A MASS WASTING INVENTORY FOR SUMAS MOUNTAIN, BRITISH COLUMBIA

A Thesis
Presented to
The Graduate Faculty
Central Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Resource Management

by
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August 2007

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

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ABSTRACT

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Southwestern British Columbia's expanding population has pushed residential development onto steep topography, historically resulting in mass wasting conflict. Agricultural land reserve on the north, south and west forces Abbotsford, British Columbia's second fastest growing city, to expand east onto Sumas Mountain. To examine spatial suitability of residential development, I identified, mapped, classified and dated mass wasting, created activity maps and made management recommendations based on predicted future activity.

Avalanche, fall, flow, and rotational and translational slides totaled 129 features, covering 54% of the 52 km^2 area. In the past 50 years, 65% were active. Movement probability was highest on high slope angle, glacial outwash, and quartz diorite bedrock terrain, and lowest on low slope angle, alluvium and sedimentary bedrock. Analysis of the 0.27 injuries/m median rockfall rate suggests linkage to colder temperatures and Pacific Decadal Oscillation cold events. Residential development should be restricted to areas of low mass wasting susceptibility.

ACKNOWLEDGMENTS

I would like to acknowledge the support of the Fraser Valley Regional District in the completion of this thesis, including Graham Daneluz and Shannon Sigurdson, who provided data and consultation during the formative stage of research. I would also like to thank the Canadian Forest Service, who provided data integral to the completion of this project.

The Resource Management Program at Central Washington University has supported me through 2 years of research assistantships, expanding my learning opportunities, and making this project possible. I would like to thank the faculty involved in the program, especially those on my committee. Dr. Lisa Ely, thank you for reviewing drafts and providing useful feedback. Dr. Anthony Gabriel, thank you also for reviewing drafts and acting as a sounding board for potential methodologies. A special thank you goes to Dr. Karl Lillquist whose encouragement, endless proofreading and expert opinion have made this process an enjoyable learning experience. Thanks also go to the Central Washington University Office of Graduate Studies and Research who provided both a master's research grant and summer research grant to aid in the process of this research.

I would like to also thank the Northwest Scientific Association whose generous grant made it possible to travel to the study area and complete fieldwork.

My family has supported me well during this period, especially my wife, who has been betrayed many hours of my time for this project. My parents have been an

encouragement from the start, never expecting anything less from me. They also provided a base from which to complete fieldwork.

Final thanks go to David Jordan, who introduced me to the wonderful world of dendrogeomorphology and thereby added great depth to this project. Your time, effort, consultation and encouragement have been greatly appreciated, not only during this research but throughout my university career. I look forward to working with you in the future.

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CHAPTER I

INTRODUCTION

Research Problem

Slopes and valleys are the essential components of landscapes (Trenhaile, 2004). Landscapes evolve under a variety of processes including mass wasting. When mass wasting has the potential to occur in close relation to urban or suburban development, the process is labeled a hazard and conflict is often the result. Throughout the world, growing populations are expanding into marginal lands, commonly with unstable slopes (Schuster, 1996). Further development of these marginal areas, combined with the need to save the most readily developable, flat lands for agricultural purposes, creates an environment where human/land conflict is faced on a regular basis (Pattison, 1990).

Annual damages due to landslide processes in Canada are estimated at $50 million, 10% of which occurs in the province of British Columbia (Brabb & Harrod, 1989). Many studies document the different types of mass wasting processes throughout British Columbia and a large number focus within the population center of the province, the Fraser Valley, in southwestern British Columbia (Eisbacher & Clague, 1981; Guthrie, 2005; Leir, English, & Savigny, 1994; Matthews & McTaggart, 1978; O'Loughlin, 1972) (see Figure 1). In southwestern British Columbia, conflict between human infrastructure and mass wasting generally occurs in several types of environments. Rockfall and slide occur on major transportation routes resulting in delays in the transport of goods and high costs in mitigation (Hungr, Evans, & Hazzard, 1999; Peckover, 1975). Housing developments based on alluvial cone surfaces below the high relief Coast Mountains

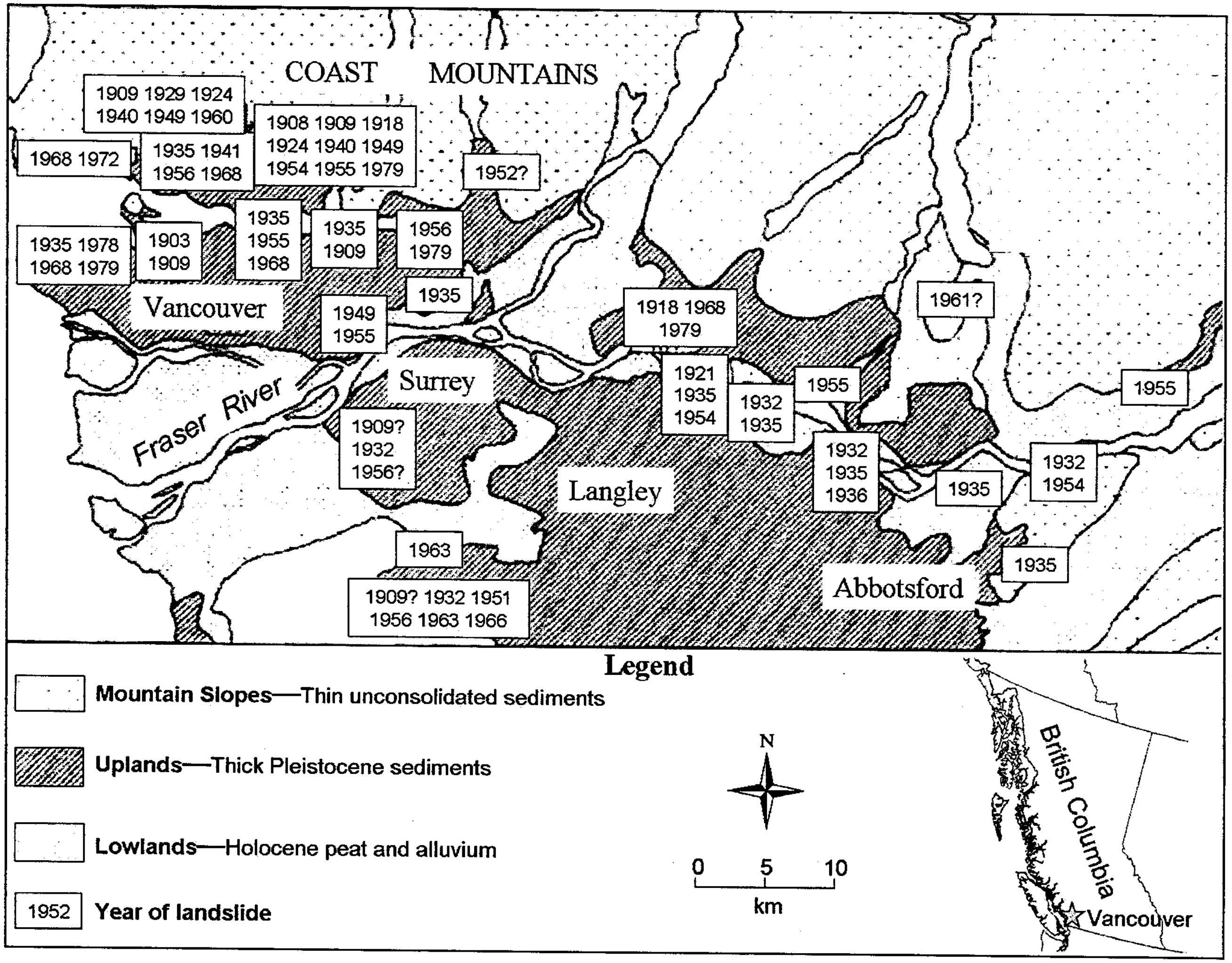

Figure 1. Locations of significant historic landslide events in the lower Fraser Valley. Adapted from Eisbacher and Clague (1981).

are susceptible to debris flow (Evans & Savigny, 1994). Pleistocene escarpments in the Fraser Lowland are exploited for housing development because of their general exclusion from the Agricultural Land Reserve (ALR), a farmland protection act. The weakly consolidated deposits of these escarpments are especially susceptible to movement following heavy rains because of the presence of impervious geologic layers and their position above the baseline of the Fraser River Delta (Eisbacher & Clague, 1981).

The province of British Columbia has set a precedent for mass wasting-induced hazard reduction with proactive zoning policies and government assistance (Mustard et al., 1998). However, in the Fraser Valley, no studies have been done to inventory mass wasting processes on exposed granitic intrusions in the area, such as the highly developed Burnaby Mountain or developing Sumas and Chilliwack Mountains. The city of Abbotsford, located in the Fraser Valley, is British Columbia's second fastest growing city, with an average annual growth rate of 2.49% (Statistics Canada, 2006) (see Figure 2). Abbotsford is bounded by the ALR on the north, west and south, forcing expanding development east into Provincial Electoral Area "H" (PEAH). PEAH is a large tract of land, currently outside the city boundary and provincially governed, located on the steeply sloped, granitic intrusion of Sumas Mountain. The proximity of Sumas Mountain to the exploding population of Abbotsford, British Columbia means that it will be under intense development pressure in a few short years. Preliminary studies have warned of the possibility of future mass wasting events on Sumas Mountain (Gerath & Smith, 2002), but no comprehensive study has been done to show where events have occurred in the past and where they are likely in the future. As an ecologically and economically

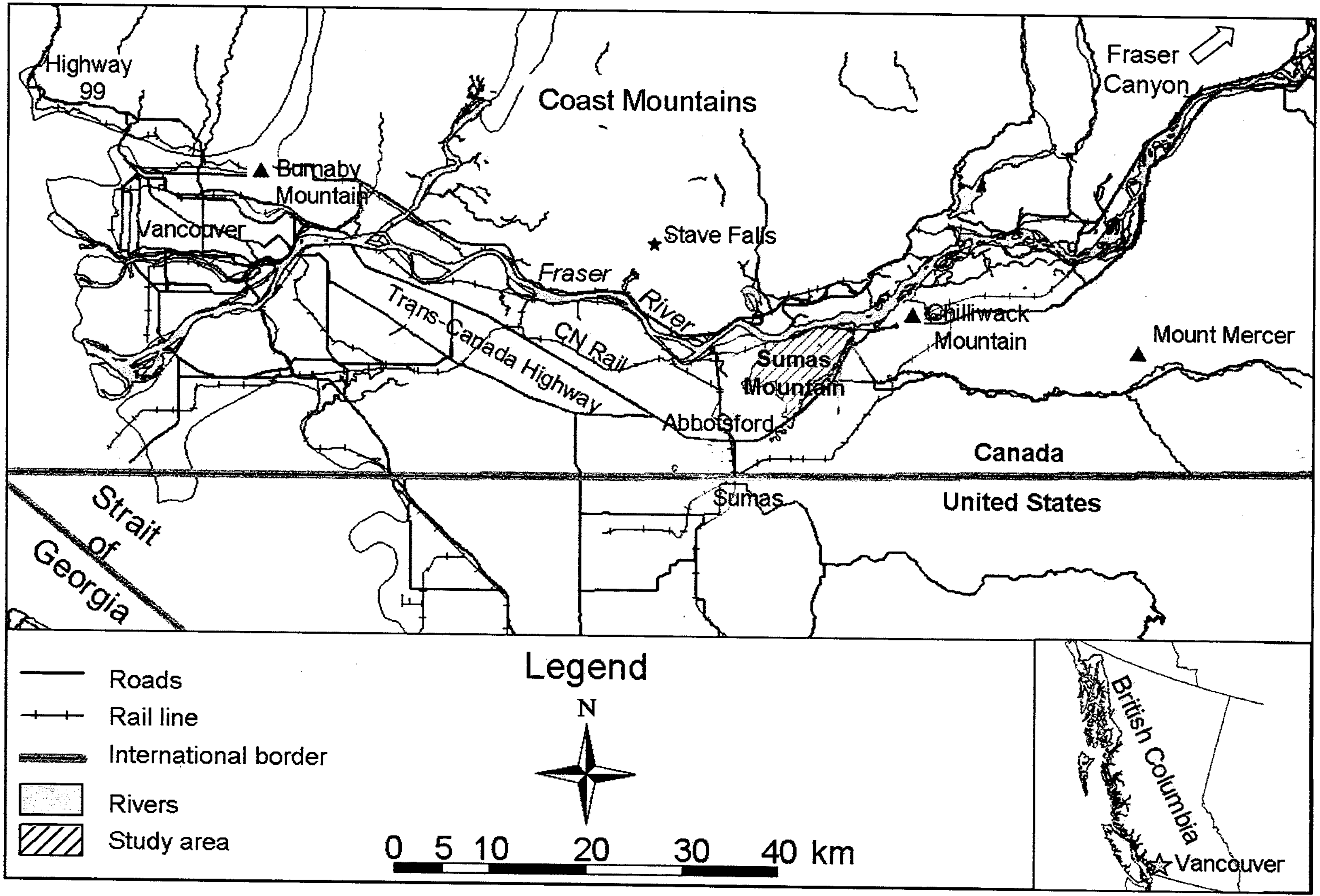

Figure 2. Regional context of Sumas Mountain, British Columbia.

significant land resource of the Fraser Valley, the need for the careful management of Sumas Mountain is clear.

Research Purpose

The purpose of this study was to create a mass wasting inventory for Sumas Mountain, British Columbia (see Figure 3). Current land management prescribes a mix of residential, industrial, recreational and conservation land use (Fraser Valley Regional District [FVRD], 2003); however, it is not clear where these land uses are best suited spatially, given mass wasting hazards. Through mapping and dating of mass wasting events on Sumas Mountain, this study clarified the land use situation and provided guidelines for future land management. Specifically, I (a) identified, mapped, and

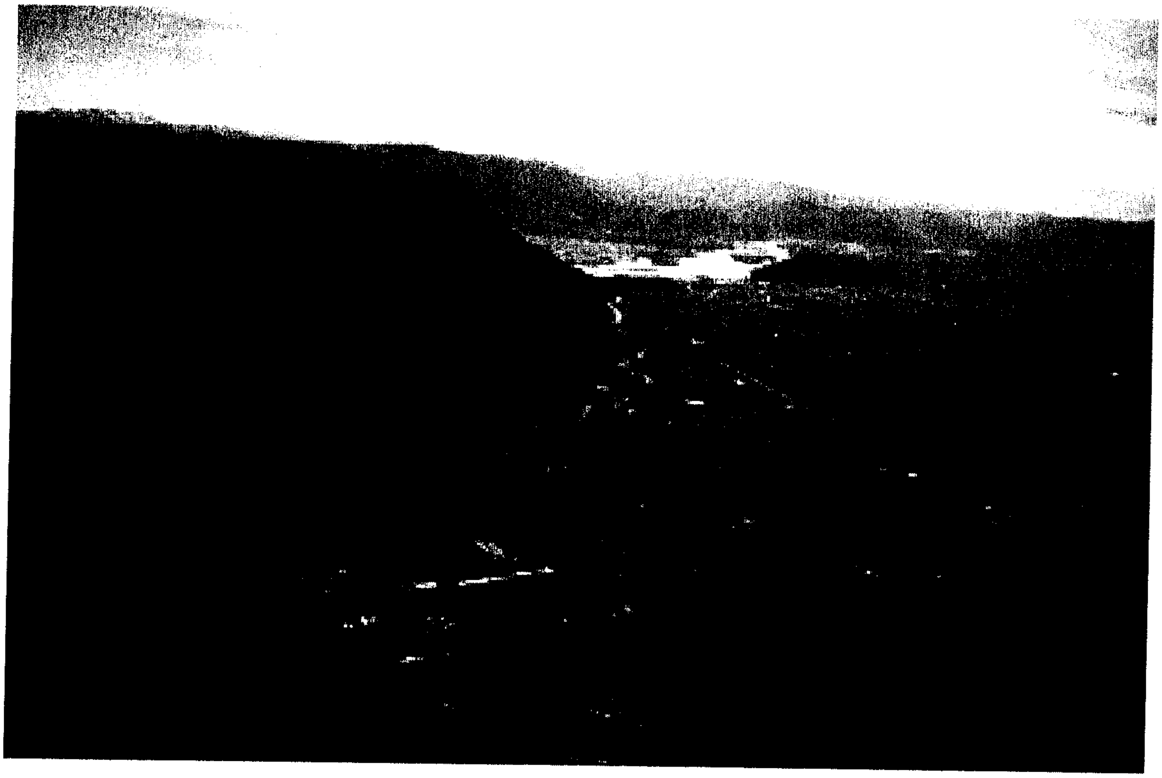

Figure 3. Oblique view looking east along the southern slope of Sumas Mountain, British Columbia. Photograph from Natural Resources Canada (2006).

classified past mass wasting features on Sumas Mountain; (b) dated mass wasting features; (c) created mass wasting activity maps; (d) analyzed mass wasting variables controlling frequency to predict areas of future activity; and (e) made land management recommendations based on mass wasting location and frequency.

Research Significance

Mass wasting inventories are relatively inexpensive, replicable, and reliable methods for predicting the suitability of landscapes for future development, and therefore are applicable in both developing and developed nations. Expected outcomes of this study have significance for the many different stakeholders involved with the future land management of Sumas Mountain. It provides suggested guidelines for land management, given mass wasting considerations, to individual landowners (including residential and commercial), land tenure managers (such as forestry and mining holdings), First Nations groups (specifically the Sumas First Nation), and special interest groups (such as the Land Conservancy of British Columbia and the Fraser Valley Mountain Bikers Association). It also provides suggested guidelines for land management to both governing bodies in the area, the Municipal Government of Abbotsford which controls Abbotsford's interest and the British Columbia provincial government which controls PEAH. Abbotsford and PEAH managers now have another tool to determine where possible residential expansion may occur with greater safety.

Significance beyond the study area includes its use as an analogue for other areas facing similar situations. Chilliwack, British Columbia and King County, Washington, with a program similar to the ALR called Transfer of Development Rights (White, 1998; Wolfram, 1981), both face similar future problems in development. As the populations of cities and counties grow throughout Canada and North America, they are faced with issues of developing on marginal lands (Karrow & White, 1998). Sprawl also affects areas in developing countries. In this environment, rather than middle class suburban sprawl, squatter settlements spring up around the city where little to no development regulation exists and slopes are not properly analyzed for stability (Gupta & Ahmad, 1999). This combination can be disastrous and, as a result, developing nations have the highest death rates from mass wasting processes (Nadim, Kjekstad, Peduzzi, Herold, & Jaedicke, 2006). Therefore, developing countries may also profit from an inexpensive and comprehensive analysis of existing mass wasting processes.

CHAPTER II

LITERATURE REVIEW

Overview

Throughout the world mass wasting inventories have been successful in identifying and quantifying mass wasting hazards (Brabb & Harrod, 1989). This chapter is an overview of the different methodologies involved in mass wasting inventories, as well as an introduction to some of the common mass wasting processes and the planning policies in place to deal with them in southwestern British Columbia.

Mass Wasting Identification, Mapping, and Classification

Mass wasting is a generic term used to describe the down-slope movement of earth materials, at varying speeds, due to the force of gravity (Trenhaile, 2004). One of a suite of geomorphic, subaerial processes like glaciation and fluvial activity, the many variables involved in mass wasting create a wide variety of physical expressions in the Quaternary environment (Cruden & Varnes, 1996).

Mass Wasting Identification

Mass wasting processes are recognized through aerial photograph analysis, using features, visible at the scale of analysis, known to reflect mass wasting processes (Crozier, 1984). Features are identified by three general characteristics: morphology, vegetation, and drainage (Soeters & van Westen, 1996). These features are analyzed against a series of decision rules meant to eliminate other geomorphic processes as the root cause (Pack, 2005; van Westen, Seijmonsbergen, & Mantovani, 1999). Decision rules vary from environment to environment because of the different conditions under which mass wasting processes occur (Soeters & van Westen) and are based on the experience of geomorphologists working in the area. Therefore, it is often best to check the selected decision rules with a trial analysis and associated field check where mass wasting features are positively identified on the ground and related to process. Basic outlines of appropriate decision rules can be found in Crozier (1984), Pack, and Soeters and van Westen.

Mass Wasting Mapping

A mass wasting inventory is an attempt to exhaustively map, classify and record mass wasting activity, age, type, process and triggers which occur in a given area. Inventories are usually organized in a database and displayed with a map to show the spatial extent of each mass wasting event recorded. The events recorded in the inventory are mapped and combined with frequency analyses to create mass wasting activity maps or mass wasting density maps (Soeters & van Westen, 1996). Basic mass wasting inventories only include recent events and simply identify location and movement type (Hansen, 1984a). More comprehensive inventories may use historic, stereographic, aerial photographs to create a multi-temporal record, analyze event frequency to show relative risk, and identify variables associated with movement such as geology or geomorphic conditions (Gerstel, 1999). The further back a mass wasting inventory stretches, the more difficult it is to confirm mass wasting features because of landscape recovery (Malamud, Turcotte, Guzzetti, & Reichenbach, 2004). The classification systems reviewed above work best in conjunction with single, recent events; however, they are applicable to large scale inventories where multiple events are being analyzed over a historic timeframe.

Three approaches are used to conduct mass wasting inventories: heuristic, statistical, and deterministic. The heuristic approach is a direct method which utilizes professional judgment in delineating event boundaries. For example, Reichenbach, Galli, Cardinali, Guzzetti, and Ardizonne (2004) studied the Umbria region in central Italy, defining landslide areas based on experience with previous landslides in the area and aerial photograph interpretation. It has been shown that this type of approach needs to be backed up with considerable field checking to inventory events too small to be identified on aerial photographs (Brardinoni, Slaymaker, & Hassan, 2003). The statistical approach, an indirect method, exploits variables which have historically contributed to mass wasting development to predict future events. Leir et al. (1994) used variables including fault lines, plutonic contacts and hydrology to statistically predict where landslides would occur in the lower Fraser Valley, British Columbia. Deterministic analysis, another type of indirect approach, depends on mathematical analysis of slopes and physics to analyze slide susceptibility. This process uses slope modeling to calculate an actual factor of safety for given slopes (Soeters & van Westen, 1996). For example, VanDine (1985) outlines a method for predicting where creeks may be susceptible to debris flows using critical slopes measurements and drainage area size.

For a large scale inventory, heuristic analysis involving aerial photograph interpretation, combined with extensive field investigation, can yield reliable results (Malamud et al., 2004). Cruden et al. (1989) recommends a catalogue of damaging historic landslides be kept up-to-date throughout Canada. The response to this in British Columbia resulted in a mass wasting inventory covering 8,000 km^2 in the upper Fraser Valley (Leir et al., 1994). Hungr et al. (1999) compiled records spanning 40 years to inventory rockfall events along British Columbia's major transportation routes. Eisbacher and Clague (1981) inventoried storm-induced, mass wasting events in the lower Fraser Valley. No detailed mass wasting inventory has been done for Sumas Mountain.

Mass Wasting Classification

A strategic classification system identifies variables controlling mass wasting to systematically predict future mass wasting features (Carrara, 1983; van Westen, 2002), easing future mass wasting and human conflict through educated land management techniques (McHarg, 1969). Several attempts have been made to categorize mass wasting features, including those based on geology (Ladd, 1935) and on type of movement, morphology and material (Hutchinson, 1968, 1988; Coates, 1977; Crozier, 1986). However, these classifications largely fail to encompass all mass wasting types due to the high amount of movement possibilities and complex flow (Cruden & Varnes, 1996). One of the most appropriate and widely used classifications comes from Varnes (1978) who classifies types based on variables which control the morphology of the movement. This is especially useful for land management applications where experts can immediately know the variables controlling events (Cruden & Varnes; Hansen, 1984b). Unfortunately, as a result of the many variables considered in the classification, this method is more suited to individual site visits than a mass wasting inventory solely based on successive aerial photographs (Soeters & van Westen, 1996). Therefore, classification should be based on variables visible through aerial photograph analysis (Reichenbach et al., 2004; Soeters & van Westen).

Mass Wasting Activity

Movement activity describes whether the mass wasting process is still in a stage of movement, or whether it is currently static. Several classifications exist for movement activity (Cruden & Varnes, 1996; Erskine, 1973; McCalpin, 1984). Generally, however, if movement is still occurring an event is classified as active and if movement has stopped, it is classified as inactive. Complexity enters the classification when the period for which a movement has been inactive is considered. This complexity is discussed further in the Dating Mass Wasting Features section.

Material

Rock and soil are the two main source materials for movement (Shroder, 1971; Varnes, 1978). The rock classification is applied to movements originating from a solid mass of rock, intact prior to movement (Cruden & Varnes, 1996). Examples of this type of movement in southwestern British Columbia are the large rock avalanches such as the Hope Slide or the Cheam Rock Avalanche (Orwin, Clague, & Gerath, 2004). Rock has also been the material involved in topples and fall, like those near Hells Gate in the Fraser Canyon (Hungr et al., 1999), and in rotational bedrock movement at Mount Mercer, British Columbia (Kinakin, 2002) (Figure 2). Soil incorporates both earth and debris. Earth is material dominated by sediment smaller than 2 mm. Rotational sliding in this type of material occurs on the Interior Plateau of British Columbia, in glaciolacustrine silts (Hungr et al.). Debris is sediment dominated by clasts over 2 mm (Cruden & Varnes). Debris flows and debris avalanches, especially devastating in southwestern British Columbia (Friele & Clague, 2005; Rollerson, Millard, & Collins, 2005), consist of sediment mixed with trees and other organic debris.

Movement Type

The type of movement is perhaps the most identifiable variable in mass wasting classification. This involves how the displaced mass physically moves down slope either through the action of fall, slide, or flow (Cruden & Varnes, 1996). A fall is defined by movement mainly through the air by falling, bouncing or rolling down steeply angled slopes (Luckman, 2007).

Generally, granitic rocks, like those found at Sumas Mountain, are thought to be fairly stable. Fresh granite has been shown to withstand slopes of 70°, if the jointing pattern is random (Terzaghi, 1962). Luckman (2007) indicates that many slopes which appear active due to a large accumulation of talus may be relics of the early Holocene and may currently be inactive. However, fresh granitic rock can still be susceptible to rockfalls, especially in massive granites where unloading fractures increase surficial weathering (Walkinshaw & Smith, 1996). Dendrogeomorphology can help identify the frequency at which rockfall is occurring under heavy forest cover (Schweingruber, 1996), resolving yearly rockfall data at a high spatial resolution over a long period of time (Perret, Stoffel, & Kienholz, 2006). This method supplements the use of aerial photographs and confirms that active rockfall is occurring on the slopes of Sumas Mountain during the contemporary period. In British Columbia, rockfall is most notably a hazard on transportation routes, where it can disrupt the flow of economic goods and create high repair costs (Hungr et al., 1999; Peckover, 1975). On Sumas Mountain, issues have been identified with erosion and rockfall hazard from exposed quartz diorite cliffs (P. Machibroda Engineering, Ltd., 1998).

Slides are defined by either translational movement, along a planar failure surface, or a back-tilting, rotational movement along a curved failure surface (Cruden & Varnes, 1996; Hansen, 1984b). Catastrophic translational slides classified as rock avalanches have occurred in the North Cascades near the border of British Columbia and Washington. Most notable among these was the 1965 rockslide-avalanche near Hope, British Columbia, which has been attributed to glacial debuttressing, sagging, and an earthquake trigger (Matthews & McTaggart, 1978). Translational sliding has recently occurred on Sumas Mountain as a result of anthropogenic forcing. A movement following heavy rains in January 2005 occurred in the western part of the study area on a private residence, disrupting the local hydrology and destroying part of a building (Toth, 2005). It was classified as an active, very rapid, wet, debris slide, and may have been a result of artificial loading on the slope by the neighbor above (Perkins, 2005). Glaciolacustrine sediments may have a high incidence of rotational sliding, especially when undercut by stream action, because of their uniform, unconsolidated structure (Jones, 1961), especially in wet, coastal environments. Some slopes on Sumas Mountain were identified as being susceptible to this hazard when weakened through road building (P. Machibroda Engineering, Ltd., 1998). This type of sliding can also occur in more solid rock but it is limited to fractures influencing the structure of the rock and the overall resistance of sliding beds to shear (Trenhaile, 2004). A study on nearby Mount Mercer found that large scale rock slump (rotational movement in massive rock), may be occurring. This type of movement may be possible on Sumas Mountain where massive bedrock exists in similar environments.

Flows are some of the largest scale slope events (Trenhaile, 2004). For the purposes of this study, types of flow will be broken into debris flow, bedrock flow, and debris avalanche. Debris flows indicate relatively small, open slope or channelized movements with high moisture content. Glaciolacustrine sediments on the Interior Plateau of British Columbia are susceptible to rapid earthflows, especially when downcut by river erosion (Trenhaile, 1990). Intensive rainfall generated by the dramatic rise of marine air masses over the Coast Mountains and the steep drainage basins create the opportunity for debris flows with volumes as high as 50,000 m^3 (Mustard et al., 1998). This type of activity, although on a smaller scale, has been identified on Sumas Mountain, where debris flows are concentrated in glacial sediments cut by steep mountain streams (Gerath & Smith, 2002). The Fraser Lowland provides opportunity for this type of movement in deposits of unstable Pleistocene sediments (Eisbacher & Clague, 1981; Hungr et al., 1999) where individual storms can cause many discrete mass wasting events (Eisbacher, 1983). Several complex, extremely rapid, debris flow movements have been identified on Sumas Mountain, and are thought to be related to a nearby granodiorite/andesite contact (P. Machibroda Engineering, Ltd., 1998). Bedrock flow (i.e., *sackung* or *rock slump)* incorporates an increasingly-well understood suite of movements, based on deep failure planes or slow plastic deformation, resulting in a flow of rock structure over a large area (Varnes, Radbruch-Hall, & Savage, 1989). In mountain environments, glacial debuttressing of slopes and high pore water pressures have contributed to these types of events (Holm, Bovis, & Jakob, 2003; Kinakin, 2002; Orwin et al., 2004).

A subtype of flows are avalanches. Avalanches in debris are reserved for larger scale movements on open slopes. Rock avalanches are often complex movements combined with sliding and possibly preceded by fall. Examples of this type of movement include the Cheam rock/avalanche which occurred in prehistoric times in the upper Fraser Valley (Orwin et al., 2004), and the 1965 Hope event. The 1915 Jane Camp landslide, just north of Vancouver, British Columbia, occurred after 3 days of thaw produced cracks in a bedrock bluff above the mining encampment. A mass of rock and mud with an estimated volume of less than 100,000 m^3 swept down the bluff, destroying the camp (Evans, 2000).

Dating Mass Wasting Features

Determining frequency of mass wasting events is paramount in understanding the hazard they pose to humans (Reichenbach et al., 2004). Several traditional approaches to dating mass wasting features exist and can be broadly broken down into absolute and relative methods. The concurrent use of both methods gives a more comprehensive picture of activity than each by itself (Gonzalez-Diez, Remondo, Diaz de Teran, & Cendrero, 1999).

Absolute Dating Methods

Traditional Methods

Absolute methods give an actual date for which an event occurred (Lang, Moya, Corominas, Schrott, & Dikau, 1999). Where available, this can include the use of historic records, such as newspaper or corporate maintenance reports, to create an inventory of event frequencies (Decaulne, 2004; Hungr et al., 1999). Successive sets of aerial photographs or satellite imagery may be used to set up limiting dates on historic mass wasting events (Pack, 2005; Soeters & van Westen, 1996). Older events may be dated by radiocarbon dating of organic material within the colluvium (Gonzalez-Diez et al., 1999; Lang et al.), cosmogenic nuclide dating of transported sediments (Kubik, Ivy-Ochs, Masarik, Frank, & Schluchter, 1998; Nishiizumi et al., 1993), lichenometric dating of exposed debris (Bull, 2003; Dawson, Matthews, & Shakesby, 1986; Decaulne, 2004), dendrogeomorphology of tilted, scarred or buried trees (Alestalo, 1971; Fantucci & Sorriso-Valvo, 1999; Perret et al., 2006), and even pollen analysis of lake sediments to show removal of vegetation as a result of landslide recurrence (Dapples et al., 2002).

Dendrogeomorphology

Dendrogeomorphological methods have recently increased in their application to mass wasting methods, and several methods exist to exploit the annual growth rings of trees for dating mass wasting events. The identification of soil creep was one of the first applications of dendrogeomorphology (Keinholz, 1930). Alestalo (1971) was one of the first to use annual growth rings in wood to indicate mass movement processes. If a forested slope undergoes large scale rotational or translational movement, the trees on that slope may remain alive. However, reaction wood, variation in annual ring width in response to environmental change, may grow to compensate for the ground movement (Fantucci & Sorriso-Valvo, 1999; Schweingruber, 1993). The heavy forest cover of a humid study area can prevent identification of small, discrete mass wasting features, such as rockfall, through aerial photograph analysis (Brardinoni et al., 2003). Using annual growth rings in combination with the reaction wood, the date of slope movement can be determined with yearly and, in some cases, seasonal precision (Schweingruber, 1996). If a mass wasting event resulted in the complete removal of a forest stand, dating trees reestablished on the slope can yield a minimum age for the movement (Lang et al., 1999). Similarly, by crossdating a buried tree in slide debris with a larger sample of trees in the area (i.e., a master tree ring chronology), a maximum date for the slide may be determined (Lang et al.).

The dating of scars and traumatic resin ducts (TRDs) in tree tissue caused by the impact of falling rocks is one of the most recent developments in dendrogeomorphology (Schweingruber, 1996). Perret et al. (2006) found that simply observing the surface of trees for scarring severely underestimated the actual rockfall rate, whereas the analysis of TRDs associated with rockfall impacts can highly improve these results. Results can be used to understand relationships between climate and mass wasting activity over a period longer than available through aerial photograph analysis and may also be used in land use planning and mitigation. Proper mitigation techniques depend on the correct understanding of mass wasting frequencies and through understanding these frequencies at one site, mitigation processes can be applied at similar sites across the study area.

Relative Dating Methods

Relative dating methods are applied in situations where absolute methods are not practical due to high costs, no absolute methods apply, or the event is too old to date using conventional methods. Over time, features of inactive mass wasting processes become subdued (Keaton & DeGraff, 1996). Therefore, relative dating is done through observing the current morphological condition of a past event. The subjective identification of eroded headscarps, incised drainages, vegetated debris, and a generally fuzzy boundary can lead to a relative age classification. The observation of these data should take into account the type of movement because some movements, which occur at a slow rate, may appear to be inactive when they are truly active. Several morphological dating methods are common (Flageollet, 1996; Gonzalez-Diez et al., 1999; McCalpin, 1984; Wieczorek, 1984).

Lillquist (2001) simplified McCalpin's (1984) classification into active, inactive-young, inactive-mature and inactive-old categories. Active movements are defined by movement within the last cycle of seasons and sharply visible features on the landscape with clear debris and no vegetation. Inactive-young events have not been active within the last cycle of seasons, but are still sharply visible on the landscape. Inactive-mature events are partially revegetated and have a moderately weathered scarp. Inactive-old events are nearly unrecognizable on the landscape with a highly weathered scarp, complex drainage and completely revegetated body.

Mass Wasting Activity Maps

Mass wasting activity maps bring the ability to communicate the spatio-temporal aspects of events in a given area. They are based heavily on heuristic analysis of multi-temporal aerial photographs (Soeters & van Westen, 1996) and can successfully show event frequencies and magnitudes, guiding land use management policies.

The process of mass wasting activity mapping begins with the creation of a geomorphic map. Proper imagery for large scale mappping consists of panchromatic or color stereographic aerial photographs in the scale range of 1:5,000-1:20,000 (Brardinoni et al., 2003; Soeters & van Westen, 1996). After mass wasting events have been identified and mapped on aerial photographs for each successive period using appropriate decision rules, they are transferred to a map either in a geographic information system (GIS) or paper format and overlain on top of one another to determine frequency

(Reichenbach et al., 2004). Morphological and dendrogeomorphologic methods may be used to corroborate aerial photograph analysis and to date features older than available aerial photographs (Lang et al., 1999). This is the final output of the mass wasting activity map, showing spatial locations for the events and their associated frequencies.

Difficulties may be encountered with the use of stereographic aerial photographs to identify mass wasting events on the landscape. As noted above, older features are less visible on the imagery. Heavy forest cover can mask smaller mass wasting features leaving out the identification of a significant portion of hazard (Brardinoni et al., 2003). This difficulty is overcome through extensive field checking (Crozier, 1984); the combination of aerial photograph analysis with other methodologies, such as the use of Light Detection and Ranging (LIDAR) imagery to identify mass wasting features (Pack, 2005); or dendrogeomorphological studies to identify mass wasting frequencies (Perret et al., 2006). However these methodologies also have limitations in scale of analysis, cost, and availability of data.

Mass Wasting Controlling Variables

Causes of Susceptibility

When constructing a mass wasting inventory, it is necessary to consider the variables controlling the event recorded in order that future events may be predicted (Sarkar & Kanungo, 2004). The variables controlling a large rock avalanche event are different than those for a local fall and lead to different management techniques (Schwab, Gori, & Jeer, 2005). Two types of factors generally control mass wasting: those that make a slope susceptible to mass wasting and those which actually trigger a mass wasting event (Crozier, 1986). This section will concentrate on those preparatory variables which make a slope susceptible to movement and their use in predicting mass wasting events.

Cruden and Varnes (1996) suggest four main causes of mass wasting susceptibility: (a) geological, (b) morphological, (c) physical, and (d) human. Geological causes are those which are structurally controlled either through a weakness in materials, differences in permeability, or differences in plasticity. Morphological causes could be due to uplift (isostatic or tectonic), erosion of slope base or flanks, depositional loading of a slope, or the removal of vegetation. Physical causes can include intensive rainfall, rapid snowmelt, seismic or volcanic activity, thawing, frost-shatter, freeze-thaw, or shrink and swell activity. Human causes include removal of vegetation, loading above slopes, removal of toe support, artificial vibration, or water storage issues. These four categories can be broken down into variables which control where mass wasting will occur spatially and temporally.

Spatial Variables

Types

Variables within a region, including bedrock geology, Quaternary geology, and slope, can control spatial differences in mass wasting susceptibility. Movement types such as rockfall, bedrock rotational movements, and debris avalanches may all be affected by bedrock geology type based on jointing, weathering and permeability (Cruden & Varnes, 1996; Whalley, 1984). The Coast Mountains exhibit mass wasting in a wide variety of intrusive and extrusive bedrock, including the dacite of the Rubble Creek rock avalanche (Evans, 1991) and the rock avalanche in the Pemberton Dioritic Complex at Mystery Creek (Evans & Savigny, 1994).

Some mass wasting depends more on the depth of Quaternary cover over bedrock than the rock type itself, such as the debris flows mapped in the Coast Mountains by O'Loughlin (1972). Different Quaternary sediment types have unique characteristics, including permeability, stoniness, depth and vegetation growth, which, in turn, affect slope stability (Wu, 1996).

Every material has an angle of repose beyond which cohesion is overcome and the mass fails. Large scale sliding in the Coast Mountains generally occurs on slopes between 30° and 40° (O'Loughlin, 1972). Slopes with angles less than this do not have the angle required for loss of cohesion and slopes with angles greater than this are generally quite rocky and are very cohesive. Rockfall in massive granodiorite to quartz diorite begins at a slope angle of 70° (Terzaghi, 1962). The initiation angle for debris flows in the Coast Mountains is between 20° and 50°, according to VanDine (1985) and Slaymaker (1990). The angle necessary for transportation and deposition is considerably less.

Weighting

Heuristic analysis may be a reliable method for observing past mass wasting events but more replicable methods may be desired in the prediction of future events. Predictive methods are based on the assumption that future mass wasting will occur where it has in the past (Tangestani, 2003). Traditional predictive approaches use multivariate and bivariate statistics to weight variables. These methods analyze the presence or absence of mass wasting in relation to a random sampling of landscape variables (Soeters & van Westen, 1996). However, the large amount of data collection needed, the transfer of nonquantitative data, such as geology type, soil type and land use, into a numerical equivalent, and the lack of experiential input by geomorphologists with knowledge of the area can actually make this a less accurate method of mass wasting prediction (Soeters & van Westen).

Proportional weighting is another option for weighting controlling variables in the prediction of future mass wasting events. This method accounts for different contributing factors through the creation of terrain units which are measured for their area in correlation with mass wasting events. A higher proportion of mass wasting events occurring with the same terrain unit results in a higher weight for that variable (Soeters & van Westen, 1996). These weights are qualitatively displayed as areas of high, medium and low risk for mass wasting allowing for the ready integration of qualitative data while limiting the prediction of future mass wasting events to the variables with the greatest control on past events.

McHarg's (1969) land use approach consisted of mapping areas of limited suitability for development and inverting these maps to show areas of higher suitability for development of human infrastructure. Through inverting a map of future mass wasting susceptibility, areas suitable for future development should become apparent. O'Loughlin (1972) completed a simple version of this type of analysis while inventorying mass wasting in British Columbia's Coast Mountains. He surmised that most events initiated in drainage depressions with soils that were strongly gleyed, on slopes between 31° and 39°, and maintained a southern aspect (O'Loughlin).

Temporal Variables

In smaller study areas, the variable of climate is important in predicting when mass wasting may occur rather than where. Temperature and precipitation are two of the most important factors in mass wasting susceptibility (Wieczorek, 1996). Freeze-thaw, frost-shatter and intense rainfall events can be related to historical increases in mass wasting events, determined through the analysis of successive aerial photographs or dendrogeomorphology, using climate data from weather stations near the study area (Eisbacher & Clague, 1981).

Mass Wasting and Land Management

In North America, the history of mass wasting and human conflict begins with the First Nations and Native American record. Oral tradition shows a history of villages which were impacted by various types of mass wasting including rockfall induced tsunamis (van Zeyl, Stead, & Bornhold, 2006), and rock avalanches (Mathewes, 1987; Orwin et al., 2004). In England, as far back as 1825, mass wasting hazards were considered in road engineering (Roberts, 1840). As the human relationship to the environment has changed, it has become commonplace for anthropogenic activities to contribute to mass wasting processes. For example, the deadliest mass wasting disaster in Canada, the Frank, Alberta rock avalanche, is thought to have occurred due to poor mining practices (Benko & Stead, 1998). Careful planning is seen as a partial solution to this conflict.

Mass Wasting in Planning

The recognition of need for integration of mass wasting studies in the planning process is clear. Mass wasting processes are underrecognized in terms of socio-economic cost (Schuster, 1996), underestimated in terms of danger (Schuster & Kockelman, 1996), and perceived by the public as discrete, low-frequency events (DeChano & Butler, 2001). In southwestern British Columbia, mass wasting conflicts with humans on a regular basis, and a difference between perception and reality exists (Eisbacher & Clague, 1981; Evans & Savigny, 1994). The reality of high-frequency events is recognized by the insurance companies, and insurance is generally unavailable to the public, forcing the government of British Columbia to take proactive mitigation measures.

The lack of private insurance dealing with mass wasting processes in North America (Schuster & Kockelman, 1996) puts the onus on the government to plan for and understand the risks associated with development (Schwab et al., 2005). This means the government must have a clear outline of what level of risk is acceptable for development (Gerath, Jakob, Mitchell, & VanDine, 2006). Given this outline, geoscientists and engineers can plan and mitigate for an event of certain risk, policies can guide in terms of a certain level of risk, and legal action can take place in areas where this risk is ignored. In terms of impact, the local community plan seems to be one of the most successful ways to guide development away from hazards (Cave, 1991).

Planning Policies in British Columbia

Currently, in British Columbia, several legislative acts attempt to cover mass wasting processes in planning. The Association of Professional Engineers and Geoscientists in British Columbia outlined these policies in a 2006 report suggesting upgrades to current management (Gerath et al., 2006). Section 86 of the Land Title Act gives the "approving officer" control to refuse a subdivision of property if "land slip" (a general term for mass wasting) is likely. The Local Government Act gives areas with an official community plan the right to require a "development permit" and Section 56 of the community charter may deny building permits if there is need to protect a development from hazardous conditions, including slides, mudflows, torrents of debris, and rockfall, as identified by a building inspector. Finally, Section 910 of the Local Government Act (1996), under Floodplain Development Guidance, refers to "Flood Hazard Area Land Use Management Guidelines." These guidelines suggest avoiding development where debris flows occur, although exemptions apply.

The Fraser Valley Regional District (FVRD), in which Sumas Mountain is located, has three measures for acceptable mass wasting hazard (Cave, 1991). The first is derived from the provincial flood-proofing program which supports a design for events with a 1-in-200-year return interval. The second comes from a provincial Ministry of Transportation report which suggests geotechnical engineers design for a 1-in-500 year return interval. The final guideline comes from a British Columbia Supreme Court precedent set in 1973 when a subdivision was denied approval because it was below a site exposed to a 1-in-10,000-year return frequency event (Moore & Matthews, 1978).

Abbotsford, which governs a part of southwest Sumas Mountain known as Mckee Peak, completed a planning study in 2005 which outlined possible hazards and mitigation strategies (City of Abbotsford, 2005). Mass wasting types identified in the area from aerial photograph analysis and field traverse included debris slides, rockfall and rockslide. A large rockfall/slide feature on the south side of Mckee Peak had an estimate volume between 150,000 and 400,000 m^3 (UMA Engineering, Ltd., 2005). The study identified high debris slide and fragmental rockfall hazard on and directly below steep slopes. It also suggested future movements, similar to the large rockfall/slide identified, would be unlikely. Suggestions for mitigation included careful water management, setbacks from bedrock escarpments, and further testing for stability (UMA Engineering, Ltd.). This study has limited impact on the study area, however, because of its notably different geologic structure then the majority of the study area (as part of the sedimentary Huntingdon Formation).

Mitigation Strategies

Mass wasting events have been shown to be a concern worldwide and be of great financial burden to countries in which they are common (Brabb & Harrod, 1989). The large socio-economic loss associated with mass wasting drives attempts for identification and mitigation of events (Spiker & Gori, 2000). The most effective methods of mitigation can be expensive and destructive to the natural environment so the plan of action may be to avoid development altogether in those areas with very high susceptibility and to focus on the low susceptibility areas. Douglas (1988) lists three responsibilities for the urban geomorphologist working with mass wasting: (a) understand the environment on which the infrastructure sits, (b) understand the geomorphic processes active in the area and how they are modified through development, and (c) predict the future change to geomorphic process accompanying expanding development. Essentially, this is the process of planning and instituting policies for development based on the physical environment and the limits which it emplaces.

If the placement of infrastructure in hazardous areas is unavoidable, then two types of measures are available for mitigation: active and passive. Active strategies call for either a reduction in driving forces, increase in resisting forces, or increase in internal strength (Holtz & Schuster, 1996). The primary driving force for mass wasting is gravitational pull. If this can be mitigated through weight reduction or slope reduction, mitigation is possible. By building up the toe of a movement with anchors or walls, resisting forces may be increased, preventing future movement. Internal strength may be increased through installation of drainage, or use of reinforcing structures such as anchors or pilings.

The transportation networks of British Columbia are excellent examples of how active mitigation can be achieved through engineering. Massive debris flow retainment structures line the Highway 99 corridor (VanDine, 1985) just north of the study area. Rock bolts, shotcrete and toe protection are common along the Fraser Canyon Highway (Evans & Savigny, 1994), northeast of the study area. However, these same transportation networks also show active mass wasting (VanDine, 1983) proving that active mitigation is not always successful.

Passive mitigation is a less popular method of dealing with mass wasting hazards because it is concerned with saving lives rather than infrastructure (Schuster & Kockelman, 1996) and also has technical and legal problems (VanDine, 1985). Warning systems such as extensometers, tiltmeters, piezometers, electrical fences, video, and vibration meters can be used to provide early warning of movement (Schuster & Kockelman). One of the most successful methods of passive mitigation has been observed in San Francisco, California, where the National Weather Service and the United States Geological Survey (USGS) combine to issue warnings when extreme storm events are predicted to trigger widespread mass wasting (Keefer et al., 1987).

CHAPTER III

STUDY AREA

Overview

Located in southwestern British Columbia at 49°06'23"N, 122°10'29"W, and 910 m elevation, Sumas Mountain, the southernmost expression of the Coast Mountain Range, is 10 km north of the Canada-U.S. border and 7 km from downtown Abbotsford (Figure 2). It lies 70 km southeast from the city of Vancouver and incorporates two management districts, PEAH, and Abbotsford. The Fraser River and the Canadian National (CN) railway line mark the northern boundary of the 52 km^2 study area on the mountain (see Figure 4). The rail line has been broken historically by mass wasting processes (Septer & Schwab, 1997). The southern boundary is flanked by the Sumas River and the Trans-Canada Highway. The highway is too far from the mountain to be affected by most mass wasting processes, but local roads, such as Batt Road, leading to Sumas Regional Park, have been shut down after damage by mass wasting. The eastern base of the mountain is delineated by Vedder Canal and the western base is surrounded by Matsqui Flats, a productive farming community. Five roads provide main access to the western part of the study area: Upper and Lower Sumas Mountain Roads, Dawson Road, Batt Road. Glen-Neish road provides access to the dendrogeomorphology study area (Figure 4). The eastern part of the study area has no public access roads except around the base of the mountain. Hiking trails, including the Trans-Canada Trail, provide access to areas not reachable by road.

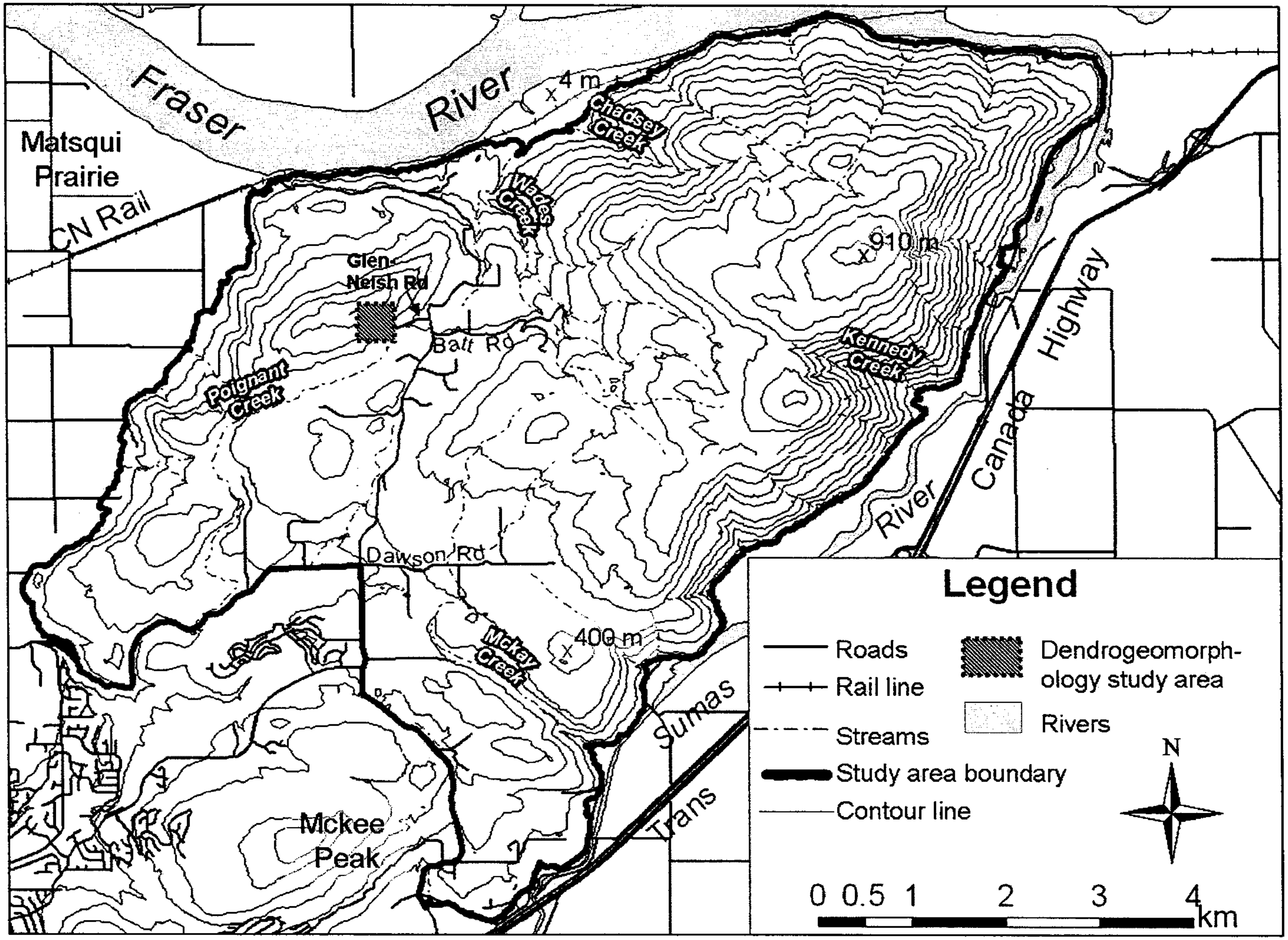

Figure 4. Topography of Sumas Mountain, British Columbia. Note the dendrogeomorphology study area within the larger study area. Contour interval is 60 m. Adapted from Integrated Land Management Bureau (2002).

The dendrogeomorphology study area is a 1-ha plot located on the south-facing slope of a northeast-trending ridge in the northwest section of the study area (Figure 4). It was chosen as an area relatively free of historic fire, tree harvest and insect outbreak. Rockfall is the dominant geomorphic activity on the slope and rockfall impacts with *Pseudostuga menziesii* (Douglas fir), the dominant tree species, are clearly visible.

Geology and Geomorphology

Sumas Mountain is a 14 × 4 km mass of various rock types which are part of the Coast Morphogeological Belt of the Canadian Cordillera. The mountain trends in a northeast to southwest direction and rises 910 m above the surrounding Fraser River floodplain (Figure 4).

Three major rock types constitute the majority of the mountain (see Figure 5). The largest of these, covering 59% of the study area, is a block of intrusive bedrock, located along the north and eastern sides of the mountain. This block was formed during the early-middle to late Jurassic (Monger & Journeay, 1994b) and is classified as granodiorite to quartz diorite (Roddick, 1965). The dendrogeomorphology study site is located in this geology type. The next block, covering 40% of the study area, is largely andesite from the mid-Jurassic (Roddick), part of the Harrison Formation to the north and correlated with the Wells Creek volcanics in Washington's western North Cascade Mountains (Monger & Journeay, 1994b). The last geologic unit, part of the Huntingdon Formation, occupies around 1% of the study area. It is continuous outside the study area as a large sedimentary complex, 425 m thick, incorporating mudstone grading to sandstone and conglomerate (Mustard & Rouse, 1994). This formation dates to the late

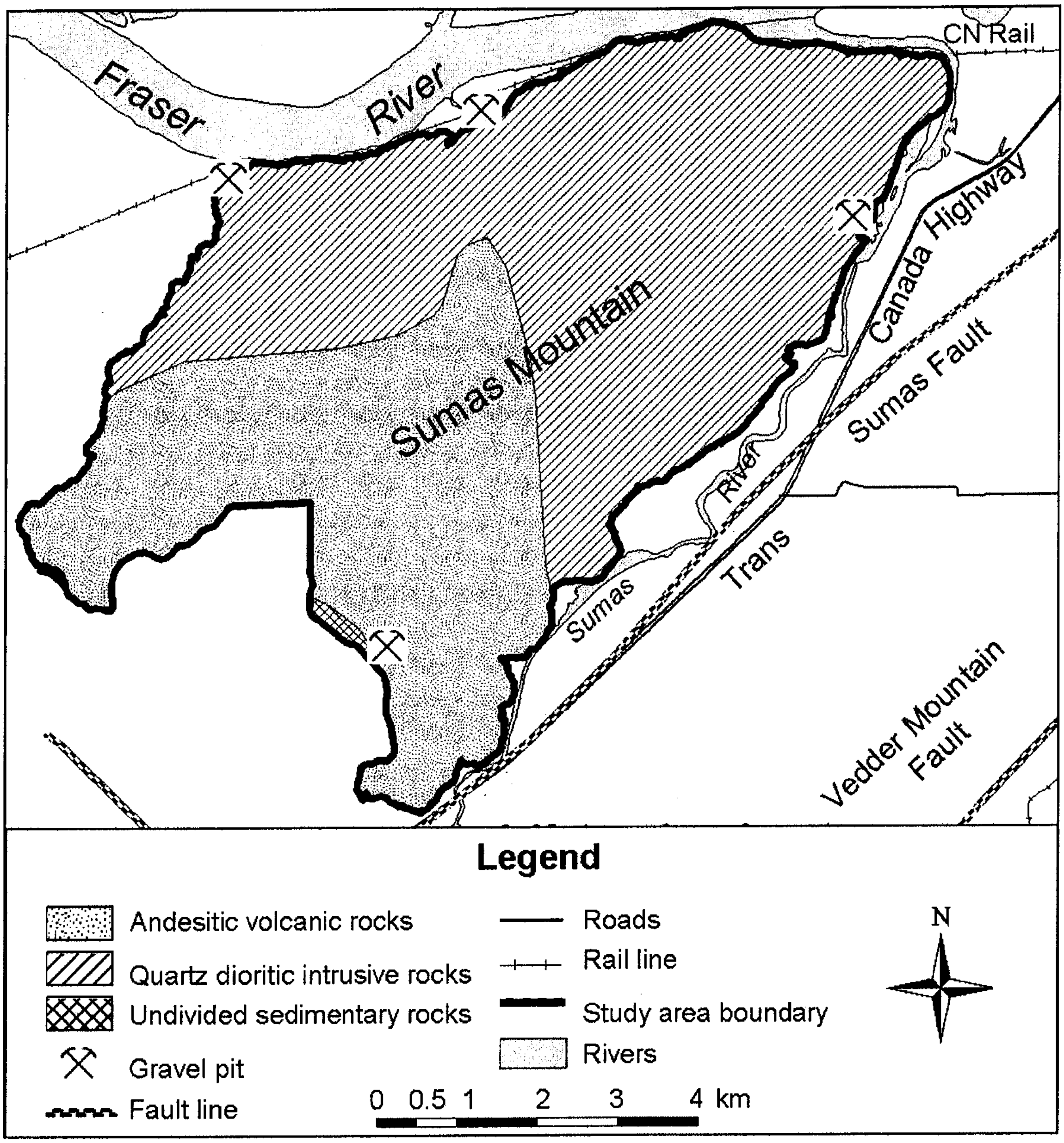

Figure 5. Bedrock geology of Sumas Mountain, British Columbia. Adapted from Ministry of Energy, Mines and Petroleum Resources (2005).

Paleocene/Eocene to early Oligocene (Ministry of Energy, Mines and Petroleum Resources, 2001).

Sumas Mountain was greatly affected by numerous glacial advances during the Pleistocene, most recently during Fraser Glaciation (Armstrong, 1984). The Chilliwack

Valley, just 16 km east of the study area, was forested until 16,000 carbon years-before-present (^{14}C yr B.P.). By 14,000 ^{14}C yr. B.P., the Puget Lobe had reached Seattle, covering the study area with a 2-km-thick ice sheet (Clague & James, 2002). By 13,000 ^{14}C yr. B.P., the lobe had retreated back to the study area where it advanced and retreated several more times during the Sumas Stade. By 10,500 ^{14}C yr. B.P., the study area was completely ice free (Booth, Troost, Clague, & Waitt, 2004; Clague & James). Glacial deposits dominate the northern and western portions of Sumas Mountain. The deeply incised Clayburn and Poignant creeks (Figure 4) show sandy and substratified Sumas Till up to 11 m thick (Armstrong, 1960; see Figure 6). The lower regions of these drainages also expose glaciolacustrine deposits (Armstrong, 1960). Most other areas are exposed bedrock mantled with colluvium (Eisbacher & Clague, 1981), eolian deposits, glaciofluvial deposits (Runka & Kelley, 1964) or Sumas Till less than 8 m thick (Armstrong, 1960), and soil to depths of less than 1 m (Central Fraser Valley Regional District [CFVRD], 1986).

Earthquakes in the area may be related to the Sumas Fault (Easterbrook, Kovanen, & Engebretson, 2000; Figure 5), which was at a peak of activity 25-14 Ma (Monger & Journeay, 1994a). The largest recent earthquake along this fault was a magnitude 5.0 in 1964, although the epicenter was southwest of the study area (Easterbrook et al.). The fault forms a graben, in association with the Vedder Fault across the valley (Cameron, 1989; Monger & Journeay, 1994a; Figure 5) and is responsible for the steep southern edge of the mountain. The recently discovered Kendall Scarp, located along the Boulder Creek fault, 20 km southeast of the study area, has potentially produced up to three shallow earthquakes over the last 12,000 years (Haugerud, 2007).

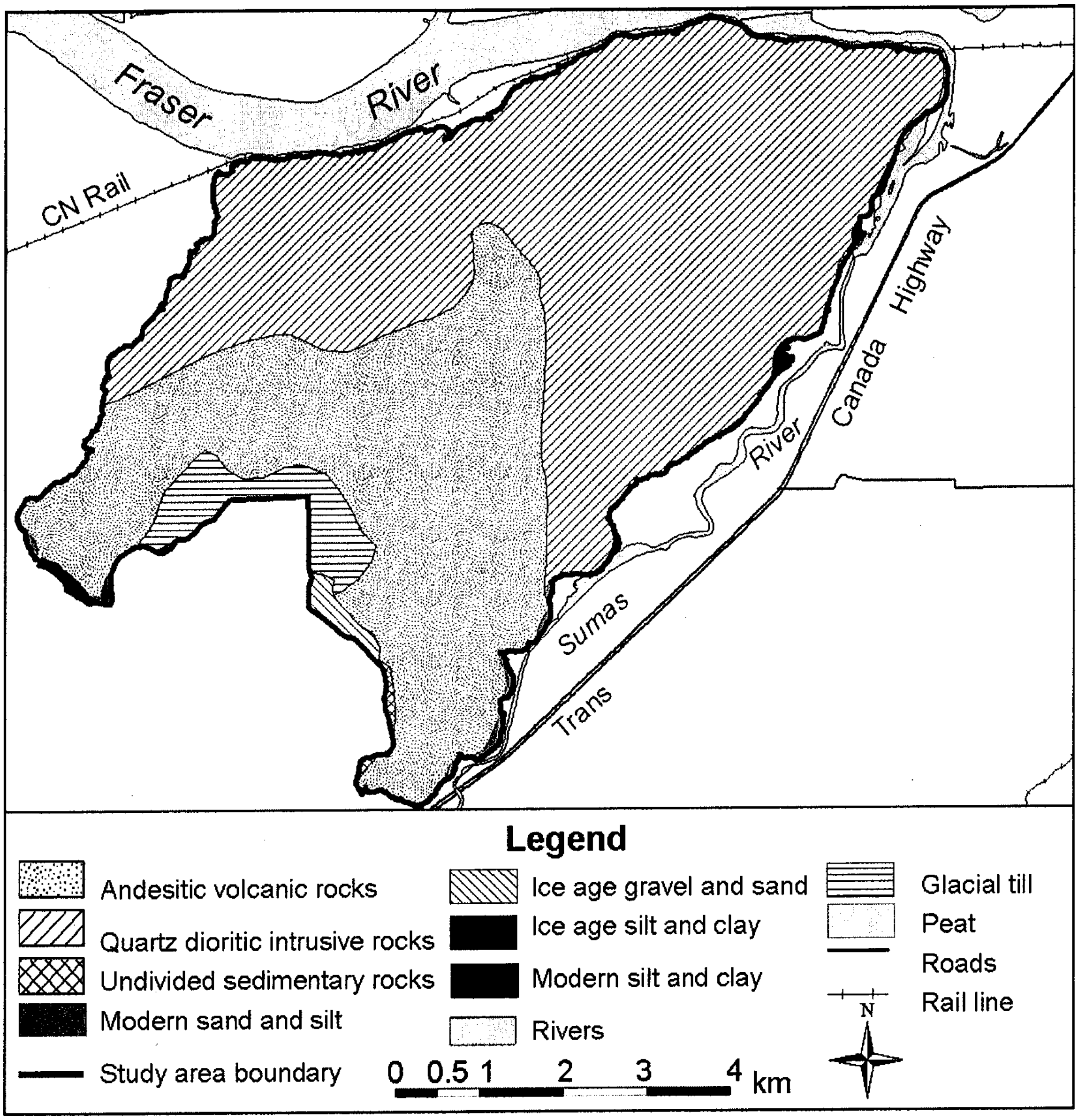

Figure 6. Quaternary geology of Sumas Mountain, British Columbia. Adapted from Natural Resources Canada (2005).

Larger, subduction zone earthquakes occur on a low frequency basis in this area (Hyndman et al., 2006). Seismic shaking is often linked to large mass wasting events in the Pacific Northwest (Levson, Matysek, Monahan, & Watts, 2003; Pringle, Schuster, & Logan, 1998).

The general topography of the study area consists of a main southwest-to-northeast-trending ridge, a steeply sloping south face and gentler, step-like, north slope (Figure 4). Deeply incised streams and glacially eroded bedrock knobs combine to provide rugged topography. Slope angles on the mountain vary widely. In the west uplands, where Abbotsford expansion is currently occurring, slopes are generally less than 20°. The dendrogeomorphology study area and the eastern mountain slopes are generally greater than 30° (CFVRD, 1986, p. 3). The total study area varies in its slope from less than 20° to greater than 30°, reaching a maximum of 75° on the southern face (Figure 4).

Climate

Located along the west coast of British Columbia, the Fraser Valley generally experiences a marine West Coast climate. The closest weather station to the study area is located at Abbotsford Airport (49°1'N, 122°21'W), 17 km southwest of Sumas Mountain. Moisture-laden air masses from the Pacific Ocean advance up the Fraser Valley to Sumas Mountain and provide an average annual precipitation of 1,573 mm (Environment Canada, 2006) (see Figure 7). The study area receives 70% of its annual precipitation between October and March. November is the wettest month with an average 241 mm of precipitation, while the driest month is August with an average 49 mm of precipitation. The area can experience intensive rainfall events and extreme daily rainfall has reached 95 mm (Environment Canada). Research on shallow landslides in the Fraser Valley by M. Miles and Associates Ltd. (2001) have shown that extreme rainfall events measured in Abbotsford exceed Caines criteria, a measure of threshold initiation for shallow

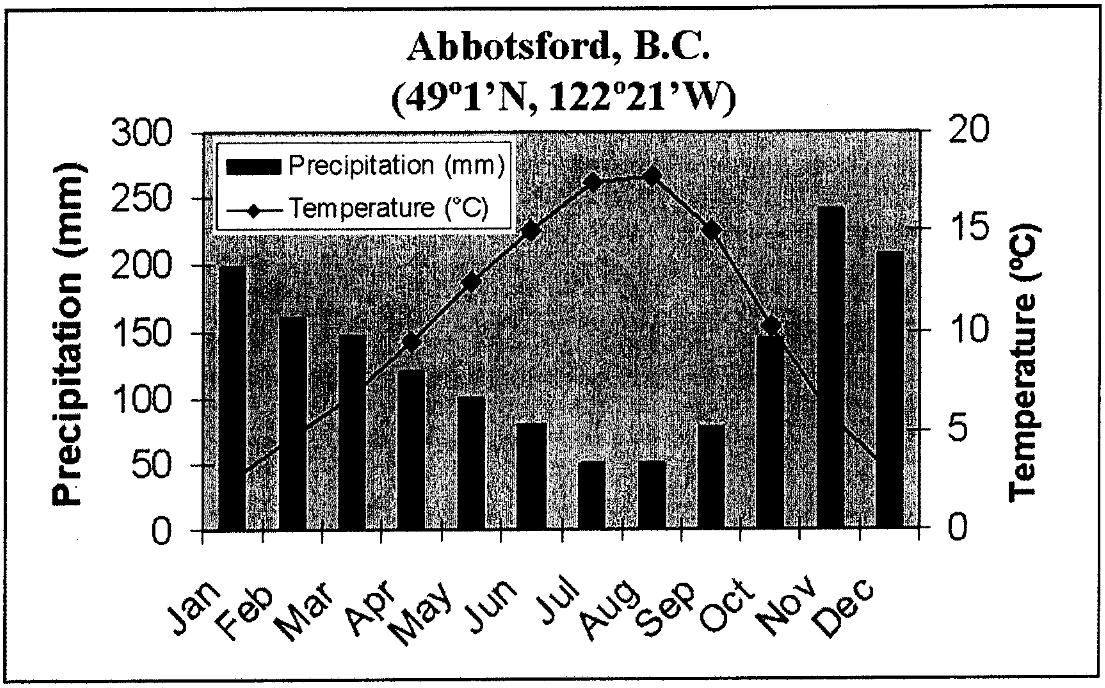

Figure 7. Climograph based on 1971-2000 climate normals for Abbotsford, British Columbia, approximately 17 km from Sumas Mountain, British Columbia. Data from Environment Canada (2006).

landslides (Caine, 1980), over 5-, 10- and 15-min periods of intense rainfall with a return frequency of 2 years (M. Miles and Associates Ltd.).

The study area has a mild average annual temperature of 10 °C. The lowest mean monthly temperature (2.6 °C) occurs in January and the highest mean monthly temperature (17.7 °C) occurs in August (Environment Canada, 2006). During the months of December and January daily temperature fluctuates around freezing level, creating the opportunity for freeze-thaw weathering, and subsequent creep and rockfall.

High winds often accompany winter storms in the study area, funneled through the Fraser Valley, equalizing high pressure arctic air masses in the northeast and low pressure systems off the Pacific Coast. In summer, wind direction reverses bringing lower wind-speeds from the south. High windstorms have been responsible for massive effects on the landscape, including the October 1962 storm associated with tropical storm Freda. During the height of this storm, sustained windspeed was 89 km/h with gusts of up to 145 km/h (Environment Canada, 2006). The storm caused over $10 million damage in the Vancouver area (Phillips, 1990) and the windthrow effects are clearly visible on 1963 aerial photographs used in this research project. During fieldwork for this project, windthrow was seen to contribute to mass wasting through the displacement of soil cover and the exposure of bedrock fractured through root action (see Figure 8).

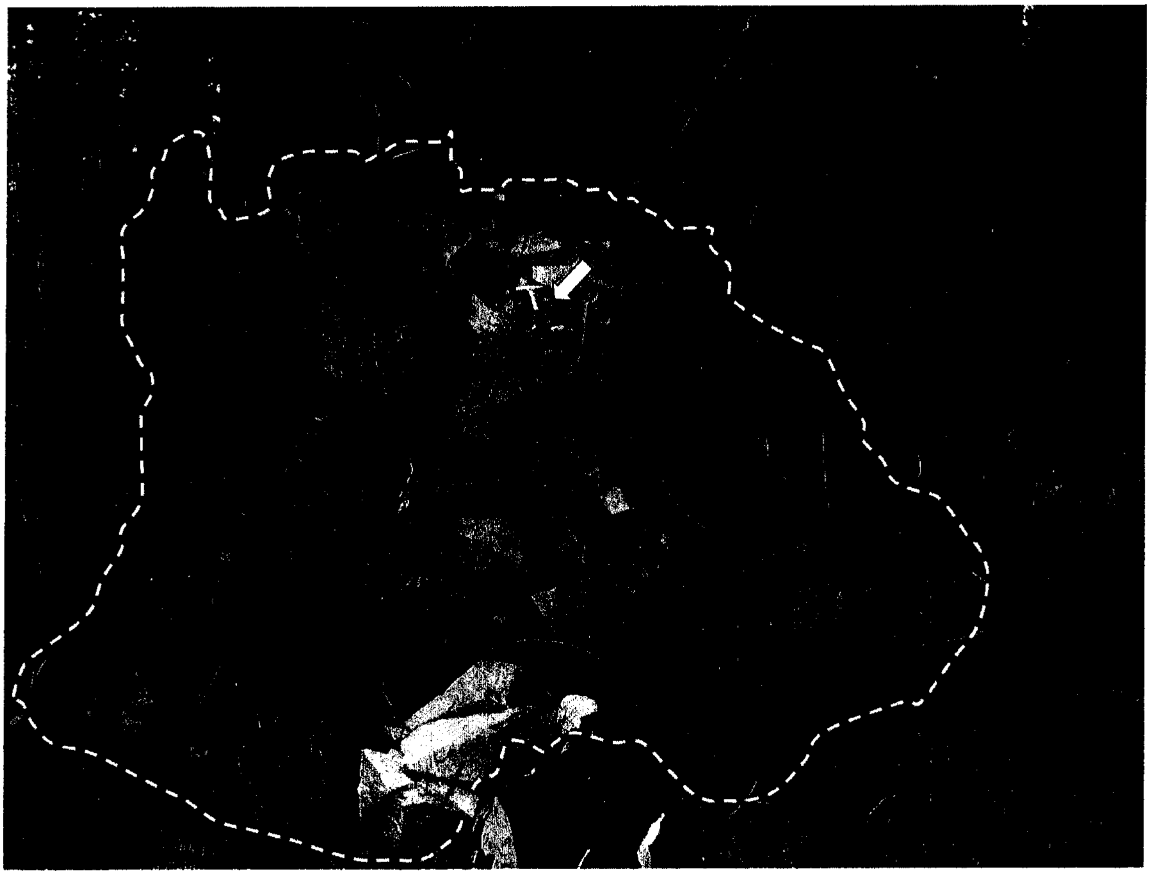

Figure 8. Rootball of a windthrown tree on Sumas Mountain, British Columbia. The roots still cling to the uplifted, fracture bedrock. Note rock hammer for scale.

Despite the normal associations of vegetation with mass wasting mitigation, windthrown trees can have an adverse effect on slope stability (Gray & Leiser, 1982; Gray & Sotir, 1996) and may be a factor in the study area.

The decadal climate cycle known as Pacific Decadal Oscillation (PDO) is a sudden shift in climate regime over the Pacific Ocean (Mantua & Hare, 2002). It affects the study area by bringing anomalously dry weather during warm PDO periods and anomalously wet weather during cold PDO periods (Mantua & Hare). Four PDO periods have been identified in the past century. Cold periods were present between the years 1890 and 1924 and 1947 and 1976, and warm periods were present between the years 1925 and 1946 and 1977 through the mid-1990s (Mantua & Hare). Generally, anomalously cold and wet periods should bring a more mass wasting than the anomalously warm and dry periods.

Hydrology

Four main watersheds exist in the study area. Clayburn watershed drains the western slopes and includes Poignant and Clayburn creeks (Figure 4). Sumas watershed drains the entire south side of the mountain and includes Mckay, Kilgard, and Kennedy creeks which flow into the Sumas River. Wades watershed drains Wades and Chadsey creeks on the north slopes into the Fraser River. Vairell watershed is a small drainage basin on the north slopes that has no major streams, but drains a prominent ridge (Community Mapping Network, 2005). Most of these streams are highly seasonal in flow and have steep, forested ravines (Fraser River Action Plan, 1999). Mass wasting boundaries are often equal to watershed boundaries and can be affected by the size of the drainage.

Vegetation

Vegetation on the mountain consists of mostly the coastal western hemlock and coast Douglas fir biogeoclimatic zones (Nuszdorfer & Boetger, 1994). Current mature forest occupies 288 ha and is mostly second or third growth Douglas fir, dominant in the dendrogeomorphology study area, and *Tsuga heterophylla* (western hemlock). Douglas fir normally has a deep root system (Schweingruber, 1993), but is limited in the study area by shallow soils. This results in horizontal root growth rather than vertical, making trees susceptible to windthrow. Deeper root growth is facilitated by fractures in the bedrock and root growth can be a mechanism for physical weathering of the bedrock. This is somewhat offset, however, by the ability of root structure to prevent shallow soil slides. Western hemlock generally has a much shallower root system than Douglas fir (Schweingruber, 1993), therefore it does not have such a great effect on the stability of the soil or the physical weathering of the bedrock. Deciduous trees, such as *Alnus rubra* (red alder), *Betula papyrifera* (paper birch) and *Acer macrophyllum* (big leaf maple), have repopulated many earlier deforested areas (CFVRD, 1986; Nuszdorfer, 1999). A 20-ha patch of *Quercus garryana* (Garry oak) ecosystem on the east side of the mountain is one of only two known stands in mainland British Columbia (Fuchs, 2001). It is now designated as an ecological reserve (CFVRD).

Land Use

Prior to European contact, the study area was used as a gathering place and for hunting by groups of the Sto:lo First Nation (Carlson, 2001). Many important cultural resources exist on the mountain including archaeological sites for pit houses, spirit rocks, and culturally significant caves.

The first European Canadian settlers came to the area in 1893 and attempted to farm the flatter topography on the mountain. On the mountain, agriculture was practiced mostly for subsistence and attempts to expand were abandoned as forestry was seen to have greater economic benefits.

Forestry took over prominence in the early 1900s and continues today. The northern section of the mountain was deforested first, as logs could be easily transported to the Fraser River, the major log transportation route. Harvest gradually followed a southwest pattern around the mountain (CFVRD, 1986). Prior to 1981, lands were deforested at a rate of 47 ha per year. After a moratorium on new harvest licenses in 1986, this average fell to around 20 ha per year (British Columbia Ministry of Forests, 1992). Many of the current paved roads on the mountain were originally skid roads or rail beds (CFVRD). Today, forestry is controlled on a license basis by the Ministry of Forests. Current forestry regulations require the mapping of potential mass wasting hazards and the influence of sediment deposition in or near streams.

Major economic mining processes on Sumas Mountain began with the removal of high quality fireclay. This material was used in the making of bricks and sewer pipes and was originally the only true fireclay deposit known in British Columbia (Cummings & McCammon, 1952). Although these mines still operate today, they have been overtaken in economic significance by the mining and crushing of gravel, in pockets on the northern, western and southern sections of Sumas Mountain. Mainland Sand and Gravel Ltd., operates the 10th most productive aggregate mine in Canada. Located on the north side of the mountain, this operation takes advantage of the Fraser River, shipping aggregate by barge. The CN rail line is also used to transport gravel from the mine.

Highland Quarry, located toward the center of the mountain, depends on trucks to remove its gravel. Both quarries, as well as several other smaller operations, provide aggregate to a booming construction industry in the Fraser Valley.

Recreational uses are varied on the mountain. Mountain biking is a popular activity and the Fraser Valley Mountain Biking Association actively builds and maintains trails on public and private property. The Trans-Canada Trail has a section which traverses the north side of the mountain, passing by Chadsey Lake. This trail receives use from hikers and horseback riders. The mountain has even seen limited usage as a launch area for hang-gliding. Sumas Mountain Regional Park recently expanded to an area of 1,445 ha, split in two sections on the mountain (FVRD, 2003). The first section, known as the Eastern Escarpment, incorporates Chadsey Lake, Sumas Peak (the summit proper) and a large area of the southeastern slopes. The second section, the Western Flank, preserves a large area on the western edge of the mountain.

Population in British Columbia's Fraser Valley has grown to a size five times what it was in 1950 (FVRD, 2003). The city of Abbotsford, a major suburb Vancouver, has been projected to more than double in population by 2021, reaching 170,000 (see Figure 9). It is currently British Columbia's second fastest growing city (Statistics Canada, 2006). The expanding population, coupled with the fact that over 74% of the city's land is locked up in ALR, creates a pressure to move development up slope. Currently, only 7.4% of the city's land is slated for urban residential use. This translates to a little over 2,750 ha (City of Abbotsford, 2005). Figure 10 shows the situation with ALR surrounding the city and also the area available in PEAH. PEAH, which covers the majority of the study area, is a provincially governed area, developed only to rural-

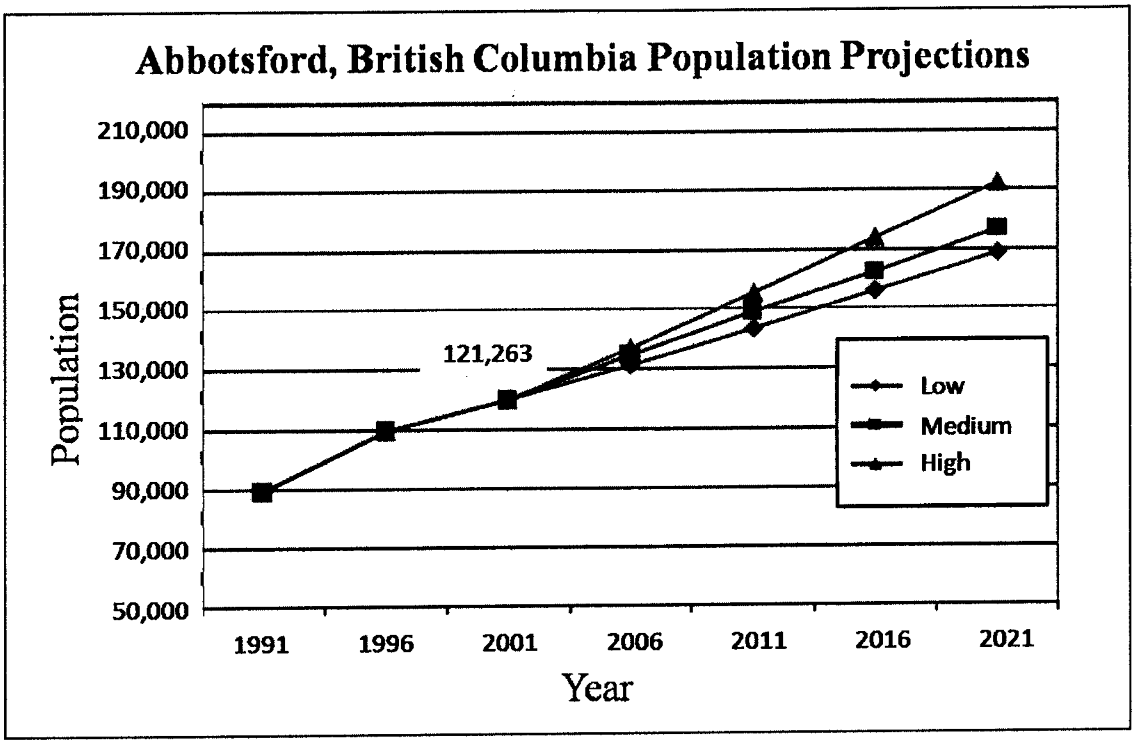

Figure 9. Population growth model for Abbotsford, British Columbia. Adapted from FVRD (2003).

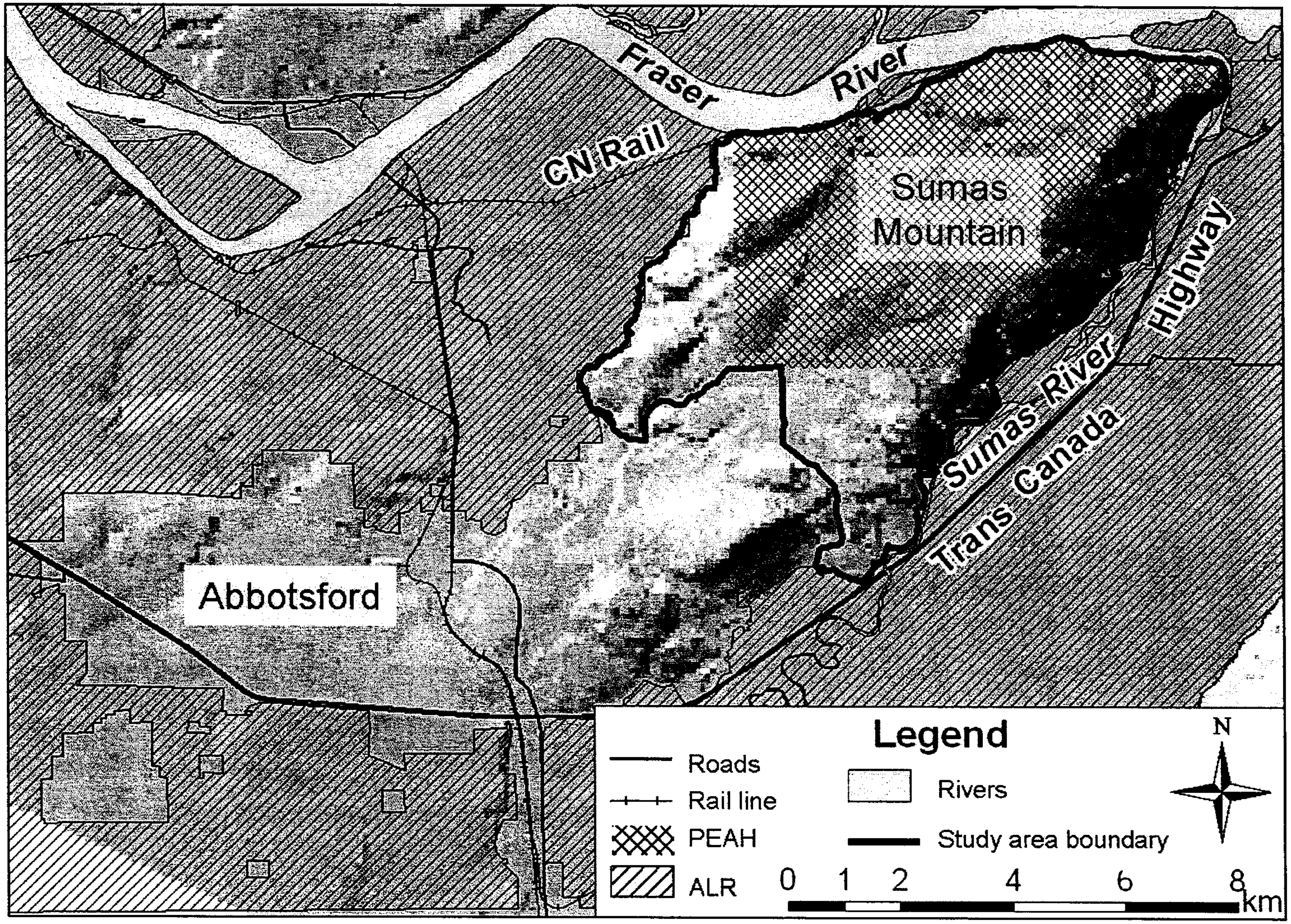

Figure 10. Locations of ALR and PEAH around Abbotsford, British Columbia. Adapted from City of Abbotsford (2005) and FVRD (2003) data.

residential standards (FVRD). Currently, Abbotsford is negotiating with the provincial government to incorporate PEAH into its municipal boundaries in order to solve some its population growth issues.

Even with such a large area of potential expansion represented by PEAH, steep slopes often cannot absorb housing of more than one house per three acres, because of design limitations (McHarg, 1969). This creates the need for a comprehensive understanding of the geomorphic processes at work on the landscape, including mass wasting, so that consequent planning and management of land is properly informed. The mass wasting inventory and associated analysis, laid out in the methods section and reported in the results section, will permit more informed planning and land management in the study area.

CHAPTER IV

METHODS

Overview

This chapter is an overview of the methods constructed to carry out a mass wasting inventory for Sumas Mountain. These consisted of (a) identifying, mapping, and classifying mass wasting features; (b) dating mass wasting events; (c) creating mass wasting activity maps; (d) analyzing mass wasting controlling variables; and (e) making management recommendations.

Mass Wasting Identification, Mapping, and Classification

Identifying Mass Wasting Features

Mass wasting features were identified for this project using two methods: aerial photograph interpretation and field observation. Aerial photograph interpretation allowed the most comprehensive analysis available, covering the entire study area over multiple time periods. Field observation was limited both spatially and temporally because of limited access, rugged topography, and travel funding. Both datasets were compiled into a geo-database, allowing the attributes of each event to be spatially represented and easily recalled.

The aerial photograph interpretation portion of this study was completed using four sets of hardcopy stereographic aerial photographs over a 39-year period: 1963, 1974, 1990, and 2002. Imagery was obtained from the British Columbia Integrated Land Management Bureau (Victoria, British Columbia, Canada). Aerial photograph years were chosen for their appropriate scale and comprehensive coverage of the study area.

Stereographic pairs were used because of their ability to accentuate slope morphology, the primary attribute being examined (Soeters & van Westen, 1996). The aerial photograph sets varied between natural color and panchromatic, the season in which they were taken, and in scale between 1:12,000 and 1:15,000, which is suitable for this level of analysis (Malamud et al., 2004; see Table 1).

Table 1

Aerial Photograph Sets Used for Aerial Photograph Interpretation

Year and roll number	Photograph number	Scale	Natural color	Flight date
2002				
30BCC02026	02-07, 101-107, 124-128	1:15,000	Yes	Aug. 12
1990				
30BCC90014	112-116, 124-131, 145-151	1:15,000	Yes	July 9
1974				
15BC5584	29-35, 76-78, 164-170, 213-220	1:12,000	No	Nov. 31
15BC5575	123-126	1:12,000	No	Nov. 31
15BC5580	188-191	1:12,000	No	Nov. 31
1963				
15BC5065	28-36, 180-188, 250-254	1:12,000	No	May 4
15BC5064	211-222	1:12,000	No	May 4

Features were identified based on morphology, vegetation and drainage patterns represented through photographic characteristics. Attention was given to looking for concave or convex topographic features, slide blocks, semilunar headscarps, hummocky topography, differential vegetation growth, water ponding, and deranged drainage patterns (Soeters & van Westen, 1996).

Mapping

Aerial photographs were examined along flightlines and compared with hardcopy topographic maps (1:20,000) to identify evidence of mass wasting. Using a grease pencil, mass wasting features, including scarp, body and toe, were mapped directly on the stereopairs. The features were then manually transferred onto 0.25-m pixel digital orthophotos (Integrated Mapping Technologies, Ltd., 2004) overlain with a 20-m contour interval using ArcMap 9.2 (ESRI, 1999), following the direct hazard mapping methodology set out by van Westen et al. (1999).

Classification

This study only considers three of the main controlling variables for classification set out by Cruden and Varnes (1996): activity, material, and type of movement. This is because the use of aerial photographs in the analysis of mass wasting prevents the classification scheme from being as rigorous compared to individual site visits to each mass wasting feature (Hansen, 1984b; Soeters & van Westen, 1996). Activity includes only analysis of active or inactive process, not event geometry (Cruden & Varnes) as this goes beyond the scope of the study. Material was generalized into the two main groups of rock and soil as the differentiation between earth and debris was not clearly visible through aerial photograph analysis. Activity classes were modified from Wieczorek (1984) and Lillquist (2001).

Actual mass wasting processes are not seen directly on aerial photographs. Rather, they are interpreted through a variety of features visible on the landscape. Decision rules were used to identify mass wasting features based on the combination of methodologies laid out by Soeters and van Westen (1996) and Pack (2005) (see Table 2).

Table 2

Decision Rules for Mass Wasting Delineation Through Aerial Photograph Analysis Used in This Study

Movement type	Interpretive points from aerial photograph analysis
Fall	
Morphology	Bare rock wall and talus buildup
Vegetation	High length:width scars, patches of vegetation outside of normal path
Drainage	No visible drainage
Rotational slide	
Morphology	Hummocky, convex runout lobe, back-tilting blocks, semilunar headscarp
Vegetation	Clear contrast with unaffected area
Drainage	Sag ponds, drainage parallel to contour, seepage at toe
Translational slide	
Morphology	Plane of failure parallel to slope, hummocky runout, blocks decreasing in size from scarp
Vegetation	Lack of vegetation in slide path, differential regrowth
Drainage	No sag ponds, toe affecting streams at base, deranged drainage
Flow	
Morphology	Semilunar backscarp, hummocky ground, berms parallel to flow, step morphology, complete removal of vegetation in slide path
Vegetation	Lack of vegetation and stunted regrowth
Drainage	Steep fan and toe affecting streams at base, deranged drainage
Avalanche	
Morphology	Linear path with source area, concave slope features, hummocky ground, toe may have been removed by stream work
Vegetation	Lack of vegetation and stunted regrowth
Drainage	Sag ponds, shallow gully down flow path

These decision rules were tested in an easily accessible area located in the northwest part of the study area and field checked for accuracy in August 2006, before the majority of the study was carried out. Several updates were made to the aerial photograph decision rules including a differentiation between fall and exposed bedrock, and the use of vegetation to better delineate slide boundaries. A second field check for accuracy was carried out over 3 days in March 2007, after all aerial photograph analysis was complete.

Thirty-five percent of features over 21 km^2 were chosen for field checking based on accessibility and a desire to field check all of the different types of mass wasting environments in the study area. In the field, features identified on the aerial photographs were confirmed using mass wasting features such as scarps, hummocky topography, vegetation patterns, and debris. Only two mass wasting events mapped on the aerial photograph analysis were not present on the actual landscape. Both were mapped as rockfall and were actually just exposed bedrock. A total of 10 features were discovered through field work alone and were not seen through aerial photograph analysis. These were mostly rockfall and small scale flow movements.

Dating Mass Wasting Features

Successive Aerial Photographs

Successive sets of aerial photographs covering the same area can be used to date mass wasting events, looking at change over time (Soeters & van Westen, 1996). Four sets of aerial photographs between 1963 and 2002 were used to date mass wasting frequency across the study area (Table 1). Working forward from the oldest photographs to the newest, mass wasting features were mapped as polygons in ArcMap 9.2 and recorded in a geo-database. If features were seen in the mapped polygon on the 1963 aerial photographs but were not fresh (recent scars, lack of vegetation, etc.), the events were dated pre-1963. If fresh activity was visible on the 1963 aerial photographs, the event was dated as 1963. If new activity was seen on the 1974 aerial photographs, in the same polygon, frequency was again recorded. This was done for all sets of photographs resulting in a frequency count for each mass wasting polygon mapped between 1963 and 2002 and a recording of events which occurred prior to 1963. The frequency is broken down into low, medium, high and very high frequency events, based on the number of times movement was visible in the 39-year period covered by the aerial photographs (Reichenbach et al., 2004; see Table 3).

Table 3

Mass Wasting Frequency Scheme Used for This Study

No. of events observed	Mass wasting frequency	
	Category	Ratio
1	Low	1 : 39
2	Medium	2 : 39
3	High	3 : 39
> 3	Very high	> 3 : 39

Note. Adapted from Reichenbach et al. (2004).

Dendrogeomorphologic Dating

The dendrogeomorphologic dating methodology I used in this project was based on that set out by Perret et al. (2006), where TRDs, caused by rockfall impacts, were utilized to identify rockfall frequency on a slope. The intensive fieldwork and analysis needed for this work prevented the application of this method throughout the study area. Instead, the study was focused in a representative location in the northwest of the larger study area (Figure 4). The study was designed so that frequency data could be extrapolated to other similar slopes on Sumas Mountain (Soeters & van Westen, 1996).

Data Collection

The dominant geomorphic factor affecting tree growth on the slope was rockfall impact (DeGraff & Agard, 1984; Lang et al., 1999), although it should be noted that some injury may be due to impacts from falling trees. Douglas fir exhibits good annual ring resolution, the ability to produce TRDs (Schweingruber, 1993), incomplete healing from scarring (Butler, 1987), fast growth, and local chronologies at similar altitudes and environments exist (Brubaker, 1976; Dobry & Klinka, 1992). Therefore, this species was chosen for sampling.

A 1-ha plot was set out on the slope to include areas within and outside of the predicted main rockfall path (Schweingruber, Kairiukstis, & Shiyatov, 1990). Before sampling began, an overview of the study site was done to record macro wood anatomical features, such as scars in the bark or cambium, tilted or S-shaped stems, and broken crowns. A stratified random sample, selecting only trees with visible signs of rockfall, was completed, resulting in the amplification of the desired characteristics so they may be identified apart from other processes (Butler, 1987; Fritts & Swetnam, 1989).

Nondestructive sampling was done using 5-mm-diameter, 60-cm-long and 5-mm-diameter, 90-cm-long Haglof increment borers (Haglof, Inc., Madison, MS). In the field of dendrochronology, generally it is considered that a tree should be of a minimum of 100 years old before it is included in a chronology. This is not always possible in dendrogeomorphology, especially when measuring more recent, stand-replacing events. The oldest tree measured on site was 120 years and the youngest was 61 years (see Figure 11). Forty-six trees were sampled for this project to ensure a robust sample size (Schweingruber et al., 1990).

The slope angles of 35° and 38° were likely to result in rolling and bouncing rocks (Stoffel & Perret, 2006). Therefore, it should be expected that some scars should be visible above ground level and samples were taken at several heights on the tree stem to compensate for this (Butler, 1987; Stoffel & Perret). Increment boring procedures followed Jozsa (1998). First, a core was taken at 30 cm above the ground and 90° to the slope, done with the purpose of avoiding scars and intercepting as many growth rings as possible. This core would serve as the age dating core. Through the field overview done prior to sampling, it was noted that most scars at the site occurred between the ground and 100 cm high on the tree stems. Therefore, three additional cores were taken at heights of 50, 75 and 100 cm above the ground at 0° to the slope on the uphill side of the tree.

Each core was described in terms of the tree from which it was taken and the site conditions. This included data on the health of the core wood, the height of the core, whether the core intersected the pith of the tree, and whether the core intersected any visible scars. These data were combined with information on the individual trees being sampled, including diameter at breast height, spatial location, slope, elevation, presence of macro wood anatomical features, and presence of environmental factors such as rocks

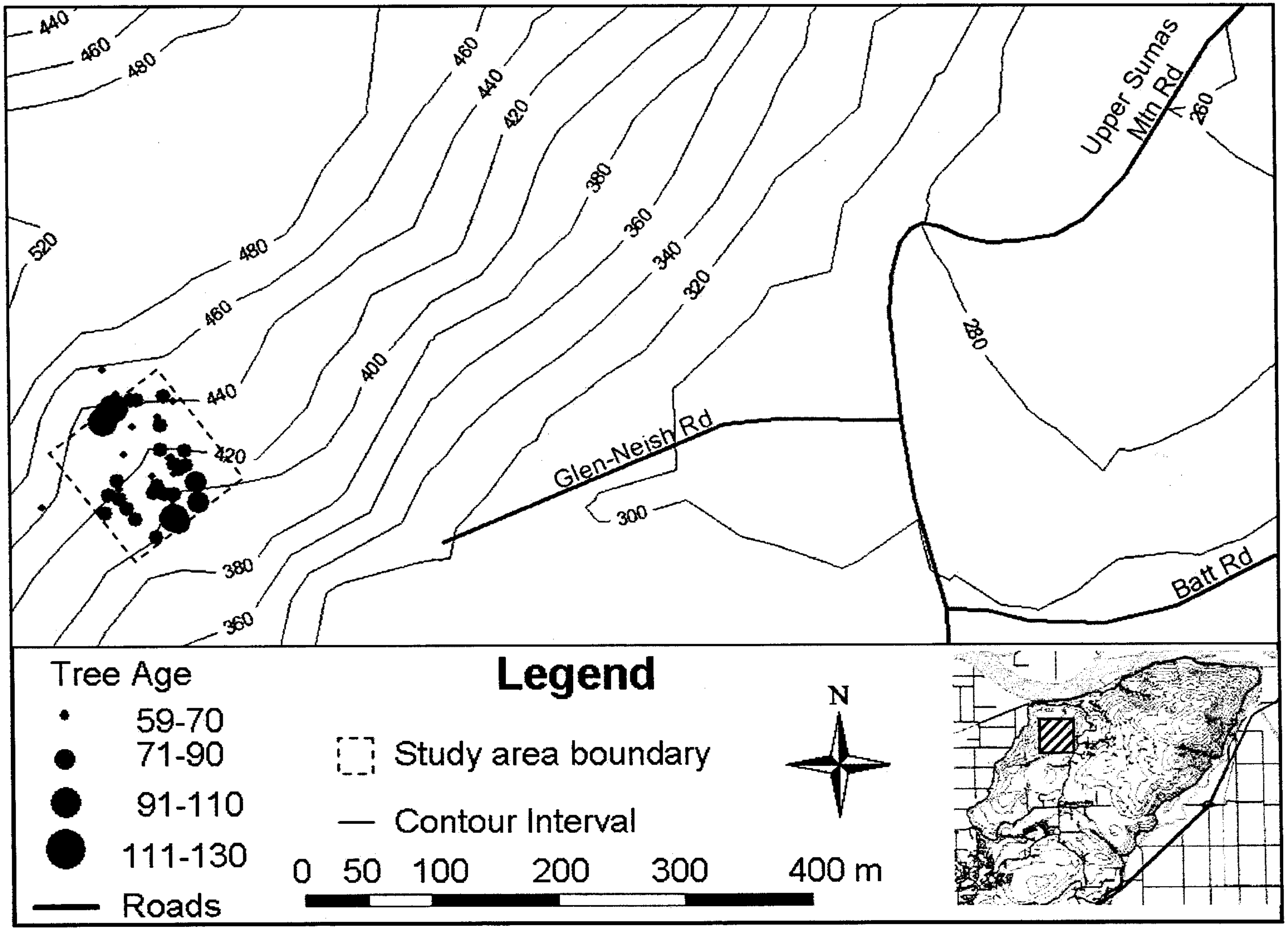

Figure 11. Tree sample age and location, dendrogeomorphology study area, Sumas Mountain, British Columbia. Contour interval is 20 m.

contacting the stem (DeGraff & Agard, 1984). Information was recorded in the field on an inventory sheet and entered into a geo-database on return from the field.

Laboratory Methods and Analysis

Cores were transported back to a lab at Trinity Western University (Langley, British Columbia, Canada), where I prepared them following methodology set out by DeGraff and Agard (1984) and Stokes and Smiley (1996). The first stage of lab analysis, age dating, is important in understanding stand dynamics (Wong & Lertzman, 2001). Counting backwards from the outermost rings, age dating was done for all cores, using a compound stereo microscope (10-40 × magnification) (Butler, 1987). The core sampled at 90° to the slope for each tree was used to age-date each tree. If the pith was missed on the core, an age correction was made using the Duncan (1989) method. The other cores were used for the analysis of TRDs.

Computer-aided cross-dating adds value to any dendrogeomorphic study because it eliminates errors in visual age dating, such as the omission of missing or double rings (Eckstein, 1990). The computer program MeasureJ2X (VoorTech Consulting, 2007) was used in combination with a Velmex A40 measuring system (Velmex, Inc., Bloomington, NY) and a compound stereo microscope. Each core was passed through the measuring system and each ring-width was measured individually. The final dataset was analyzed with the computer program COFECHA (Holmes, 1983), which examines high-frequency variance in ring widths and, comparing data proportionally year by year, searches for outlier data which may reflect missing or double rings, or an error in age dating (Grissino-Mayer, 2001). Using the output of this program, the tree cores were updated to where they fit best within the master chronology and age corrections were made.

Morphologic Dating

Morphology can also be a useful way in which to date mass wasting processes. In this research, morphological dating was used to define mass wasting activity, a part of the classification process. Four classifications were used and adapted from Lillquist (2001): active, inactive-young, inactive-mature, and inactive-old (see Table 4). The humid, temperate climate of the study area provides a mechanism for faster weathering and greater vegetation growth than that experienced in Washington's Eastern Cascades by Lillquist. Therefore, ages assigned by this adapted classification have been decreased to reflect the faster breakdown of morphological indicators (Table 4). Active features are considered to have seen activity in the last 10 years, inactive-young features are between 11 and 50 years old, inactive-mature features are between 51 and 500 years old and inactive-old features are older than 500 years.

Features were classified in these categories based on the visible degradation of the features which defined their classification (i.e., main scarp, morphology, vegetation, and runout zone). Degradation was analyzed using the most recent aerial photographs (2002, 1:15,000) and decision rules based on Wieczorek (1984) and Lillquist (2001; Table 4).

Mass Wasting Activity Maps

Mass wasting activity generally occurs repeatedly in the same location or under the same conditions (Eisbacher & Clague, 1981; Reichenbach et al., 2004). The purpose of the mass wasting activity map is to show where this is most true on the landscape. This was first done by combining the recurrence of each event mapped, through aerial photograph analysis and dendrogeomorphology, to its spatial location, forming a mass wasting activity map (Soeters & van Westen, 1996).

Table 4

Decision Rules for Mass Wasting Activity Class and Morphologic Dating Used in This Study

Activity	Description
Active	
Morphology	Sharp, exposed bedrock, visible cracks, parallel to scarp, hummocky terrain, clear runout zone
Vegetation	Disrupted, crooked vegetation
Drainage	Fresh sag ponds
Inactive-young	
Morphology	Weathered bedrock visible, cracks are not visible, runout zone may be partially eroded
Vegetation	Partially overgrown scarp, hummocky terrain is overgrown, younger vegetation than surrounding area
Drainage	Flank streams have developed small tributaries
Inactive-mature	
Morphology	Bedrock may not be visible, rolling topography, smooth hummocks, runout zone eroded
Vegetation	Scarp is overgrown
Drainage	Lack of sag ponds, drainage extends across runout zone
Inactive-old	
Morphology	Features barely distinguishable from surrounding slope, smooth, rolling topography
Vegetation	Vegetation has mixed with surrounding area
Drainage	Drainage has evolved into dendritic pattern across slope

Note. Adapted from Wieczorek (1984) and Lillquist (2001).

Successive Aerial Photograph Frequency Analysis

The frequencies of each event mapped in the study area were derived from the successive aerial photograph analysis. Using the frequency classes derived from Reichenbach et al. (2004) (Table 3), the study area was divided into areas with low, medium, high and very high frequencies of mass wasting events. Areas with mass wasting events observed through features on the landscape but which had not recurred in modern times (i.e., were not seen to be active on any of the aerial photographs) were classified as low hazard. This map was combined with the predictive mass wasting susceptibility map to show areas of low, medium, high, and very high mass wasting susceptibility.

Dendrogeomorphologic Frequency Analysis

Dendrogeomorphologic techniques include visual growth analysis of micro-wood-anatomical features resulting from rockfall impacts (Schweingruber, 1996), to estimate a proxy for the actual rockfall rate. Each ring of each tree core was analyzed for proportional width and for the presence of scarring or TRDs. Narrow and wide rings were recorded after methodology by Stokes and Smiley (1996). Scars were recorded and differentiation was made between fire scars and scars from other disturbance. Following methodology by Perret et al. (2006), resin ducts were only considered traumatic if they formed compact, continuous and tangential lines (see Figure 12). Compact means they were close together rather than spread apart. Continuous TRDs extended across the entire tree core. Tangential resin ducts occurred in a line perpendicular to the direction of ring growth. TRDs were recorded on a three-degree system based on their properties. If they fulfilled only one of the preceding requirements, they were first degree; if they fulfilled two, they were second degree; and if they fulfilled all three, they were third degree. The only other TRD-producing activity present on the slope was the impact of falling trees; however, those impacts observed during fieldwork did not penetrate past the bark of the trees, and would likely not have produced TRDs, unlike most rockfall, which

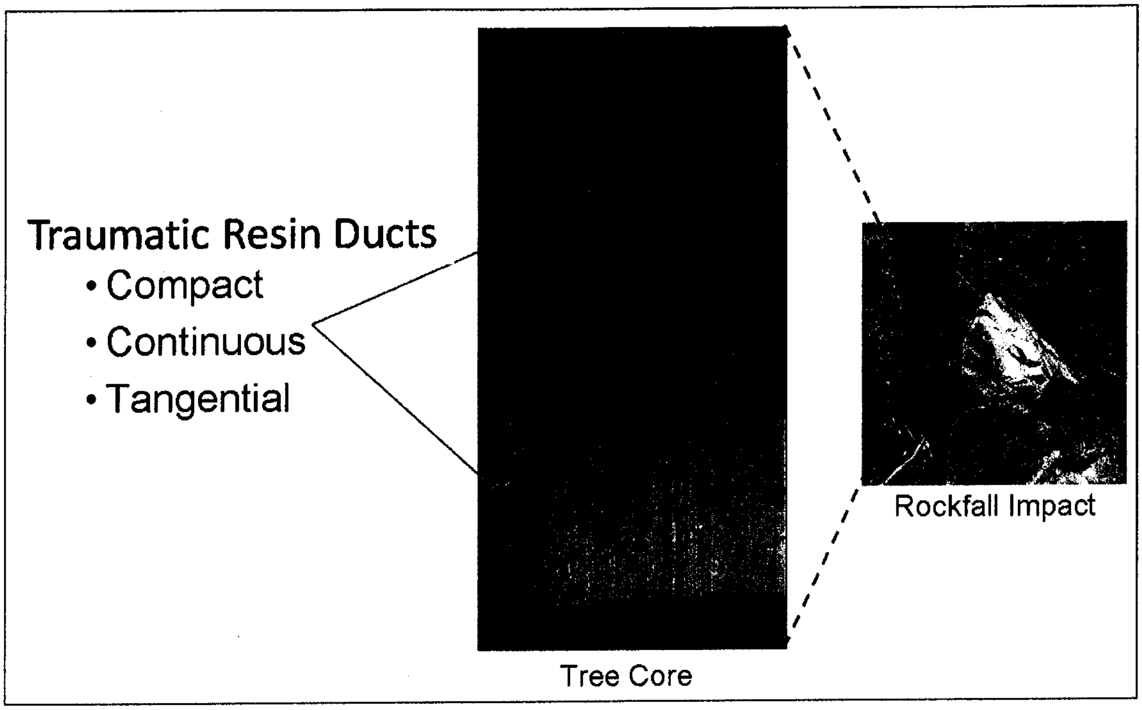

Figure 12. TRDs on a Douglas fir tree core. Note compact, continuous, and tangential nature of first row TRDs as compared to second row.

cuts through the bark to the cambium. Therefore, the conclusion was made that all third-degree TRDs were considered to be as a result of rockfall impact with the tree (Perret et al., 2006). All second-degree TRDs were considered to be the result of rockfall impact only if they were accompanied by growth suppression in the years immediately following. First-degree TRDs were not considered to be a result of rockfall impact with the tree because it could not be confirmed if they were actually TRDs or part of natural growth processes. The visual growth analysis data were entered into the geo-database and combined with the field data to provide a comprehensive dataset on rockfall injury.

A proxy for annual rockfall rate was produced for each tree by dividing the injuries recorded in each year by the sum of tree diameter in that year (Stoffel & Perret, 2006). This proxy was then averaged over the entire slope to give a proxy for annual rockfall rate across the slope. The results for the rockfall rate coefficient were then analyzed spatially using Nearest Neighbor Analysis (Stoffel & Perret). The spatial location of each tree was combined with its rockfall rate and a linear interpolation of each tree with its ten nearest neighbors was done using inverse distance weighting in a GIS to show where rockfall rates were highest. This resulted in a rockfall rate frequency map where areas of higher and lower rockfall within the study site could be distinguished.

The dendrogeomorphologic rockfall rate was displayed across Sumas Mountain in locations equal to the dendrogeomorphology study area in bedrock geology, Quaternary geology, and slope. This proxy rockfall activity map can be used in correlation with the mass wasting activity map derived from aerial photograph analysis to give a further estimate of rockfall frequency in certain parts of the study area.

Mass Wasting Controlling Variables

Spatial Variables

Types

Some of the dominant controls on mass wasting process and frequency are easily interpreted through the use of existing maps. These include bedrock geology, Quaternary geology, and slope (Soeters & van Westen, 1996). Originally, aspect was also included in the list of variables as it may be an important control in a slope's stability because of the type of vegetation it can support, the temperature it endures, and the amount of wind it may face. This variable was later removed; however, after analysis showed that it displayed a random distribution in terrain units associated with mass wasting.

The geology of the study area was broken up into three basic types: quartz diorite, andesite, and undivided sedimentary rocks of the Huntington formation. Three basic

Quaternary geology units occur in the study area: glacial outwash, eolian sediments over glacial outwash, and alluvium/floodplain sediments. Slopes were divided into four categories based on typical failure limits seen in the Coast Mountains (Durgin, 1977; O'Loughlin, 1972; Slaymaker, 1990; VanDine, 1983). Failure was expected to occur in the categories 0°-20°, 21°-40°, 41° -60° and > 60°.

These variables were used to predict where future mass wasting events will occur through proportional weighting and map overlay. Through associating types of mass wasting events with certain mass wasting variables, weighting these variables, and extrapolating them over the entire study area, a mass wasting susceptibility map was created for the study area. The variables measured were not analyzed according to each mass wasting type because of the small sample size of some types (e.g., only eight avalanches exist over the entire study area).

Weighting

Variables were mapped as polygons in ArcMap 9.2 and combined as terrain units, each with a different combination of variables (see Table 5). Mass wasting variables act in combination to increase mass wasting susceptibility and this methodology allowed the variables to be measured in combination rather than separately (Soeters & van Westen, 1996). Terrain units were weighted based on the amount of area they occupied in the initiation zones of past mass wasting features and their extent across the study area. The area of each terrain unit within a mass wasting initiation zone was divided by the total area of the terrain unit across the study area, yielding a proportion. This proportion was extrapolated to the terrain unit across the study area. The terrain unit weights were then broken down into four groups equivalent to low, medium, high, and very high

Table 5

Organization of Variables Into Terrain Units for This Study

Terrain unit identification	Bedrock geology	Quaternary geology	Slope (°)	Percentage of study area
1	Sedimentary	Alluvium/floodplain	0-20	0.1
2	Sedimentary	Eolian/glacial outwash	0-20	0.3
3	Andesite	Eolian/glacial outwash	> 60	0.3
4	Andesite	Alluvium/floodplain	41-60	0.1
5	Andesite	Alluvium/floodplain	21-40	0.1
6	Andesite	Alluvium/floodplain	0-20	1.4
7	Andesite	Eolian/glacial outwash	0-20	31.3
8	Andesite	Eolian/glacial outwash	21-40	5.9
9	Quartz diorite	Alluvium/floodplain	0-20	0.6
10	Andesite	Eolian/glacial outwash	41-60	0.5
11	Andesite	Glacial outwash	21-40	0.4
12	Quartz diorite	Alluvium/floodplain	21-40	0.7
13	Quartz diorite	Eolian/glacial outwash	0-20	17.2
14	Andesite	Glacial outwash	41-60	0.1
15	Quartz diorite	Glacial outwash	41-60	2.5
16	Andesite	Glacial outwash	0-20	0.7
17	Quartz diorite	Eolian/glacial outwash	41-60	3.9
18	Quartz diorite	Glacial outwash	21-40	7.5
19	Quartz diorite	Eolian/glacial outwash	> 60	0.1
20	Quartz diorite	Eolian/glacial outwash	21-40	20.4
21	Quartz diorite	Glacial outwash	0-20	6.0
22	Quartz diorite	Glacial outwash	> 60	0.1
23	Quartz diorite	Alluvium/floodplain	41-60	0.1

susceptibility to future mass wasting using natural breaks in the dataset (van Westen, 2002; see Table 6).

The map was updated to include the successive aerial photograph mass wasting activity map to create the final map. Frequencies derived from Reichenbach et al. (2004) were matched up with mass wasting susceptibility so that older, inactive events would

Table 6

Correlation of Frequency Classification to Mass Wasting Susceptibility and Terrain Unit Weight Used in This Study

Frequency	Mass wasting susceptibility	Terrain unit weight
No recorded event	Low	0
Low	Medium	1-22
Medium	High	23-37
High, very high	Very high	> 38

show areas of medium mass wasting susceptibility while young, active events would show areas of high to very high mass wasting susceptibility (Table 6).

Temporal Variables

Climate is an important variable for determining when, rather than where, future mass wasting may occur. Successive aerial photograph analysis can reveal associations between climate and mass wasting by comparing mass wasting frequency in different years to the climate patterns of those years. Dendrogeomorphological analysis can also yield results for the relationship between mass wasting, especially rockfall, and climate. This section lays out the methodology by which these variables were analyzed and reported.

Successive Aerial Photographs

Successive aerial photographs were used to show a relationship between climate and mass wasting frequency to predict when future mass wasting events may occur. The frequency of mass wasting events for each year of aerial photograph analysis was compared to precipitation and temperature records for that year. Climate data for the three coldest and wettest months of the year in the study area (December, January, February) were taken from the Abbotsford Airport Weather Station for the years 1963, 1974, 1990, and 2002. Datasets were formed for mean daily precipitation and daily low temperature for the period of the cold months. The data were put through an analysis of variance (ANOVA) test using the program Statistix (Analyticial Software Inc., 2000) to look for significant differences in the datasets over time. Mass wasting frequencies for each aerial photograph year were also visually compared to the climate datasets to look for patterns with temperature and precipitation averages.

Dendrogeomorphology

In order to examine controls on rockfall frequency, the results were statistically analyzed for trends over time and correlation with climate patterns recorded from two nearby weather stations using the program Statistix. Temperature and precipitation have previously been found to have significant effects on rockfall rates (Whalley, 1984), especially in southwestern British Columbia (Peckover, 1975). Therefore, these climate parameters were the tested against the rockfall rate calculated for the study area. Specifically, rockfall rate was tested against the coldest and wettest months from December to February, as this is when rockfall rate has previously been identified as highest for southwestern British Columbia (Peckover). Two Spearman's rank correlation tests were completed at $\alpha = 0.05$ measuring precipitation and temperature data against rockfall rate. Climate data were available from Environment Canada (2006) for Abbotsford Airport (49.03° N, 122.36° W, 58 m elevation; the same weather station used for climate normals over the larger study area) and Stave Falls (49.23° N, 122.37° W, 102 m elevation) weather stations. Combined, they provided climate data coverage for the entire tree ring chronology. A Kolmogorov-Smirnov statistical test was done to compare overlapping data from the stations for significant difference between 1944 and 2004. Results showed no significant difference for either temperature or precipitation between the two stations at the 0.05 significance level, and therefore, could be combined into a continuous dataset used in analysis for the study area between 1920 and 2005.

The rockfall rate was measured against change over time and against climatic factors to determine if there has been a significant change over this time period and if there are any indicators as to when rockfall rate might increase. First, rockfall rate was correlated, using a Spearman's rank correlation test, with increasing year from 1920 to 2005. This was done to determine if there had been any change over time. To confirm these results, the dataset was split in two datasets of equal length, an early cohort from 1920 to 1962 and a late cohort from 1963 to 2005. A two-tailed, Mann-Whitney *U* test was applied at $\alpha = 0.05$, comparing both datasets for significant difference. In order to analyze these results in relation to how climate has changed over the same time period, a Spearman's rank correlation test was completed on winter month (December, January, February) temperature and precipitation patterns against increasing year from 1920 to 2005. This test yielded results which help with the interpretation of the overall patterns in rockfall rate.

The rockfall rate was also tested for correlation with the climate pattern PDO. The rockfall rate dataset was split in two, one cohort representing the cold/wet PDO periods (1947-1976) and one cohort representing the warm/dry PDO periods (1924-1946, 1977-1995) (Mantua & Hare, 2002). A two-tailed, Mann-Whitney *U* test was run at $\alpha = 0.05$ to determine if a significant difference existed between the two data cohorts.

Map Combination

The final analysis was done by overlaying the produced mass wasting susceptibility maps using a spatial overlay approach showcasing potential for mass wasting hazards (McHarg, 1969). After the mass wasting activity map, this map is the second stage in creating land use recommendations for the study area. Combined with the mass wasting activity map, it shows areas of greatest mass wasting potential. The third and final stage in the process is also derived from McHarg, and involves the inverting of the mass wasting susceptibility map to show areas where residential development will be possible, with varying degrees of mass wasting mitigation. This final map is on what land management recommendations were based.

CHAPTER V

RESULTS AND DISCUSSION

Mass Wasting Identification, Mapping, and Classification

Five types of mass wasting were observed on the landscape: avalanche, fall, flow, rotational slide, and translational slide. A total of 129 discrete events were observed through aerial photograph analysis, covering 28 km^2 (or 53%) of the 52 km^2 study area. The smallest feature mapped from the aerial photographs was just over 600 m^2 suggesting any smaller movements were too small to identify. This also suggests that with the limitations of the aerial photograph analysis, limited field checking, and the limits of the dendrogeomorphologic investigation, mass wasting is probably under-reported by this study.

Avalanche

Avalanche type movements occurred predominantly along the steep southern slopes of the study area, above the Sumas River. They were also found with intrusive dikes in the interior of the study area. One rock avalanche with an area of 51,560 m^2 and seven avalanches in soil material, with an average area of 209,420 m^2, were recorded in the study area (see Table 7). This constitutes 1.39% of the total area mapped with mass wasting activity.

Avalanche movements are similar to flows but occur on open slopes and generally have larger clast sizes (Cruden & Varnes, 1996). They were generally not confined to channels and may be combined with other movements such as rockfall or slide, breaking away from slopes as large, intact masses before crumbling due to stresses on soil

Table 7

Descriptive Statistics for Mass Wasting Inventory Results

Type and material	Number	Total area (m^2)	Mean area (m^2)	Minimum area (m^2)	Maximum area (m^2)	Total mass wasting area (%)
Avalanche						
Rock	1	51,560	51,560	51,560	51,560	0.18
Soil	7	340,211	209,421	3,885	159,886	1.21
Fall						
Rock	33	3,361,446	216,926	604	1,416,829	12.00
Flow						
Soil	35	1,346,781	211,878	618	238,052	4.81
Rotational slide						
Rock	19	19,166,061	420,919	17,367	6,797,804	68.42
Soil	16	258,131	27,756	1,301	74,510	0.92
Translational slide						
Rock	12	3,334,600	302,917	28,748	826,682	11.90
Soil	6	155,462	286,684	1,691	51,648	0.55
Total	129	28,014,252				

structure (O'Loughlin, 1972). They were not found in the study area on the scale of other large rock avalanches in the region, but usually on a smaller scale (see Figure 13). The one rock avalanche in the area had a small elevational difference between headscarp, toe, and runout zone making it difficult to determine whether it should be classified as an avalanche or rockfall. The lack of runout distance meant that there would be little time for the movement to initiate as rockfall and translate into an avalanche type movement (Hungr & Evans, 2004). However, the presence of similar colluvial material, buried

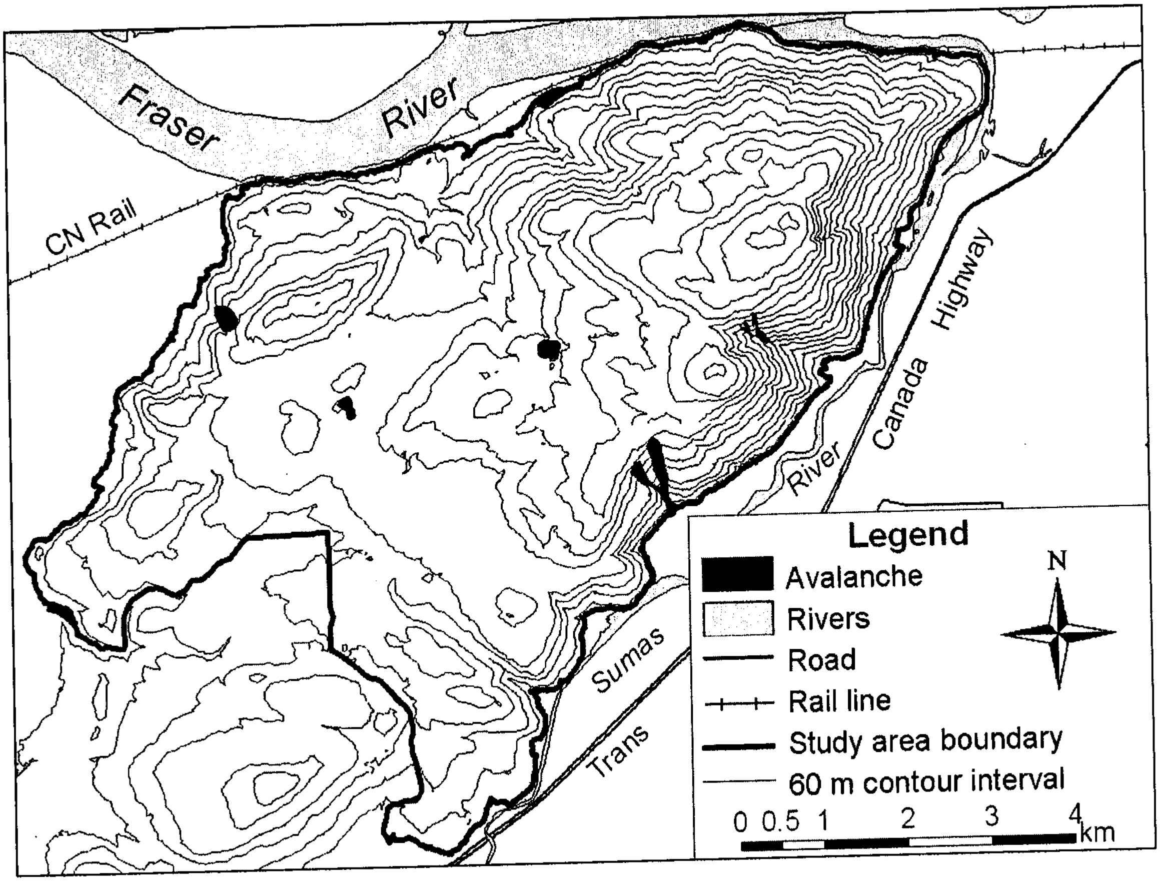

Figure 13. Distribution of rock and soil avalanches, Sumas Mountain, British Columbia.

beneath and extending past the more recent debris, suggests that previous activity had a longer runout zone in the area and may have more accurately reflected avalanche type movement. The slope is currently receding through active rockfall, but the dominant movement was mapped as an avalanche because of the older deposits present at the site. This type of small rock avalanche movement (less than 1,000,000 m^3) is quite common in the Coast Mountains (Evans & Savigny, 1994).

Soil avalanches in the study area were probably generated by intensive rainfall and the buildup of pore pressures in shallow soils above bedrock. This trigger has been documented in the steeply sloped, forested Quaternary cover of British Columbia's forests (Durgin, 1977). At least one soil avalanche was associated with road building, as predicted by O'Loughlin (1972).

Fall

Thirty-three areas of fall were inventoried in the study area, accounting for 12% of the total area of mass wasting activity. They occurred mostly on steep, south-facing slopes (see Figure 14), as expected, where slope angles are highest (Luckman, 2007).

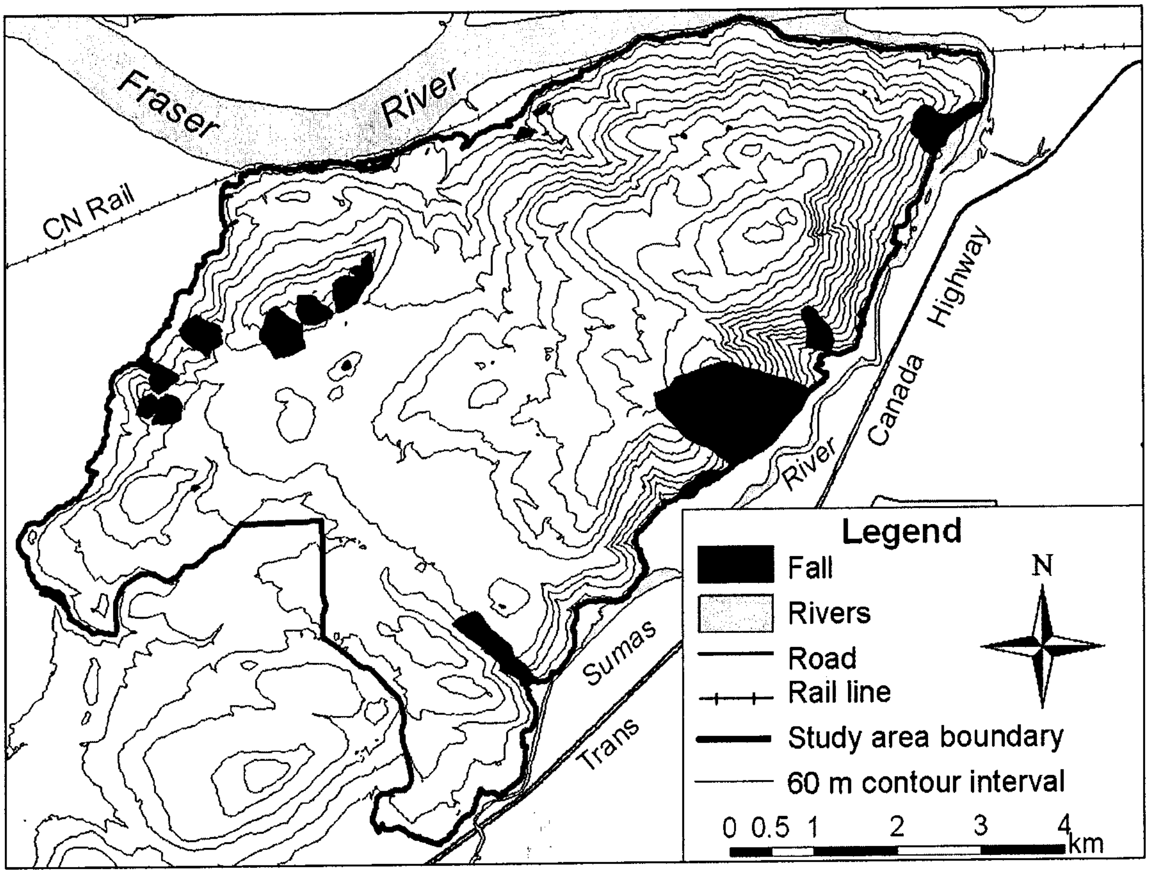

Figure 14. Distribution of rockfall, Sumas Mountain, British Columbia.

This type of movement was one of the most extensive in the area. Field checking and dendrogeomorphic analysis (see dendrogeomorphology results section below) showed that the actual amount observed through aerial photograph analysis was a small percentage of the real amount visible through detailed fieldwork (Brardinoni et al. 2003). Therefore, it is probable that this is the most extensive type of mass wasting in the study area. Soil falls are generally restricted to mass wasting along streams in alluvial floodplains and were too small to map from aerial photographs (Cruden & Varnes, 1996).

Falls in the study area were low in magnitude but high in frequency, reflecting current knowledge about frequency/magnitude relationships (Whalley, 1984). The smallest fall, visible on the aerial photographs, was just over 600 m^2. Fall was ubiquitous in the study area where bedrock was exposed at the surface. Quartz diorite bedrock cliffs were responsible for 85% of rockfall while covering only 59% of the total study area, paralleling expected results from the limited forestry study done near the center of the study area (P. Machibroda Engineering, Ltd., 1998). The other 15% occurred in andesite bedrock, which covers 40% of the study area. Chi-square analysis confirms that a significant difference exists between rockfall in quartz diorite and andesite bedrock at a *p* value of 0.05. Quartz diorite is much more active, therefore, than the andesite, despite the fact that andesite has bedding planes. This could be related to the steeper slope angles found with the quartz diorite in the area. Slopes angles between 30° and 50° account for 53% of rockfall. This is closer to the fall angles expected for sheeted granite (Durgin, 1977), suggesting the bedrock may be massive but probably includes joint planes along which weathering is occurring (Walkinshaw & Smith, 1996). Field work revealed few high vertical cliffs in quartz diorite, but rather a series of stepped ledges on which clasts rest during lags between activity (Whalley). The low-magnitude, high-frequency nature of the rockfall and the physical expression of the rockfall on the landscape points toward a constant weathering of surface rock through freeze-thaw, root pry, and chemical weathering rather than a structurally controlled failure mechanism (Whalley).

Flow

Flow occurred in the study area, mostly in conjunction with steep drainages (Trenhaile, 2004) and shallow Quaternary sediments (see Figure 15). These were the most common type of movement, along with rotational failures, with 35 events recorded,

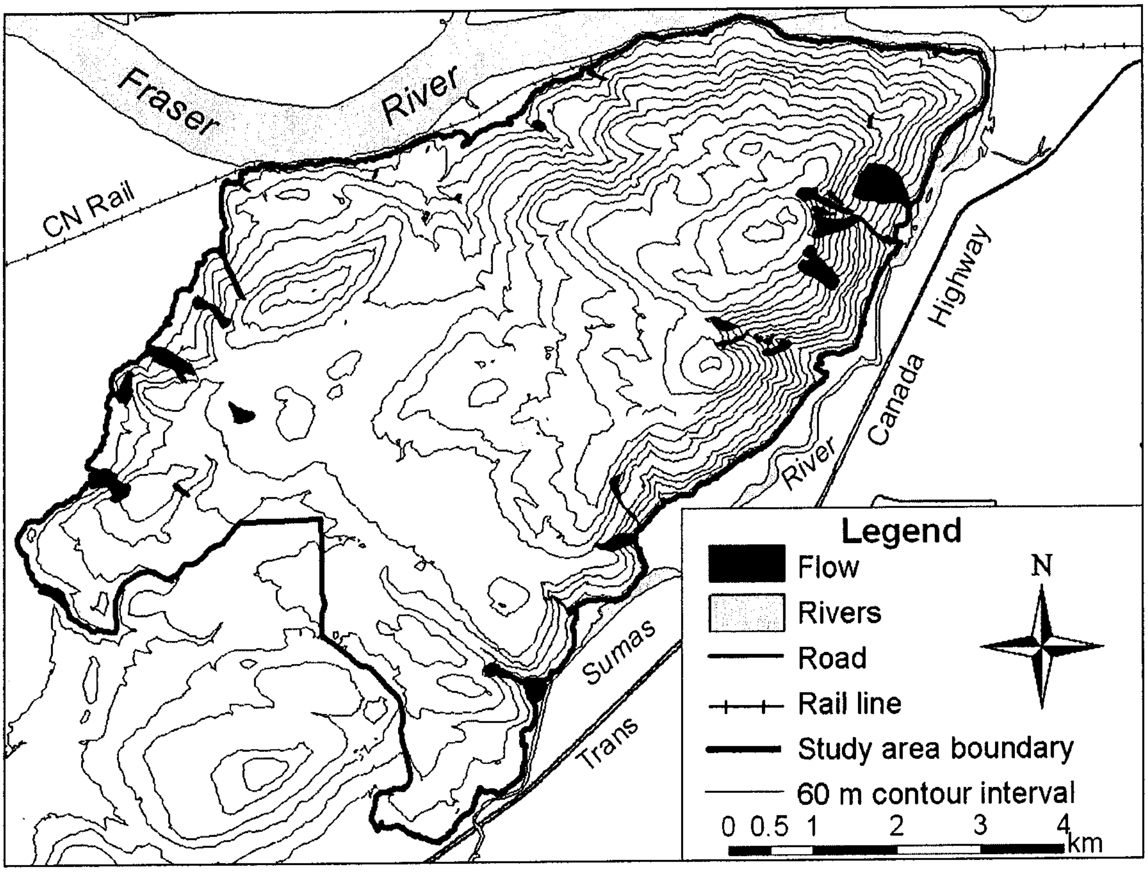

Figure 15. Distribution of soil flows, Sumas Mountain, British Columbia.

covering an area of 1,346,781 m^2 and an average area of 211,877 m^2. Flows constitute 4.81% of the total area covered by mass wasting. Well-drained, shallow, Quaternary sediments, usually 10 to 50 cm deep (Luttmerding, 1980), account for 70% of the area covered by flow movements and all flow movements mapped were in soil material. Flow movements were especially common to the steep slopes and drainages of the southern part of the mountain above Sumas River, but also on the steep northwest side of the mountain which leads out onto Matsqui Prairie (Figure 4).

Flows are generally recorded in the Coast Mountains environment during intensive rainfall events, where well drained, shallow Quaternary sediments are located directly above smooth bedrock (O'Loughlin, 1972; Savage & Baum, 2005). These results are similar to those found by a study done for western Sumas Mountain in 2002, where debris flows were concentrated in well-drained glacial sediments cut by steep mountain streams (Gerath & Smith, 2002). Results were also equal to those of O'Loughlin (1972), who reported this movement type in the Coast Mountains occurring in the upper soil mantle within 0.6 m of the surface. Field work revealed flow morphology with areas where lateral deposits (levees) were clearly visible on the landscape (see Figure 16) (Cruden & Varnes, 1996). These lateral deposits suggest that the volume of the debris flow exceeded the original channel depth, leading to the buildup of material along the sides of the channel. This movement type was spatially limited to the flanks of the mountain where drainages were steepest and depositional fans were visible through aerial photograph analysis (Cruden & Varnes). Source areas for debris flows initiation seemed to be fairly independent as each source area was matched with a

Figure 16. Debris flow deposits found during fieldwork on southeastern side of study area, Sumas Mountain, British Columbia. Note buildup of lateral deposits (levees).

movement (Johnson & Rodine, 1984). However, debris flow channels were not exclusive, as several instances were observed where multiple areas of initiation eventually led to the same outlet channel and with a large fan at base level (see southeastern flows in Figure 15).

It is possible that bedrock flow is present in the study area but was not visible through aerial photograph analysis. Fieldwork revealed areas where geomorphologic evidence, such as antislope scarps, grabens and benched topography could be reflecting bedrock flow (Varnes et al., 1989) and this type of movement has been documented in the Coast Mountains (Evans & Savigny, 1994); however, the results were not conclusive enough to include in this study.

Rotational Slides

Rotational slides occurred in the study area in both bedrock and debris materials (Cruden & Varnes, 1996). Along with flows, rotational slides were the most common in the study area with 35 occurrences. They were also the most extensive as they covered a total area of 19,424,192 m^2 (19.4 km^2) and 69% of the total area covered by mass wasting. This size is mostly due to the movements on the northern slopes of the study area (see Figure 17), which are movements, similar to those identified on Mount Mercer

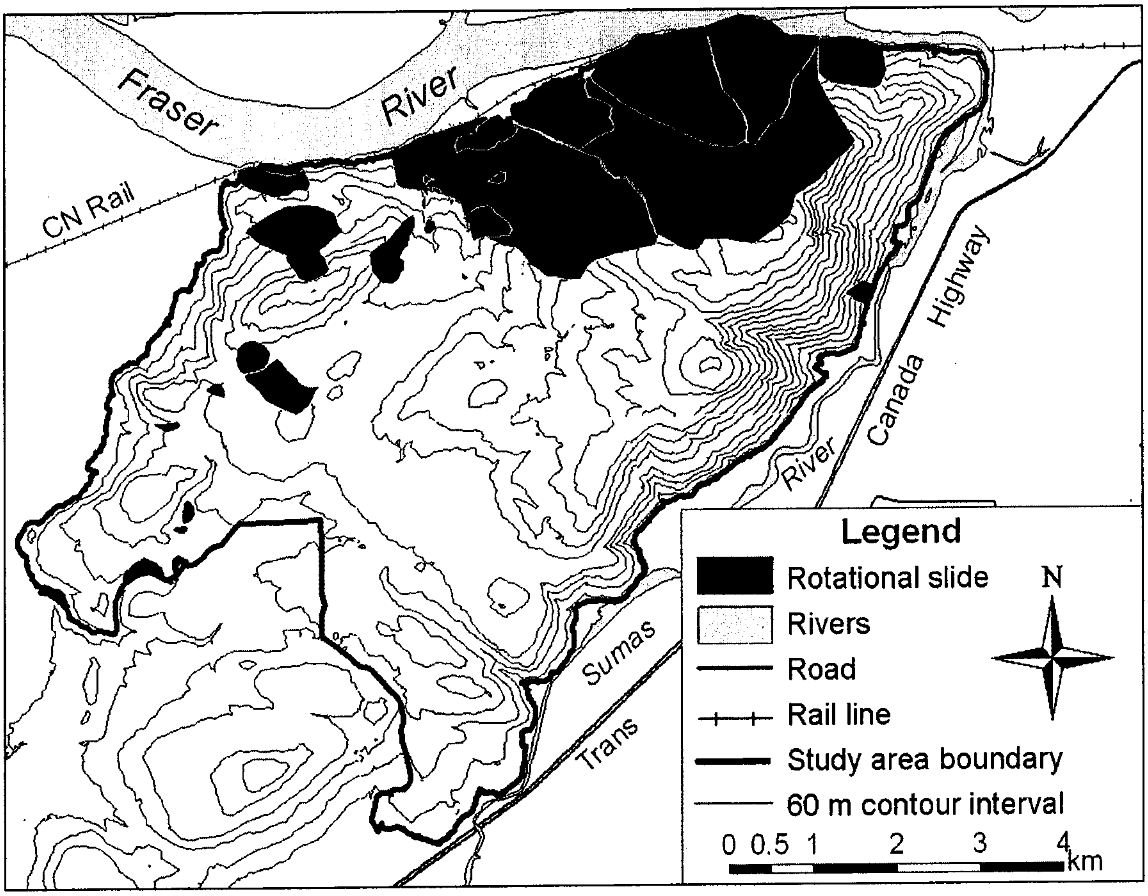

Figure 17. Distribution of rotational slides, Sumas Mountain, British Columbia.

by Kinakin (2002), covering an area of 19,166,061 m^2 (19.2 km^2) with an average size of 420,918 m^2 (0.42 km^2). Large rotational bedrock movements are usually associated with very minimal annual movement and therefore were classified as slow (Cruden & Varnes).

These features were classified as large scale rotational movements because of several features that matched well with Kinakin's (2002) description of rotational bedrock movements. They had well-defined main scarps, visible using the stereographic aerial photographs, and midslope topographic benches, reflecting rotated blocks, much like a rotational movement in soil (Kinakin). Steep toe edges of the mapped areas reflected bulging of the lower slope resulting from plastic flow of the bedrock (Varnes et al., 1989). Rotational bedrock movements have also only been mapped on peaks above 305 m elevation, and the study area exceeds this limit (Thorson, 1992; Varnes et al.), with a peak elevation of 910 m. On a ridge in the northwest section of the study area there was also evidence of antislope scarps, parallel to the main ridge, behind which ponds had formed (Cruden & Varnes, 1996). Ridge splitting, resulting in the formation of a small graben atop this same ridge, also points to rotational bedrock movement or possibly bedrock flow. Further investigation needs to be done to determine whether other attributes of rotational bedrock movements exist here.

Rotational movements in Quaternary sediments were generally located in steep drainages, where stream undercutting of glacial sediments is common (Jones, 1961; P. Machibroda Engineering, Ltd., 1998). These types of movement are predicted to increase with increased construction (P. Machibroda Engineering, Ltd.). Along Poignant, Chadsey, and Wades creeks these movements were common and old, overgrown movements were visible in these areas during fieldwork. Although rotational movements are generally expected in homogenous sediments (Cruden & Varnes, 1996), this is rarely found in the natural environment. Instead, rotational movement occurs along a discontinuity, creating a failure plane along which moisture can collect or friction is overcome. This may be the case with the glacial and eolian sediments mapped in the study area where a discontinuity exists between the successive layers. The surficial geology map also shows some areas of glaciolacustrine deposits up the valley now occupied by Poignant Creek (Armstrong, 1960). These glaciolacustrine deposits are homogenous and unconsolidated and may be partially responsible for some of the rotational movements in this area.

Translational Slides

Translational slides occurred on steep southern slopes, but evidence was also seen for translational slides on the gentler slopes in the interior of the study area (see Figure 18). Translational movements covered a total area of 3,490,061 m^2 (3.5 km^2), and each movement had a mean size of 589,600 m^2 (0.6 km^2). A total of 18 translational movements were seen in the study area, accounting for 12% of the total area covered by mass wasting features. Twelve events occurred in rock material, 11 in quartz diorite and 1 in andesite bedrock. Six events were mapped in shallow soil environments. Some movements were related to deforestation practice and others due to possible weaknesses in bedrock or lack of soil cohesion.

The movement on the eastern tip of the study area was probably caused, at least in part, through deforestation activity (Figure 18). Here, shallow Quaternary cover and lack

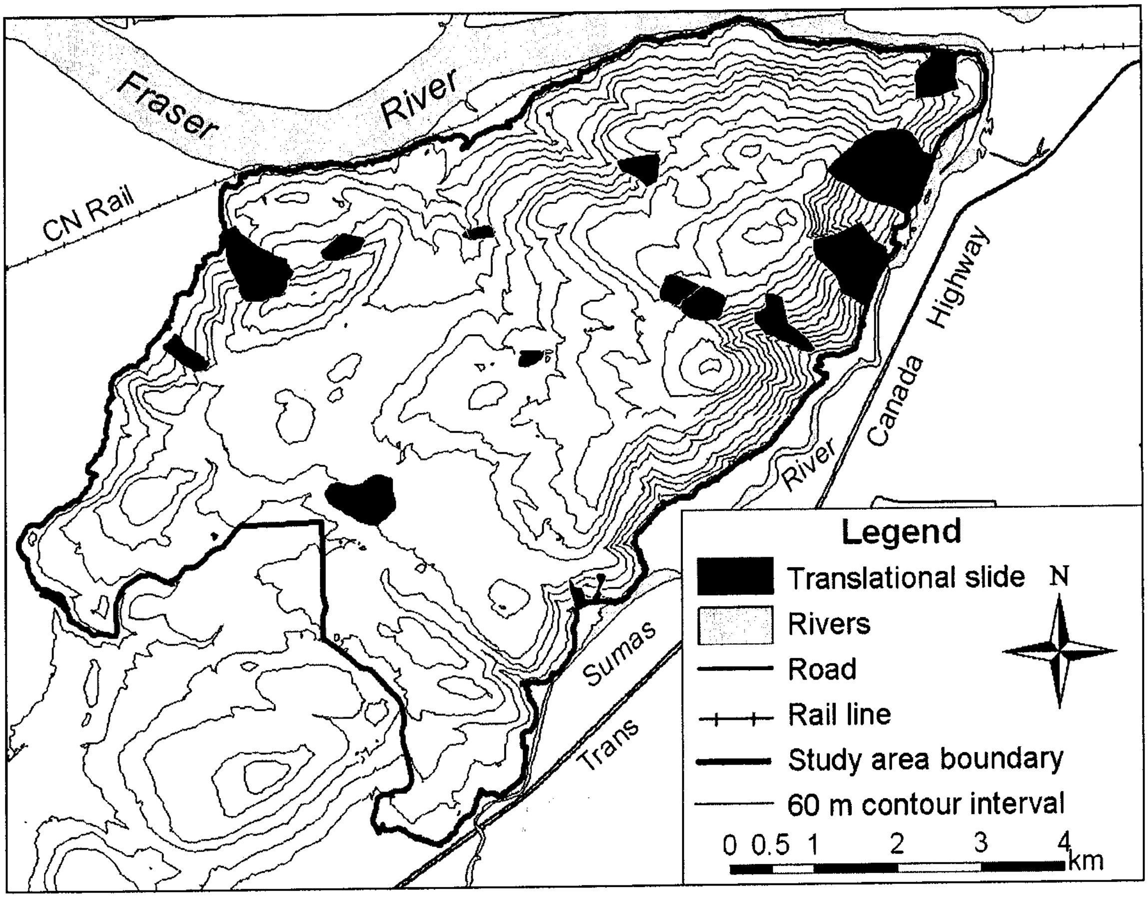

Figure 18. Distribution of translational slides, Sumas Mountain, British Columbia.

of vegetation, combined with temporary road cuts created an area susceptible to translational sliding. This resulted in hummocky ground at the depositional end of the movement and lineaments parallel to the slide (Soeters & van Westen, 1996). Drainage was also affected in this area with streams being upset by road construction and also the deposition of debris by the sliding movement. Translational slides should be considered in relation to future road building, as past events have damaged roads within the study area (P. Machibroda Engineering, Ltd., 1998).

Translational movements account for the second largest percentage area mapped as mass wasting out of all types and occur mostly in shallow Quaternary cover and weathered bedrock.

Dating Mass Wasting Features

Successive Aerial Photographs

The four sets of aerial photographs showed how mass wasting has modified the study area over the last 39 years. As noted above, a total of 129 mass wasting features were mapped on the landscape. Fifty-two (40%) features had recurring movement in the same location, visible on the analysis of successive aerial photographs. Including these recurring events, the total number of actual mass wasting events is 234 (see Table 8).

Table 8

Total Occurrence of Mass Wasting Events Including Recurring Events, Sumas Mountain, British Columbia

Aerial photograph year	Avalanche	Fall	Flow	Rotational	Translational	Total
Pre-1963	7	16	23	31	14	91
1963	2	12	14	4	3	35
1974	2	10	10	3	3	28
1990	4	21	12	2	2	41
2002	3	19	12	3	2	39
Total	18	78	71	43	24	234

By far, the greatest number of events (91, or 38%) occurred before the aerial photograph period and were identified through subdued features on the 1963 aerial photographs (see Figure 19). A total of 143 events occurred during the period covered by aerial photographs (see Figure 20). The 1990 aerial photograph set had the greatest number of fresh events with 41 (18% of the total). The 1990 aerial photograph set also had the longest gap between aerial photograph sets (16 years), partially explaining the higher total. The 1974 aerial photograph set had the lowest number of mass wasting events identified with 28 (12% of the total). This year was the lowest quality aerial photograph

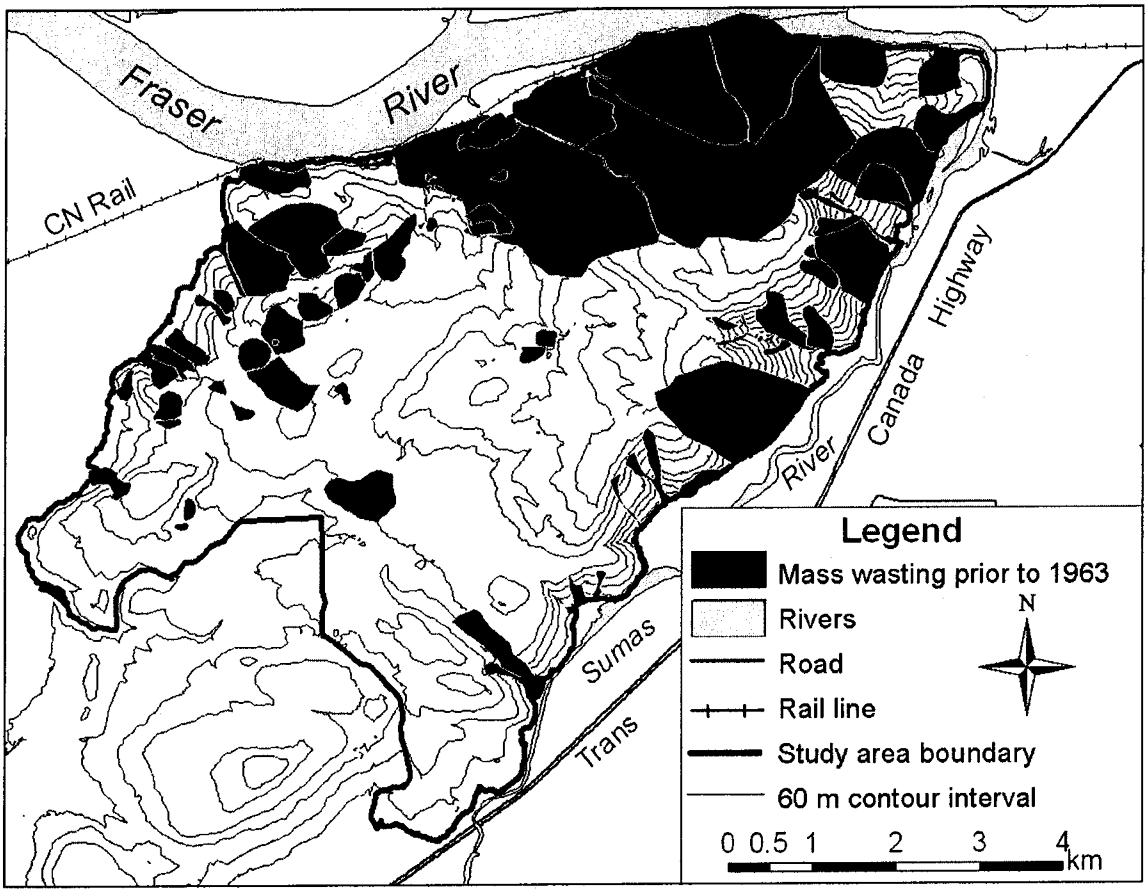

Figure 19. Mass wasting activity prior to 1963 on Sumas Mountain, British Columbia.

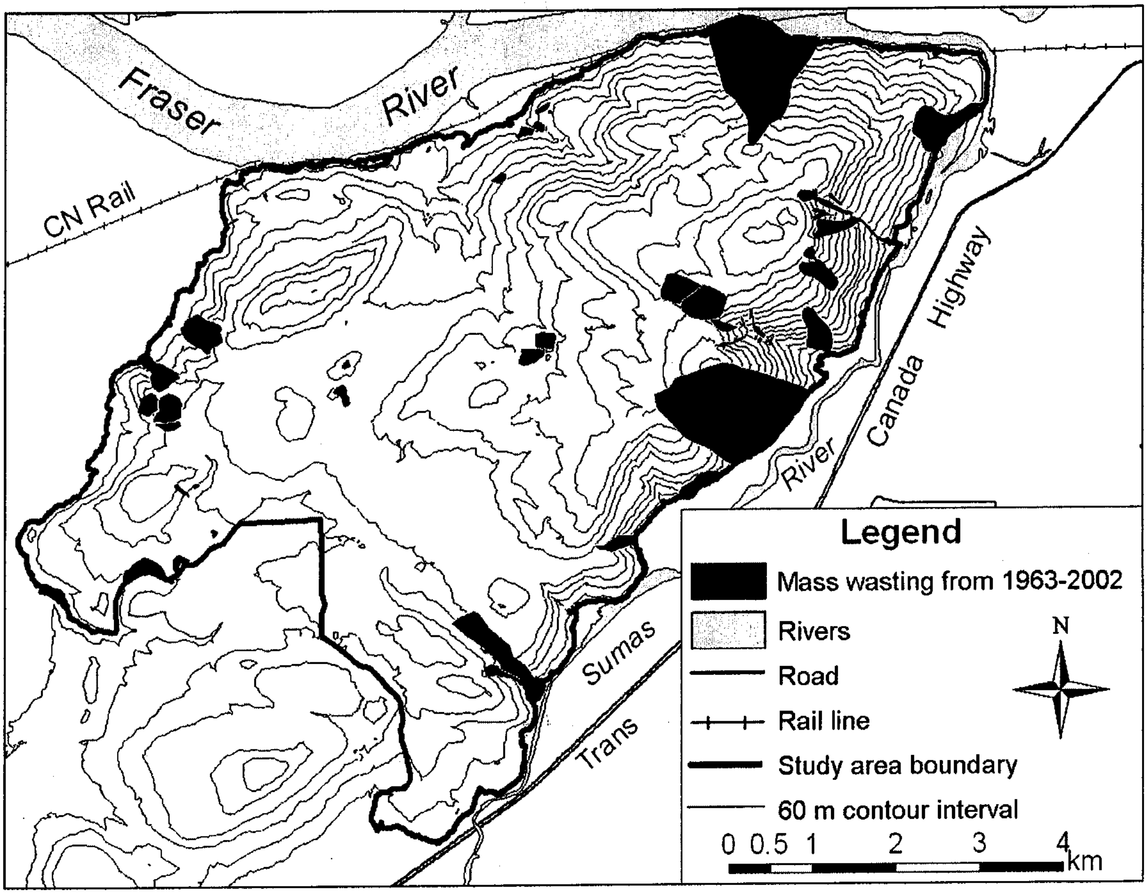

Figure 20. Mass wasting activity from 1963 to 2002, the period of aerial photograph analysis, on Sumas Mountain, British Columbia.

set, with extreme parallax at the edges, making it difficult to positively identify mass wasting features.

Rotational and translational movements were mostly dated prior to the aerial photograph period, with several examples of regressive sliding, where the main scarp continually advanced headward, and recurring movement essentially occurred over the same area (Jones, 1961). Flows had a greater amount of return, with six of 35 features (17%) recurring in all four sets of aerial photographs. Falls had the greatest amount of return, with 10 features out of 33 (30%) visible on all four aerial photograph sets. This would be expected as fall is a continuous type of movement where recession of the main scarp continues along joints or fractures in the rock (Luckman, 2007; Walkinshaw & Smith, 1996). The fluctuation of winter temperatures around 0 °C may cause freeze-thaw weathering in the rock joints, contributing to this high rate of return (Peckover, 1975). Avalanches had a variable return rate, with four features occurring only once and four features occurring between two and four times.

Dendrogeomorphologic Dating

In order to maintain a robust sample, the age of analysis was limited from 1920 to 2005. This allowed a sample depth of at least seven trees, until 1920 when there were not enough old trees to supply further sampling. The median number of injuries recorded through the analysis of TRDs was three per tree from 1920 to 2005 (see Table 9).

Table 9

Descriptive Statistics for Dendrogeomorphological Sampling, Sumas Mountain, British Columbia

Variable	Mean	Median	Mode	Range	Maximum	Mininimum
Tree age (years)	76	73	73	61	120	59
Tree diameter (cm)	35.5	25.5	21.0	111	122.0	11.0
No. of injuries	3.7	3.0	1.0	15	15	0
Rockfall rate (injuries/m)	0.34	0.27	0	1.3	1.3	0

The maximum number of impacts recorded by one tree was 15 and five trees revealed no impacts. A total of 170 different injuries were recorded through the analysis on the 46 different trees. The proxy for rockfall rate was calculated based on the 46 sample trees and the tree diameter for each year. The median rockfall rate coefficient over the time period from 1920 to 2005 was 0.27 injuries/m (Table 9). This rate basically shows that for every 4 linear meters, perpendicular to a slope of 35° or greater, one rock will roll through every year.

Morphologic Dating

Morphology was used in this study, not only for the classification of mass wasting events, but also for the determination of mass wasting activity. The classification for state of activity, adapted from Lillquist (2001), was applied to all of the mass wasting events in the inventory (see Table 10). Most of the larger rotational and translational

Table 10

Morphology Dates by Movement Type, Sumas Mountain, British Columbia

Type	Active (0-10 years old)	Inactive-young (11-51 years old)	Inactive-mature (51-500 years old)	Inactive-old (> 500 years old)
Avalanche	3	3	1	1
Fall	14	17	2	0
Flow	6	23	6	0
Rotational	0	15	17	3
Translational	1	2	12	3
Total	24	60	38	7

features in the study area had a subdued appearance on the landscape. This suggests that this type of movement is not as frequent and probably occurred before settlement of the area by European Canadians. This agrees with the successive aerial photograph analysis which shows little of this type of movement active on the landscape. Some of the oldest events may be remnants of early postglacial movements (Luckman, 2007). The inactive-young and active features are much more fresh on the landscape. Most of these included fall-, flow-, and avalanche-type movements. These types of movements were also the most frequent, as recorded by the successive aerial photograph analysis. The more active events are also generally smaller than the rotational and translational events (Whalley, 1984), suggesting their features are more rapidly eroded from the landscape.

The spatial distribution following the morphologic dating closely replicates the distribution of frequencies measured on the aerial photograph analysis. Most of the active events are located along the steep, southern slopes of the mountain whereas the oldest, inactive movements are located along the northern slopes. The largest cohort, the inactive-young, were also located mostly along the southern slopes but also along a ridge in the northwestern section of the study area.

Mass Wasting Activity Maps

Successive Aerial Photograph Frequency Analysis

The frequency analysis of mass wasting events resulted in the production of a mass wasting activity map used in conjunction with the mass wasting susceptibility map (Soeters & van Westen, 1996; see Figure 21). The results from the successive aerial photograph analysis were used to populate a frequency chart, using Reichenbach et al.

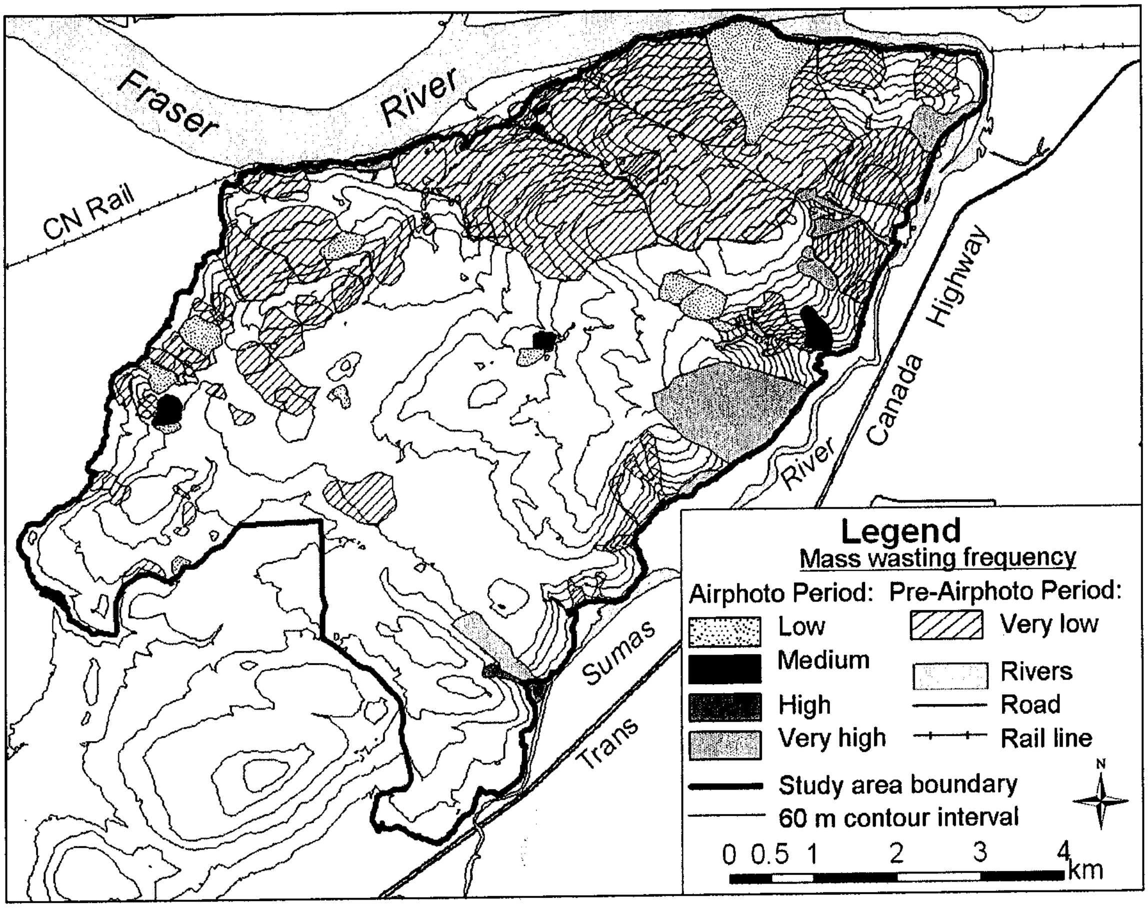

Figure 21. Mass wasting activity map for Sumas Mountain, British Columbia.

(2004), outlining the expected frequency of different mass wasting types (see Table 11). A total of 19 events of different movement types are classified as having a very high return frequency, 6 with a high return frequency and 27 with a medium return frequency. Low return frequency events accounted for well over half of the events recorded during the analysis. High and very high frequency events were mostly located along the southern slope. This reflects the steep slopes found in this area (up to 75°) and the highly recurrent rockfall. Low and very low frequency events, occur with greatest extent on the gentler, northern slopes of the study area.

Table 11

Classification of Movement Frequency Based on Aerial Photograph Analysis

Type	Low (1/39)	Medium (2/39)	High (3/39)	Very high (> 3/39)
Avalanche	4	1	1	2
Fall	13	7	3	10
Flow	18	9	2	6
Rotational	30	4	0	1
Translational	12	6	0	0
Total	77	27	6	19

Note. Based on Reichenbach et al. (2004).

A fairly even split exists between events occurring only prior to the aerial photograph analysis and those occurring during aerial photograph analysis. Sixty of the 129 events (46%) occurred only prior to the aerial photograph period and are inactive-mature to inactive-old (Wieczorek, 1984). Sixty-nine of the events (54%) have been active in the historic aerial photograph period. The highest frequencies are along the high angle, southern slopes where rockfall is dominant (Whalley, 1984) and well-defined channels exist for flow-type movements.

A higher frequency of movement also occurs where a geologic contact exists between quartz diorite and andesite as documented by P. Machibroda Engineering, Ltd.

(1998). Recent rockfall activity was seen on every aerial photograph year analyzed. The large, rotational rock slide movements on the north slopes are the least frequent events. These may be active; however, they are classified as inactive because movement is imperceptible over the aerial photograph period. Many of the events in the northwestern section of the study area are low frequency events also, having reached geomorphologic equilibrium with the surrounding environment.

Dendrogeomorphologic Frequency Analysis

The dendrogeomorphologic analysis for this project had the purpose of showcasing rockfall frequencies in areas which may be missed in normal aerial photograph analysis. Forty-six trees were cored in the dendrogeomorphology study area near Glen Neish Road (Figure 4) on Sumas Mountain. Corrected ages for the tree cores taken at 30 cm above ground level showed a clear sampling cohort age of about 90 years old, before which there may have been a stand replacing event where all trees were removed (see Figure 22).

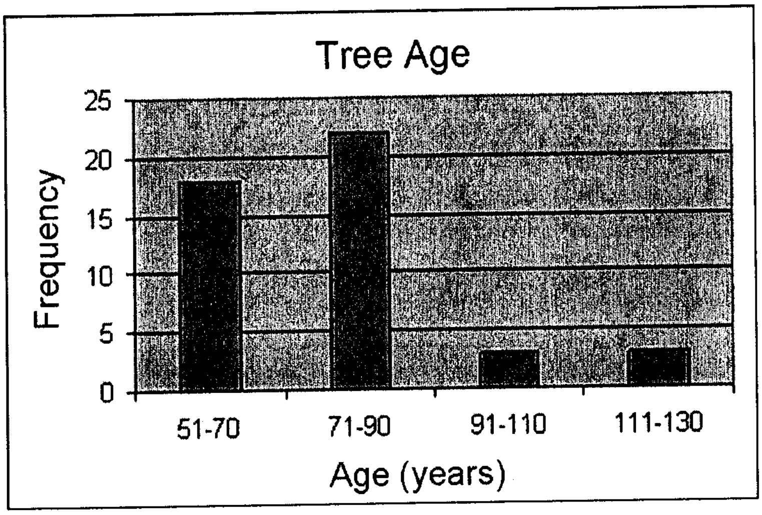

Figure 22. Frequency of age in trees sampled during dendrogeomorphologic analysis, Sumas Mountain, British Columbia.

The oldest trees were 120 years old and the youngest sampled were 59 years old, giving a continuous sample for 59 years. Mean tree diameter was 35.5 cm. The oldest trees in the dendrogeomorphology study area are located very near the north, east and west boundaries. The oldest trees in the northern section were probably above the source unit for the rockfall and the oldest trees in the southeast section are located outside the rockfall chute, the area of most frequent activity.

Nearest neighbor analysis of the rockfall rate resulted in a map showing rockfall rate density over the study area (see Figure 23). The map shows that rockfall rate is

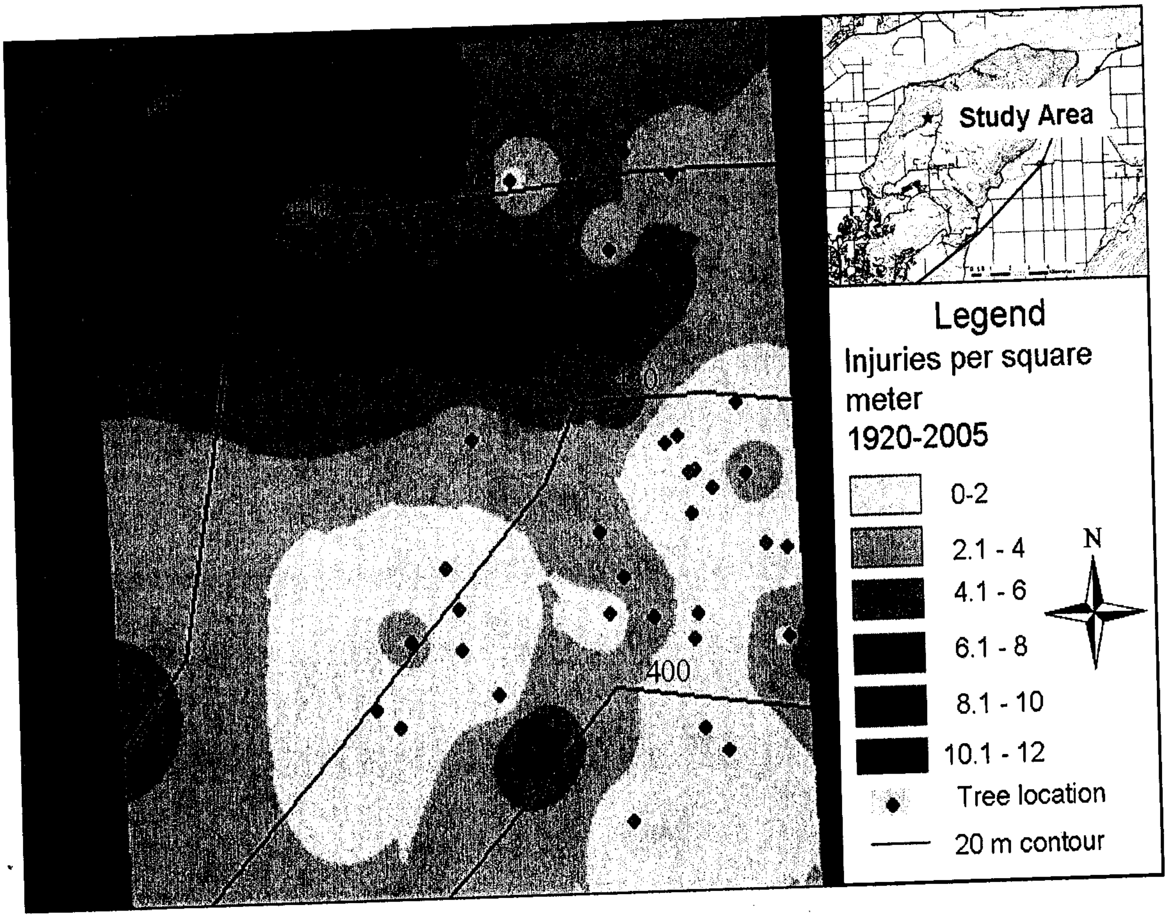

Figure 23. Map of nearest neighbor analysis and inverse distance weighting for rockfall rate density, dendrogeomorphology study area, Sumas Mountain, British Columbia.

significantly higher down the center of the study area, in what was identified in the field as a probable rockfall chute, and around the higher elevations of the study area, near the source unit. Rockfall is less common down the sides of the study area which were away from the chute. This gives some ideas as to how to mitigate for rockfall events. Most rockfall occurs very close to the source unit, and down well outlined chutes. If these are recognized, and development occurs away from these areas, mitigation can be efficient and successful.

Median rockfall frequency (0.27 injuries/m) was extrapolated across Sumas Mountain in locations equal to the dendrogeomorphology study area in bedrock geology, Quaternary geology, and slope. This resulted in a proxy rockfall frequency map for selected parts of the study area (see Figure 24) which may be used in conjunction with the mass wasting activity map to give a better estimation of actual rockfall rates in select locations.

Mass Wasting Controlling Variables

Overview

The distribution of mass wasting susceptibility is based on where events occurred in the past. The weighting categories discussed in chapter IV show which terrain units had a greater effect on past mass wasting events. Terrain units defined by sedimentary bedrock had a weight of zero on all occasions and were the lowest rated terrain units (see Table 12). Quartz diorite combined with glacial outwash and variable slope units were the terrain units with the highest mass wasting rating. Quartz diorite bedrock did not have less than a medium mass wasting rating.

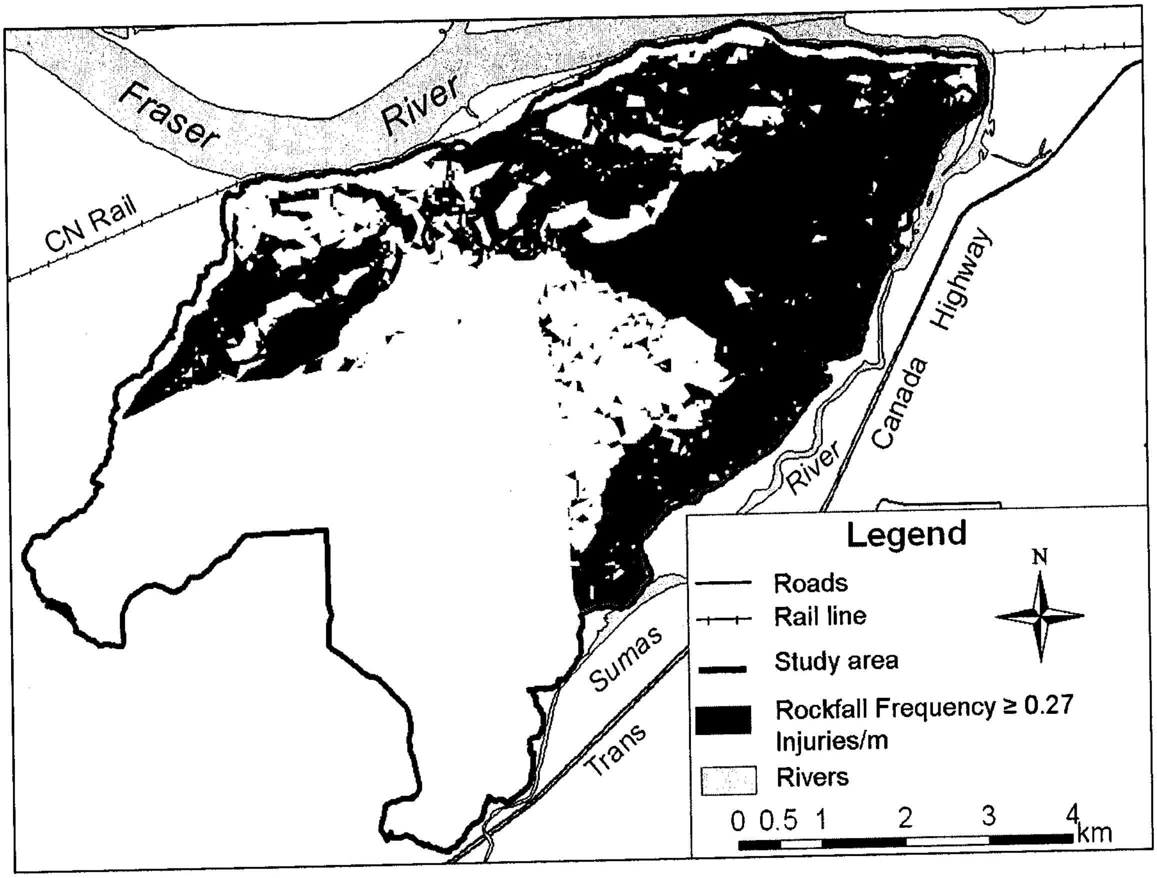

Figure 24. Proxy rockfall frequency map showing terrain units in the study area with an estimated rockfall rate of 0.27 injuries/m or greater.

Table 12

Terrain Units Used for This Study, in Order of Increasing Weight

Terrain unit identification	Bedrock geology	Quaternary geology	Slope (°)	Weight	Mass wasting susceptibility class
1	Sedimentary	Alluvium/floodplain	0-20	0	Low
2	Sedimentary	Eolian/glacial outwash	0-20	0	Low
3	Andesite	Eolian/glacial outwash	> 60	0	Low
4	Andesite	Alluvium/floodplain	41-60	0	Low
5	Andesite	Alluvium/floodplain	21-40	0	Low
6	Andesite	Alluvium/floodplain	0-20	1	Medium
7	Andesite	Eolian/glacial outwash	0-20	3	Medium
8	Andesite	Eolian/glacial outwash	21-40	5	Medium
9	Quartz diorite	Alluvium/floodplain	0-20	13	Medium
10	Andesite	Eolian/glacial outwash	41-60	16	Medium
11	Andesite	Glacial outwash	21-40	22	Medium
12	Quartz diorite	Alluvium/floodplain	21-40	29	High
13	Quartz diorite	Eolian/glacial outwash	0-20	33	High
14	Andesite	Glacial outwash	41-60	33	High
15	Quartz diorite	Glacial outwash	41-60	37	High
16	Andesite	Glacial outwash	0-20	37	High
17	Quartz diorite	Eolian/glacial outwash	41-60	50	Very high
18	Quartz diorite	Glacial outwash	21-40	50	Very high
19	Quartz diorite	Eolian/glacial outwash	> 60	54	Very high
20	Quartz diorite	Eolian/glacial outwash	21-40	57	Very high
21	Quartz diorite	Glacial outwash	0-20	62	Very high
22	Quartz diorite	Glacial outwash	> 60	72	Very high
23	Quartz diorite	Alluvium/floodplain	41-60	88	Very high

The slope variable, expected to have the largest effect on mass wasting, actually had the most variable affect, according to the weighting scheme. Generally, however, terrain units with glacial outwash needed the smallest slope angle to be susceptible to mass wasting.

Bedrock Geology

The weighting for bedrock geology is as expected. The quartz diorite bedrock which covers the majority of the study area is a somewhat stable, massive structure (Terzaghi, 1962). Instances of rockfall, flow, and rotational movements are common; however, especially where bedrock is at the surface, easily weathered through freeze-thaw and root pry, or close to the surface, creating an impervious surface beneath surficial materials (O'Loughlin, 1972). Andesite generally had a lower weight than quartz diorite bedrock. Fewer mass wasting features were mapped in the andesite bedrock even though it is an extrusive rock, present in both massive and columnar form in the study area (P. Machibroda Engineering, Ltd., 1998). This is probably because slope angles were generally less in areas of andesite bedrock and higher in areas of quartz diorite bedrock. However, the jointed andesite bedrock is easily weathered and can be especially susceptible to mass wasting depending on the direction of jointing (Walkinshaw & Smith, 1996).

The sedimentary rock in the study area is spatially limited and had no documented mass wasting events. Sedimentary rocks should be considered within the larger picture, however, as mass wasting has been documented to the west of the study area in this geology type (Septer & Schwab, 1997; UMA Engineering, Ltd., 2005). The majority of the sedimentary rock on Sumas Mountain was left out of this study because of a hazard study already completed for the area dominated by sedimentary rock, at Mckee Peak (Figure 4). This study is quite comprehensive and similar in methodology to this study.

It should be consulted if more detail is required about possible mass wasting in the sedimentary rock of the study area (UMA Engineering, Ltd.).

Quaternary Geology

Quaternary geology was the second variable considered in mass wasting susceptibility. Glacial outwash materials had a large weight because they drain quickly and are generally shallow depth to impervious bedrock. This, combined with the fact that they are generally not well consolidated, leads to conditions where moisture builds up between the bedrock and the sediment and a failure plane is created (O'Loughlin, 1972). Alluvium/floodplain Quaternary geology was found in some of the highest weighted terrain units. This was unexpected but could be related to the presence of depressions and wetlands created by mass wasting and contributing to further mass wasting through increased pore-water pressure (Wieczorek, 1996). This type of relationship was documented by O'Loughlin in the Coast Mountains, where mass wasting was found to be much more common in areas of drainage depressions underlain by impermeable surfaces.

Eolian sediments over glacial outwash sediments were found in some of the lowest weighted terrain units. This could be a result of the lower permeability of these sediments. Lower permeability could result in a greater number of shallow movements, with water collecting nearer the surficial layers. The features of these movements were less visible in the heavy forest cover and therefore underreported through aerial photograph analysis, leading to a lower weight for the terrain unit.

Slopes

Slopes from 20° to 40° had the greatest weight when combined with glacial outwash, as expected based on the literature, which documents this zone as highly susceptible to debris flows, especially in the Coast Mountains (VanDine, 1983); however, this slope estimate is for initiation of the debris flow only and sliding may still occur on slopes less than or exceeding this angle as is shown by terrain unit 21. Hungr, McDougall, and Bovis (2005) document erosion from debris flows on slopes as low as 10° when the movement activity is fully initiated.

Mass Wasting Susceptibility

The terrain units were combined into a map showing mass wasting susceptibility (see Figure 25). This map shows areas of low, medium, high, and very high mass wasting susceptibility and, when inverted, is used to show areas where residential development is most suited in the study area, given mass wasting hazards.

Dendrogeomorphologic Analysis of Mass Wasting Variables

Results testing the change of rockfall rate over time showed that at $\alpha = 0.05$, a significant negative correlation (−0.42) exists between increasing year and rockfall rate (see Figure 26). This is interpreted to mean that rockfall rate has been significantly decreasing over time. A confirmation test was done by splitting the dataset into two cohorts and using a Mann-Whitney *U* test for significant difference. The datasets were found to be significantly different ($p = 0.007$), the early cohort having a significantly higher rockfall rate than the late (see Table 13).

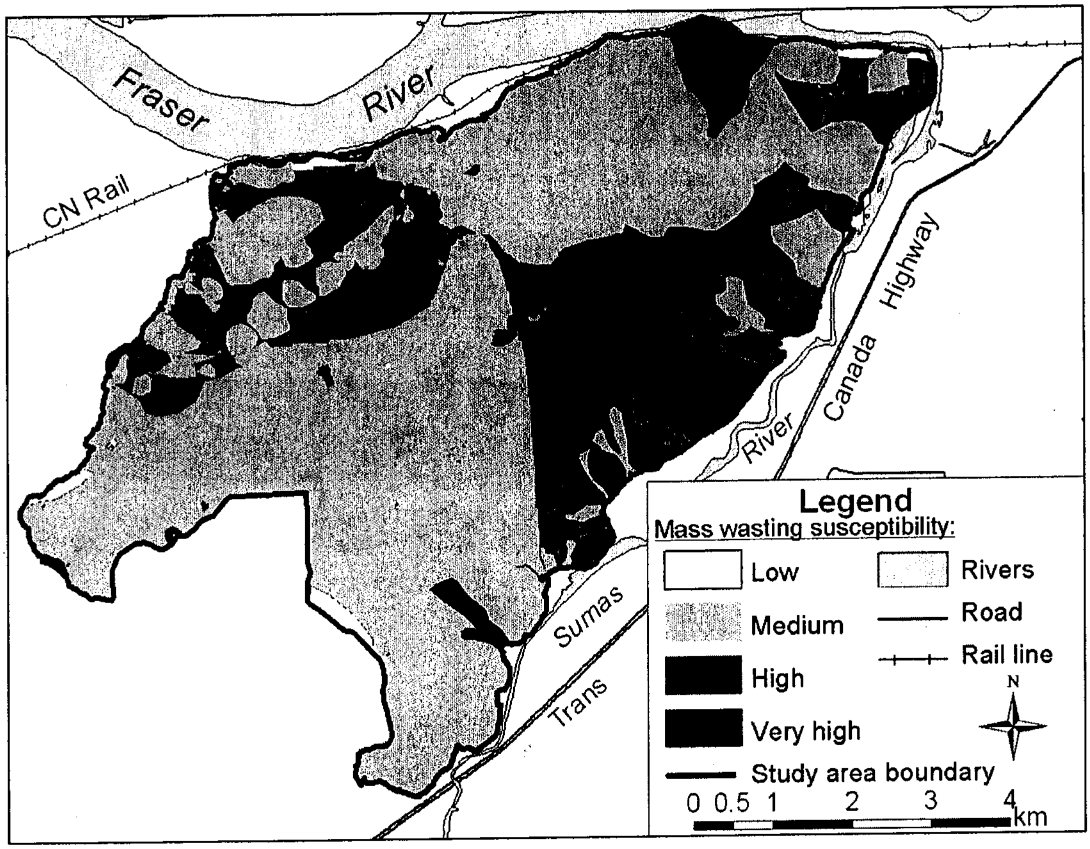

Figure 25. Mass wasting susceptibility map, Sumas Mountain, British Columbia.

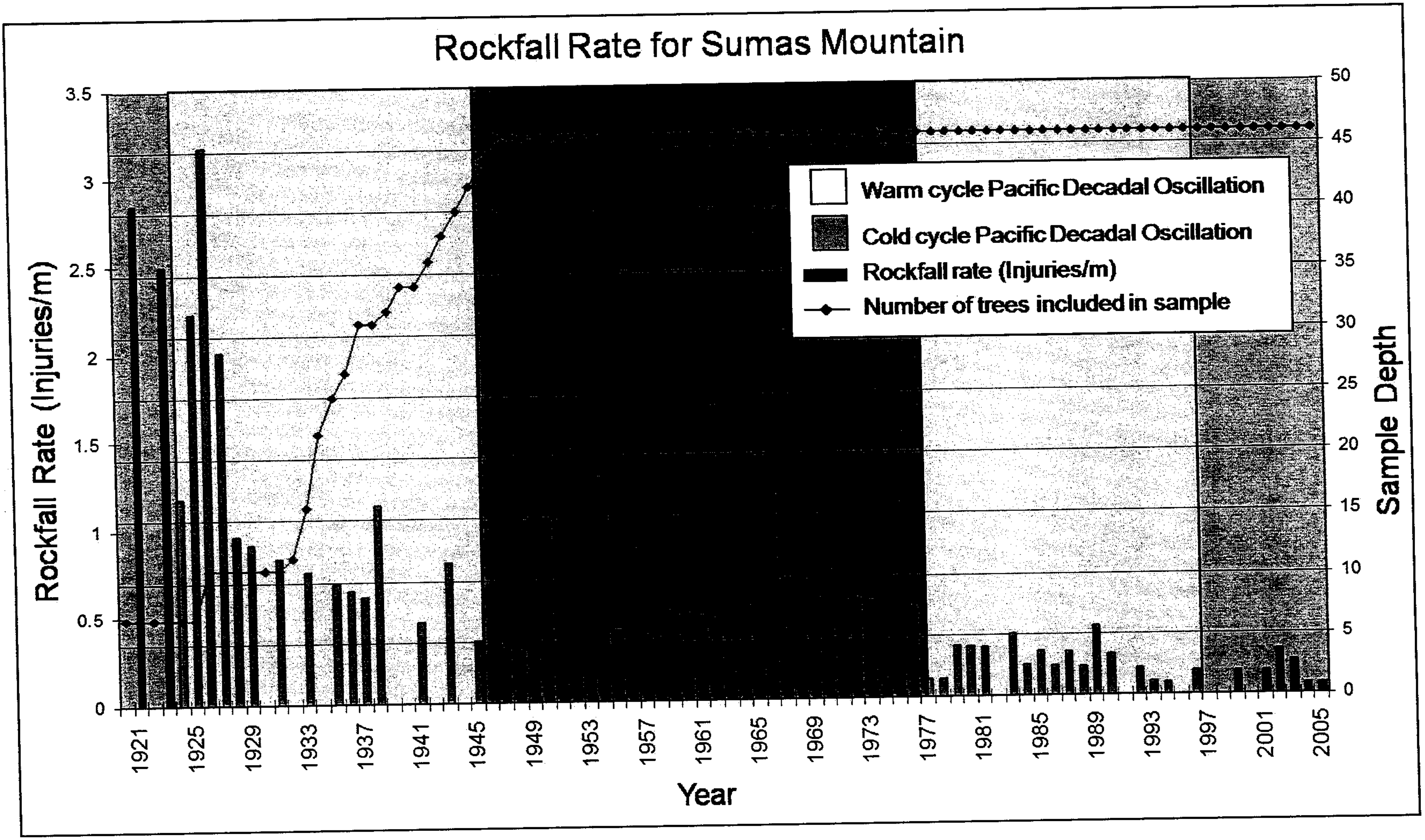

Figure 26. Rockfall rate associated with PDO climate cycle, Sumas Mountain, British Columbia (median = 0.27 injuries/m). Data from field work and Mantua and Hare (2002).

Table 13

Descriptive Statistics for Mann-Whitney U Test on Difference in Rockfall Rate

Cohort	*U*	*n*	Minimum	Maximum	Median	Interquartile range
Early	1,236	43	0	3.17	0.46	0.72
Late	613	43	0	1.22	0.19	0.30

Normally, a decreasing rockfall rate over time could be the result of several factors such as anthropogenic changes in vegetation, insect or fire disturbance; however, the careful site selection process eliminates these possibilities. Therefore, this result is probably not because of a change in vegetation (other than successional). A better explanation might be changing weather and climatic conditions (M. Miles and Associates Ltd., 2001). If freeze-thaw is the dominant force determining rockfall rate in humid, late Holocene environments (Luckman, 2007; Whalley, 1984), then it may be that a warmer climate is preventing temperatures from completing this cycle. A Spearman's rank correlation test measured the change in temperature and precipitation patterns over the time period from 1920 to 2005. Results showed that, over time, a significant positive correlation (0.28) existed between increasing year and mean, cold month temperature (between December and February). Therefore, average cold month temperature has increased over time. Furthermore, a significant negative correlation (−0.35) existed between increasing year and precipitation patterns, showing that average cold month precipitation is decreasing over time. These correlations show a winter climate which is warming and exhibiting less precipitation over time.

These findings agree with literature on climate change in western Canada, which documents warming trends of as much as 1.5 °C between 1946 and 1995 (Vincent & Gullet, 1999). It is also congruent with research on the influence of climate warming on mass wasting frequency in northern British Columbia (Egginton, 2005). Warmer temperatures and less precipitation should result in lower rockfall, as driving forces are eased (i.e., freeze-thaw and hydrostatic forcing; Whalley, 1984).

To determine if there is any correlation between large, overarching climate patterns and rockfall, the rockfall rate was also correlated with the PDO climate pattern. Investigations into the effects of temperature and precipitation on rockfall rate revealed mixed results. With a p value of 0.0944 ($\alpha = 0.05$), the rockfall rate was found to be not significantly correlated with cold month precipitation. This is surprising, given the relationships thought to be significant in rockfall forcing, including hydrostatic pressure in rock joints (Terzaghi, 1962). Temperature was also measured against rockfall rate and with a p value of 0.0238 and a Spearman's rank correlation of −0.24, a moderate correlation with temperature was shown. This means that the rockfall rate increases with decreasing temperature, which is what one would expect in this marine climate, given the weathering process of freeze-thaw, and rock-crack weathering (Whalley, 1984).

Significant relationships were drawn between the climate pattern PDO and rockfall rate. With a p value of 0.0113, the results of a Mann-Whitney U test show a significant difference between cold (1947-1976) and warm (1925-1946 and 1977-1995)

PDO climate periods (see Table 14), with the cold periods seeing a significantly higher median value of 0.49 injuries/m than the warm periods with a median value of 0.25 injuries/m (Figure 26). This was confirmed by retesting with only the most recent warm and cold periods, where rockfall rate sample size was steady at 47 (Figure 26). At a *p* value of < 0.01, the cold period had a significantly higher rockfall rate (Table 14). These results are helpful for predicting future trends in rockfall rate. The rockfall rate can be extrapolated to areas of similar slope, geology and aspect in the study area and could be used in future studies determining what types of mitigation might be successful for rockfall protection.

Table 14

Descriptive Statistics for Mann Whitney U Test on Rockfall Rate and PDO

Cohort	*U*	*n*	Minimum	Maximum	Median	Interquartile range
First test						
Cold PDO	871	30	0	3.17	0.49	0.51
Warm PDO	419	43	0	1.22	0.25	0.69
Retest						
Cold PDO	513	30	0.11	1.28	0.49	0.31
Warm PDO	57	19	0	0.40	0.17	0.20

Note. PDO = Pacific Decadal Oscillation.

Land Management Recommendations

The final stage of this investigation was to invert the mass wasting susceptibility map to show areas suitable for future development. Three maps were produced from this process: (a) areas suitable for future residential development with minimal mitigation, (b) areas suitable for future residential development with moderate to major mitigation, and (c) areas unsuitable for future residential development because of mass wasting.

Two basic approaches exist for land management in mass wasting prone areas: avoidance and mitigation. Although it is advisable that an independent, onsite, geotechnical review be done before any development process in the study area, as per local planning guidelines (FVRD, 2003), the safest areas for development are those with a low classification for mass wasting susceptibility (see Figure 27). These areas will require

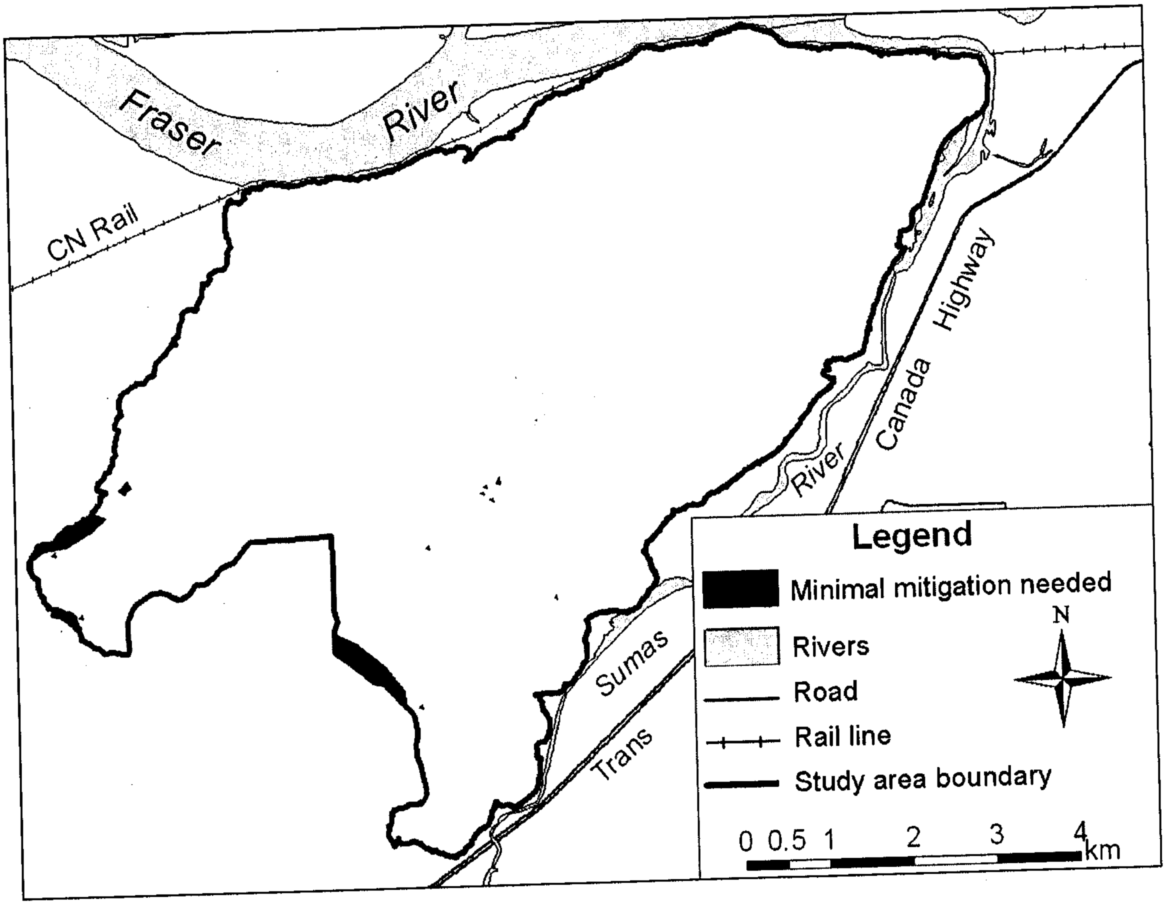

Figure 27. Areas of Sumas Mountain suitable for residential development with minimal mitigation of mass wasting processes.

the least amount of upgrading or mitigation against possible mass wasting events. Minimal mitigation areas cover 0.3 km^2 or 0.6% of the total study area. Normally found on slopes between 0° and 20°, in andesite or sedimentary bedrock, or in correlation with deeper, slower draining soils and where mass wasting events have not been mapped, these locations will be best for future residential development. The majority of this type of terrain is found in the southwestern part of the study area (Figure 27). The medium- to high-susceptibility areas will require some mode of mitigation, depending on the type of mass wasting to which they are most susceptible. These areas are located in the southwestern and northeastern parts of the study area and cover 36.0 km^2 (69.3%) and 7.7 km^2 (14.8%) of the study area respectively (see Figure 28).

High slope areas in both quartz diorite and andesite with bedrock at or close to the surface will be susceptible to rockfall. Rockfall is basically a problem solved through increased distance and a decrease in slope angle (Price, 2005). Unfortunately, in the areas available for development on Sumas Mountain, space is at a premium and increased distance from the base of slopes is not always an option. Therefore, mitigation measures, such as leaving a natural protection forest on the slope to absorb rockfall, can partially mitigate the hazard (Dorren, Berger, le Hir, Mermin, & Tardif, 2005). Other possibilities for mitigating rockfall in these areas include strengthening rock through bolts, netting or shotcrete, reducing the slope angle, or removal of unstable rock (Wyllie & Norrish, 1996).

The medium-rated areas also include mass wasting events mapped as inactive old (Figure 28). These have been stable for a long period of time; however, they may be

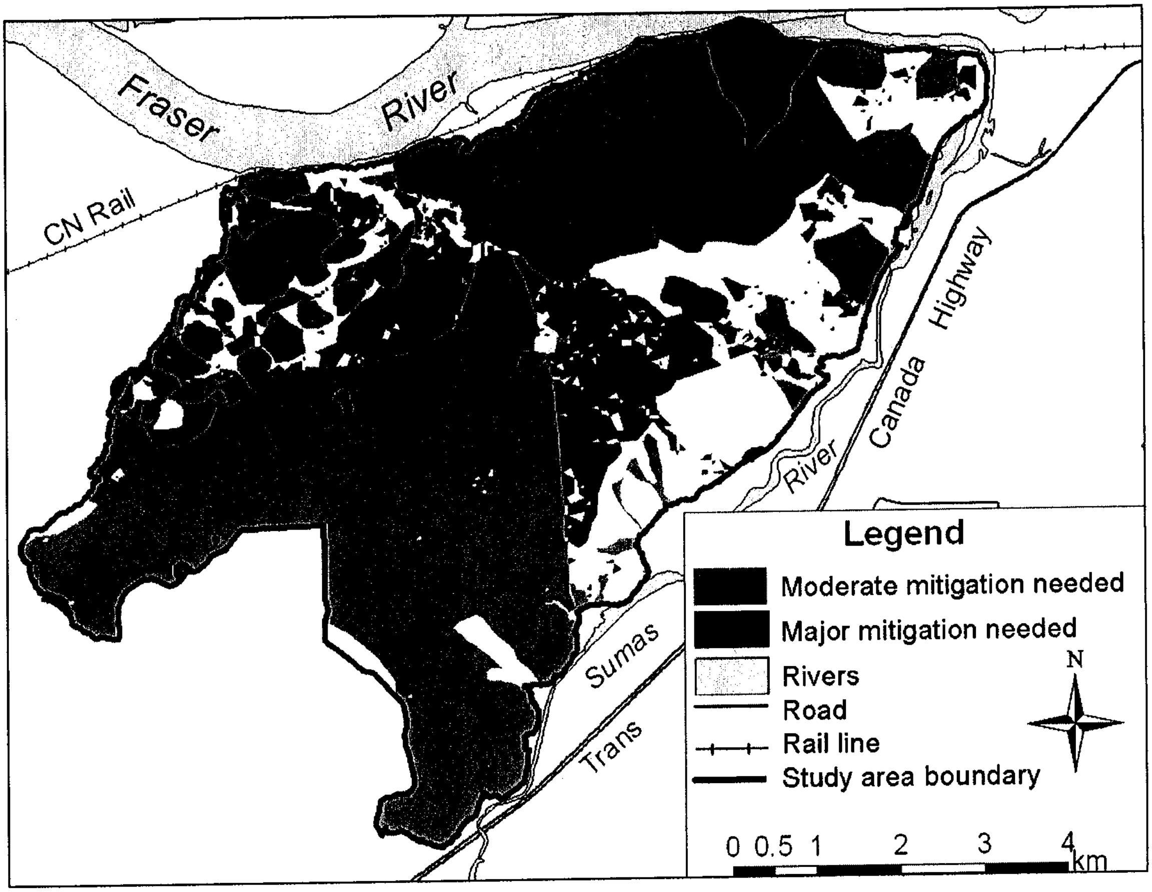

Figure 28. Areas of Sumas Mountain suitable for residential development with moderate to major mitigation of mass wasting processes.

reactivated at any time and if development should occur in these areas development practice should consider the possibility of reactivation.

Areas deemed unsuitable for residential development were located on the southeastern slopes of the study area and in the northwest of the study area (see Figure 29). These areas were classified as unsuitable on the basis that it would most likely be uneconomical to mitigate to such a degree and there would be a heavy impact on the natural environment associated with mitigation. They occupy 8.0 km^2 (15.3%) of the study area. Therefore other uses, including recreation, industry, and preservation or a

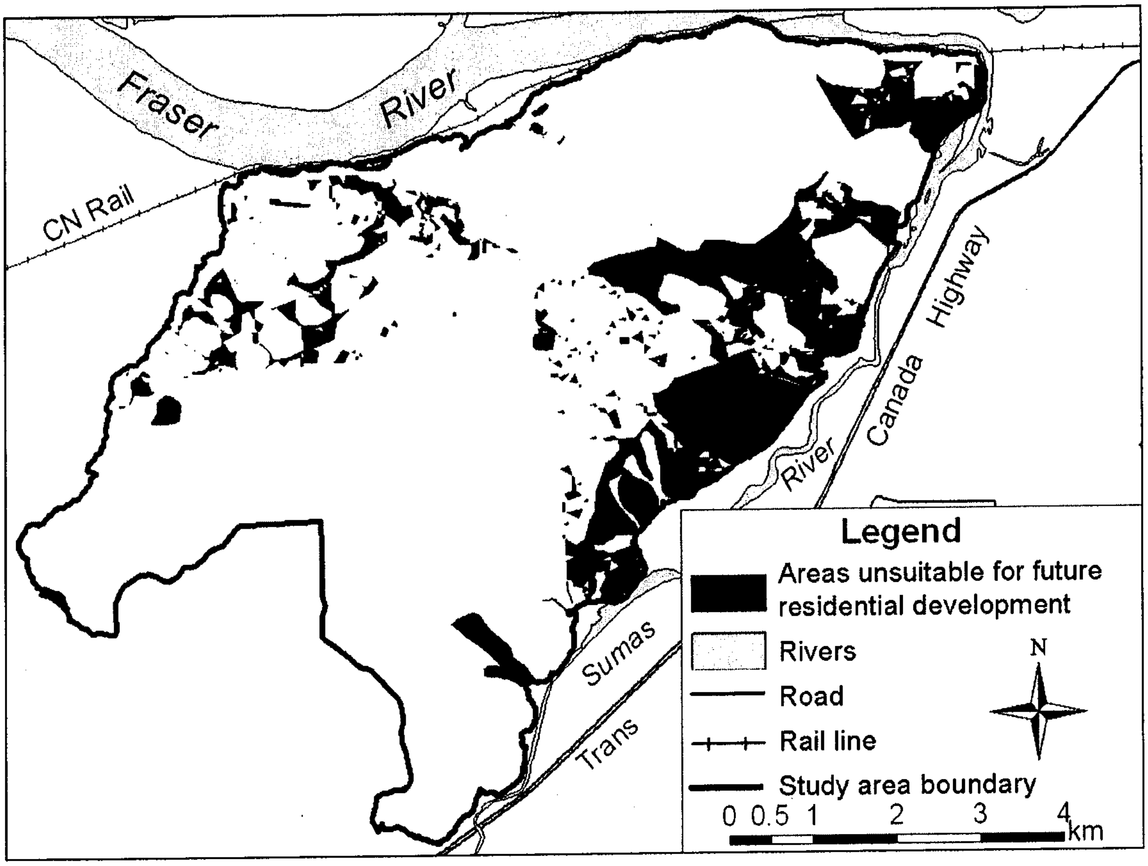

Figure 29. Areas of Sumas Mountain unsuitable for future residential development because of mass wasting hazard.

combination of these, is suggested for this area. Recreational uses such as mountain biking, hiking, or hang-gliding are much less intensive use of the land temporally, providing less of a chance for conflict between humans and mass wasting processes. Industry such as forestry, or mining operations would be more suitable for these areas than residential development. However, these activities can also be affected by mass wasting processes and have their own effect on activating mass wasting processes. As a result, care should be taken to account for that in planning. Preservation for multiple use might be the best possible use for this land. The large population growth in the lower

Fraser Valley brings with it a need for the preservation of natural areas where the population can feel removed from the city environment and recreate.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

Objectives

The high annual damages resulting from mass wasting processes in Canada, estimated at $50 million per year, are cause for serious consideration of mass wasting conflict with development. This study looked at the mass wasting processes that have shaped Sumas Mountain, a large tract of land near Abbotsford in southwestern British Columbia. Specifically, I (a) identified, mapped, and classified mass wasting features on Sumas Mountain; (b) dated mass wasting features; (c) created mass wasting activity maps; (d) analyzed mass wasting variables controlling frequency to predict areas of future activity; and (e) made land management recommendations based on frequency and location. The analysis resulted in the production of a mass wasting inventory for Sumas Mountain, maps showing areas of relative susceptibility to mass wasting, and recommendations for land management.

Mass Wasting Identification, Mapping, and Classification

A total of 129 individual mass wasting features were mapped in the 52-km^2 study area. These ranged between avalanche, flow, fall, rotational slide, and translational slide, covering a total area of 28 km^2 within the study area. This large number is deceiving as 68% (19.2 km^2) of this area was mapped as bedrock rotational slides, which are slow moving, may be currently inactive, and should be verified through further analysis. Flows and rotational slides were the most common types, each with 35 discrete features mapped, while avalanche was the least common with only eight total features mapped.

Dating Mass Wasting Features

Fifty-two of the 129 features mapped recurred at least once, and up to four times over the 39-year aerial photograph period, leading to a total of 234 actual mass wasting events. Nineteen of these features had a very high return frequency (four events recorded over 39 years). Morphologic dating revealed that 84 features (65%) were active or inactive-young (occurring within the last 50 years), whereas 45 features (35%) were greater than 50 years old (inactive-mature to inactive-old).

Between 1920 and 2005, dendrogeomorphologic dating of rockfall frequency recorded a median annual rockfall rate of 0.27 injuries/m. This is a proxy for the actual rockfall rate, and was extrapolated over the rest of the study area in locations of similar bedrock and Quaternary geology and slope. The rate confirms active rockfall is occurring on the slopes of Sumas Mountain and should be considered in land management.

Mass Wasting Controlling Variables

The variables seen to have the most influence on mass wasting in the study area were slope angle and Quaternary geology. Slope angles greater than 60° were generally much more susceptible to mass wasting, as would be expected. Similarly, Quaternary geology exemplified by shallow, glacial outwash also contributed greatly to mass wasting susceptibility, probably because of the shallow depth to less permeable bedrock and the possible creation of a failure plane at this discontinuity. Other variables, such as aspect and bedrock geology were less important when considering future mass wasting susceptibility, based on where mass wasting had occurred in the past.

Statistical analysis of rockfall proxy data also showed that rockfall rate has been decreasing since 1920 and is positively correlated with decreasing overall precipitation, increasing temperatures, and fluctuation between cold and warm PDO periods (rockfall is higher during cold PDO periods). Dendrogeomorphologic analysis showed that rockfall frequency has been significantly decreasing over time as climate has been warming. The rockfall rate was also related to the climate cycle PDO, increasing in cold periods and decreasing in warm periods; however, further research should be done before this link can be confirmed.

Land Management Recommendations

Frequency analysis and the analysis of mass wasting controlling variables resulted in the production of a mass wasting activity and mass wasting susceptibility map. The mass wasting activity map showed the relative frequencies of mass wasting events over the study area with the majority of high-frequency events occurring on the southern slopes, and less-frequent events occurring along the northern and western slopes. The mass wasting susceptibility map showed areas of different, relative mass wasting susceptibility, based on the weighting and distribution of mass wasting controlling variables. This map was inverted to show areas that may be developed with varying degrees of mass wasting mitigation. In the northwest and midsoutheast sections, covering 0.6% of the study area, were the most readily developable lands with minimal mitigation measures needed for residential development. Areas along the steeper southern slopes and in the southwestern portion of the study area, where the less stable andesite bedrock exists, are developable with moderate mitigation efforts. These areas cover 69.3% of the study area, the largest proportion any category. Areas where major mitigation would be required covered 14.8% of the study area. Other areas on Sumas Mountain, including locations where frequent mass wasting events have been mapped, are deemed unsuitable for residential development given mass wasting susceptibility and cover a total of 15.3% of the study area. This includes much of the southern slopes and parts of the western slopes. These areas would be better suited to temporally limited uses such as recreation or preservation. Other suggestions for future mitigation include the use of protection forests to absorb rockfall and planning to develop areas safer for residential use, and leave areas that are unsafe.

Future Research

Identifying, Mapping, and Classifying Mass Wasting Features

Many future research opportunities have resulted from this study and will be significant to future development of the Sumas Mountain area. One significant area of investigation is further field investigation of identified mass wasting processes to determine their extent in order to obtain a greater understanding of the mechanisms controlling movement. This would aid in the prediction of future movements and the engineering of mitigation measures. Future research efforts could also focus on different means of interpreting mass wasting features on the landscape, in order to check the quality of the inventory. For example, the use of LIDAR or further aerial photograph coverage might further corroborate the findings of the mass wasting inventory. A comparison of the mass wasting investigation done for the Mckee Peak area of sedimentary rock next to the study area could compare results with this study, allowing for further interpretation of mass wasting patterns.

Dating Past Features

Future dendrogeomorphologic work could include investigation of a site near the center of the study area where a stand of red alder and Douglas fir appear to have been part of a translational mass wasting process. Future dendrogeomorphologic analysis on this slope could determine whether the Douglas fir cohort was truly established after the red alder and if significant annual ring width suppression exists in the red alder population. Analysis of reaction wood could yield a date for movement and determine whether the slope is still active. Further studies similar to the dendrogeomorphologic analysis done in this investigation could aid in the extension of data across the study area. It would also be interesting to complete a similar study in the andesite bedrock area to determine differences in rockfall pattern between the two bedrock types.

Further dating techniques, including radiocarbon and tephra dating, might be possible in some of the mass wasting created wetlands of the study area to determine minimum dates for movement and to verify the relative dating aspects of this study.

Mass Wasting Variables

Investigation and more detailed mapping of surficial geology, the composition of depositional fans from the steep drainages, as well as more accurate mapping of the bedrock geology would yield a more accurate susceptibility map and certainly would help with future development planning.

Areas exist on Sumas Mountain for safe residential expansion from Abbotsford. Through careful planning and the management of current and potential mass wasting hazards using mass wasting susceptibility maps these areas may be identified and utilized for the relief of population pressure on the city center. Further research will allow for the updating of mass wasting controlling variables and more accurate mapping of areas most readily developable with minimal mitigation techniques.

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