

TERRAIN STABILITY MAPPING ON BRITISH COLUMBIA FOREST LANDS: A HISTORICAL PERSPECTIVE

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RÉSUMÉ

La gestion des terrains liée aux pratiques de sylviculture en Colombie Britannique (C.-B.) a fait développer, de façon considérable, les connaissances et les méthodes dans la préparation de cartes d'aléas de stabilité de terrain. La cartographie de susceptibilité aux mouvements de terrain a commencé au début des années 1970 en C.-B. À ce moment-là, la gestion de forêt se dirigeait vers les pentes plus abruptes, ce qui endommageait les ressources forestières en provoquant de nombreux glissements de terrains associés à la construction de routes forestières et aux déboisements. Les méthodes utilisées pour la préparation de cartes de susceptibilité ont évolué avec le temps. Dans la planification du territoire forestier, on a identifié les aléas de glissements de terrain et on les a incorporés dans la classification forestière pour ensuite tracer les secteurs sensibles sur des cartes. Ces cartes de susceptibilité aux mouvements de terrain ont été utilisées pour la première fois sur les îles de la Reine Charlotte, en 1974. Dans les années 1980, d'autres experts ont utilisé la méthode en C.-B. pour la planification forestière le long de la côte et par la suite, pendant les années 1990, vers l'intérieur de la C.-B. On a témoigné une amélioration au cours des années à cause d'un gain de nouvelles connaissances, de l'introduction de normes cartographiques et de normes dans la compilation et la production de cartes numériques. En 1995, on a établi de façon formelle la cartographie générale et détaillée de susceptibilité aux mouvements de terrain en divisant les aléas en trois et cinq classes, respectivement. Plus récemment, des approches qualitatives et semi-quantitatives pour prévoir l'occurrence de mouvements de terrain basées sur les inventaires de glissements de terrain ont été ajoutées à la préparation des cartes de susceptibilité aux mouvements de terrain.

ABSTRACT

Land management associated with forest practices in British Columbia (BC) has over the last three decades provided considerably impetus for the development of methods used for terrain stability hazard mapping. Terrain stability mapping (TSM) in BC originated in the early 1970's, when forest development was progressing on to steep unstable terrain with resultant damage to forest resources from road and clear-cut associated landslides. The methods with respect to the art and science used for the preparation of (TSMs) have undergone continuous evolution. First, with the recognition of terrain hazards incorporated into the forest classification system to delineate environmentally sensitive areas for forest land-use planning. Later, operational terrain stability maps were introduced on the Queen Charlotte Islands of BC in 1974. This method was subsequently used by others for forest development planning along the BC coast in the 1980s, and then extended to the BC interior in the 1990s. The system was refined over time based on new knowledge and the introduction of mapping standards including standards for capture and presentation of digital maps. In 1995, reconnaissance terrain stability mapping and detailed terrain stability mapping were formalized with three and five hazard classes, respectively. More recently, qualitative and semi-quantitative approaches to predict landslide occurrence based on terrain and landslide inventories have been incorporated into the techniques for TSM used in BC.

1. INTRODUCTION

Forest harvesting in British Columbia's coastal forest lands moved on to steep terrain in the 1960s and early 1970s without a systematic method for the identification of unstable terrain or down slope risks associated with road construction and timber harvesting. The results were devastating; many landslides initiated in cut blocks and from roads during west coast rain storms (Figures 1 and 2). These landslides had a considerable cost with the loss of life, degradation of fish habitat and forest land, lost investment in forest roads, and lost silviculture investment (Schwab 1988; Hogan *et al.* 1998).

Forest practices on steep potentially unstable terrain have evolved over the past 30 years. This has resulted in improved road construction practices through unstable terrain, improved water management along roads and simply the awareness and avoidance of unstable terrain. Part of this evolution was the recognition of unstable landscapes at a planning level and the field identification of site indicators of slope instability. There was (and remains) an urgent need to provide landslide hazard information to professionals in the forest industry. The information needed to be presented in a manner that could be easily interpreted for forest and environmental management planning. Hence, the development of slope



Figure 1. Landslides from roads caused by slope overloading and inadequate drainage.



Figure 2. Landslide initiated in a cut block on a 38 degree slope. Note historic landslides (arrows) in relation to more recent landslides.

stability hazard mapping or terrain stability mapping. Its origins are in the terrain classification system (Environment and Land Use Committee Secretariat 1976) that was based on the work of Fulton *et al.* (1979). The objective of terrain mapping is to categorize, describe, and delineate characteristics and attributes of surficial materials, landforms, and geological processes within the natural landscape (Howes and Kenk 1988, 1997; Resource Inventory Committee 1996). Comprehensive standards and guidelines for terrain mapping in British Columbia have also been described (Ryder 1994). Geoscientists create terrain maps through aerial-photographic interpretation. Landscape features, the presence of geomorphic processes (landslides and erosion), hillslope gradient, bedrock, soil, and drainage characteristics are identified through experience and professional judgment. Terrain stability maps (TSMs) are derived from these source terrain maps through professional interpretation. They utilize the terrain and terrain map polygon attributes to delineate polygons where timber harvesting or road construction may cause landslides or erosion (BCMOF and BCMOE 1999).

2. TERRAIN STABILITY MAPS

The BC Ministry of Forests and Range first recognized and mapped potentially unstable terrain for forest land-use planning in the 1970s. Forest cover polygons that showed evidence of landslides were delineated as environmentally sensitive areas (BCMOF 1992). The productive forest landbase for forest harvesting cut control calculation was then reduced accordingly. Limitations of the approach resulted in ratings being attached to large forest cover polygons, not a specifically terrain delineated unit, no distinction of the type of instability present, and no information in support of the rating (Es1 – Unstable terrain, terrain with active landslides; Es2 – potentially unstable terrain). The first operational terrain stability maps were introduced on the Queen Charlotte Islands in 1974 by W.W. Bourgeois of MacMillan Bloedel Ltd. (Bourgeois 1975, 1978; Bourgeois and Townsend 1977). Various terrain scientists, working within the Land Use Planning Advisory Team of MacMillan Bloedel Ltd., advanced the methods and the identification of unstable terrain. These mapping methods were subsequently used by others for forest development planning along the BC coast in the 1980s, and then extended to the BC interior in the 1990s. Over time, the system underwent considerable refinements (Schwab 1982, 1993; Howes 1987; Howes and Swanston 1994). With the publications from the BC Ministries of Forests and Environment, came the introduction of reconnaissance terrain stability mapping (RTSM) and detailed terrain and terrain stability mapping (DTSM) with three and five hazard classes, respectively (BCMOF and BCMOE 1995a, 1999). A relative comparison of the terrain stability mapping classes used on forest land in BC is provided in Table 1.

Table 1. Comparison of the classes of the terrain stability mapping systems used on forest land in BC¹

Detail Terrain Stability Class	Reconnaissance Stability class	ESA ² Soil Sensitivity class
I	S	Not classified
II	S	Not classified
III	S	Not classified
IV	P	Es2
V	U	Es1

¹Table is modified from BCMOF and BCMOE (1999); stability classes are explained in Section 2.1 and Table 3.

²ESA—Environmental Sensitive Area

The criteria used to delineate terrain stability classes are defined in terms of slope gradient, surficial materials, material texture, slope morphology, moisture conditions and ongoing geomorphic processes. Few specific criteria apply across all regions of the province because of variations in climate, geology and soils. Criteria for RTSM are less rigorous than for DTSM; with reconnaissance-level mapping completed primarily through aerial photographic interpretation. With DTSM, terrain types that experience landslides related to logged areas and roads are

documented. This information is then used to develop hazard rating criteria and rank different terrain types for the expected likelihood of landslides associated with forest development. A systematic approach to collecting this type of terrain data is termed a terrain attribute study (Rollerson *et al.* 1997).

2.1 Reconnaissance Terrain Stability Mapping

The objective of RTSM is to identify and map stable and potentially unstable terrain over large land areas that have a low occurrence of potentially unstable terrain and/or to identify land areas of high potential terrain stability hazards for detailed terrain stability mapping. Only polygons of unstable and potentially unstable terrain are mapped (Figure 3). Areas not designated are assumed stable. RTSM unlike DTSM does not involve preparing a terrain map first. Mapping relies primarily on stereoscopic aerial photographic interpretation supplemented with helicopter reconnaissance and very limited ground-checking. Maps are presented at a scale of 1:20 000 to 1:50 000.

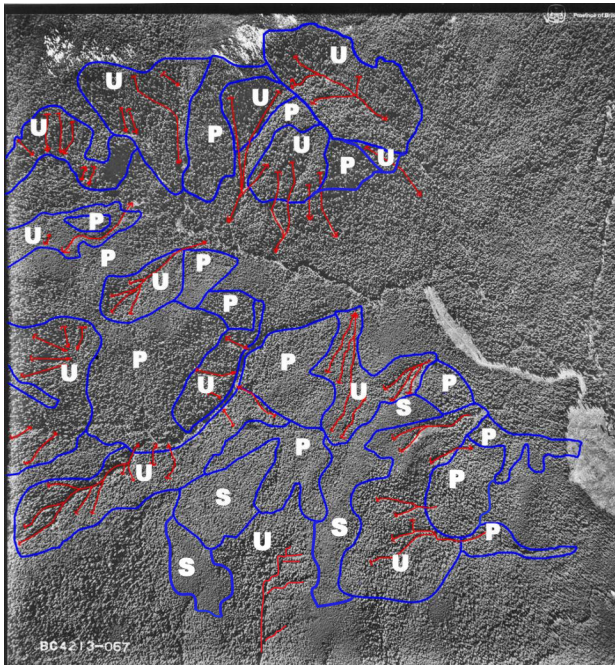


Figure 3. Example of typed aerial photograph with delineated RTSM hazard classes U, P and S. Debris flow channels are highlighted in red, polygon boundaries in blue. Note, the entire photograph is not typed.

The RTSM classes are stable (S), potentially unstable (P), and unstable (U). On the maps, classes P and U include a terrain symbol, geomorphic process (Table 2), and a slope range. The terrain and slope information provide some background information as to the assigned terrain stability class.

Table 2. Subclasses for mass movement processes¹

Subclass name	Map symbol
Initiation zone	"
Soil creep	c
Rock creep	g
Tension cracks	k
Rock spread	p
Soil spread	j
Debris fall	f
Rock fall	b
Debris flow	d
Debris torrent	t
Earthflow	e
Rock slump	m
Soil slump	u
Slump–earthflow	x
Debris slide	s
Rock slide	r

¹table modified from Howes and Kenk (1997).

2.2 Detailed terrain and terrain stability mapping

Detailed terrain mapping is carried out to collect and present information about the physical characteristics and properties of the land surface and its geologic materials and to provide detailed interpretive data on terrain stability and soil erosion potential. The detailed terrain map forms the basis for the preparation of the interpreted detailed terrain stability map. Unstable and potentially unstable areas identified on the interpreted map enable planners to avoid areas where forest harvesting activities could cause landslides and helps identify where field-based assessments are necessary.

Ground checks are undertaken for 20-50% of map polygons through foot traverses supported by vehicle and helicopter flights. Field checks tend to be directed toward unstable or potentially unstable terrain units. Maps are generally presented at 1:20 000.

Mapping standards follow guidelines and standards for terrain mapping in BC (Resource Inventory Committee (RIC) 1996), digital terrain data capture and presentation (RIC 1998) and the Terrain Classification System for BC (Howes and Kenk 1997) (Figure 4). In addition, terrain polygon labels include descriptions for slope gradient (maximum and minimum range) and soil drainage as described by the Canadian System for Soil Classification (Agriculture Canada 1998). On site symbols are generally used to identify features that are important for terrain stability interpretations but too small to be mapped as a distinct polygon (e.g. a small landslide, gully, terrace scarp). Relevant information on bedrock geology is sometimes included where terrain stability is influenced by bedrock geology (e.g. strike, dip, and faults).

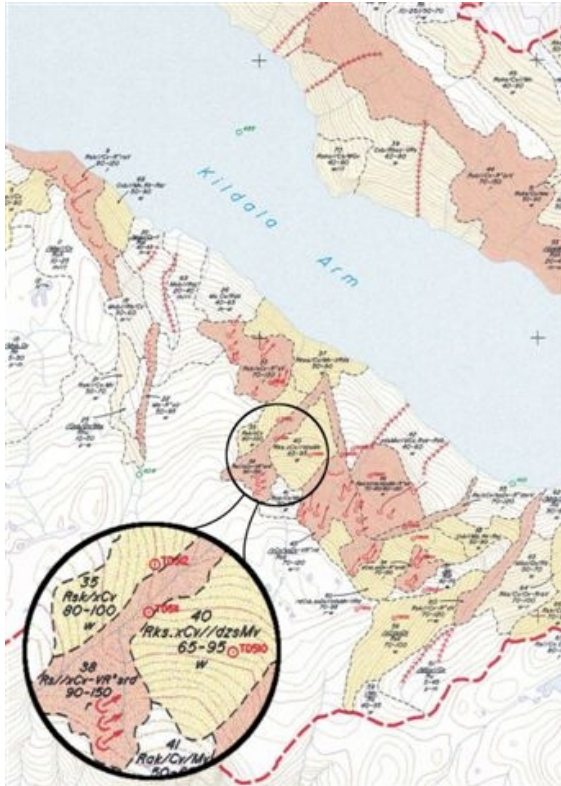


Figure 4. Terrain map showing the terrain polygon number, terrain symbol, slope gradient, soil drainage, onsite landslide symbols and the field inspection plots.

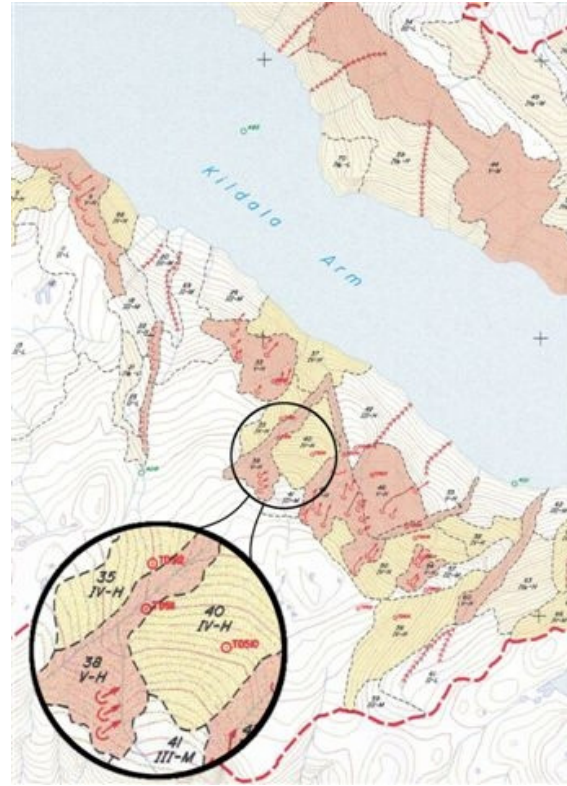


Figure 5. Terrain stability map showing the terrain stability class polygons with erosion subclasses (V-H). Polygon number, field inspection plot and on site landslide symbols are also shown.

The DTSM terrain stability classes provide a relative ranking of the likelihood of a landslide occurring after timber harvesting or road construction (Figure 5). The assignment and interpretation of the terrain stability classes is subjective and specifically focused for forest management purposes. DTSM polygons are derived from terrain data collected, mapped and interpreted by the geoscience professional. Terrain stability polygons are assigned a symbol (I to V) to indicate the likelihood of landslide initiation. The classes give no indication of the expected magnitude and frequency of landslides or the potential down slope or down stream damage from a landslide. The terrain stability classes I, II, III, IV and V range from stable to unstable under natural conditions (Table 3; Figure 6).

Other interpretations are often added to the terrain stability symbol. These include: the potential for landslide debris to enter streams; soil erosion potential; and risk of sediment delivery to streams (BCMOF and BCMOE 1999). The potential for landslide debris to enter streams is an interpretation of the likelihood of colluvium and organic debris to enter a stream. It is based on a consideration of hillslope gradient and length, and slope morphology down slope of the mapped polygon, as well as evidence of previous landslide runout, presence or

absence of a runout zone, and presence of gullies that connect directly to a stream.

Table 3. Detailed terrain stability classification¹

Terrain stability class	Interpretation ¹
I	<ul style="list-style-type: none"> No significant problems exist Very low likelihood of landslides from timber harvesting or road construction
II	<ul style="list-style-type: none"> Minor slumping expected in road cuts Minor instability
III	<ul style="list-style-type: none"> Low likelihood of landslides from timber harvesting or road construction
IV ²	<ul style="list-style-type: none"> Moderate likelihood of landslides from timber harvesting or road construction
V	<ul style="list-style-type: none"> High likelihood of landslides from timber harvesting or road construction

¹table modified from Chatwin *et al.* 1994; and BCMOF and BCMOE 1999. The classification addresses landslides greater than 0.05 ha in size, conventional timber harvesting practices, and sidecast road construction.

²modifiers are sometimes added, for example, "IVR" to indicate landslide initiation following road construction.



Figure 6. Example polygons of five class terrain stability mapping. Projection is onto a landscape on the BC north coast. Classification is presented in Table 3.

Soil erosion potential for fine sediment production from exposed surfaces on roads and trails is assigned to terrain polygons. Simple soil erosion potential ratings are based on the genetic material, slope gradient, material texture and soil drainage. The risk of fine sediment delivery to streams or the likelihood that sediment from the source polygon will be transported and delivered to a stream can also be provided for polygons that have a high or very high surface erosion potential.

Terrain stability mapping is now an integral part of forest development planning in British Columbia; however it is somewhat narrowly focused on the hazard of landslide initiation. Polygons are rated for the likelihood that a landslide might initiate within the polygon following forest harvesting activities, but not on whether a landslide may impact it. Even though a terrain polygon may be in the travel path of a landslide, the mapped terrain stability polygon is unlikely to be a class IV or V unless the associated terrain symbol indicates a landslide initiation zone (Table 1, 2). Therefore, as an example, despite their vulnerability and exposure to impact by landslides, fans receive low terrain stability class designation (e.g. Class I or II). A separate analysis is sometimes undertaken to evaluate the travel

distance of a landslide, and hence the likelihood of sediment entering a stream (Maynard 1987; Hogan and Wilford 1989). Further, since the terrain stability classification system was developed for steep terrain, shallow soils, and relatively simple landslides (debris flows on open slopes or in fluvial channels), complex large landslides are not adequately addressed (Geertsema and Schwab 2006).

Hazard maps with slope stability classes (I-V) were created with interpretations specifically for application in forest development planning. As such, these hazard maps are not suitable for general planning although similar terrain/hazard mapping methods are sometimes employed. Land use zonations (Hungry *et al.* 1994) in association with infrastructure or residential development require a rigorous landslide hazard assessment and landslide risk assessment (APEGBC 2006).

A standard for terrain stability assessments in the BC forest sector is presented in a document prepared by the Associations of Professional Engineers and Geoscientists of BC (APEGBC 2003) and is currently under revision by APEGBC and the Association of BC Forest Professionals.

3. TERRAIN ATTRIBUTES

TSM methods use terrain attributes that are either qualitative or quantitative, with the qualitative systems based mainly on field observations or research studies. Hence, considerable effort was made concurrent with the development of mapping methodology to identify terrain subject to landslides within the forest landscape. BC coastal research is summarized by Hogan *et al.* (1998), and BC interior research by Jordan and Orban (2002). Research first sought to provide qualitative and semi-quantitative approaches to predict landslide occurrence, (Wilford and Schwab 1982; Chatwin *et al.* 1994) and evaluate gully susceptibility to landslide hazard (Hogan *et al.* 1995; BCMOF and BCMOE, 1995a; 1995b). Qualitative approaches to identify terrain subject to high landslide frequencies sought to correlate landslide frequency with individual landscape attributes and combinations of attributes in mapped terrain polygons (Rollerson and Sondheim 1985; Rollerson *et al.* 1997; Rollerson *et al.* 2001a, 2001b; Millard *et al.* 2002). Recent work (Rollerson *et al.* 2004) uses categorical and scale data from terrain and landslide inventories to produce semi-quantitative landslide hazard maps for forest management. Detailed studies in BC coastal gullies by Millard (1999) address factors associated with debris flow initiation. Wilford *et al.* (2004) propose a model using watershed (basin) and terrain characteristics to differentiate between watersheds prone to debris flows and other hydrogeomorphic processes.

In the BC interior, landslide frequency is comparatively low and generally attributed to road construction and water management practices, making it impractical to contrast attributes of landslide and non-landslide terrain polygons. Hence research has focused on describing terrain attributes of individual landslides (Pack 1995; Jordan 2002; Ward *et al.* 2002). The objective is to establish whether development-related landslides can be determined with reference to terrain attributes that can be mapped, or whether landslide occurrence is essentially independent of such factors. VanBuskirk *et al.* (2005) compared terrain attributes at sites with landslides to attributes at sites without landslides. The findings enabled the identification of critical terrain attributes for road construction and road drainage.

4. RESEARCH AND MANAGEMENT

Forest management policy and practices associated with landslide management in British Columbia are presented in a two part article by Fannin *et al.* 2008. The first article reports on the evolution of forest practices in BC as they relate to landslide management and the second reports on field research and monitoring in support of our understanding in landslide management on BC forest lands. Readers are encouraged to refer to the article for information on BC research covering landslide initiation, landslide travel distance and landslide risk.

Terrain management strategies within the BC forest sector have moved to include principles of risk analysis in order to balance environmental and timber management objectives.

Wise *et al.* (2004) in a hand book provide case study examples of illustrate qualitative and quantitative methods of risk analysis, with application to cut blocks, roads, gullies, and fans in coastal and interior BC forest landscapes. The handbook provides the terms and concepts for effective communication among forest resource managers, terrain stability professionals, and stakeholders. Terrain mapping, terrain stability mapping and terrain assessments are a key input to risk management planning concerning landslide hazards. Matrices consisting of hazard and consequence categories (very low to very high) for roads and cut blocks determine risk levels. The results are then presented as calculated risks for the areas or features of interest; these methods allow forest managers to make informed decisions regarding the risks of proposed forest development (Horel and Higman 2006).

5. SUMMARY

Landslides are a common natural process on the steep forest landscapes in British Columbia. In the 1970s, landslide frequency increased from roads and within cut blocks after forest harvesting advanced onto steep slopes. In response, a systematic method for identifying and mapping slope stability was developed to guide forest management in landslide prone terrain. Evidence suggests that landslide management components of terrain mapping, terrain stability mapping, and terrain stability assessments combined with improved road construction and water management practices have reduced the number of landslides that result from forest harvesting practices. Their implementation has been strengthened through judgment derived from field observation and research. Recent advancement has introduced the principles of risk analysis to Landslide management on forest lands in BC.

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