L	89005 - 159 - N10	os	5	1	4		S	New - #198/197	
L	89005 - 159 - N11	os	5	1	4		S	New - #198/197	into gully
L	88010 - 443 - N12	os	5	1	4		S	New - #18/19	
L	88010 - 435 - N12	os	5	1	4		S	New -#86/197/298	
L	88010 - 443 - N17	os	5	1	4		S	New - #18/19	
L	89005 - 157 - N32	os	5	1	4		S	New - #158	
L	89005 - 157 - N11	gh	5	2	4		S	New - #158	
L	88010 - 443 - N14	gs	5	2	4		S	New - #18/19	
L	88010 - 303 - N2	os	5	2	4		S	New - #166	
L	89005 - 158 - N5	os	5	2	4		S	New - #197	
L	88010 - 443 - N13	os	5	2	4		S	New - #18/19	
L	88010 - 435 - N14	os	5	2	4		S	New -#86/197/298	
L	88010 - 443 - N15	os	5	2	4		S	New - #18/19	
L	89005 - 157 - N39	rr	5	2	4		S	New - #158	
L	88010 - 443 - N9	gs	5	1	5		S	New - #18/19	
L	89005 - 158 - N10	os	5	1	5		S	New - #197	into gully
L	88010 - 443 - N11	os	5	1	5		S	New - #18/19	
L	89005 - 157 - N14	os	5	1	5		S	New - #158	into gully
L	89005 - 158 - N3	gs	5	2	5		C	New - #197	

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
L	89005 - 158 - N3	gs	5	2	5		C	New - #197	
L	89005 - 158 - N3	gs	5	2	5		C	New - #197	
L	89005 - 158 - N3	gs	5	2	5		C	New - #197	
	Unlogged								
uL	88010 - 437 - N7	os	2	0	2		S	New - #197/195	
uL	88010 - 380 - N2	os	2	1	5		S	New - #302	
uL	88010 - 439 - N2	os	3	0	1		S	New - #160/161	
uL	88010 - 388- N3	os	3	2	1		S	New - #16	into gully
uL	88010 - 443 - N2	os	3	2	1		S	New - #18/19	
uL	88010 - 372 - N1	os	3	0	2		S	New - #162	
uL	88010 - 437 - N9	os	3	0	2		S	New - #197/195	
uL	88010 - 445 - N4	os	3	0	2		S	New - #298/18	
uL	88010 - 386- N1	os	3	0	2		S	New - #300	
uL	88010 - 387- N3	os	3	0	2		S	New - #300	
uL	88010 - 301 - N3	os	3	2	2		S	New - #14	
uL	89005 - 171 - N1	os	3	2	2	x	S	New - #158	
uL	89005 - 155 - N2	os	3	2	2		S	New - #158/159	
uL	88010 - 370 - N1	os	3	2	2		S	New - #193	
uL	88010 - 387- N1	os	3	2	2		S	New - #300	
uL	88010 - 387- N2	os	3	2	2		S	New - #300	
uL	88010 - 387- N4	os	3	2	2		S	New - #300	
uL	88010 - 445 - N7	rr	3	2	2	x	S	New - #298/18	
uL	88010 - 397 - N2	os	3	0	4		S	New - #195	
uL	88010 - 445 - N8	os	3	0	4		S	New - #298/18	
uL	88010 - 380 - N1	os	3	0	4		S	New - #302	
uL	88010 - 394- N9	os	3	2	4		S	New - #161/194/195	
uL	88010 - 370 - N2	os	3	0	5		S	New - #193	
uL	88010 - 395- N1	os	3	1	5		S	New - #194-16 Ass	
uL	88010 - 441 - N4	os	3	2	5		S	New - #162	
uL	88010 - 372 - N2	os	4	0	1		S	New - #162	
uL	88010 - 388- N1	os	4	1	1		S	New - #16	
uL	88010 - 303 - N4	os	4	1	1		S	New - #166	
uL	89005 - 155 - N1	os	4	0	2		S	New - #158/159	
uL	88010 - 437 - N8	os	4	0	2		S	New - #197/195	
uL	88010 - 399 - N2	os	4	0	2		S	New - #87	
uL	88010 - 394- N5	os	4	1	2		S	New - #161/194/195	
uL	88010 - 392- N3	os	4	1	2		S	New - #163/162	

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
uL 88010 - 437 - N1	os	4	1	2		S	New - #197/195	
uL 88010 - 397 - N3	os	4	2	2		S	New - #195	
uL 88010 - 437 - N4	os	4	2	2		S	New - #197/195	
uL 88010 - 435 - N6	os	4	2	2		S	New -#86/197/298	
uL 88010 - 397 - N1	os	4	1	4		S	New - #195	
uL 88010 - 437 - N3	os	4	1	4		S	New - #197/195	
uL 88010 - 398 - N2	os	4	1	4		S	New - #87	
uL 88010 - 394- N3	gs	4	2	4		S	New - #161/194/195	
uL 88010 - 301 - N2	os	4	2	4		S	New - #14	
uL 88010 - 437 - N2	os	4	2	4		S	New - #197/195	
uL 88010 - 437 - N6	os	4	2	4		S	New - #197/195	
uL 89005 - 157 - N20	os	4	1	5		S	New - #158	
uL 88010 - 302 - N5	os	5	0	1		S	New - #166/14	
uL 89005 - 157 - N38	gs	5	1	1		S	New - #158	
uL 88010 - 378 - N1	os	5	0	2		S	New - # 15/14	into river
uL 88010 - 378 - N2	os	5	0	2		S	New - # 15/14	into river
uL 88010 - 395- N5	os	5	1	2		C	New - #194/195	
uL 88010 - 395- N6	os	5	1	2		C	New - #194/195	
uL 88010 - 394- N12	os	5	2	2		S	New - #161/194/195	
uL 88010 - 374 - N2	os	5	2	2		S	New - #163	
uL 88010 - 443 - N3	os	5	2	2		S	New - #18/19	bis
uL 88010 - 395- N2	os	5	2	2		S	New - #194/195	
uL 88010 - 436 - N2	gs	5	0	4		S	New - #196	
uL 88010 - 303 - N5	os	5	0	4		S	New - #166	
uL 88010 - 435 - N3	gh	5	1	4		S	New -#86/197/298	
uL 88010 - 445 - N2	gs	5	1	4		S	New - #298/18	
uL 89005 - 157 - N19	os	5	1	4	x	S	New - #158	
uL 88010 - 394- N7	os	5	1	4		S	New - #161/194/195	into gully
uL 88010 - 394- N8	os	5	1	4		S	New - #161/194/195	into gully
uL 88010 - 374 - N4	os	5	1	4		S	New - #163	
uL 88010 - 374 - N5	os	5	1	4		S	New - #163	
uL 88010 - 302 - N3	os	5	1	4	x	S	New - #166/14	
uL 88010 - 434 - N7	os	5	1	4		S	New - #85/86	
uL 88010 - 435 - N1	os	5	1	4		S	New -#86/197/298	into gully
uL 88010 - 435 - N2	os	5	1	4		S	New -#86/197/298	into gully
uL 88010 - 302 - N1	os	5	1	4		C	New - #166/14	
uL 88010 - 302 - N2	os	5	1	4		C	New - #166/14	
uL 89005 - 157 - N18	os	5	2	4		S	New - #158	

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
uL	88010 - 439 - N1	os	5	2	4		S	New - #160/161	
uL	88010 - 392- N2	os	5	2	4		S	New - #163/162	
uL	88010 - 303 - N3	os	5	2	4		S	New - #166	
uL	88010 - 395- N9	os	5	2	4		S	New - #194/195	
uL	88010 - 395- N10	os	5	2	4		S	New - #194/195	
uL	88010 - 445 - N5	os	5	2	4		S	New - #298/18	
uL	88010 - 445 - N6	os	5	2	4		S	New - #298/18	bis
uL	88010 - 380 - N4	gh	5	1	5		S	New - #302-3	
uL	89005 - 157 - N17	os	5	1	5	x	S	#158-6 + more	Newer, above old
uL	89005 - 172 - N1	os	5	1	5		S	New - #158	into a gully
uL	88010 - 394- N6	os	5	1	5		S	New - #161/194/195	into gully
uL	88010 - 374 - N3	os	5	1	5		S	New - #163	
uL	88010 - 392- N1	os	5	1	5		S	New - #163/162	
uL	88010 - 442 - N4	os	5	1	5		S	New - #19	
uL	88010 - 398 - N1	os	5	1	5		S	New - #87	
uL	88010 - 435 - N4	os	5	1	5		S	New -#86/197/298	into gully
uL	88010 - 435 - N5	os	5	1	5		S	New -#86/197/298	into gully
uL	88010 - 392- N5	gs	5	2	5		C	New - #163/162	
uL	88010 - 392- N5	gs	5	2	5		C	New - #163/162	

The following 34 failures are not new, they correspond to failures on the old photographs

	Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
L	88010 - 443 - N18	os	4	1	5		S	#19-4	
L	88010 - 443 - N19	os	4	1	5		S	#19-4	
L	88010 - 385- N4	os	4	1	5		S	#301-1	bis
oL	88010 - 381 - N1	os	4	2	2		C	#302 - no id	zis
oL	88010 - 381 - N3	os	4	2	2		C	#302 - no id	zis
L	89005 - 171 - N2	rr	4	2	5		S	#158-1	
L	89005 - 155 - N5	gh	5	1	5		S	#158-10	
uL	88010 - 385- N8	os	1	0	1		S	#301 - no id	
uL	88010 - 394- N1	os	3	0	5		S	#194-15	
uL	88010 - 388- N2	os	3	1	5		S	#16-1	
uL	88010 - 392- N4	os	3	1	5		S	#162-3	
uL	88010 - 395- N3	os	4	1	5		S	#194-7	
uL	88010 - 380 - N3	os	4	1	5		S	#302-2	
uL	88010 - 437 - N5	os	4	1	5		S	#195-8	
uL	88010 - 395- N8	os	4	1	5		S	#195 - no id	
uL	89005 - 157 - N21	os	4	1	5		S	#158-2	bis

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
uL 88010 - 394- N4	os	4	2	5		S	#194-12	
uL 88010 - 394- N2	os	5	2	2		C	#194 - old, no id	
uL 88010 - 445 - N3	gs	5	1	4		S	#298-1	
uL 88010 - 445 - N1	os	5	1	4		S	#298-2	
uL 88010 - 374 - N1	gh	5	1	5		S	#163-2/3	
uL 88010 - 391- N9	gh	5	1	5		S	#162-2	
uL 88010 - 394- N10	gh	5	1	5		S	#161-1	
uL 89005 - 157 - N16	gh	5	1	5	x	S	#158-9	
uL 88010 - 436 - N1	os	5	1	5		S	#196-1	
uL 88010 - 399 - N1	os	5	1	5		S	#86-3	
uL 89005 - 155 - N3	os	5	1	5		S	#159-3	
uL 88010 - 395- N4	os	5	1	5		S	#194-2	
uL 88010 - 395- N7	os	5	1	5		S	#195-4	
uL 88010 - 434 - N8	os	5	1	5		S	#85-3	
uL 88010 - 445 - N9	os	5	1	5		S	#18-13	bis
uL 88010 - 434 - N9	os	5	1	5		S	#86-1	
uL 88010 - 391- N10	os	5	1	5		S	#19-1	
uL 88010 - 394- N11	os	5	1	5		S	#195-3	
OLD Photography								
77063-197-O6	os	2	1	5		S	#157 gone	
77063-021-O4	os	2	1	5		S	gone	
77063-198-O8	rr	2	1	5		S	#159 gone	
77064 - 85 -O8	os	3	1	5		S	#434 gone	old old logging
77064 - 87 -O2	os	3	1	5		S	#398/399 no id	
77064 - 87 -O3	os	3	1	5		S	#398/399 no id	
77063-197-O5	os	3	1	5		S	#157 gone	
77063-166-O2	os	3	1	5		S	#303/302 no id	
77063-194-O15	os	3	1	5		S	#394-1	
77063-163-O9	os	3	1	5		S	no id	
77063-163-O11	os	3	1	5		S	no id	
77063-162-O3	os	3	1	5		S	#392-4	
77062 - 300 - O2	os	3	1	5		S	no id	
77062 - 300 - O5	os	3	1	5		S	no id	
77063-014-O1	os	3	1	5		S	no id	
77063-014-O2	os	3	1	5		S	no id	
77063-018-O10	os	3	1	5		S	no id	
77063-016-O1	os	3	1	5		S	#388-2	
77063-194-O16	os	3	1	5		C	Ass with #394-1	zis

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
77063-194-O16	os	3	1	5		C	Ass with #394-1	zis
77063-194-O16	os	3	1	5		C	Ass with #394-1	zis
77063-018-O5	os	3	1	5		C	no id	
77063-166-O3	gh	3	1	5		S	#303/302 no id	
77063-162-O6	gh	3	1	5		S	no id	
77063-018-O8	gh	3	1	5		S	no id	
77064 - 85 -O5	gs	3	1	5		S	#434 no ID	old old logging
77063-162-O1	gs	3	1	5		S	no id	
77063-018-O11	gs	3	1	5		S	no id	
77064 - 85 -O6	aw	3	1	5		S	#434 gone	old old logging
77063-158-O4	rr	3	1	5		S	gone	
77064 - 87 -O4	os	4	1	5		S	#398/399 no id	
77064 - 87 -O5	os	4	1	5		S	#398/399 no id	
77064 - 87 -O10	os	4	1	5		S	#398/399 no id	
77063-197-O1	os	4	1	5		S	#435 no id	
77063-197-O7	os	4	1	5		S	#157 gone	
77063-197-O8	os	4	1	5		S	#157 gone	
77063-197-O9	os	4	1	5		S	#157 gone	
77063-198-O1	os	4	1	5		S	#159 gone	
77063-198-O4	os	4	1	5		S	#159 gone	
77063-198-O5	os	4	1	5		S	#159 gone	
77063-166-O1	os	4	1	5		S	#303/302 no id	
77063-193-O1	os	4	1	5		S	no id	
77063-194-O1	os	4	1	5		S	no id	
77063-194-O4	os	4	1	5		S	no id	
77063-194-O5	os	4	1	5		S	no id	
77063-194-O7	os	4	1	5		S	#395-3	
77063-194-O8	os	4	1	5		S	no id	
77063-194-O10	os	4	1	5		S	no id	
77063-194-O11	os	4	1	5		S	no id	
77063-194-O12	os	4	1	5		S	#394-4	
77063-194-O13	os	4	1	5		S	no id	
77063-194-O14	os	4	1	5		S	no id	
77063-195-O1	os	4	1	5		S	no id	
77063-195-O2	os	4	1	5		S	no id	
77063-195-O7	os	4	1	5		S	no id	
77063-163-O1	os	4	1	5		S	no id	
77063-163-O5	os	4	1	5		S	no id	

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
77063-163-O12	os	4	1	5		S	no id	
77063-162-O5	os	4	1	5		S	no id	older, veg at bottom
77063-161-O6	os	4	1	5		S	no id	
77062 - 301 - O1	os	4	1	5		S	#385-4	bis
77062 - 301 - O2	os	4	1	5		S	no id	bis
77062 - 301 - O3	os	4	1	5		S	no id	bis
77062 - 300 - O1	os	4	1	5		S	no id	
77062 - 300 - O4	os	4	1	5		S	no id	
77063-158-O2	os	4	1	5		S	#157-21	
77063-018-O2	os	4	1	5		S	no id	into gully
77063-019-O4	os	4	1	5		S	#443-18-19	
77063-198-O2	os	4	1	5		C	#159 gone	
77063-198-O3	os	4	1	5		C	#159 gone	zis
77063-198-O3	os	4	1	5		C	#159 gone	zis
77063-198-O3	os	4	1	5		C	#159 gone	zis
77063-195-O6	os	4	1	5		C	no id	zis
77063-195-O6	os	4	1	5		C	no id	
77063-195-O6	os	4	1	5		C	no id	zis
77063-195-O8	os	4	1	5		C	#437-5	zis
77063-195-O8	os	4	1	5		C	#437-5	zis
77062 - 302 - O2	gh	4	1	5		S	#380-3	
77063-018-O3	gh	4	1	5		S	no id	
77063-018-O12	gs	4	1	5		S	no id	
77063-018-O14	gs	4	1	5		S	no id	
77064 - 85 -O1	aw	4	1	5		C	#434 no ID	
77063-158-O1	rr	4	1	5		S	#171-2	
77063-021-O1	rr	4	1	5		S	gone	
77064 - 85 -O2	os	5	1	5		S	#434 gone	
77064 - 85 -O3	os	5	1	5		S	#434-8	
77064 - 86 -O1	os	5	1	5		S	#434-9	
77064 - 86 -O2	os	5	1	5		S	#434/435/399 gone	
77064 - 86 -O3	os	5	1	5		S	#399-1	
77064 - 87 -O1	os	5	1	5		S	#398/399 no id	
77064 - 87 -O6	os	5	1	5		S	#398/399 no id	
77064 - 87 -O7	os	5	1	5		S	#398/399 no id	
77064 - 87 -O8	os	5	1	5		S	#398/399 no id	
77064 - 87 -O9	os	5	1	5		S	#398/399 no id	

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
77064 - 87 -O11	os	5	1	5		S	#398/399 no id	
77064 - 87 -O12	os	5	1	5		S	#398/399 no id	
77064 - 87 -O13	os	5	1	5		S	#398/399 no id	
77064 - 87 -O14	os	5	1	5		S	#398/399 no id	
77064 - 87 -O15	os	5	1	5		S	#398/399 no id	
77064 - 87 -O16	os	5	1	5		S	#398/399 no id	
77063-197-O4	os	5	1	5		S	#157 gone	
77063-198-O6	os	5	1	5		S	#159 gone	
77063-166-O4	os	5	1	5		S	#303/302 no id	
77063-166-O5	os	5	1	5		S	#303/302 no id	
77063-166-O6	os	5	1	5		S	#303/302 no id	
77063-166-O7	os	5	1	5		S	#303/302 no id	
77063-166-O8	os	5	1	5		S	#303/302 no id	
77063-166-O9	os	5	1	5		S	#303/302 no id	
77063-193-O2	os	5	1	5	x	S	no id	old logged area
77063-194-O2	os	5	1	5		S	#395-4	
77063-194-O6	os	5	1	5		S	no id	
77063-194-O9	os	5	1	5		S	no id	
77063-195-O4	os	5	1	5		S	old old	
77063-195-O5	os	5	1	5		S	no id	
77063-195-O9	os	5	1	5		S	no id	
77063-196-O1	os	5	1	5		S	#436-1	
77063-163-O4	os	5	1	5		S	no id	
77063-163-O8	os	5	1	5		S	no id	
77063-162-O4	os	5	1	5		S	no id	
77063-161-O1	os	5	1	5		S	#394-10	
77063-161-O2	os	5	1	5		S	no id	
77063-161-O3	os	5	1	5		S	no id	
77063-161-O4	os	5	1	5		S	no id	
77063-161-O5	os	5	1	5		S	no id	
77063-159-O1	os	5	1	5		S	gone	large
77063-159-O2	os	5	1	5	x	S	gone	into a gully
77063-159-O3	os	5	1	5	x	S	#155-3	
77063-021-O2	os	5	1	5		S	gone	
77063-021-O3	os	5	1	5		S	gone	
77062 - 300 - O3	os	5	1	5		S	no id	
77062 - 298 - O2	os	5	1	5		S	#445-1	
77062 - 298 - O3	os	5	1	5		S	no id	

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
77063-158-O3	os	5	1	5		S	gone	
77063-158-O5	os	5	1	5		S	gone	into a gully
77063-158-O6	os	5	1	5		S	#157-17 + new	into a gully
77063-158-O9	os	5	1	5		S	#157-16	into a gully
77063-014-O3	os	5	1	5		S	no id	into a gully
77063-014-O4	os	5	1	5		S	no id	into a gully
77063-018-O1	os	5	1	5		S	no id	
77063-018-O4	os	5	1	5		S	no id	
77063-018-O7	os	5	1	5		S	no id	
77063-018-O9	os	5	1	5		S	no id	
77063-018-O13	os	5	1	5		S	#445-9	bis
77063-019-O1	os	5	1	5		S	#391-10	huge!
77063-019-O2	os	5	1	5		S	no id	
77063-019-O3	os	5	1	5		S	#442-4	into a gully
77063-018-O6	os	5	1	5		C	no id	
77063-162-O7	os	5	1	5		C	no id	
77063-162-O8	os	5	1	5		C	no id	
77063-162-O9	os	5	1	5		C	no id	
77064 - 86 -O6	gh	5	1	5		S	#434/435/399 gone	
77064 - 86 -O7	gh	5	1	5		S	#434/435/399 gone	
77063-163-O2	gh	5	1	5		S	#374-2	
77063-163-O3	gh	5	1	5		S	no id	
77063-163-O10	gh	5	1	5		S	no id	
77063-162-O2	gh	5	1	5		S	#391-9	
77062 - 302 - O3	gh	5	1	5		S	#380-4 +new	
77063-158-O8	gh	5	1	5		S	gone	
77063-158-O10	gh	5	1	5		S	#155-5	
77063-197-O3	gh	5	1	5		C	#157 gone	zis
77063-162-O10	gh	5	1	5		C	no id	
77063-162-O11	gh	5	1	5		C	no id	
77064 - 85 -O4	gs	5	1	5		S	#434 gone	
77064 - 86 -O4	gs	5	1	5		S	#434/435/399 gone	
77064 - 86 -O5	gs	5	1	5		S	#434/435/399 gone	
77063-197-O2	gs	5	1	5		S	#157 gone	
77063-195-O3	gs	5	1	5		S	#394-11	
77063-163-O6	gs	5	1	5		S	no id	
77063-163-O7	gs	5	1	5		S	no id	
77062 - 302 - O1	gs	5	1	5		S	no id	

Failure Number	Type	SRS	ESA	SGA	Cut Bdy	Event	Associated Photo's	Comments
77062 - 298 - O1	gs	5	1	5		S	S445-3	
77063-198-O7	gs	5	1	5		C	#159 gone	large zis
77063-198-O7	gs	5	1	5		C	#159 gone	large zis
77063-198-O7	gs	5	1	5		C	#159 gone	large zis
77063-198-O7	gs	5	1	5		C	#159 gone	large zis
77063-194-O3	aw	5	1	5		C	no id	zis
77063-158-O7	aw	5	1	5		C	gone	zis
77063-198-O9	rr	5	1	5		C	#159 gone	

Table A5.3 : Tabular Comparisons of the Failure Event Inclusion in Each Stability Class - McClinton Bay

5 Class

McClinton Bay		SRS						
		1	2	3	4	5	sum	User Acc
	1	0	4	3	6	3	16	0%
SGA	2	0	0	8	9	21	38	0%
	3	0	0	0	0	0	0	
	4	0	0	3	8	9	20	40%
	5	0	0	0	1	21	22	95%
	sum	0	4	14	24	54	96	
	Prod Acc		0%	0%	33%	39%		30%

3 Class

McClinton Bay		SRS				
		1	2	3	sum	User Acc
SGA	1	4	26	24	54	7%
	2	0	11	9	20	55%
	3	0	1	21	22	95%
	sum	4	38	54	96	
	Prod Acc	100%	29%	39%		38%

3 Class

McClinton Bay		SRS				
		1	2	3	sum	User Acc
ESA	1	4	9	10	23	17%
	2	0	7	7	14	50%
	3	0	22	37	59	63%
	sum	4	38	54	96	
	Prod Acc	100%	18%	69%		50%

3 Class

McClinton Bay		ESA				
		0	2	1	sum	User Acc
SGA	1	17	11	26	54	31%
	2	4	2	14	20	10%
	3	2	1	19	22	82%
	sum	23	14	59	96	
	Prod Acc	74%	14%	32%		40%

Table A5.4 : Tabular Comparisons of the Failure Event Inclusion in Each Stability Class - Louise Island

5 Class

Louise Island		SRS						
		1	2	3	4	5	sum	User Acc
SGA	1	0	3	10	5	5	23	0%
	2	1	7	31	26	12	77	9%
	3	0	0	0	0	0	0	
	4	1	4	20	38	46	109	83%
	5	0	2	5	8	20	35	57%
	sum	2	16	66	77	83	244	
	Prod Acc	0%	44%	0%	49%	24%		27%

3 Class

Louise Island		SRS				
		1	2	3	sum	User Acc
SGA	0	11	72	17	100	11%
	2	5	58	46	109	53%
	1	2	13	20	35	57%
	sum	18	143	83	244	
	Prod Acc	61%	41%	24%		36%

3 Class

Louise Island		SRS				
		1	2	3	sum	User Acc
ESA	0	12	49	13	74	16%
	2	4	56	27	87	64%
	1	2	39	42	83	51%
	sum	18	144	82	244	
	Prod Acc	67%	39%	51%		45%

3 Class

Louise Island		ESA				
		1	2	3	sum	User Acc
SGA	1	43	40	17	100	43%
	2	29	38	42	109	35%
	3	2	9	24	35	69%
	sum	74	87	83	244	
	Prod Acc	58%	44%	29%		43%