Nat Hazards (2010) 53:63–75
DOI 10.1007/s11069-009-9410-3

ORIGINAL PAPER

Terrain stability mapping on British Columbia forest lands: an historical perspective

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Received: 26 March 2009 / Accepted: 29 May 2009 / Published online: 28 June 2009
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Abstract Land management associated with forest practices in British Columbia (BC) over the last three decades has led to the development of terrain stability hazard mapping. Terrain stability mapping (TSM) in BC originated in the early 1970s, when forest harvesting was progressing from valley bottoms onto steep, unstable terrain, which led to an increase in harvesting- and road-related landslides. Since then TSM methods have been evolved. Beginning in the early 1970s, terrain hazards were incorporated into the forest inventory classification system to delineate environmentally sensitive areas for land-use planning. By 1974, operational terrain stability maps were introduced by the MacMillan Bloedel forest company on the Queen Charlotte Islands. In the 1980s, this method was adopted by other forest companies and government agencies along the BC coast and then extended to the BC interior in the 1990s. The system was refined over time, based on new knowledge and on 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.

Keywords Terrain stability mapping · Landslides · Forestry · British Columbia

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

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were devastating, many landslides initiated in cut blocks and from roads during west coast rain storms (Figs. 1, 2). These landslides exacted a considerable cost with loss of life, degradations of fish habitat and forest land, and lost investments in forest roads and in silviculture(Schwab 1988; Hogan et al. 1998).

Forest practices on steep, potentially unstable terrain have evolved over the past 30 years (Fannin et al. 2008). This has resulted in improved road construction practices, improved water management along roads, and simply the awareness and avoidance of unstable terrain. Part of this evolution was the recognition of both 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 stability hazard mapping or terrain stability mapping (TSM). Origins of TSM 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; Resources 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).

The purpose of this article is to discuss the various TSM methods in British Columbia as they developed over the last four decades.

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

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

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.

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

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

Detail terrain stability class	Reconnaissance stability class	ESA[a] soil sensitivity class
I	S	Not classified
II	S	Not classified
III	S	Not classified
IV	P	Es2
V	U	Es1

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

[a] Environmentally sensitive area

landslides associated with forest development. A systematic approach to collect this type of terrain data is termed a terrain attribute study (Rollerson et al. 1997).

2.1 Reconnaissance terrain stability maps

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 (Fig. 3). Areas not designated are assumed stable. RTSM, unlike Detailed Terrain Stability Mapping (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 1:20000–1:50000.

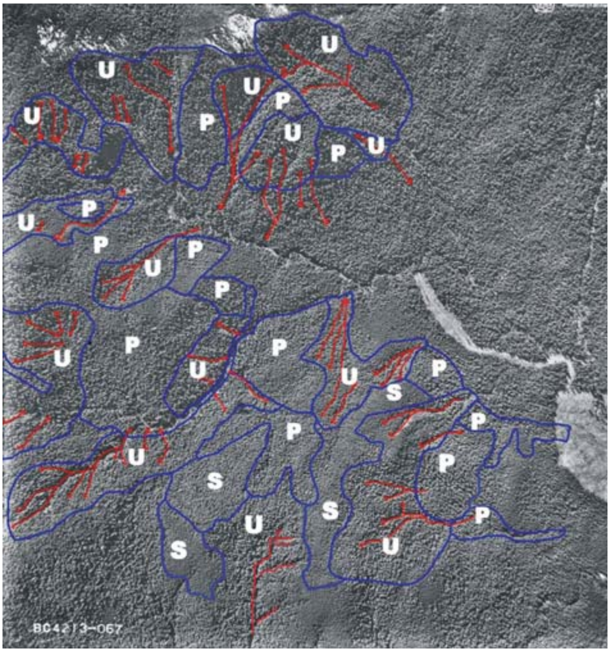

Fig. 3 Example of typed aerial photograph with delineated RTSM hazard classes *U*, *P*, and *S*. Debris flow channels are highlighted in *red*, polygon boundaries in *blue*. Note, the entire photograph is not typed

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.

2.2 Detailed terrain and terrain stability maps

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 1:20000.

Mapping standards follow guidelines and standards for terrain mapping in BC (Resources Inventory Committee (RIC) (1996), digital terrain data capture and presentation (RIC 1998) and the Terrain Classification System for BC (Howes and Kenk 1997; Fig. 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 (Soil Classification Working Group 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).

Table 2 Subclasses for mass movement processes

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

Table modified from Howes and Kenk (1997)

The DTSM terrain stability classes provide a relative ranking of the likelihood of a landslide occurring after timber harvesting or road construction (Fig. 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–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; Fig. 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.

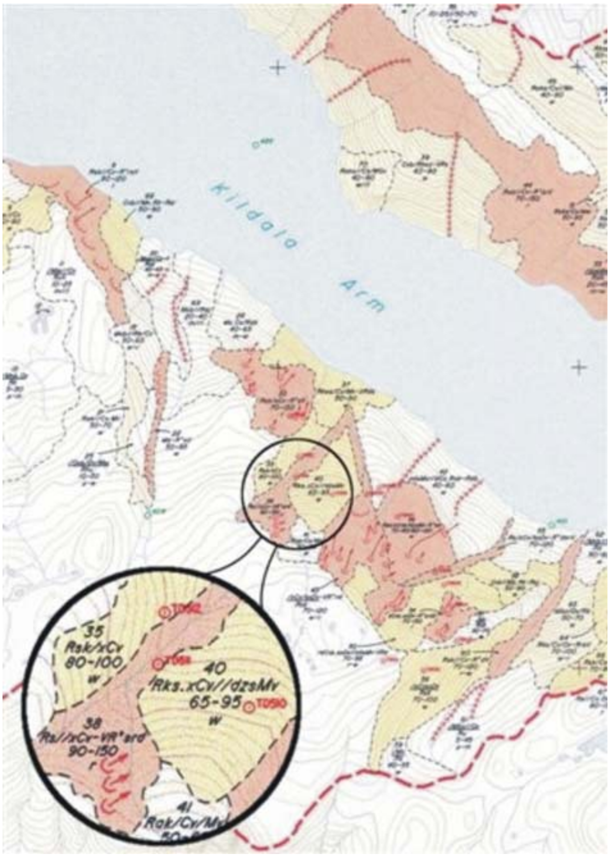

Fig. 4 Terrain map showing the terrain polygon number, terrain symbol, slope gradient, soil drainage, onsite landslide symbols, and the field inspection plots

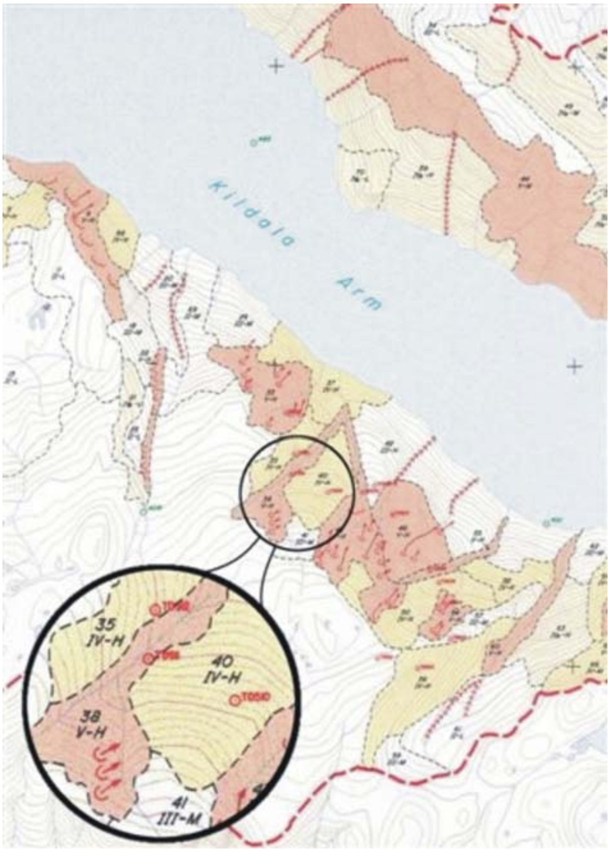

Fig. 5 Terrain stability map showing the terrain stability class polygons with erosion subclasses (V–H). Polygon number, field inspection plot and on site landslide symbols are also shown

Table 3 Detailed terrain stability classification

Terrain stability class	Interpretation[a]
I	• No significant problems exist
II	• Very low likelihood of landslides from timber harvesting or road construction • Minor slumping expected in road cuts
III	• Minor instability • Low likelihood of landslides from timber harvesting or road construction
IV[b]	• Moderate likelihood of landslides from timber harvesting or road construction
V	• High likelihood of landslides from timber harvesting or road construction

[a] Table modified from Chatwin et al. (1994); and B·C. Ministry of Forests (BCMOF) and B·C. Ministry of Environment (BCMOE) (1999). The classification addresses landslides >0.05 ha in size, conventional timber harvesting practices, and sidecast road construction

[b] Modifiers are sometimes added, for example, "IVR" to indicate landslide initiation following road construction

Fig. 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.

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 attribute studies

Terrain stability mapping methods use terrain attributes that are either qualitative or quantitative, with the qualitative systems based mainly on field observations and/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. Coastal BC landslide research is summarized by Hogan et al. (1998), and BC interior landslide research by Jordan and Orban (2002). Researchers 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). Quantitative, univariate statistical approaches to identify terrain subject to high landslide frequencies sought to correlate landslide frequency with individual landscape attributes (Rollerson and Sondheim 1985) and multivariate statistics using CHAID analyses examined combinations of attributes in mapped terrain polygons (Rollerson et al. 1997, 2001a, 2001b; Millard et al. 2002). More recently Rollerson et al. (2004) used 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 problems, 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 Risk analyses

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 Other tools

One mapping system, not widely used in British Columbia, is the SINMAP system developed by Pack et al. (1998). SINMAP combines infinite slope parameters and a steady-state hydrology model with a digital elevation model (DEM) to produce a slope stability map. The system works best in simple terrain with shallow soils. The model is also useful for determining concentrated drainage from the pirating of water by roads. It does not work very well for deep-seated landslides, or where the topography is significantly more complicated than captured on the DEM.

British Columbia researchers have been at the forefront of developing landslide runout models, such as DAN-W (Hungr 1995) and DAN-3D (McDougall and Hungr 2004), as well as UBCDFLOW (Fannin and Wise 2001). These dynamic models are useful tools for predicting landslide travel distances, and upon further calibration may play a role in determining risk.

6 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 hazard was developed to guide forest management in landslide prone terrain.

6.1 Limitations

Terrain stability mapping used by the forest industry is somewhat narrowly focused on the hazard of landslide initiation. Polygons are rated for the likelihood of landslide initiation following forest harvesting activities, but not on likelihood of landslide impact. Runout has not been considered. 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 (Tables 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).

The terrain stability classification system was developed for steep terrain, shallow soils, and relatively simple landslides that are readily solved with limit equilibrium equations. Large, complex landslides are not adequately addressed (Geertsema and Schwab 2006). Examples include situations where rock slides trigger larger movements in soil through undrained loading (Geertsema et al. 2006a), and for assessing slope hazards associated with glaciomarine deposits (Geertsema et al. 2006b). Geertsema and Schwab (1997, 2006) and Carson and Geertsema (2002) argue, that in the case of quick clays involving retrogressive landslides, it is quite easy to assess a hazard (class I–V) for the initial slope failure using aerial photographs and field surveys, but impossible to know how far such landslide will retrogress. Rating the slope, behind the initial failure requires detailed knowledge of subsurface conditions.

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 (Hungr et al. 1994) in association with infrastructure or residential development require a rigorous landslide hazard assessment and landslide risk assessment (APEGBC 2006).

6.2 Successes

The influence of terrain stability mapping guidelines provided by the Forest Practices Code (BCMOF and BCMOE 1995a, 1999) was examined by the Forest Practices Board (2005). The board concluded that significantly fewer landslides occurred after the code was implemented, although forest activities still resulted in higher numbers of landslides than occurred in unlogged areas.

Acknowledgments We are grateful to two anonymous referees whose constructive criticism strengthened this article.

References

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) (2003) Guidelines for terrain stability assessments in the forest sector. Association of Professional Engineers and Geoscientists of British Columbia, Burnaby

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) (2006) Guidelines for legislated landslide assessments for proposed residential development in British Columbia. Association of Professional Engineers and Geoscientists of British Columbia, Burnaby

BCMOF (B.C. Ministry of Forests) (1992) Forest inventory manual: forest classification, sampling and environmentally sensitive areas, vol 2. Inventory Branch, BC Ministry of Forests, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1995a) Mapping and assessing terrain stability guidebook. Forest Practices Code of British Columbia, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1995b) Gully assessment procedure guidebook. Forest Practices Code of British Columbia, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1995c) Gully assessment procedure guidebook, 2nd edn. Forest Practices Code of British Columbia, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1995d) Gully assessment procedure guidebook, 3rd edn. Forest Practices Code of British Columbia, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1995e) Hazard assessment keys for evaluating site sensitivity to soil degradation processes guide book. Forest Practices Code of British Columbia, Victoria

BCMOF and BCMOE (B.C. Ministry of Forests and B.C. Ministry of Environment) (1999) Mapping and assessing terrain stability guidebook, 2nd edn. Forest Practices Code of British Columbia, Victoria

Bourgeois WW (1975) Geotechnical inventory of a portion of Louise Island (QCI). Forestry Division, MacMillan Bloedel, Nanaimo, p 60

Bourgeois WW (1978) Timber harvesting activities on steep Vancouver Island terrain. In: Proceedings 5th North American forest soils conference, Colorado State University, Fort Collins, pp 393–409

Bourgeois WW, Townsend RB (1977) Geotechnical report, memkey watershed. Forestry Division, MacMillan Bloedel, Nanaimo Report No. 11

Carson MA, Geertsema M (2002) Mapping in the interpretation and risk assessment of flowslides in sensitive quaternary muddy sediments. In: Bobrowsky PT (ed) Geoenvironmental mapping, methods, theory and practice. A.A. Balkema Publishers, The Netherlands, pp 667–698

Chatwin SC, Howes DE, Schwab JW, Swanston DN (1994) A guide for management of landslide-prone terrain in the Pacific Northwest, 2nd edn. B.C. Ministry of Forests, Victoria Land Management. Handbook 18, Victoria

Environment and Land Use Committee Secretariat (1976) Terrain classification system. B.C. Ministry of Environment, Resource Analysis Branch, Victoria, p 56

Fannin RJ, Wise MP (2001) An empirical-statistical model for debris flow travel distance. Can Geotech J 38:982–994

Fannin RJ, Moore GD, Schwab JW, VanDine DF (2008) The evolution of forest practices associated with landslide management in British Columbia: part I and part II. Streamline Watershed Manage Bull 11:5–16

Forest Practices Board (2005) Managing landslide risk from forest practices in British Columbia. Special investigation. FPB/SIR/14, pp 32

Fulton RJ, Boydell AN, Barnett DM, Hodgson DA, Rampton VA (1979) Terrain mapping in northern environments. In: Romaine MJ, Ironside GR (eds) Proceedings of a technical workshop to develop an integrated approach to base data inventories for Canada's Northlands. Supply and services Canada, Ottawa, Ont. ecological land classification series, No. 21

Geertsema M, Schwab JW (1997) Retrogressive flowslides in the terrace-kitimat, British Columbia area: from early post-deglaciation to present—and implications for future slides. Proceedings, 11th vancouver geotechnical society symposium, Vancouver, pp 115–133

Geertsema M, Schwab JW (2006) Challenges with terrain stability mapping in northern British Columbia. Streamline Watershed Manage Bull 10:18–26

Geertsema M, Clague JJ, Schwab JW, Evans SG (2006a) An overview of recent large catastrophic landslides in northern British Columbia, Canada. Eng Geol 83:120–143

Geertsema M, Cruden DM, Schwab JW (2006b) A large rapid landslide in sensitive glaciomarine sediments at mink creek, northwestern, British Columbia, Canada. Eng Geol 83:36–63

Hogan DL, Wilford DJ (1989) A sediment transfer hazard classification system: linking erosion to fish habitat. In: Proceedings watershed'89, a conference on the stewardship of soil, air and water resources, Juneau. US Department of Agriculture Forest Service, Alaska Region, pp 143–154

Hogan DL, Rollerson TP, Chatwin S (1995) Gully assessment procedures for British Columbia forests. B.C. Ministry of Forests. Water Restoration Technical Circular, p 46

Hogan DL, Tschaplinski PJ, Chatwin S (eds) (1998) Carnation creek and queen charlotte islands fish/forestry workshop: applying 20 years of coastal research to management solutions. Research Branch, B.C. Ministry of Forests, Victoria, p 275 Land Management Handbook 41

Horel G, Higman S (2006) Terrain management code of practice. Streamline Watershed Manage Bull 9(2):7–10

Howes DE (1987) A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity—a case study from the southern coast mountains of British Columbia. B.C. Ministry of Environment and Parks. Technical Report 28, p 38

Howes DE, Kenk E (1988) Terrain classification system for British Columbia. Revised edition. B.C. Ministry of Environment, Victoria. Manual 10, p 90

Howes DE, Kenk E (1997) Terrain classification system for British Columbia (version 2). B.C. Ministry of Environment, Recreational Fisheries Branch, and B.C. Ministry of Crown Lands, Surveys and Resource Mapping Branch, Victoria

Howes DE, Swanston DN (1994) A technique for stability hazard assessment. Chapter 2. In: Chatwin SC, Howes DE, Schwab JW, Swanston DBC (eds) A guide for management of landslide prone terrain in the Pacific Northwest. Ministry of Forests, Victoria, pp 19–84 Land management handbook no. 18

Hungr O (1995) A model for the runout analysis of rapid flow slides, debris flows and avalanches. Can Geotech J 32:610–623

Hungr O, Gerath F, Van Dine DF (1994) Landslide hazard mapping guidelines for British Columbia. Report to the Earth Sciences Task Force, B.C. Government Resources Inventory Committee, Victoria

Jordan P (2002) Landslide frequency and terrain attributes in Arrow and Kootenay lakes forest districts. In: Jordan P, Orban J (eds) Terrain stability and forest management in the interior of British Columbia: workshop proceedings. May 23–25, 2001, Nelson. B.C. Ministry of Forests, Research Branch, Victoria. Technical Report 003, pp 80–102

Jordan P, Orban J (eds) (2002) Terrain stability and forest management in the interior of British Columbia: workshop proceedings. May 23–25, 2001, Nelson. B.C. Ministry of Forests, Research Branch, Victoria. Technical Report 003, pp 80–102

Maynard DE (1987) Terrain classification, terrain stability, and surface erosion potential, Kiteen river watershed. Prepared for Skeena Cellulose Inc., Terrace

McDougall S, Hungr O (2004) A model for the analysis of rapid landslide motion across three-dimensional terrain. Can Geotech J 41:1084–1097

Millard T (1999) Debris flow initiation in coastal British Columbia gullies. B.C. Ministry of Forests, Vancouver Forest Region, Nanaimo, p 22 TR-02

Millard T, Rollerson TP, Thomson B (2002) Post-logging landslide rates in the cascade mountains, southwestern British Columbia. B.C. Ministry of Forests, Vancouver Forest Region, Research Section, Nanaimo, p 18 TR-023

Pack RT (1995) Statistically-based terrain stability mapping methodology for the Kamloops forest region, B.C. In: Proceedings of the 48th Canadian geotechnical conference, Vancouver, pp 617–624

Pack RT, Tarboton DG, Goodwin CN (1998) The SINMAP approach to terrain stability mapping. In: International congress of the international association of engineering geology and the environment, 8th, September 21–25, 1998, Vancouver, Proceedings, A.A. Balkema Publishers, Rotterdam, vol 2, pp 1157–1165

Resources Inventory Committee (1996) Guidelines and standards for terrain mapping in British Columbia. Government of British Columbia, Victoria

Resources Inventory Committee (1998) Standard for digital terrain data capture in British Columbia. Government of British Columbia, Victoria

Rollerson TP, Sondheim M (1985) Predicting post-logging terrain stability: a statistical-geographic approach. In: Proceedings of the IUFRO mountain logging section and sixth Pacific Northwest skyline logging symposium: improving mountain logging planning, techniques and hardware. May 1985. Vancouver, pp L25–L31

Rollerson TP, Thomson B, Millard TH (1997) Identification of coastal British Columbia terrain susceptible to debris flows. In: Proceedings 1st international conference on debris—flow hazards mitigation: mechanics, prediction and assessment, San Francisco, August 7–9, 1997, pp 484–495

Rollerson TP, Millard T, Jones C, Trainor K, Thomson B (2001a) Predicting post-logging landslide activity using terrain attributes: coast mountains. British Columbia Research Section, Vancouver Forest Region B.C. Ministry of Forests, Nanaimo, p 20 TR-011

Rollerson TP, Millard T, Thomson B (2001b) Using terrain attributes to predict post-logging landslide likelihood on southwestern vancouver island. Research Section, Vancouver Forest Region B.C. Ministry of Forests, Nanaimo, p 15 TR-015

Rollerson TP, Maynard D, Higman S, Ortmayr E (2004) Klanawa landslide hazard mapping pilot project. A joint conference IUFRO S3.06.00: forest operations under mountainous conditions and 12th international mountain logging conference, June 13–16, Vancouver, p 24

Ryder JM (1994) Guidelines and standards to terrain geology mapping in British Columbia. Terrain geology task group, Earth science task force. Resource inventory committee, B.C., 1993–1994, p 45

Schwab JW (1982) Slope stability mapping workshop. B.C. Ministry of Forests, Prince Rupert Forest Region, Smithers

Schwab JW (1988) Mass wasting impacts to forest land: forest management implications, Queen Charlotte Islands, Queen Charlotte timber supply area. In: Lousier JD, Still GW (eds) Degradation of forest land: forest soils at risk. Proceedings of the 10th B.C. soil science workshop. February 1986. B.C. Ministry Forests. Land management report no. 56, pp 104–115

Schwab JW (1993) Interim terrain and slope stability mapping standards. Prince Rupert Forest Region, B.C. Ministry of Forests, Prince Rupert Forest Region, Forest Sciences Section, Smithers

Soil Classification Working Group (1998) The canadian system of soil classification. Agriculture and agri-food Canada publication 1646 (Revised), pp 187

VanBuskirk CD, Neden RJ, Schwab JW, Smith FR (2005) Road and terrain attributes of road fill landsides in the Kalum forest district. B.C. Ministry Forests and Range, Research Branch, Victoria Tech. Rep. 024

Ward B, Rollerson TP, Tsang S (2002) Terrain attribute study in the Prince George forest region, British Columbia. In: Jordan P, Orban J (eds) Terrain stability and forest management in the interior of British Columbia: workshop proceedings. May 23–25, 2001, Nelson. B.C. Ministry of Forests, Research Branch, Victoria. Technical Report 003, pp 208–209

Wilford DJ, Schwab JW (1982) Soil mass movement in the rennell sound area, Queen Charlotte islands, British Columbia. Proceedings. Canadian hydrology symposium 82. National research council, Canada. Fredricton N.B., pp 521–541

Wilford DJ, Sakals ME, Innes JL, Sidle RC, Bergerud WA (2004) Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides 1:61–66

Wise MP, Moore GD, VanDine DF (eds) (2004) Landslide risk case studies in forest development planning and operations. B.C. Ministry of Forests, Research Branch, Victoria Land Management Handbook No. 56