LAND MANAGEMENT HANDBOOK

56

Landslide Risk Case Studies in Forest Development Planning and Operations

2004

BRITISH COLUMBIA

Ministry of Forests Forest Science Program

Landslide Risk Case Studies in Forest Development Planning and Operations

Mike Wise, Glenn Moore, and Doug VanDine
Editors

British Columbia
Ministry of Forests Forest Science Program

National Library of Canada Cataloguing in Publication Data

Main entry under title.

Landslide risk case studies in forest development planning and operations

(Land management handbook, ISSN 0229-1622 ; 56)

Includes bibliographical references: p.

ISBN 0-7726-5175-2

1. Landslide hazard analysis - British Columbia. 2. Landslide hazard analysis - British Columbia - Case studies. 3. Mass-wasting - British Columbia. 4. Landslides - British Columbia. 5. Logging - Environmental aspects - British Columbia. 6. Forest management - British Columbia - Planning. I. Wise, Mike. II. Moore, G. D. (Glenn Douglas). III. VanDine, D. F. (Douglas Finlay), 1949- . IV. British Columbia. Forest Science Program. V. Series.

QE599.C3L36 2004 551.3'07'09711 C2004-960065-6

Citation:
Wise, M.P., G.D. Moore, and D.F. VanDine (editors). 2004. Landslide risk case studies in forest development planning and operations. B.C. Min. For., Res. Br., Victoria, B.C. Land Manage. Handb. No. 56.
<http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh56.htm>

Editors:

Mike Wise
GeoWise Engineering Ltd.
523-1641 Lonsdale Avenue
North Vancouver, BC, Canada V7M 2J5

Glenn Moore
B.C. Ministry of Forests
Resource Tenures and Engineering Branch
PO Box 9510 Stn Prov Govt
Victoria, BC, Canada V8W 9C2

Doug VanDine
VanDine Geological Engineering Limited
267 Wildwood Avenue
Victoria, BC, Canada V8S 3W2

Prepared for
B.C. Ministry of Forests
Research Branch
PO Box 9519 Stn Prov Govt
Victoria, BC, Canada V8W 9C2

Copies of this report may be obtained, depending upon supply, from:
Crown Publications
521 Fort Street
Victoria, BC V8W 1E7
(250) 386-4636
http://www.crownpub.bc.ca

For more information on Forest Stewardship Division publications, visit our website at: http://www.for.gov.bc.ca/scripts/hfd/pubs/hfdcatalog/index.asp

Cover Photograph: Stephen Ngo; Landslide, Vancouver Island, British Columbia.

PREFACE

Landslide risk management associated with forest practices in the Province of British Columbia has progressed though a series of stages over the past 30 years. In the early 1970s, there was little understanding of landslide risks—a period of few regulatory requirements and a time of ongoing confrontation between resource agencies and forest licensees. In the mid-1970s, the first pilot terrain stability maps were introduced on the Queen Charlotte Islands. In the mid-1980s, the *British Columbia Coastal Fisheries/Forestry Guidelines* were introduced to provide a basis for landslide risk management in environmentally sensitive areas. Then, in 1995, forest practices regulations were brought into force under the *Forest Practices Code of British Columbia Act*, with protection of the environment as one of the primary objectives.

Since the inception of the Forest Practices Code, landslide risk management in landslide-prone terrain involved legislated processes, including landslide hazard identification, terrain stability hazard mapping, and terrain stability field assessments to evaluate potential or existing effects of forest development on terrain stability. Often, the avoidance of all landslide risk was considered the best option within the realm of the Forest Practices Code requirement to conserve and protect forest resources.

In February 2004, forest management in British Columbia began a transition to results-based management under the *Forest and Range Practices Act*. Under this Act, "…a person who carries out a primary forest activity must ensure that the primary forest activity does not cause a landslide that has a material adverse effect on forest resource values." In addition, persons responsible for forest development will need to apply landslide risk management within a decision-making framework to adequately balance environmental and timber supply objectives associated with the planning and operations for forest roads and trails, and timber harvesting. Therefore, effective communication of landslide risk by terrain stability professionals becomes paramount so that forest resource managers can make sound decisions.

Land Management Handbook 18, *A Guide for the Management of Landslide-Prone Terrain in the Pacific Northwest*, published in 1991 (with a second printing in 1994), arose out of the Fish-Forestry Interaction Research Program of the 1980s. This handbook provided needed information on landslide processes, techniques for recognition of landslide-prone terrain, and measures to manage unstable terrain. More recently, workshops, discussions, and expert input on snow avalanches culminated in 2002 with the publication of Land Management Handbook 55, *Snow Avalanche Management in Forested Terrain*. Acceptable practices are identified in that handbook for proactive forest management of snow avalanche risk in avalanche-prone terrain.

In 2003/2004, the desire for better landslide management practices brought together terrain stability professionals working in the British Columbia forest sector with an objective to provide a common framework for landslide risk management. This handbook (Land Management Handbook 56, *Landslide Risk Case Studies in Forest Development Planning and Operations*) is the result. It is based on the general framework for risk management described in the 1997 Canadian Standards Association document, *Risk Management: Guideline for Decision-Makers* and in the 2000 Australian Geomechanics Society document, *Landslide Risk Management Concepts and Guidelines*. This handbook also provides a basis for a common understanding of terms and concepts for effective communication among forest resource managers, terrain stability professionals, and stakeholders. Case study examples are provided to demonstrate risk analysis for cutblocks, roads, gullies, and fans in coastal and interior settings. The case studies demonstrate qualitative and quantitative methods of risk analysis, and various types of risk management.

We believe that this handbook will help provide a rational basis for informed and defensible decisions pertaining to landslide risk management associated with forest practices in British Columbia.

James W. Schwab, RPF, PGeo
Research Geomorphologist
B.C. Ministry of Forests
Northern Interior Forest Region
Smithers, BC, Canada

Steve Chatwin, PGeo
Special Projects Manager
Forest Practices Board
Victoria, BC, Canada

ACKNOWLEDGEMENTS

This Land Management Handbook would not have been possible without the contributions, support, and collaborative efforts of many dedicated individuals in the British Columbia Ministry of Forests, private forest industry, and consultants working in the forest sector. We gratefully acknowledge those individuals who contributed to the preparation and development of this handbook.

The idea for development of this handbook is credited to Mike Wise, who, among other terrain stability professionals working in the forest sector of British Columbia, recognized the growing need in professional practice to have a consistent means of analyzing landslide risks and of communicating the results of the analyses to decision makers. In February 2003, the outline of the handbook was established in a meeting of the Risk Task Group of the Division of Engineers and Geoscientists in the Forest Sector (DEGIFS)—a division of the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC)—consisting of the following terrain stability professionals: Timothy Smith (chair), Doug VanDine, Robert Gerath, Al Chatterton, Mike Wise, Calvin VanBuskirk, Kevin Turner, and Doug Nicol. The meeting was facilitated by Rick Ellis and coordinated by the B.C. Ministry of Forests.

In October 2003, DEGIFS sponsored a one-day session on *Landslide Risk Case Studies in Forest Development Planning and Operations* as part of APEGBC's Annual Conference in Penticton, British Columbia. Many of the contributors of the handbook presented portions of the handbook, under development at that time. We appreciate the efforts of the presenters, and also acknowledge the coordination efforts of Janet Guscott of APEGBC and Doug Dewar of DEGIFS. We would also like to thank the many geoscientists, engineers, foresters, and other interested individuals who attended the session. Their encouraging feedback and participation validated the need and content of the handbook, and made the session a success.

This handbook is the cooperative work of three senior editors and 17 authors. The senior editors, Mike Wise, Glenn Moore, and Doug VanDine, critically reviewed the drafts of the case studies, and verified that the terminology was consistent throughout the document. Mike Wise is the primary author of Chapters 1, 2, and 5, with contributions by Glenn Moore and Doug VanDine. Doug VanDine is the primary author of Chapter 3, with contributions by Glenn Moore, Mike Wise, Calvin VanBuskirk, and Robert Gerath. The authors of the eight case studies are: Alan Chatterton (Case Study 4.1); Timothy Smith (Case Study 4.2); Neil Singh (Case Study 4.3); Jonathan Fannin, Derek Bonin, and David Dunkley (Case Study 4.4); Tom Millard (Case Study 4.5); Calvin VanBuskirk (Case Study 4.6); David Wilford, Matt Sakals, John Innes, and Dave Ripmeester (Case Study 4.7); and Doug Nicol (Case Study 4.8).

We would also like to thank the following terrain stability professionals who reviewed and provided valuable comments and useful criticisms on drafts of Chapters 1–3, case studies in Chapter 4, and Appendices: Tim Giles, Jim Schwab, and Kevin Turner (B.C. Ministry of Forests); Steve Chatwin (Forest Practices Board); Tim Stokes (Terra Firma Geoscience Services); and Bruce Thomson (B.C. Ministry of Water, Land and Air Protection). Other individuals provided significant contributions and helpful comments to the case study authors, and the case study authors acknowledge them within each case study. Additionally, we also thank Wendy Bergerud (B.C. Ministry of Forests) for providing review comments on the statistical aspects of Chapter 3 and selected case studies, and Terje Vold (B.C. Ministry of Forests) for providing a policy review of the document.

Linda Turnbull of the B.C. Ministry of Forests assisted with word processing of the manuscript. Steve Milroy of Wonderworks Mural and Sculpture assisted with production of the technical illustrations in Chapter 3; Steven Justin Smith provided English services, and Donna Lindenberg of Newport Bay Publishing Limited prepared the document for printing. Thanks also to Paul Nystedt and Rick Scharf of Production Resources, B.C. Ministry of Forests for coordinating the production of the handbook.

Funding for the development and production of this handbook was provided by Resource Tenures and Engineering Branch, B.C. Ministry of Forests. Special thanks go to John Mallett, Engineering and Real Estate Operations Section, B.C. Ministry of Forests for his support of the preparation of this handbook.

CONTENTS

APPENDICES

TABLES

FIGURES

LIST OF CONTRIBUTORS

In alphabetical order:

Derek Bonin, RPF
Superintendent, Watershed Planning
Greater Vancouver Regional District
Policy and Planning Department
4330 Kingsway, Burnaby, BC, Canada V5H 4G8
email: derek.bonin@gvrd.bc.ca

Alan Chatterton, RPF, PGeo
TimberWest Forest Corporation
Box 130
Crofton, BC, Canada V0R 1R0
email: chattertona@timberwest.com

David Dunkley, PGeo
Geoscientist/Watershed Planner
Greater Vancouver Regional District
Policy and Planning Department
4330 Kingsway, Burnaby, BC, Canada V5H 4G8
email: ddunkley@gvrd.bc.ca

Jonathan Fannin, PhD, PEng
Professor, Department of Forest Resources
Management and Civil Engineering
FSC Building, University of British Columbia
Room 2211-2424 Main Mall
Vancouver, BC, Canada V6T 1Z4
email: jonathan.fannin@ubc.ca

Robert Gerath, PGeo
Thurber Engineering Ltd.
200-1445 West Georgia Street
Vancouver, BC, Canada V6G 2T3
email: rgerath@thurber.ca

John Innes, PhD
Professor, FRBC Chair of Forest Management
Department of Forest Resources Management
FSC Building, University of British Columbia
Room 2045-2424 Main Mall
Vancouver, BC, Canada V6T 1Z4
email: innes@interchange.ubc.ca

Tom Millard, PGeo
Research Geomorphologist
B.C. Ministry of Forests
Coast Forest Region
2100 Labieux Road
Nanaimo, BC, Canada V9T 6E9
email: tom.millard@gems8.gov.bc.ca

Glenn Moore, PEng, MBA
B.C. Ministry of Forests
Resource Tenures and Engineering Branch
PO Box 9510 Stn Prov Govt
Victoria, BC, Canada V8W 9C2
email: Glenn.Moore@gems2.gov.bc.ca

Doug Nicol, PEng
Geotechnical Engineer
B.C. Ministry of Forests
Southern Interior Region
1907 Ridgewood Road
Nelson, BC, Canada V1L 6K1
email: Doug.Nicol@gems3.gov.bc.ca

Dave Ripmeester, RPF
Forestry Supervisor
West Fraser Mills Ltd.
Pacific Inland Resources Division
Box 3130
Smithers, BC, Canada V0J 2N0
email: Dave.Ripmeester@westfraser.com

Matt Sakals, PAg, GIT
Research Hydrologist
Bulkley Valley Centre for Natural Resources
Research and Management
Box 4274
Smithers, BC, Canada V0J 2N0
email: msakals@interchange.ubc.ca

Neil Singh, PEng
Senior Geotechnical Engineer
Klohn Crippen Consultants Ltd.
500-2955 Virtual Way
Vancouver, BC, Canada V5M 4X6
email: nsingh@klohn.com

Timothy Smith, PGeo
Engineering Geologist
Westrek Geotechnical Services Ltd.
15839 Cliff Avenue
White Rock, BC, Canada V4B 1W7
email: tsmith.westrek@shaw.ca

Calvin VanBuskirk, PEng, PGeo
Terratech Consulting Ltd.
1181-6th Avenue NE
PO Box 201
Salmon Arm, BC, Canada V1E 4N3
email: calvinvb@sunwave.net

Doug VanDine, PEng, PGeo
VanDine Geological Engineering Limited
267 Wildwood Avenue
Victoria, BC, Canada V8S 3W2
email: vandine@islandnet.com

David Wilford, PhD, RPF, PGeo
Research Forest Hydrologist
B.C. Ministry of Forests
Northern Interior Forest Region
Regional Service Centre
Bag 6000
Smithers, BC, Canada V0J 2N0
email: dave.wilford@gems3.gov.bc.ca

Mike Wise, PEng
GeoWise Engineering Ltd.
523-1641 Lonsdale Avenue
North Vancouver, BC, Canada V7M 2J5
email: wise1@telus.net

CHAPTER 1 INTRODUCTION

MIKE WISE, GLENN MOORE, AND DOUG VANDINE

1.1 Background

A landslide is the "movement of a mass of rock, debris or earth down a slope" (Cruden 1991). Numerous types of landslides exist, generally classified on the material involved and the form of movement. Landslides can play an important role in natural stream systems. For example, some streams depend on landslides to supply gravel for spawning areas. Most of the time, however, landslides adversely affect (or have the potential to adversely affect) elements of social, environmental, and economic value, and therefore are considered hazards.

Landslides are a fundamental concern for forest development planning and operations (hereafter referred to as forest development) in mountainous terrain. This concern relates mainly to the potential effect of landslides on elements such as forest resources (e.g., water quality and fish habitat), infrastructure (e.g., buildings, and transportation and utility corridors), and people. Forest development for forest roads and trails, as well as for the harvesting of hillslope areas, can significantly contribute to the occurrence of landslides.

Landslide risk analysis involves estimating the *probability* of a landslide occurring and the *consequence* of such an occurrence. Probability of occurrence (qualitatively referred to as *likelihood*) is an estimate of the chance of a landslide occurring. Consequence is the effect, or expected effect, of the landslide on a specific element. Landslide risk evaluation compares the results of the risk analysis with acceptable or tolerable thresholds of risk. The terms probability and consequence have specific definitions associated with landslide risk, as discussed in Chapters 2 and 3.

Landslide risks associated with forest development can differ from those due to natural landslides or landslides associated with other types of development, such as large construction projects or residential development. These differences can include the often large geographic extent and various types of forest activities carried out on hillslopes, as well as the wide range of elements that can be at risk, including productive forest site fish habitat, and human life. In addition, the risks associated with abandoned forest roads often must be considered during the planning of forest development.

FIGURE 1 *Steep slopes with branch roads, cutblocks, and gully areas above mainline forest road and utility corridors, coastal British Columbia (M. Leslie photo).*

The 1997 Canadian Standards Association (CSA) document *Risk Management: Guidelines for Decision Makers* describes the risk management process. Forest resource managers make decisions with respect to forest development, and they can initiate the process of landslide risk management in a number of ways. For example, forest resource managers can:

- retain terrain stability professionals to map areas of potential landslides that would follow forest development (such as terrain stability mapping);
- based on local experience or terrain stability mapping, identify terrain types (such as gully areas) or proposed forest development activities (such as sidecast road construction on steep slopes) that are associated with landslides; and
- inspect or investigate recent events and maintain a landslide inventory.

Risk analysis and risk assessment are two key processes within the framework for managing landslide risk. For activities that may affect hillslope stability, landslide risk analyses are part of the terrain stability assessments (also called terrain stability field assessments) conducted by terrain stability professionals. Forest resource managers can then evaluate the results, make decisions to control risk if necessary, and monitor activities where appropriate.

Risk management can be simple or complex, depending on a given site. Simple risk management examples are the avoidance of all risk or the acceptance of all risk. Given the various legislative, public, and corporate thresholds for acceptable or tolerable risk, however, risk management can be a complex process. In addition to the complications arising from ambiguous thresholds, risk management can also be complicated by uncertainties in the results of the analysis, as well as by ineffective communication among forest resource managers, terrain stability professionals, and stakeholders.

A structured framework to landslide risk management offers several benefits:

- it allows for the consideration of the distinct aspects of probability of occurrence, consequence, and risk, rather than probability of occurrence alone;
- it provides a rational basis for informed, explicit, and defensible decisions during forest development; and
- it can form the basis of a due diligence defence in the event of litigation.

1.2 Purpose, Scope, and Structure of the Handbook

This handbook presents a framework for landslide risk management, describes technical terms and methods of landslide risk analysis, and provides a set of landslide risk case studies in forest development. It has been prepared for both forest resource managers and terrain stability professionals.

The objectives of the case studies are:

- to demonstrate approaches for the analysis of landslide risk in forest development, based on a common framework, terms, and concepts;
- to illustrate different types of analyses for estimating landslide probability and consequence for cases with differing site conditions and elements; and
- to highlight the application of current terrain stability research in professional practice in the British Columbia forest sector.

The case studies focus on landslide risks. Forest resource managers may be required to also evaluate other types of risks, such as financial risk, that are not within the scope of this handbook.

This document is divided into five chapters.

- Chapter 1 introduces landslide risks in forest development.
- Chapter 2 contains fundamental terms and a framework for landslide risk management.
- Chapter 3 builds on the information contained in Chapter 2, further develops the terms, and introduces methods of landslide risk analysis.
- Chapter 4 contains the case studies using the terms, framework, and methods presented in Chapters 2 and 3.
- Chapter 5 summarizes key aspects of landslide risk management.

The accompanying appendices present associated reference material.

Where practical, references and explanations are not repeated between chapters. Rather, where appropriate, readers are referred to specific sections of the handbook for more detailed explanations.

1.3 Disclaimer and Limitation of Liabilities

The information presented in this handbook represents the interpretations, conclusions, and recommendations of experienced and knowledgeable terrain stability professionals. However, this document does not constitute a standard of practice for landslide risk management in forest development. Rather, it illustrates various techniques that have been used to analyze, assess, and manage risks at specific sites in British Columbia. Professionals analyzing landslide hazard and risk are responsible for selecting approaches and techniques that are suitable to their specific sites and to the particular elements that may be at risk.

Acts governing registered professionals are designed, in part, to promote and maintain competent practice. Since a key aspect of competent practice is to use appropriate information, professionals specializing in landslide risk analyses should also review other relevant technical references and professional guidelines to complement the information contained in this handbook.

The case studies in Chapter 4 are not "case histories" since some material facts regarding the risk analysis, evaluation, mitigation, and control were deliberately changed to demonstrate the terms, framework, and methods presented in Chapters 2 and 3 of this handbook.

The authors, contributors, reviewers, and editors who prepared this handbook, including their affiliate organizations, are not liable for any misrepresentations, errors, or omissions. Under no circumstances will these parties be liable to any person or business entity for any direct, indirect, special, incidental, consequential, or other damages based on any use of the information in this handbook.

CHAPTER 2 DEFINITIONS OF TERMS AND FRAMEWORK FOR LANDSLIDE RISK MANAGEMENT

MIKE WISE, GLENN MOORE, AND DOUG VANDINE

2.1 General Definitions

Chapter 1 introduced aspects of landslide risk associated with forest development. This chapter defines the terms and describes a conceptual framework for the management of landslide risk. As such, it links the introduction in Chapter 1 with the more technical terms and methods for landslide risk analysis in Chapter 3 and the case studies in Chapter 4.

The definitions of terms and framework are adapted largely from three documents:

- *Risk Management: Guidelines for Decision Makers* developed by the Canadian Standards Association (CSA)(1997)
- *Quantitative Risk Assessment for Slopes and Landslides – The State of the Art* developed by the International Union of Geological Sciences' Working Group on Landslides, Committee on Risk Assessment (IUGS 1997), and the
- *Landslide Risk Management Concepts and Guidelines* developed by the Australian Geomechanics Society (AGS 2000).

The CSA document provides a generic framework for risk management, while the IUGS and AGS documents address risk management specifically for landslides. These publications do not directly address landslide risk management associated with forest development.

The following terms are basic to landslide risk management, and are discussed in more detail in Chapter 3.

Hazard is a source of potential harm, or a situation with a potential for causing harm, in terms of human injury; damage to property, the environment, and other things of value; or some combination of these (CSA 1997). With respect to landslide risk management, the landslide is the source of potential harm—it is the hazard. A future landslide that has no harmful potential is not a hazard, but is simply a natural geological or geomorphological process or feature.

Probability of landslide occurrence is an estimate of the chance for a landslide to occur. An estimate of probability is expressed quantitatively, using a number between 0 (a landslide will not occur) and 1 (a landslide will certainly occur). The term ***likelihood*** is used to provide a qualitative estimate of probability, referred to as a probability rating. Likelihood estimates are typically expressed using relative qualitative terms, such as *very low* to *very high* or *very unlikely* to *almost certain.* Qualitative terms must be defined to avoid ambiguity.

Elements of social, environmental, and economic value (or simply ***elements***) are humans, property, the environment, and other things of value, or some combination of these that are put at risk (adapted from CSA 1997). The B.C. Ministry of Forests (2002) lists potental elements as human life and bodily harm, public and private property (including building, structure, land, resources, recreational site, and cultural heritage feature), transportation system/corridor, utility and utility corridor, domestic water supply, fish habitat, wildlife (non-fish) habitat and migration, visual resource, and timber. When elements are known to be at risk, they are referred to as ***elements at risk*** (or again simply ***elements***). Specialists (e.g., fisheries biologists, archaeologists, and structural engineers) are often required to inventory elements and characterize the effects of potential landslides.

Consequence is the effect on human well-being, property, the environment, or other things of value; or a combination of these (adapted from CSA 1997). Conceptually, consequence is the change, loss, or damage to the elements caused by the landslide.

Risk is the chance of injury or loss as defined as a measure of the probability and the consequence of an adverse effect to health, property, the environment, or other things of value (adapted from CSA 1997).

The following additional terms are also associated with landslide risk management:

Stakeholders are any individual, group, or organization able to affect, be affected by, or believe they might be affected by, a decision or activity. Note that decision-makers are stakeholders (CSA 1997).

Residual risk is the risk remaining after all risk control strategies have been applied (CSA 1997).

Acceptable risk is a risk for which, for the purposes of life or work, stakeholders are prepared to accept "as is," and for which no risk control is needed. Stakeholders do not generally consider expenditure in further reducing such risks as justifiable (adapted from AGS 2000). Different stakeholders can have differing levels of acceptable risk, and in such situations establishing explicit thresholds of acceptable risk can facilitate discussion and consensus among stakeholders.

Tolerable risk is a risk that stakeholders are willing to live with so as to secure certain net benefits, knowing that the risk is being properly controlled, kept under review, and further reduced as and when possible. In some situations, risk may be tolerated because the stakeholders cannot afford to reduce risk even though they recognize that it is not properly controlled (adapted from AGS 2000). Tolerable risks exceed established or acceptable thresholds of risk.

Individual risk is a risk of fatality or injury to any identifiable (named) individual who lives within the zone affected by, or potentially affected by, a landslide, or who follows a particular pattern of life that might subject him or her to the consequences of the landslide (adapted from AGS 2000).

Societal risk is a risk of multiple fatalities or injuries in society as a whole: society would have to carry the burden of a landslide causing a number of deaths and injuries, and financial, environmental, and other losses (AGS 2000).

Voluntary risk is a risk that an individual or society usually takes willingly. Examples include rock climbing, skiing, and motorcycle riding.

Involuntary risk is a risk that is usually imposed on an individual or society. Examples include building structural failure, dam failure, and lightning strikes.

2.2 Framework for Landslide Risk Management

Effective risk management decisions often result from following consistent and logical steps in the decision-making process. Figure 2, adapted from CSA (1997), shows six steps in the decision-making framework for risk management and provides typical objectives in the context of landslide risk management. After each step, a decision must be made: go forward to the next step, go backward to the previous step, or take action. The process is iterative, and it is not unusual in landslide risk management projects for a stakeholder to revisit previous steps. Periodic review throughout the process can be beneficial to improve or streamline the procedure. Risk communication with stakeholders is an important part of each step in the process, as shown on the left side of Figure 2. As discussed in Chapter 1, using a structured framework for landslide risk management offers several benefits.

The flow chart in Figure 2 illustrates that the general processes of risk analysis, risk assessment, and risk management comprise the following:

Risk analysis involves the steps of preliminary analysis and risk estimation. It includes the systematic use of information to identify hazards and to estimate the chance for, and severity of, injury or loss to individuals or populations, property, the environment, or other things of value (CSA 1997);

Risk assessment combines risk analysis and the step of risk evaluation to determine if the risk is acceptable or tolerable. It does not include considering options for risk control, nor does it include actions to control risk or monitor performance of site works over time;

Risk management is a complete process involving all six steps in the decision-making framework and communicating about risk issues.

Within the framework for managing landslide risk in forest development, there are usually four distinct individuals, or stakeholders, who are involved in the various aspects of the interdependent steps shown in Figure 2:

- A ***forest resource manager*** typically makes decisions related to planning and operations associated with forest roads, trails, and timber harvesting. To adequately protect forest resources, the forest

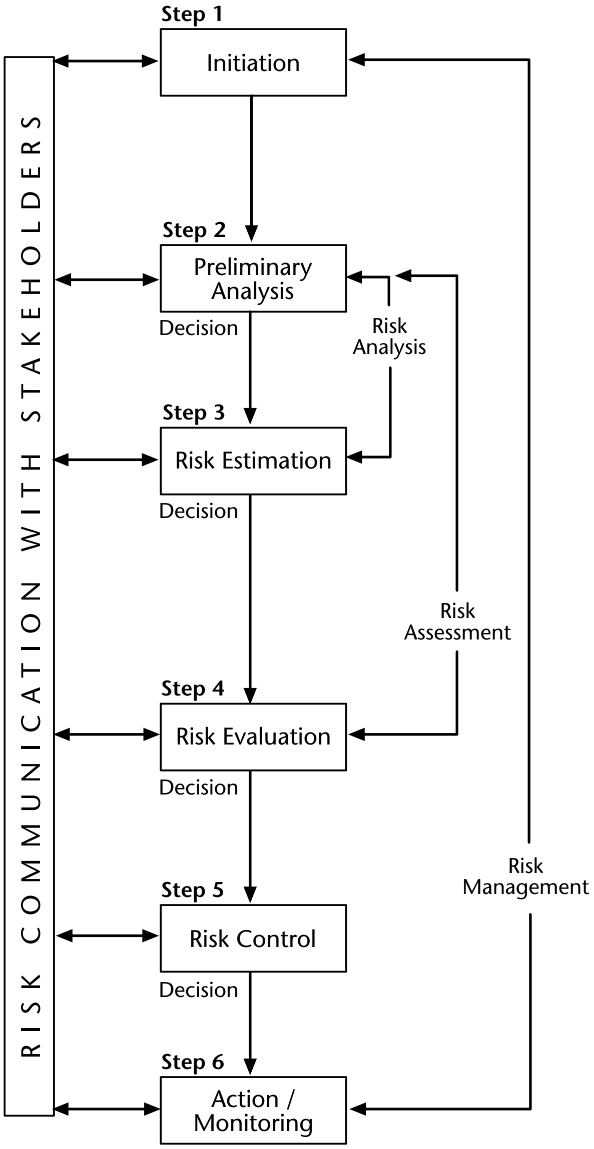


FIGURE 2 *Six steps in the decision-making framework for risk management (adapted from CSA 1997).*

Typical objectives related to landslide risk management

Step 1: Initiation of Landslide Risk Management Project

- general recognition of landslide risk
- identify element(s) present
- identify stakeholders
- select and retain professionals with expertise in landslide hazard and risk analysis

Step 2: Preliminary Analysis

- confirm that risk exists, determine type of landslide(s)
- identify study area, time frame of study
- evaluate background information and constraints
- determine type and scope of landslide hazard/risk analysis

Step 3: Risk Estimation

- determine potential landslide trigger mechanisms
- estimate probability/likelihood of landslide occurrence
- estimate probability/likelihood of landslide affecting element(s) at risk
- if within the scope, estimate potential loss and worth of element(s) at risk
- estimate risk to element(s) from landslide(s)
- clearly communicate results of risk analysis

Step 4: Risk Evaluation

- compare analysis results with thresholds of acceptable or tolerable risk (legislative, public, corporate)
- include issues relating to agency or stakeholder perceptions of risk
- if risk is within thresholds of acceptable or tolerable risk, control is not necessary
- determine whether more accurate risk analysis is needed

Step 5: Risk Control (if necessary)

- if risk is unacceptable, develop options to reduce likelihood of landslide occurrence or to protect element(s) at risk
- select preferred alternative based on reduction in landslide risk and cost-effectiveness
- develop implementation plan that contains preferred option for risk control

Step 6: Action/Monitoring

- implement plan with preferred option to reduce landslide risk
- carry out field reviews during/following site work, as needed
- over extended periods of time, compare risk estimates with performance of site works

resource manager may need to retain and coordinate professionals specializing in terrain stability and forest resources to analyze landslide hazards and risks. The forest resource manager may be a project manager or coordinator, a registered professional, a forest resource specialist, or another similarly qualified person. This individual usually evaluates the results of landslide risk analyses in terms of legislative and corporate requirements, and often considers the viewpoints of other stakeholders (such as government agencies and the general public).

- A ***terrain stability professional*** typically carries out the technical aspects of the landslide risk analysis (Association of Professional Engineers and Geoscientists of British Columbia [APEGBC] 2003). This individual should have training and experience relating to landslides, such as geomorphology, hydrology, airphoto interpretation, and soil mechanics. These basic qualifications should be supplemented by training and experience in: forest road construction and deactivation; soil erosion analysis and control; geologic hazard and risk identification and analysis; landslide avoidance, prevention, and remediation; slope stability analysis; and harvesting and silviculture methods (APEGBC 2003).
- A ***forest resource specialist*** (e.g., professional forester, professional biologist) may be requested to identify and characterize the elements within the development area and to provide inventory information for use in the landslide risk analysis. A forest resource specialist can provide important information on specific aspects of the landslide risk analysis, such as the potential loss or damage associated with landslide risk.
- A ***government agency representative*** may be requested to provide advice regarding the forest development. The advice provided by the agency representative might also consider the viewpoints of other stakeholders, including the general public.

Teamwork is critical in landslide risk management. In British Columbia, the involvement of the above four stakeholders may be described or implied in legislation, such as the *Forest Practices Code of British Columbia Act* and regulations, the *Forest and Range Practices Act* and regulations, and other applicable federal and provincial legislation. Additionally, the roles and responsibilities of terrain stability professionals are outlined in professional practice guidelines, such as those developed for terrain stability assessments in the forest sector (APEGBC 2003). An understanding of the roles and level of involvement of each team member is important for effective risk communication, starting from the collection of background information during the initial stages to the monitoring of construction and risk control work.

2.3 Steps for Landslide Risk Management

The six steps in the decision-making process for landslide risk management are described in further detail below. The case studies in Chapter 4 provide examples of the framework for landslide risk management related to various aspects of forest development.

2.3.1 Initiation of a landslide risk management project – Step 1

Initiation of a landslide risk management project follows the recognition of some level of landslide hazard or risk that must be managed, along with the identification of the elements present. During the early stage of landslide risk management, the purpose and scope of managing the landslide risk should also be established. Note that a project may have multiple objectives. For example, risk assessments along an existing forest road network may involve analysis of landslide risks for both road maintenance and deactivation.

A forest resource manager usually initiates the project. A project may be initiated, for example, after a review of landslide hazard mapping (terrain stability mapping) that identified potentially unstable terrain or existing landslides, or after site observations of unstable road fill or uncontrolled road drainage. A project may also be initiated where there are elements of high social, environmental, and economic value at risk downslope or downstream of the forest development.

The forest resource manager usually retains a terrain stability professional with expertise in landslide risk analysis. The complexity of the site and the type of potential landslide often determine the required experience level and specialization of the professional. For example, managing landslide risk related to proposed harvesting within or near a gully system may require a terrain stability professional with expertise in geomorphology and/or windthrow, whereas a proposed road through a bedrock bluff may require a professional with expertise in controlled blasting and rock slope stability.

In general, the early stages of a landslide risk management project should also consider assigning responsibility for the different aspects of the project (e.g., analysis, evaluation, control, action, and monitoring). It is important to initiate communication with stakeholders in this step of the risk management process, particularly if the anticipated risks are considerably different from those previously analyzed or if there is a risk to high-value elements or human health and safety. Case Study 4.1 discusses the initiation of the landslide risk management process in the context of a large watershed restoration project in the San Juan River watershed.

2.3.2 Preliminary analysis – Step 2

Preliminary analysis involves confirming that a landslide risk exists that warrants further analysis, determining some initial landslide characteristics and possible trigger mechanisms, and identifying the study area for the analysis. The preliminary analysis also considers the elements that may be potentially at risk from the landslide.

Typically, most of this work is carried out by a terrain stability professional often using available information such as airphotos, maps, forest resource inventory information, overview terrain stability mapping, preliminary road designs and harvesting layout, gully assessment results, and previous local experience. (Appendix 1 lists types of useful background information.) Case Study 4.2 presents a landslide risk analysis in the Oliver Creek watershed, and discusses how terrain mapping and other planning constraints need to be reviewed during the preliminary analysis.

It is important to determine the type, scope, and scale of landslide hazard or risk analysis required. For example, during the initial stages of forest development, reconnaissance-level hazard analysis (such as terrain stability mapping) may be sufficient to qualitatively determine areas of likely landslide occurrence following development, with little consideration of elements potentially at risk. As development proceeds, more detailed risk analyses may be needed to estimate the probability of occurrence of landslides and the consequence at specific sites where development is planned.

The method of analysis also depends upon the elements potentially at risk. Case Study 4.8 on the Summit Lake road repair demonstrates that the risk analysis to determine potential damage to fish habitat may be different from the risk analysis to determine the expected costs to repair a secondary highway affected by a landslide. Analyses may also differ depending upon the options available for risk control. The risk analysis in Case Study 4.7 for the Kitseguecla Creek fan differs from the risk analysis in Case Study 4.3 for the Hummingbird Creek fan due to the differing types of elements.

2.3.3 Risk estimation – Step 3

Estimation of landslide risk is the second step in risk analysis. Usually, a terrain stability professional carries out risk estimation. This step usually involves visiting the site to estimate:

- potential landslide trigger mechanisms;
- type, size, and characteristics of the potential landslide (see Appendix 1); and
- probability (likelihood) of landslide occurrence and travel path, based on terrain conditions, evidence of previous instability, and proposed development activities.

When consequence is estimated, forest resource specialists are often involved in identifying elements potentially at risk and estimating their vulnerability.

Methods for risk estimation are typically selected based on the type of landslide risk analysis necessary and the applicable thresholds for acceptable or tolerable risk. Methods can also vary, depending on the amount and reliability of the site data and the accuracy required for the analysis. Risk estimation may be carried out using quantitative or qualitative analysis methods, depending on the type and scope of the analysis (see Chapter 3). Risk estimation is a focus of most of the case studies in Chapter 4.

Risk estimates should be communicated in clear and direct terms to the forest resource manager and other stakeholders. It is important to present the results in a manner that allows for simple comparison with established thresholds of acceptable or tolerable risk. Terrain stability professionals and forest resource specialists involved in estimating risk should clearly document their assumptions, methodologies, and rationales. While specific aspects of the risk estimation may be highly technical in nature, professionals and specialists with similar expertise should be able to understand the conclusions and recommendations based on the information in the report. Senior (or external) review is desirable, and specifically warranted where high-value elements or human health and safety are at risk, or potentially at risk.

2.3.4 Risk evaluation – Step 4

The risk evaluation step is the last stage of risk assessment. In this step, the results of the risk analysis (preliminary analysis and risk estimation) are compared with thresholds of acceptable or tolerable risk. Thresholds of acceptable or tolerable risk may be established by legislation, implied through previous acceptable practices and standard operating procedures, or implied by societal norms. Case Study 4.8 presents an example of how the results from a landslide risk analysis can be compared to existing guidelines and information to assist in the evaluation of risk near Summit Lake.

Thresholds of acceptable or tolerable risk based on legislation and those based on corporate policies can differ. For example, a logging company can require harvesting to exclude areas with a moderate or high likelihood of landslides following harvesting and include this as a corporate commitment for environmental certification, whereas legislative requirements may allow harvesting of some areas with moderate landslide hazard.

Based upon the risk evaluation, one of five outcomes is possible:

1. the landslide risk from the proposed forest development is acceptable or tolerable;
2. the landslide risk is not acceptable or tolerable, but can be managed by reducing the probability (likelihood) of landslide occurrence, thereby reducing the estimated landslide risk;
3. the landslide risk is not acceptable or tolerable, but can be managed by reducing the consequence to the elements and thereby reduce the estimated landslide risk;
4. the landslide risk does not meet the thresholds of acceptable or tolerable risk and cannot be managed by risk control; or
5. additional risk analysis is needed to better estimate the existing risk or the residual risk.

The forest resource manager typically carries out risk evaluation. Prudent forest resource managers can seek advice from government agency representatives, forest resource specialists, and/or other stakeholders to determine if the risk is acceptable or tolerable in situations where the thresholds are implied, or close to known thresholds. For such cases it is important to state the assumed acceptable or tolerable risk thresholds as part of the risk assessment. (Appendix 2 contains information regarding risk evaluation related to potential landslides associated with proposed residential development.)

2.3.5 Risk control – Step 5

Risk control should be considered where the estimated risk is evaluated as not acceptable or not tolerable. This step involves developing options to reduce the landslide risk through mitigation. Risk control can be based on:

- avoiding unstable or landslide-prone terrain;
- preventing landslides by designing measures or operating procedures to reduce the probability of landslide occurrence; or
- protecting elements at risk by implementing measures to reduce the consequence of the potential landslide.

The forest resource manager and the terrain stability professional typically work together to develop options for landslide risk control. As appropriate for each alternative option, the level of hazard and risk reduction, the residual hazard and risk, and the associated cost and operational constraints of each alternative should be considered. In Case Study 4.1, the restoration work carried out in the San Juan River watershed provides some examples of risk control for existing landslide and sedimentation risks from roads, landslides, and gully areas.

There are numerous methods to control or mitigate landslide risk. For construction of a forest road, methods can include: road design and construction recommendations, such as full bench with end-haul, engineered fills, or erosion-resistant structures; increased inspections; or deactivation immediately following harvesting. For existing roads, upgrading or deactivating the roads can reduce the probability of occurrence of landslides. In other cases, it may be more cost-effective to protect the elements at risk using structures to stop, deflect, or contain potential landslide events. Several technical publications contain examples of risk control measures in forest development, including those by Chatwin et al. (1994), United States Department of Agriculture (1994), VanDine (1996), and Atkins et al. (2001).

FIGURE 3 *Example of road deactivation to reduce probability (likelihood) of landslide occurrence (M. Wise photo).*

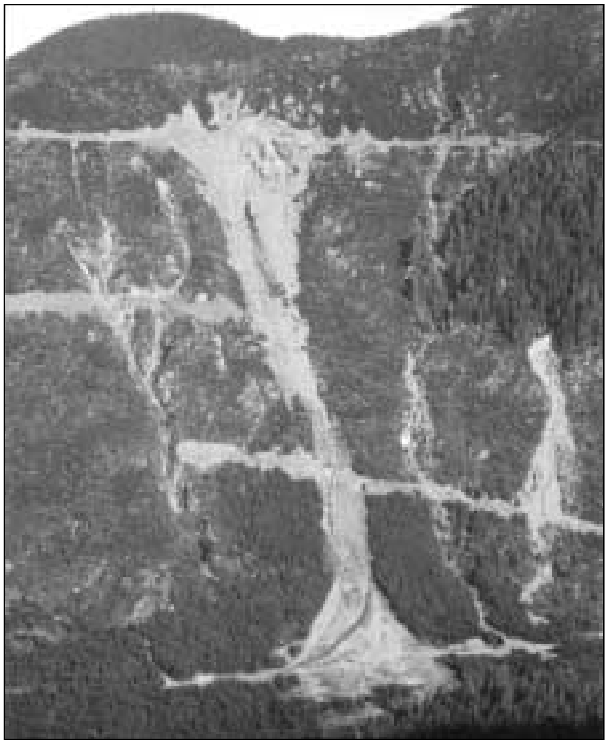


FIGURE 4 *Example of a debris flow control structure (a deflection berm) near the base of the slope to protect fish habitat (M. Wise photo).*

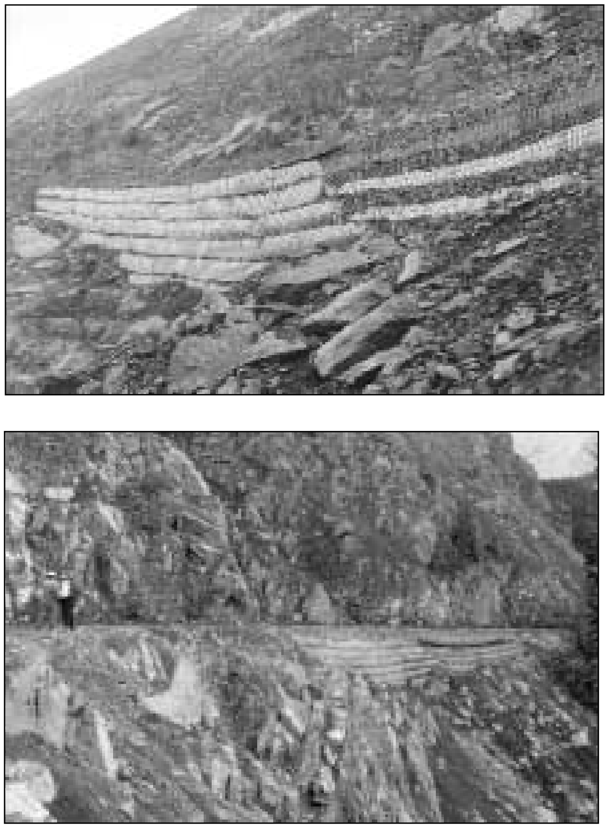


FIGURE 5 *Roadfill supported by retaining walls to reduce the amount of full bench / end-haul necessary for construction of a forest road (C. VanBuskirk photos).*

When analyzing measures to control or mitigate landslide risk, it is important to consider other potential issues that may be associated with such measures. For example, a section of road requiring full bench / end-haul construction can create significant sedimentation hazards, both from higher volume roadcuts and larger spoil areas. At such sites, engineered road fills or retaining walls may be an option to reduce the potential sedimentation hazard and construction costs. Some options to mitigate landslide risk can also involve periodic long-term maintenance, such as retaining walls at the base of ravelling slopes, and the associated costs must be considered as part of the risk evaluation.

2.3.6 Action and monitoring – Step 6

If the estimated residual risk with proposed control is acceptable or tolerable, and the forest development proceeds, the risk control should become part of the overall plan for forest development. For example, recommendations to reduce landslide risk along an existing forest road may be incorporated into the maintenance or deactivation plans for the road, and carried out as part of work along the road following harvesting.

Monitoring is an important part of the landslide risk management process. Such monitoring can include inspections during construction or deactivation, inspections along active roads, and effectiveness monitoring along previously deactivated roads. In addition, a systematic review of landslides relating to road construction can improve risk analysis and management by identifying typical sites and practices associated with landslides. A review of clearcut harvesting on slopes with a relatively high probability of landslide occurrence can provide stability-based criteria for future harvesting activities in the area. Effective risk management incorporates additional monitoring as needed to validate analyses and, when appropriate, to implement additional risk control.

Reviewing the outcomes of past risk management projects can provide valuable insights on ways to further reduce risks on other projects, particularly in cases where risk control was not successful. For example, a review of the cause of landslides from older deactivated forest roads on Vancouver Island indicated that full retrieval of thick roadfills above unstable slopes and at cross-ditch outlets is important and should be considered on future road deactivation projects. Lessons learned from such reviews and adjustments to deactivation techniques to address any shortcomings can significantly reduce the residual risk associated with road deactivation on steep slopes (Wise et al. 2001).

FIGURE 6 *Effectiveness monitoring can provide information on inadequate risk control, such as this section of road deactivation (M. Wise photo).*

CHAPTER 3 TECHNICAL TERMS AND METHODS

DOUG VANDINE, GLENN MOORE, MIKE WISE, CALVIN VANBUSKIRK, AND ROBERT GERATH

3.1 Introduction

This chapter further develops landslide risk terms discussed in Chapters 1 and 2 as well as the methods applied to the case studies in Chapter 4.

Traditionally, ***risk*** (R) has been mathematically expressed as the product of two components, ***probability of occurrence*** (P) and ***consequence*** (C).

$$R = P \times C \qquad (1)$$

The type of the landslide risk analysis carried out depends on the purpose of the analysis. In forest development in British Columbia, such analyses are usually carried out prior to road construction, timber harvesting, and road deactivation to determine existing landslide risks, and to predict resulting risks, or resulting residual risks. They can also be carried out for existing development or after a landslide has occurred.

Table 1 summarizes the various types of landslide risk analyses. The case studies presented in Chapter 4, and listed in Table 1, illustrate a range of these analyses. Appendix 3 provides other examples of published landslide risk analyses.

3.2 Hazard and Probability

In the past, the term ***hazard*** has sometimes been used synonymously with the terms ***probability*** and ***likelihood*** *of occurrence* (see Chapter 2). Hazard, however, describes a harmful or potentially harmful

TABLE 1 *Types of landslide risk analyses**

Type of analysis	Symbol	Description of analysis	Case study in Chapter 4
Landslide	P P(SL)	Probability of occurrence of any landslide Probability of occurrence of a specific landslide	None
Hazard	P(H)	Probability of occurrence of a specific hazardous landslide	4.1–4.8
Partial risk	P(HA)	Probability of occurrence of a specific hazardous landslide and the probability of it reaching or otherwise affecting the site occupied by a specific element	4.1–4.5
Specific risk	R(S)	Risk to a specific element, but worth of the element is not considered	4.6, 4.7
Specific value of risk	R(SV)	Risk to a specific element, and worth of the element is considered	4.1, 4.8
Multiple risk	R(M)	Risk to multiple elements or risk to one element from multiple landslides	4.1, 4.5–4.8
Total risk	R(T)	Risk to all elements from all landslides	None

* The types of analyses and terms in this table are described in the following sections.

landslide, while probability and likelihood of occurrence describe the potential for that landslide to occur. The interchangeable use of these terms has led to confusion in communication, and is discouraged.

Probability of occurrence should be expressed over a specified period of time, such as an *annual probability of occurrence* (Pa), where "a" represents annual, or a *long-term probability of occurrence* (Px), where "x" is a given number of years.

With certain limitations and as a first approximation (discussed in Appendix 4), Pa and Px can be mathematically related as:

$$Px = 1-(1-(Pa))^{X} \qquad (2)$$

For example, the probability that at least one landslide will occur in a 50-year period, given an annual probability of occurrence of 1:500, is:

$$\begin{aligned} P50 &= 1-(1-(1/500))^{50} \\ &= 0.095 \end{aligned}$$

A probability of 1 indicates certainty that the landslide will occur; a probability of 0 indicates certainty that a landslide will not occur.

Table 2 shows an example relationship between qualitative *probability of occurrence ratings* (likelihood of occurrence), quantitative annual probability of occurrence, quantitative probability of occurrence over a 20-year design life of a forest road, and associated qualitative descriptions. In this example, the ranges of annual probability of occurrence arbitrarily increase by a factor of 5 with each rating. Refer to Table A5.1 in Appendix 5 for another example.

3.3 Landslide Analyses

Landslide Analyses estimate the probability of occurrence of a landslide without considering its effects on any *elements***.** Two types of landslide analyses, **P** and **P(SL)**, are discussed below.

P *is the probability of occurrence of any landslide* of any type, size, and character (Figure 7). An example of this type of landslide analysis is a detailed terrain

TABLE 2 *An example showing the relationship between qualitative and quantitative probabilities of occurrence of a landslide along a 1-km segment of road (modified from BCRIC 1996, Hungr 1997, and BCMOF 2002)*

Probability of occurrence rating (likelihood of occurrence)	Annual probability of occurrence (Pa)*	Probability of occurrence over a 20-year design life** (Px)	Example of qualitative description
Very high	> 0.05	> 0.65	Landslide is imminent in the case of an existing road, or would occur soon after road construction in the case of a proposed road.
High	0.01–0.05	0.18–0.64	Landslide is probable within the lifetime of the existing or proposed road.
Moderate	0.002–0.01	0.04–0.18	Landslide is not likely, but possible within the lifetime of the existing or proposed road.
Low	0.0004–0.002	0.01–0.04	Landslide is remote possibility within the lifetime of the existing or proposed road.
Very low	< 0.0004	< 0.01	Landslide is very remote possibility within the lifetime of the existing or proposed road.

* Pa does not consider the design life of the road.

** Px is the probability that at least one landslide will occur within the 20-year design life of the road.

Note: Probabilities may be different for cutblocks, and there may be differences between coastal and interior roads.

stability mapping project in which terrain polygons are mapped and then analyzed to delineate the relative slope stability of the polygons following road construction and timber harvesting (British Columbia Ministry of Forests 1999). The initiation locations of existing and potential landslides are located only at the polygon level. The type, size, and character of *existing* landslides may or may not be mapped, but the type, size, and character of *potential* landslides are not identified. The effects of the potential landslides on elements and potential elements are not considered.

***P(SL)** is the probability of occurrence of a specific landslide* (Figure 8) and considers the initiation location of a specific landslide, in addition to the type, size, and character of the landslide (refer to Appendix 6). Examples of P(SL) analyses include some road deactivation or terrain stability assessments where a specific landslide is considered but the elements are unknown, or where the risk to the elements will be analyzed by other forest resource specialists.

3.4 Hazard Analyses

***Hazard Analyses, P(H),** estimate the probability of occurrence of a specific hazardous landslide* (Figure 9). In other words, it is the probability of occurrence of a specific landslide and that landslide being a hazard to an element.

Although an element is identified in the analysis of P(H), its relevant nature and characteristics are not considered. In other words, P(H) does not consider

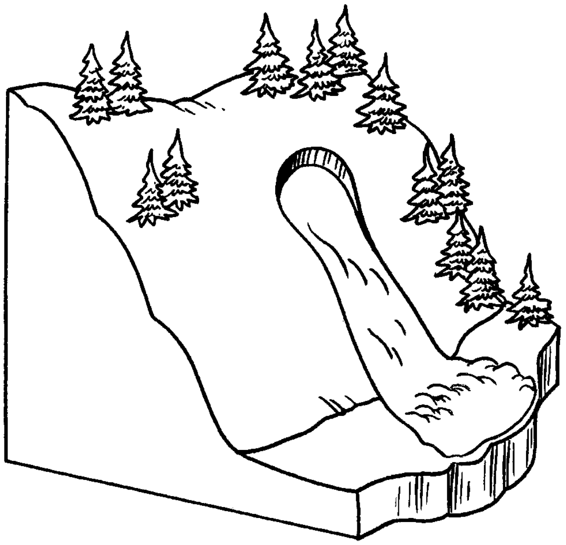


FIGURE 8 *Schematic drawing of P(SL). The initiation location, type, size, and character of the potential landslide are considered; elements potentially at risk are not considered.*

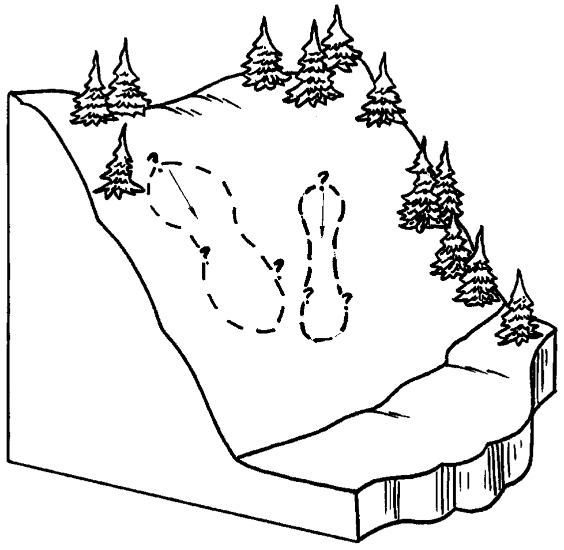


FIGURE 7 *Schematic drawing of P. The location, type, size, and character of the potential landslide are not considered.*

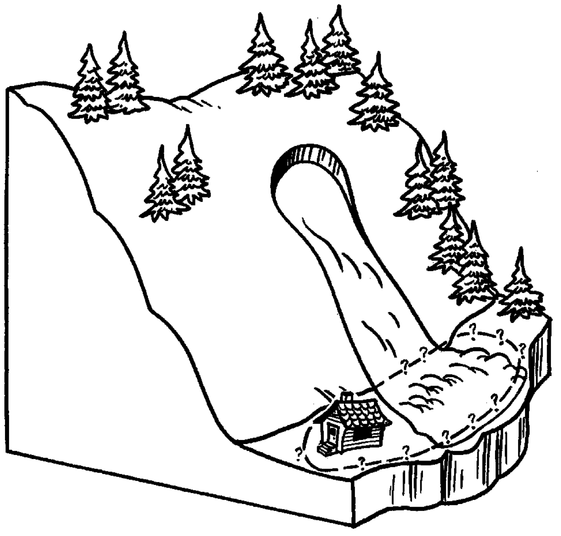


FIGURE 9 *Schematic drawing of P(H). A specific landslide is considered, but an element is considered in general terms only.*

the following factors: the probability of the landslide reaching or otherwise affecting the site occupied by the element; the probability of the element being at that site at the time of the landslide; the vulnerability of the element; and the worth of the element. These other factors are discussed in Section 3.5. Therefore, P(H) is a measure of hazard and not risk, because it does not consider the effects, or potential effects, of the landslide on the element.

3.5 Consequence

Consequence of a landslide must consider where and when the landslide occurs in relation to the *elements* and the vulnerability of the elements. The following subsections describe these components, and how they combine to form consequence.

3.5.1 Spatial probability and temporal probability

Spatial probability relates to the potential of a landslide to reach or otherwise affect the site occupied by an element. ***Temporal probability*** relates to the potential of a mobile element, such as an occupant of a house or a moving vehicle, to be at the affected site at the time the event occurs. (In the case of a person who drives into a landslide that has recently occurred, for example, temporal probability also considers the time shortly after the event.) These are conditional probabilities expressed mathematically as **P(S:H)** and **P(T:S)**, where the first term in parentheses is dependent upon the second term in parentheses.

P(S:H) *is the probability that there will be a spatial effect, given that a specific hazardous landslide occurs.* In a quantitative analysis, if it is certain that the landslide debris will reach or otherwise affect the site occupied by the element, the spatial probability is numerically 1. Otherwise, the spatial probability is between 0 and 1 to account for the possible outcome that the landslide will reach or otherwise affect the site.

P(T:S) *is the probability that there will be a temporal effect, given that there is a spatial effect.* In a quantitative analysis, if the location of the element is permanent, such as a bridge, building, or stream, the temporal probability is numerically 1 because it is certain that the element will be at the affected site when the event occurs. Otherwise, the temporal probability is between 0 and 1 to account for the possibility that a mobile element may or may not be at the site when the landslide occurs (or sometime shortly after it occurs).

Qualitatively, both spatial and temporal probabilities can be expressed by relative terms such as *very high, high, moderate, low,* and *very low.* Qualitative terms can have different meanings to different individuals, and therefore they must be defined to avoid ambiguity.

3.5.2 Vulnerability

Vulnerability (V) of an element depends upon its type and character. It is a measure of the robustness (or alternatively, the fragility) of the element, and its exposure to (or alternatively, protection from) the landslide. Specialists, such as foresters, biologists, archaeologists, and structural engineers, are often required to help estimate vulnerability. The vulnerability of an element is conditional on the element being at the site at the time of the landslide (temporal effect), and is mathematically expressed as **V(L:T)**.

Quantitatively, vulnerability can be: the estimated *probability of total loss or damage* to a specific element; or, in the case where the probability of some loss or damage is assumed to be certain, it is the estimated *proportion of loss or damage* to a specific element. Both can be expressed as a number between 0 and 1.

In a qualitative analysis, and when total loss or damage is assumed, vulnerability can be expressed by the qualitative probability of total loss or damage ratings (*vulnerability ratings*), such as *very high, high, moderate, low,* and *very low likelihood of total loss or damage.* In a qualitative analysis, and when the probability of some loss or damage is assumed to be certain, vulnerability can be expressed by the qualitative proportion of loss or damage (vulnerability ratings), such as *no loss or damage, low loss or damage, moderate loss or damage, high loss or damage,* and *total loss or damage.*

Tables 3 and 4 are examples of vulnerability ratings (assuming some loss or damage is certain) and their descriptions for the infrastructure associated with a transportation corridor and a timber resource.

3.5.3 Consequence

Consequence (C), the effect to the elements, includes consideration of spatial probability, temporal probability, and vulnerability, and is mathematically expressed as:

$$C = P(S:H) \times P(T:S) \times V(L:T) \qquad (3)$$

TABLE 3 *Example of vulnerability ratings for the infrastructure associated with a transportation corridor, excluding highway users (adapted from BCMOF 2002)*

Vulnerability rating	**Description of transportation corridor, V(L:T)***
High loss or damage	• destruction of, or extensive (not easily reparable) damage to, transportation corridor, or • long-term (>1 week) disruption to transportation corridor
Moderate loss or damage	• moderate (easily reparable) damage to transportation corridor, or • short-term (1 day to 1 week) disruption to transportation corridor
Low loss or damage	• minor (inconvenient) damage to active transportation corridor, or • very short (<1 day) disruption to transportation corridor

* It is assumed that some loss or damage is certain, therefore vulnerability refers to the proportion of loss or damage.

TABLE 4 *Example of vulnerability ratings with regards to a timber resource*

Vulnerability rating	**Description of timber resource, V(L:T)***
High loss or damage	• total or large-scale loss or extensive major damage to most of the timber
Moderate loss or damage	• some loss or moderate damage to some of the timber
Low loss or damage	• little loss or limited damage to most of the timber

* It is assumed that some loss or damage is certain, therefore vulnerability refers to the proportion of loss or damage.

Consequence can be expressed quantitatively, between 0 and 1, as a probability of total loss or damage to the element, or as a proportion of loss or damage to the element, corresponding to the unit of V(L:T) used in the analysis (refer to Section 3.5.2).

Similar to the qualitative expression for V(L:T), but including consideration of spatial and temporal probabilities, consequence can be expressed by defined *consequence ratings* such as *very high, high, moderate, low,* and *very low likelihood of total loss or damage to the element.* When the probability of some loss or damage is assumed to be certain, consequence ratings can be expressed using defined terms, such as *no loss or damage*, *minor loss or damage*, *major loss or damage,* and *total loss or damage.* Refer to Appendix 5, Table A5.2 for some examples of qualitative vulnerability and consequence ratings and their descriptions.

Note that when it is certain that the landslide debris will reach or otherwise affect the site occupied by the element P(S:H) = 1, and when the location of the element is permanent P(T:S) = 1, the consequence and vulnerability are the same.

For elements other than human life, consequence can be combined with worth, and a ***consequence value (CV)*** of the loss or damage to the *property, the environment, and other things of value* (collectively referred to as ***property***) is mathematically expressed as:

$$CV_{property} = P(S{:}H) \times P(T{:}S) \times V(L{:}T)_{property} \times E,$$

or

$$CV_{property} = C_{property} \times E \qquad (4)$$

where ***E*** is the ***worth of the element***.

The worth of an element can include direct and indirect values associated with monetary and qualitative values. Taking a secondary highway as an example, worth can include:

- *direct monetary worth:* original or replacement costs, if the highway has to be rebuilt, or cost of clearing landslide debris and making the necessary repairs, if the highway is damaged
- *indirect monetary worth:* economic loss resulting from the highway being destroyed or blocked by a landslide

- *direct qualitative worth:* the secondary highway is more valuable to the local population than a nearby highway because the former provides access to a hospital, while the latter does not
- *indirect qualitative worth:* the highway provides access to a recreational area.

Monetary worth of an element can be the total cost (e.g., original, replacement, or mitigative), or the total cost annualized (average annual), but should not be a mixture of total cost and annualized cost. Specialists and stakeholders are often required for the valuation of elements.

There is no equivalent component $CV_{\text{human life}}$, because in forestry operations human lives are considered more valuable than any direct or indirect monetary values placed on them.

Consequence value can be expressed quantitatively, usually as a dollar value, or qualitatively using defined relative *consequence value ratings* such as *very high, high, moderate, low,* and *very low dollar-value loss.* Table 5 is an example of consequence value ratings and their descriptions with regards to the worth of a timber resource. Note that this table differs from Table 4, in which the element's worth has not been included.

Caution should be used when comparing vulnerability ratings, consequence ratings, and consequence value ratings for different elements. For example, a high consequence to human life should not be compared with a high consequence to a water supply system for irrigation.

3.6 Risk Analyses

This section describes the various types of risk analyses: partial risk **P(HA)**, specific risk **R(S)**, specific value of risk **R(SV)**, multiple risk **R(M)**, and total risk **R(T)**. Appendix 1 describes the landslide site information required for landslide risk analyses.

3.6.1 Partial risk

***Partial Risk*, *P(HA)*,** *is the product of the probability of occurrence of a specific hazardous landslide and the probability of that landslide reaching or otherwise affecting the site occupied by a specific element.* This is also referred to in this handbook as *the probability of a specific hazardous affecting landslide.* To determine

TABLE 5 *Example of consequence value ratings with regards to worth of a timber resource (modified from BCMOF 2002)*

Consequence value rating	Description of timber resource, including worth $CV_{\text{property}}{}^{*} = P(S{:}H) \times P(T{:}S) \times V(L{:}T) \times E$
High dollar loss	• total or large-scale loss or extensive (major) damage to timber, and the timber is mature and harvestable, with the timber value in the top 1/3 for the region (implies a high site productivity area)
Moderate dollar loss	• some loss or moderate damage to timber, and the timber is mature and harvestable, with the timber value in the top 1/3 for the region (implies a high site productivity area), or • total or large-scale loss or extensive (major) damage to timber, and the timber is mature and harvestable, with the timber value in the middle 1/3 for the region, or • total or large-scale loss or extensive (major) damage to the timber, and the timber is juvenile and within about 20–35 years of potential harvest and the future timber value at a harvestable stage will be in the top or middle 1/3 for the region.
Low dollar loss	• little loss or limited damage to timber, and the timber is mature and harvestable, with the timber value in the top 1/3 for the region (implies a high site productivity area), or • total or large-scale loss or extensive (major) damage to timber, and the timber is mature and harvestable, with the timber value in the bottom 1/3 for the region (implies a low site productivity area), or • total or large-scale loss or extensive (major) damage to timber, and the timber is juvenile and more than 35 years away from potential harvest and the future timber value at a harvestable stage will be in the top or middle 1/3 for the region.

* It is assumed that, given a landslide, some loss or damage is certain, and the value of the loss will be proportional to the damage (e.g., if 25% of the timber resource were damaged, the value of the timber resource would be reduced by 25%).

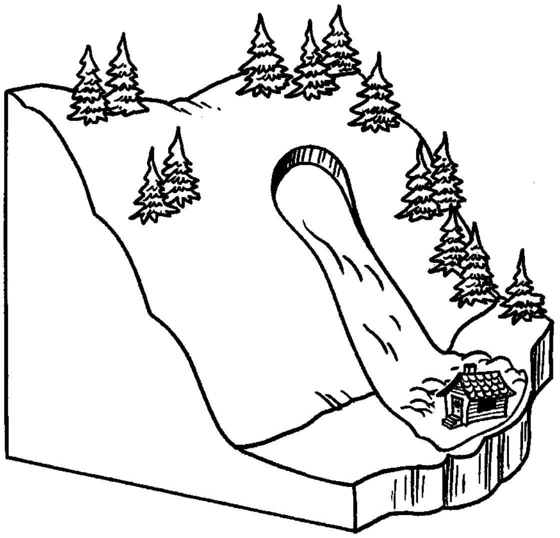


FIGURE 10 *Schematic drawing of P(HA), Partial Risk. A specific hazardous affecting landslide is considered, but the vulnerability of the element is not.*

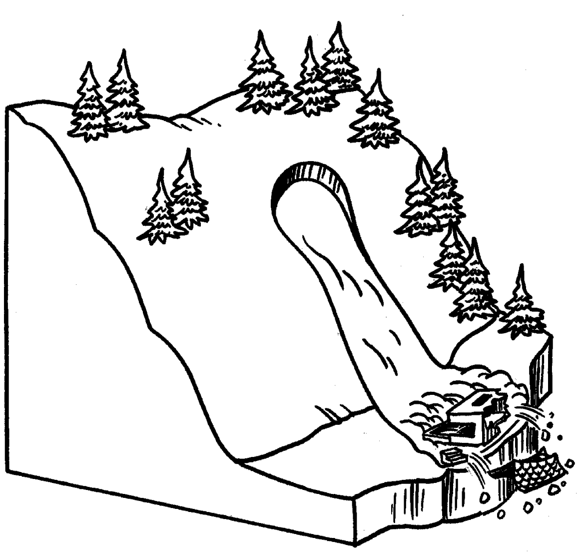


FIGURE 11 *Schematic drawing of R(S), Specific Risk. A specific hazardous affecting landslide, and the vulnerability of the element, are considered.*

if a specific landslide is a hazard to, and could reach or otherwise affect the site occupied by, a specific element, spatial and temporal probabilities must be considered (refer to Section 3.5).

Partial risk is mathematically expressed as:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S) \qquad (5)$$

Partial risk does not consider the vulnerability of the element, and therefore is not a complete estimate of risk, hence the symbol P(HA) as opposed to R. In practice, partial risk is usually the preferred type of analysis when little is known about the vulnerability of the element or where an estimate of vulnerability is not required.

Quantitatively, P(HA) is expressed as a probability (between 0 and 1) of a specific hazardous affecting landslide over a specified time period, either annual or long term, corresponding to P(H). Qualitatively, it may be expressed using qualitative risk ratings such as *very high, high, moderate, low,* and *very low likelihood* of a specific hazardous affecting landslide over a specified time period.

3.6.2 Specific risk

Specific Risk, R(S), *is the risk of loss or damage to a specific element, resulting from a specific hazardous affecting landslide* (Figure 11). Information regarding the vulnerability of the element is required to estimate specific risk.

Specific risk is mathematically expressed as any of the following three equations:

$$\begin{aligned} R(S) &= P(HA) \times V(L{:}T) \\ R(S) &= P(H) \times P(S{:}H) \times P(T{:}S) \times V(L{:}T) \\ R(S) &= P(H) \times C \qquad (6) \end{aligned}$$

Note that the last line in Equation 6 is similar to Equation 1.

Figure 12 graphically shows the relationship of the risk components for specific risk. Note the "mathematical overlap" of components P(HA) and C.

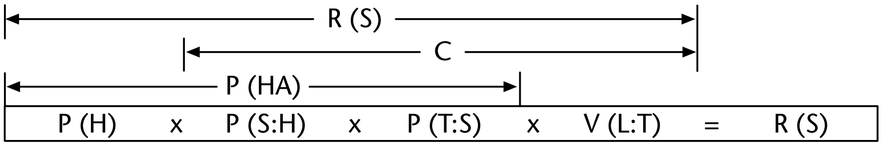


FIGURE 12 *The "mathematical overlap" of P(HA) and C, associated with Specific Risk, R(S).*

There are two types of specific risk:

- $R(S)_{property}$, specific risk related to property, the environment, and other things of value, and
- $R(S)_{human\ life}$, specific risk related to human life.

Quantitatively or qualitatively, $R(S)_{property}$ may be expressed in the same units as V(L:T) or C, but over a specified time period, either annual or long term, corresponding to P(H).

Refer to Appendix 5, Table A5.4, for some examples of qualitative risk ratings and their implications for risk managment. As with vulnerability ratings, consequence ratings, and consequence value ratings, caution should be used when comparing relative qualitative risk ratings for different elements.

Table 6 is an example of a relationship between relative qualitative terms and quantitative values for $R(S)_{property}$, for an annual probability of occurrence.

$R(S)_{human\ life}$ is also known as ***PDI, annual probability of death to an individual***, or ***PDG, annual probability of death to a group***, where a group is defined as more than one individual.

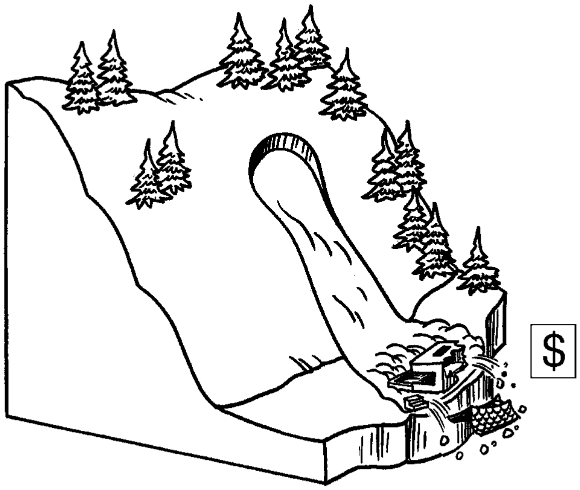


FIGURE 13 *Schematic drawing of R(SV), Specific Value of Risk. A specific hazardous affecting landslide, and the vulnerability and worth of the element, are considered.*

TABLE 6 *Example of the relationship between relative qualitative terms and quantitative values for a specific risk to property for an annual probability of occurrence (modified from Fell 1994)*

Specific risk rating	Quantitative range of specific risk for property loss
Very high	> 0.1
High	0.02–0.1
Moderate	0.005–0.02
Low	0.001–0.005
Very low	< 0.001

3.6.3 Specific value of risk

Specific Value of Risk, R(SV), *is the worth of loss or damage to a specific element, excluding human life, resulting from a specific hazardous affecting landslide* (Figure 13). As noted in Section 3.5.3, worth includes both direct and indirect, and monetary and qualitative, worth.

Specific value of risk is mathematically expressed as any one of the following five equations:

$$
\begin{aligned}
R(SV) &= P(HA) \times V(L{:}T) \times E \\
R(SV) &= P(H) \times P(S{:}H) \text{ x } P(T{:}S) \times V(L{:}T) \times E \\
R(SV) &= P(H) \times C \times E \\
R(SV) &= P(H) \times CV \\
R(SV) &= R(S) \times E \qquad (7)
\end{aligned}
$$

Figure 14 shows the relationship of the risk components. Note once again the "mathematical overlap" of components associated with specific value of risk.

Quantitatively or qualitatively, $R(SV)_{property}$ may be expressed in the same units as V(L:T) × E, or CV, but over a specified time period, either annual or long term, corresponding to P(H).

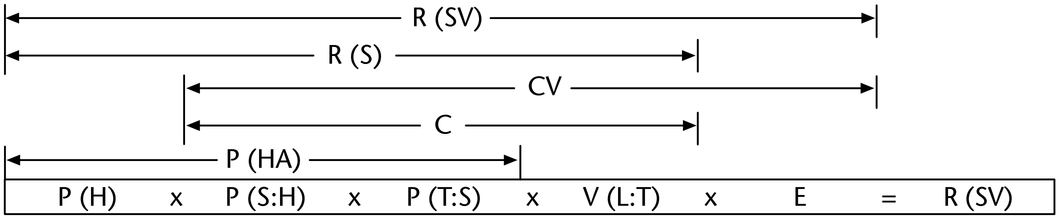


FIGURE 14 *The mathematical relationship of the risk components associated with Specific Value of Risk.*

3.6.4 Multiple risk

Multiple Risk, R(M), *is the risk to more than one specific element from a single specific hazardous affecting landslide* or *the risk to one specific element from more than one specific hazardous affecting landslide* (Figure 15).

Multiple partial risk, multiple specific risk, or multiple specific value of risk should be estimated by applying standard probability concepts (see, for example, Montgomery et al. 2002).

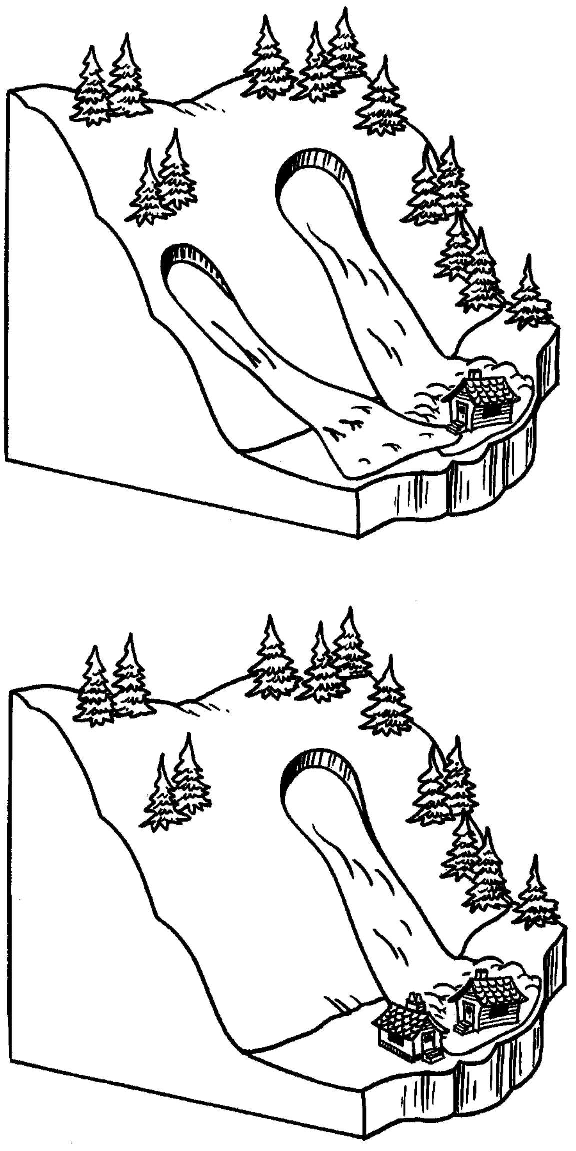


FIGURE 15 *Upper and lower schematic drawings of R(M), Multiple Risk.*

3.6.5 Total risk

Total Risk, R(T), *is the risk to all specific elements from all specific hazardous affecting landslides* (Figure 16).

Similar to multiple risk, total risk should be estimated by applying standard probability concepts (see, for example, Montgomery et al. 2002).

3.7 Methods of Landslide Risk Analysis

The results of landslide risk analyses are usually compared with some form of acceptable or tolerable threshold of hazard or risk, or compared, either in an absolute or relative sense, with those of alternative forest development options. As discussed in Chapter 2, this comparison process is risk evaluation and it helps the forest resource manager to make informed decisions about forest development. (Appendix 2 discusses landslide risk evaluation in the context of proposed residential development.)

The method of the landslide risk analysis also depends on the purpose of the landslide risk analysis, along with some understanding of the elements potentially at risk, and the availability, quality, and reliability of data. The final decision on which method to use should be based on providing the forest resource manager with the most appropriate information for decision making.

Paraphrased from CSA (1991), the landslide risk analysis method should:

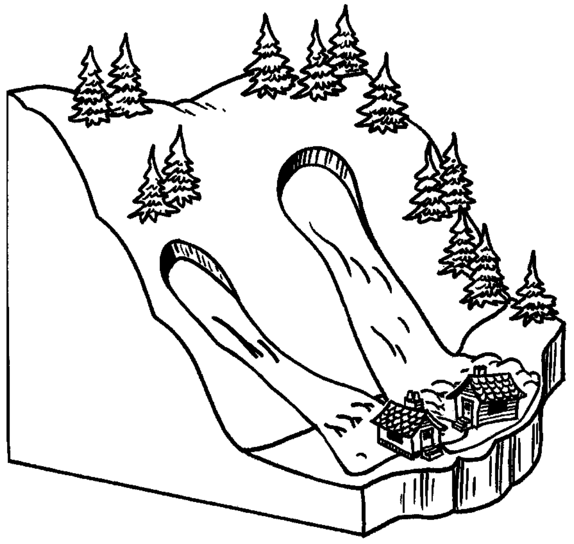


FIGURE 16 *Schematic drawing of R(T), Total Risk.*

- be appropriate to the situation, the level of risk, and the types of elements;
- provide results that can be used for risk evaluation and risk control; and
- be scientifically defensible.

No matter what the purpose, scope, and method of the landslide risk analysis, the accompanying report should clearly describe the method and assumptions, and define all terms used.

The following sections discuss:

- quantitative and qualitative methods of landslide risk analysis,
- subjective probability (the method by which most landslide-related probabilities are estimated), and
- landslide risk analysis techniques, including event tree decomposition and risk matrices.

3.7.1 Quantitative and qualitative methods

Quantitative landslide risk analysis methods use numerical values, or ranges of numerical values, of probabilities, vulnerability, and/or worth to estimate the risk. Qualitative landslide risk methods use relative qualitative ratings. Examples of each are provided in Table 7.

There are no standard definitions for qualitative ratings of probability of occurrence, vulnerability, and worth; therefore, to avoid ambiguity, they must be defined as part of a landslide risk analysis. Tables 2–7 in this chapter and Appendix 5 provide some examples.

The decision on whether to use a quantitative or a qualitative method depends on several factors, including:

- the purpose and scope of the analysis;
- the availability, quality, and reliability of the necessary information; and
- the type of acceptable or tolerable threshold data (qualitative or quantitative) available for risk evaluation.

With regard to precision, quantitative landslide risk estimates may be no better than qualitative estimates. The precision of the estimate does not depend on the use of numbers, but rather it depends on whether all the components of the analysis have been appropriately considered and on the availability, quality, and reliability of the required data.

The term "semi-quantitative" is sometimes used to describe a combination of quantitative and qualitative analysis methods. This term is a misnomer, and when quantitative and qualitative estimations are combined, the results are more appropriately referred to as "qualitative."

3.7.2 Subjective probability

Much of the following discussion on subjective probability has been abstracted from Vick (2002)—a recent and thorough review of the topic.

For natural processes that occur frequently in the same location, such as floods, snow avalanches, and some debris flows, probabilities of occurrence can be estimated by rigorous statistical analysis. For example, after measuring the annual flood data on a river for many years, the recurrence interval of the 200-year flood on that river might be estimated to be on average once every 200 years, and therefore the probability of occurrence could be expressed as 1/200 or 0.005. This is referred to as an ***objective probability*** estimate. Objective probability estimates assume that past events, and the conditions that resulted from past events, are reasonable predictors of future conditions. This in itself is a subjective assumption, and therefore no estimate is entirely objective.

Landslides, however, rarely occur frequently at a given location, and therefore it is difficult to use rigorous statistical analysis to estimate probability of occurrence. Probabilities of landslide occurrence are often estimated by ***subjective probability***. Subjective probability is a measure of one's belief that a landslide will occur. It is based on empirical evidence combined with professional judgement. Subjective probability estimates are no less valid than objective

TABLE 7 *Examples of quantitative values and qualitative ratings*

Qualitative rating	Quantitative value	Example
Low	0.001 (1 in 1000 years)	Annual probability of a hazardous landslide occurring, (PH)
Moderate	0.14 over the design life of the road	Probability of a landslide occurring along a forest road, (PH)
High	0.50 (50% or 1/2)	Proportion of the building that will be lost or damaged, V(L:T)
Moderate	\$75 000–\$100 000	Replacement cost of the bridge, E

probability estimates, provided the scientific basis for the former are well explained. Subjective probability is used not only to estimate the probability of occurrence of a landslide, but also to estimate spatial and temporal probabilities, and probabilities and proportions associated with vulnerability.

With certain caveats, the more knowledgeable and experienced the professional, the more reliable his/her subjective judgements will be. With respect to the probability of landslide occurrence, for example, knowledge and experience can include:

- published case histories;
- general and local personal experience;
- site-specific surface and subsurface observations, field and laboratory testing results, and instrumentation/monitoring results;
- reliability and applicability of landslide models; and
- results of any slope stability analysis (e.g., factor of safety).

There is no mathematical technique to combine knowledge and experience to estimate a probability, therefore some degree of "subjectivity" is required.

Whereas objective probabilities are usually expressed quantitatively, subjective probabilities can be expressed either quantitatively, by numbers between 0 and 1, or qualitatively, using defined relative rating terms such as *very high, high, moderate, low*, and *very low likelihood*. Relative ratings usually cover a range of probabilities and reflect a specified time period, such as a year, or the design life of the element.

Complete knowledge and perfect judgement would reduce quantitative subjective probability estimates to either 1 (certainty that a landslide will occur) or 0 (certainty that a landslide will not occur). However, because no professional has complete knowledge or perfect judgement, and all judgement contains some uncertainty, numerical probabilities generally lie between 1 and 0. Numerical subjective probabilities are most useful in decomposing and analyzing the components of risk and estimating the various types of risks. They are especially useful for estimating specific values of risk (usually in monetary terms), which can then readily be compared, and for estimating risk to human life, because thresholds of risk for loss of life are often quantified.

As part of estimating subjective probability, it is important to consider the time period for the analysis, and the likely site and weather conditions over that period. For example, an estimate of annual probability of landslide occurrence over a 5-year period may consider that frequent use of the road and frequent inspections and maintenance could result in an annual probability of a landslide at a particular site of Pa = 0.02. In the 5–25 years following construction, however, reduced road use, fewer road inspections, less maintenance, weathering of the cut slope, and a higher likelihood of intense rain storms could significantly increase the annual probability of landslide occurrence to, for example, Pa = 0.1.

There are a number of "heuristics" (rules of thumb) and "biases" (adapted from Vick 2002) that consciously or subconsciously influence subjective probability estimates:

- the manner in which knowledge, experience, and available published information is considered (e.g., using the most easily or vividly recalled information, overemphasizing such information, selectively using supporting information, neglecting disconfirming information, and exaggerating information)
- the degree to which adjustments (insufficient adjustments or overadjustments) are made to the initial probability selection to account for non-geotechnical factors (e.g., the level of perceived past poor or successful performance of an equipment contractor, and assumptions about an element's worth)
- the quality of the analysis—in particular, the relevance of similarities between conditions at a site and those on slopes in other geographic locations where landslides have occurred (while avoiding overemphasizing similarities, neglecting other information such as slope aspect and climatic factors, and overlooking a small sample size of similar slopes)
- over- or underconfidence about one's knowledge and experience
- motivational biases (e.g., risk aversion or willingness to take risks, for whatever reason).

The following list highlights the stages and some techniques of estimating subjective probabilities associated with landslides:

- *assemble background data* on relevant existing landslides (both topical and geographical) and

new information on the landslide or terrain under investigation: recall similar sites, search out background data and collect original information, identify and review relevant case histories, identify frequency of past landslides, list information and evidence.
- *synthesize information and evidence:* consider all types of information, question quantity and quality of data, analysis, and assumptions, avoid overly conservative or overly liberal interpretations, use your judgement.
- *assign probability:* converge on the probability rating or numerical value from both ends (1 and 0, or very high and very low), adjust probabilities up and down from initial estimate, use visual and verbal devices to assign probabilities, limit extreme probabilities by carrying out further decomposition or qualification (event trees, limiting criteria).
- *confirm:* check for mathematical coherence, adopt different perspectives, look for disconfirming evidence, review for changes, confirm that probabilities make sense collectively, perform a reality check (adapted from Vick 2002).

The following paragraph (paraphrased from Vick 2002), summarizes some tips for professionals assigning both quantitative and qualitative subjective probabilities during landslide risk analyses.

> *Subjective probability always involves uncertainty, so judgement must be applied. Judgement is the interpretive process that results from one's experience, insight, and intuition. Subjective probability requires applying this judgement to express one's belief or confidence in the state of nature, engineering properties, or outcome of a process. Use all relevant information, including your personal experience and case histories, and do not neglect simple observations or general knowledge. The object is to determine your professional opinion about how much uncertainty these factors together entail. There is no right or wrong answer, only a probability statement that describes your uncertainly as fairly and honestly as possible. Subjective probability relies on self-questioning, and it is important that you interrogate yourself carefully about all possible outcomes without discarding any prematurely. Ask why you believe that a particular outcome will occur or state of nature exists, what supports this belief, and how strongly you believe it. At the same time, account for the quality and the quantity of information, and search for evidence that might counter-indicate the most likely outcome. In the end, if you remain highly uncertain do not hesitate to assign a probability, or probability range, that reflects this uncertainty.*

3.7.3 Landslide risk analysis techniques

After considering all landslide risk components and making all appropriate simplifying assumptions, the data have to be analyzed. For geotechnical applications, event trees and risk matrices are the two methods of landslide risk analysis most commonly used.

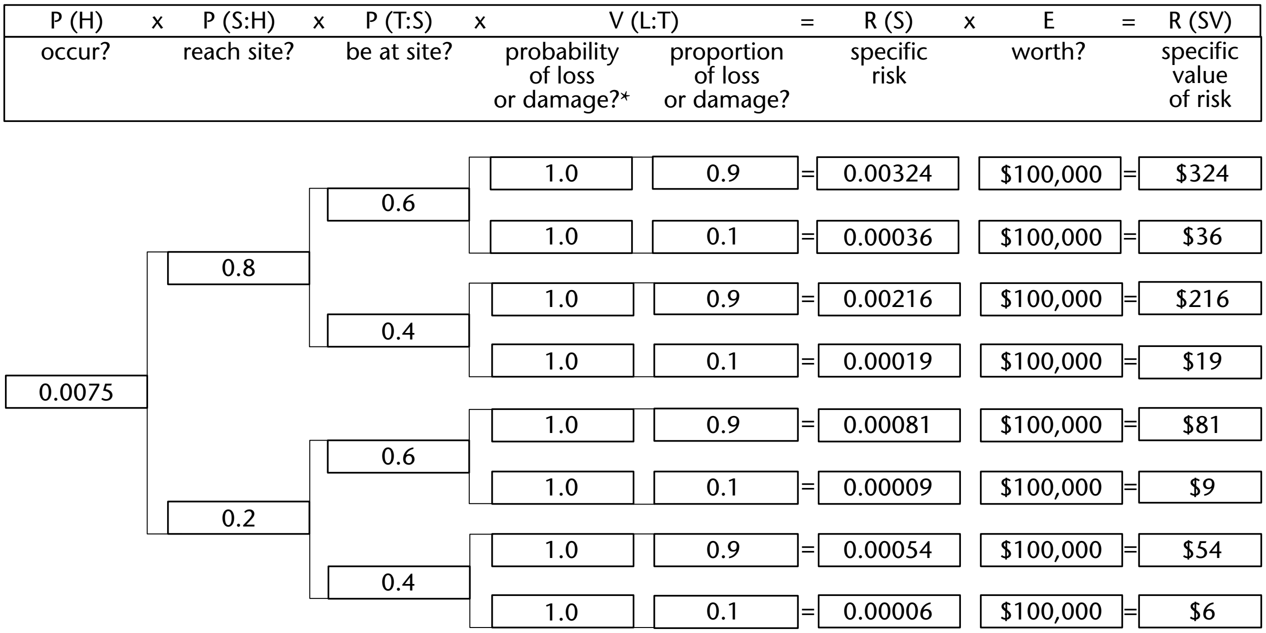
Event tree decomposition Event trees are a relatively simple and thorough method of decomposing the risk components. This method is usually associated with quantitative risk analysis, but can provide a helpful framework for qualitative risk analysis, particularly for more complex projects. An example of a simple quantitative event tree is shown as Figure 17.

Refer to Sections 3.4–3.6 for a description of the risk components. The numbers in this example event tree would have been estimated during risk analysis. For example, it would have been estimated that there is a 0.8 probability of the specific hazardous landslide reaching the site, and that there is a 1 - 0.8 = 0.2 probability of the specific hazardous landslide not reaching the site, given that the landslide occurs.

For a more complex analysis, the components can be subdivided, and more than two possible outcomes can be used to estimate any type of probability, vulnerability, and worth. The estimates can be either objective, or subjective (as is usually the case with landslides). The specific risks and specific value of risks located on the right side of each branch on Figure 17 are calculated by multiplying probabilities and values along the branch. As discussed in Sections 3.6.4 and 3.6.5, the estimation of multiple and total risk should be carried out by applying standard probability concepts (see, for example, Montgomery et al. 2002).

Several things to note that apply to all event trees:

- the sum of the outcomes of each component numerically adds up to 1. (With regard to P(H) in this example, there could be another arm showing that the probability of no failure is 1.0 - 0.0075 = 0.9925, but this is often excluded to simplify the event tree.)



* Assumes that some loss or damage is certain

FIGURE 17 *Example of a simple quantitative specific value of a risk event tree.*

- assumptions of probability or proportion = 1 simplify the event tree (see probability of loss or damage in this example), and
- one or a few components (P(H) in this example) can have a great deal of influence on the results.

Event trees encourage the analysis of many, if not all, of the appropriate components. During the analysis, if relative qualitative ratings are more appropriate than numbers, ratings can be used, but the event tree then becomes qualitative. In other cases, it may be beneficial to interpret and explain the numerical risk results using qualitative criteria. Where risk control options are being considered for analysis of specific value of risk, event trees can provide an economic basis for selecting the preferred risk control option.

Risk matrices Risk matrices are used to combine two risk components. This method is usually associated with qualitative risk analysis. Examples of two simple qualitative risk matrices are shown in Tables 8 and 9.

The risk components are in the lower left and upper right portions of the matrix. The resulting combination of the components is described in the italicized upper left portion of the matrix, and defined in the italicized lower right portion of the matrix. Criteria for the two sets of component ratings, and the resultant risk rating, must be defined. See Appendix 5, Table A5.3, for further examples.

For simplicity, the resulting risk and value of risk ratings in these tables have been assigned symmetrically, diagonally across the central portion of the matrix. This assumes some form of linear relationship between the ratings on the two axes. This is not often the case; for example, the risk from a low probability of occurrence and a very high consequence may not be equivalent to a very high probability of occurrence and a low consequence. For most practical purposes such tables will have to be modified to suit specific conditions and situations.

Risk matrices are usually qualitative, but if actual probabilities, vulnerabilities, and/or worth are expressed numerically, the resultant risk can be quantitative.

TABLE 8 *Example of a simple qualitative risk matrix for partial risk*

P(HA), annual probability (likelihood) of occurrence of a specific hazardous landslide and it reaching or otherwise affecting the site occupied by a specific element $P(HA) = P(H) \times P(S:H) \times P(T:S)$		**$P(S:H) \times P(T:S)$** **Probability (likelihood) that the landslide will reach or otherwise affect the site occupied by a specific element, given that the landslide occurs**		
		High	**Moderate**	**Low**
P(H), annual probability (likelihood) of occurrence of a specific hazardous landslide	Very high	*Very high*	*Very high*	*High*
	High	*Very high*	*High*	*Moderate*
	Moderate	*High*	*Moderate*	*Low*
	Low	*Moderate*	*Low*	*Very low*
	Very low	*Low*	*Very low*	*Very low*

TABLE 9 *Example of a simple qualitative risk matrix for specific value of risk to property*

R(SV), specific value of risk, expressed as an expected annual relative dollar loss of property value $R(SV) = P(H) \times CV_{property}$		**$CV_{property}$* $= P(S:H) \times P(T:S) \times V(L:T) \times E$** **Consequence value rating, expressed qualitatively in terms of relative dollar loss of property value**		
		High $ loss	**Moderate $ loss**	**Low $ loss**
P(H), annual probability (likelihood) of occurrence of a specific hazardous landslide	Very high	*Very high*	*Very high*	*High*
	High	*Very high*	*High*	*Moderate*
	Moderate	*High*	*Moderate*	*Low*
	Low	*Moderate*	*Low*	*Very low*
	Very low	*Low*	*Very low*	*Very low*

* It is assumed that, given a landslide, some loss or damage is certain, and the value of the loss will be proportional to the damage (e.g., if 25% of the timber resource were damaged, the value of the timber resource would be reduced by 25%).

CHAPTER 4 CASE STUDIES

4.1 Qualitative Analysis of Partial Risk and Specific Value of Risk from Roads, Landslides, and Gullies: San Juan River Watershed, Vancouver Island, British Columbia

ALAN CHATTERTON

Abstract

Watershed restoration activities were carried out in the San Juan River watershed on southern Vancouver Island to mitigate the loss of fisheries habitat due to landslides and sedimentation. To identify restoration opportunities and to maximize restoration efforts, government agencies and forest licence holders combined their efforts under the San Juan Watershed Agreement to carry out landslide risk management. Risk analysis involved compiling inventories of landslides, gully areas, and fish habitat. Additionally, reconnaissance terrain stability information was overlain on a map of the road system within the watershed to develop a qualitative ranking of potential for occurrence of road-related hazardous landslides that could adversely affect fish habitat. Risk evaluation was carried out to prioritize stabilization and restoration activities. Risk control actions included road deactivation, stabilization of active gully areas, and revegetation of existing landslides. The San Juan case study demonstrates the application of a framework for risk management to effectively address forest development–related landslide and sedimentation hazards on a watershed scale.

4.1.1 Introduction

The San Juan River watershed is a 67 000-ha drainage situated on the southwest coast of Vancouver Island (Figure 18).

Initial forest harvesting activities in the watershed were concentrated near the mouth of the San Juan River and Port Renfrew. During the 1940s and early 1950s, railway logging developed the majority of the main river valley and extended into some of the larger sub-basins. By the mid-1950s, truck logging replaced the railways. Active forest harvesting has continued to the present and has recently focused in the numerous sub-basins and their more steeply sloping terrain. Over the last 20 years, harvesting of second-growth stands in the headwaters of the watershed has accelerated (Figure 19).

The San Juan River watershed supports significant populations of salmon, steelhead, and resident rainbow and cutthroat trout. The steelhead sport fishery experienced a significant decline in the 1980s and 1990s and forest harvesting was suspected as a major

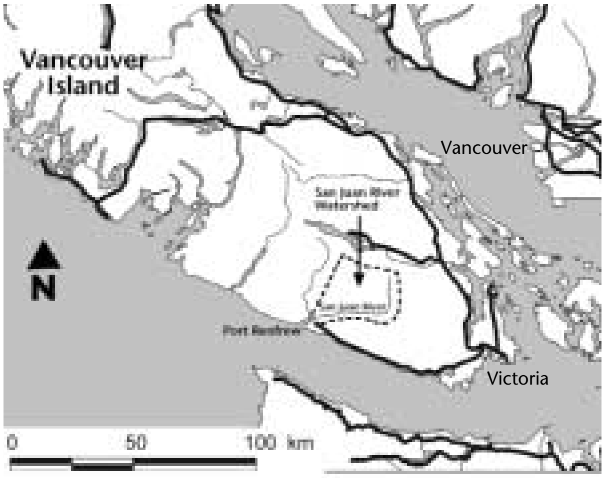


FIGURE 18 *Location of San Juan River Watershed, Vancouver Island, British Columbia.*

FIGURE 19 *Headwaters of the San Juan River valley showing recent second-growth logging (A. Chatterton photo).*

cause of fish habitat degradation. This prompted the B.C. Ministry of Environment, Lands and Parks to retain Northwest Hydraulics Consultants Ltd. (NHCL) to carry out an overview condition assessment to characterize the state of the watershed and to assess the impacts of sediment on the fisheries resource.

The NHCL (1994) report confirmed a link between "natural and harvesting-related sediment production in the watershed to changes in channel morphology and physical habitat of the San Juan River and its tributaries." The British Columbia provincial government recognized the immediate need to enhance the long-term survival of wild salmon stocks in the watershed and began to investigate opportunities with other stakeholders to restore, protect, and maintain fisheries values. Therefore, the San Juan Watershed Agreement (the Agreement) was signed on August 1, 1995 by TimberWest Forest Ltd., Pacific Forest Products Ltd., MacMillan Bloedel Ltd., Department of Fisheries and Oceans Canada, B.C. Ministry of Forests, and B.C. Ministry of Environment, Lands and Parks.

Key objectives of this agreement were to undertake a more comprehensive watershed study:

- to "identify high hazard roads, gullies, unstable slopes and channels that pose a serious risk to water quality, fish and riparian habitat"
- to "identify appropriate remedial measures to minimize or eliminate these risks"
- to "evaluate the hydrologic (discharge and sediment) regime of the San Juan River watershed with respect to forest land use history, on-going restoration measures and future monitoring needs," and
- to "identify future biophysical monitoring requirements, and establish hydrometric stations (including total suspended solids) at selected sites."

In addition, it was agreed that watershed restoration projects carried out under the Agreement would address specific sites and would be completed by December 31, 2001.

4.1.2 General site characteristics

The east-west oriented San Juan River fault bisects the San Juan River watershed. The mainstem of the San Juan River flows along the general alignment of the fault through broad, moderate to gently sloping valley-bottom terrain. To both the north and the south of this mainstem valley, several large tributary stream systems dissect more steeply sloping, bedrock-controlled terrain.

Deep glacial and post-glacial sediments predominate within the more gently sloping terrain of the mainstem valley. Natural and post-harvesting landslide processes in this area of the valley are primarily associated with steep scarp slopes that are the result of erosion processes related to the main river channel and its major tributaries. The bedrock-controlled slopes to the north and south of the mainstem valley are mantled, in large part, with shallow glacial till and post-glacial colluvial deposits. The texture of these surficial deposits reflects the character of the underlying bedrock.

On the north side of the valley, colluvial and glacial till materials consist predominantly of sand, gravel, and rubble-sized sediments derived from the relatively hard igneous rock types. On the south side of the valley, silts and clays are more abundant in the fine fraction of these materials and there is a reduced proportion of coarse fragments, reflecting the softer metamorphic bedrock of that area of the valley. Bedrock exposures are common, and the steep hillslopes are dissected by numerous smaller tributary channels that are incised in the underlying bedrock. Natural and post-harvesting instability in these more steeply sloping portions of the watershed are generally associated with these incised hillslope tributaries.

In addition, roads constructed across steeply sloping terrain have contributed to open slope landslides, predominantly debris slides and debris flows.

4.1.3 Landslide risk management

The Agreement identified several objectives and priorities for watershed restoration. To achieve these objectives, a landslide risk management process was implemented to facilitate informed resource management decisions. This process evolved as the study progressed, and eventually involved all the risk management steps from Project Initiation to Action/Monitoring.

Project initiation Project initiation involved establishing an administrative structure for the study. A Management Committee was formed, comprised of various senior personnel representing the Agreement holders. It provided general direction for the study, and established an overall budget and funding arrangements. The Management Committee appointed a Technical Steering Committee comprised of professionals having expertise in watershed processes and fishery resources. The Technical Steering Committee in turn appointed a full-time Project Coordinator to direct the day-to-day field activities in the watershed.

The role of the Technical Steering Committee was to implement the agreement, make decisions regarding risk evaluation and control, monitor and report on the various specific watershed restoration projects, prepare and release appropriate public reports, and provide for financial overview of completed watershed restoration works. It was also responsible for reviewing and directing the activities of the Project Coordinator and for reviewing and approving specific project proposals.

With input from interest groups and stakeholders, the Technical Steering Committee developed detailed terms of reference and a mission statement: "to assess and define the cause and extent of fish habitat destruction/deterioration in the San Juan watershed…and to determine remediation measures." The terms of reference related to the risk management process identified the following specific objectives for the watershed:

- review and summarize logging history;
- obtain up-to-date fish habitat inventories;
- document fish habitat restoration opportunities;
- assess stream hydrology, landslide activity, and stream channel changes;
- identify and document actual and potential sources of sedimentation;
- determine and document remedial measures required to stabilize landslides and unstable roads in riparian and upland areas that affect stream courses.

Preliminary analysis NHCL (1994) concluded that landslides were by far the greatest source of sediment delivered to stream channels. It also concluded that the majority of these landslides were associated with roads and harvesting on steeply sloping terrain. Furthermore, many of these landslides were associated with gully systems. A primary objective of the Agreement was to develop a more quantitative inventory of historic and potential landslide processes in the watershed, and this was initiated early in the San Juan study (Chatterton 1996). The specific objectives of this inventory were:

- to complete reconnaissance-level terrain stability mapping for those portions of the watershed for which no stability mapping was available, and
- to conduct a reconnaissance-level inventory of landslides and gully features in the entire watershed.

Reconnaissance terrain stability mapping existed for the southwestern half of the watershed. This terrain stability mapping was completed for the remainder of the watershed at a terrain survey intensity level D as described in Howes and Kenk (1988), BCMOF (1995b), and Chatterton (1996).

During the reconnaissance mapping, landslides showing evidence of relatively recent activity (unvegetated ground surface and/or seral brush species) and gullies with potential for failure were mapped throughout the watershed. These landslides and gullies were identified on the most recent 1:20 000 scale airphotos. The reconnaissance terrain stability mapping, landslides, and gullies were all transferred to 1:20 000-scale topographic maps. In addition, detailed databases describing the characteristics of each landslide and gully were compiled.

In order to initiate the risk analysis, fish and fish habitat inventories were completed for the San Juan River and 17 tributary stream systems. Within the watershed, detailed habitat surveys were completed at

76 locations and fish sampling was completed at 81 different sites (Griffith 1997) to determine which stream segments could be affected by sediment delivery to streams.

Risk estimation Risk estimation involved a qualitative analysis of the potential for the future road-related landslides and existing landslides and gullies, identified during the preliminary analysis to adversely affect fish habitat.

$P(HA)_{RL}$ – Partial risk analysis of future road-related landslides Because roads were identified as a major source of sediment, a map of all existing roads within the watershed was produced. By overlaying this map with the reconnaissance terrain stability map, a qualitative ranking of annual probability of occurrence of road-related hazardous landslides, $P(H)_{RL}$, was produced (Table 10).

Initially, the proximity of road segments to stream channels was used as the criterion to estimate the spatial probability that, given that a road-related landslide occurs, it would deliver sediment to a stream channel, $P(S{:}H)_{LSD}$. This criterion, however, proved to be an inaccurate indicator. An analysis of other criteria, such as the history and condition of road construction and previous deactivation, downslope site conditions, and anticipated future use of each road segment, was found to be a better indicator of $P(S{:}H)_{LSD}$.

However, the costs required to collect and analyze the information required to estimate $P(S{:}H)_{LSD}$ were considered to be excessive and not warranted. For the analysis, it was assumed that debris from any new road-related landslide would reach the fish stream and fish habitat, and therefore $P(S{:}H)_{LSD}$ was estimated to be certain. These criteria were, however, considered at the site level when subsequent road deactivation prescriptions were developed.

The streams have a fixed position, and therefore temporal probability, $P(T{:}S)$, was estimated to be certain.

Partial risk, $P(HA)_{RL}$ is mathematically expressed as:

$$P(HA)_{RL} = P(H)_{RL} \times P(S{:}H)_{LSD} \times P(T{:}S)$$

Because $P(S{:}H)_{LSD}$ and $P(T{:}S)$ were both estimated to be certain (numerically = 1), the expression for $P(HA)_{RL}$ reduces to:

$$P(HA)_{RL} = P(H)_{RL}$$

Table 11 summarizes the partial risk.

$P(HA)_{SE}$ – Partial risk analysis of sedimentation from existing landslides Airphotos were examined to locate all existing landslides within the watershed, and to identify their characteristics, such as *landslide type* (debris slide, debris avalanche, debris flow, rockslide), *landslide origin* (natural, road, clearcut), and *landslide terminus* (midslope, toe slope, tributary stream, mainstem stream).

Based on the results of the airphoto examination, qualitative estimates were made of:

- the probability (likelihood) of occurrence of hazardous soil erosion originating from the surface of an existing landslide, $P(H)_{SE}$ (Table 12), and
- the spatial probability (likelihood) that, given that soil erosion originates from the surface of an existing landslide, sediment will be delivered to a fish stream and fish habitat, $P(S{:}H)_{ESD}$ (Table 13). $P(S{:}H)_{ESD}$ is closely related to the connectivity of the landslide to the stream.

TABLE 10 *Probability (likelihood) of occurrence of road-related hazardous landslide, $P(H)_{RL}$*

$P(H)_{RL}$, expressed as an annual likelihood	**Location of road segment***
Low likelihood	Road constructed through terrain mapped as stable – a road-related landslide is unlikely, or could occur only under exceptional circumstances
Moderate likelihood	Road constructed through terrain mapped as potentially unstable – a road-related landslide could occur under very adverse conditions
High likelihood	Road constructed through terrain mapped as unstable – a road-related landslide is expected to occur, or will likely occur under adverse conditions

* Note: Since there is a lack of detailed information regarding road construction techniques, all roads were assumed to have conventional cut and fill (sidecast) construction.

Again, the streams have a fixed position, and the temporal probability, P(T:S), was estimated to be certain. Therefore, the expression for partial risk, $P(HA)_{SE}$ reduces to:

$$P(HA)_{SE} = P(H)_{SE} \times P(S:H)_{ESD}$$

A qualitative risk matrix (Table 14) was used to estimate $P(HA)_{SE}$ for existing landslides.

$P(HA)_{GF}$ – Partial risk analysis of future gully failures As in the case of the landslide inventory, the gully inventory included the collection of additional information: *gully terminus* was described (midslope, toe slope, tributary stream, mainstem stream) in the same manner as that for the landslides.

TABLE 11 *Qualitative partial risk rating of road-related landslides, $P(HA)_{RL}$*

Time period	**$P(H)_{RL}$**	**$P(S:H)_{LSD}$**	**P(T:S)**	**Probability of occurrence of a hazardous road-related landslide and probability of landslide debris reaching a fish stream, $P(HA)_{RL}$**
Annual	Low likelihood	Certain	Certain	Low likelihood
Annual	Moderate likelihood	Certain	Certain	Moderate likelihood
Annual	High likelihood	Certain	Certain	High likelihood

TABLE 12 *Probability (likelihood) of occurrence of hazardous soil erosion originating from the surface of an existing landslide, $P(H)_{SE}$*

$P(H)_{SE}$ (expressed as an annual likelihood)	**Description of existing landslide**
Nil	Stable natural landslide that has remained inactive since the inception of forest harvesting. (For the purposes of this study these landslides were not mapped).
Low likelihood	Revegetated landslide track or slide track with airphoto evidence of boulder and or bedrock substrate – sediment generation is unlikely, or could occur only under exceptional circumstances
Moderate likelihood	Partially revegetated landslide track – sediment generation could occur under very adverse conditions
High likelihood	Landslide track consists primarily of exposed, unvegetated soils and surficial materials – sediment generation is expected to occur, or will likely occur under adverse conditions

TABLE 13 *Spatial probability (likelihood) that, given that soil erosion originates from the surface of an existing landslide, the sediment will be delivered to the fish stream and fish habitat, $P(S:H)_{ESD}$ (adapted from BCMOF 1995a)*

$P(S:H)_{ESD}$	**Connectivity**	**Description of existing landslide and connectivity**
Low likelihood	Not connected	Landslide having no observable stream connectivity to downslope streams – sediment delivery is very unlikely, or could occur only under exceptional circumstances
Moderate likelihood	Indirect	Landslide that discharges into non–fish-bearing streams with a channel gradient less than 5% over a minimum distance of 100 m before reaching fish habitat – sediment delivery could occur under very adverse circumstances
High likelihood	Direct	Landslide that is connected directly to a stream channel that does not have a low-gradient buffering reach between the slide terminus and fish habitat – sediment delivery is expected to occur, or will likely occur under adverse circumstances

Based on this information, together with the logging history associated with each gully, estimates were made of:

- the probability (likelihood) of occurrence of a hazardous gully failure, $P(H)_{GF}$ (Table 15)
- the spatial probability (likelihood) that, given a gully failure, sediment will be delivered to a fish stream and fish habitat, $P(S:H)_{GSD}$.

$P(S:H)_{GSD}$ was estimated using the same criteria developed for landslides in Table 13.

Again, the streams have a fixed position, and the temporal probability, $P(T:S)$, was estimated to be certain.

The expression for partial risk, $P(HA)_{GF}$, reduces to:

$$P(HA)_{GF} = P(H)_{GF} \times P(S:H)_{GSD}$$

A qualitative risk matrix (Table 16) was used to estimate $P(HA)_{GF}$.

R(SV) – Specific value of risk to fish habitat The determination of specific value of risk to fish habitat, $R(SV)$, required estimates of the vulnerability, $V(L:T)$, and relative worth, E, of the fish habitat.

To simplify the estimate of $V(L:T)$, it was assumed that all fish and fish habitat would be lost with any amount of sedimentation delivered to the stream (numerically $V(L:T) = 1$). Therefore, the risk component $V(L:T)$ can be ignored in the estimates of $R(SV)_{RL}$, $R(SV)_{SE}$, and $R(SV)_{GF}$.

In addition to identifying the location of fish streams, the fish and fish habitat inventories provided information with respect to the relative worth, E, of the various fishery resources within the watershed. A relative qualitative rating for E of the various fish habitats (poor, fair, and good) used in Table 17, was based on specific habitat quality criteria defined by Griffith (1997).

A qualitative risk matrix (Table 17) was used to estimate specific value of risk. The specific value of risk to fish habitat from road-related landslides, soil erosion from existing landslides, and gully failures can be expressed as follows, respectively:

$$\begin{aligned} R(SV)_{RL} &= P(HA)_{RL} \times E \\ R(SV)_{SE} &= P(HA)_{SE} \times E \\ R(SV)_{GF} &= P(HA)_{GF} \times E \end{aligned}$$

TABLE 14 *Qualitative partial risk matrix for soil erosion, $P(HA)_{SE}$*

$P(HA)_{SE}$, annual probability (likelihood) of hazardous soil erosion originating from the surface of an existing landslide and it reaching fish stream and fish habitat $P(HA)_{SE} = P(H)_{SE} \times P(S:H)_{ESD}$		**$P(S:H)_{ESD}$ Probability (likelihood) that sediment from the erosion event will reach a fish stream and fish habitat**		
		Low likelihood (no connectivity to a fish stream)	**Moderate likelihood (indirect connectivity to a fish stream)**	**High likelihood (direct connectivity to a fish stream)**
$P(H)_{SE}$, annual probability (likelihood) of occurrence of hazardous soil erosion originating from the surface of an existing landslide	Low likelihood	*Very low*	*Low*	*Moderate*
	Moderate likelihood	*Low*	*Moderate*	*High*
	High likelihood	*Moderate*	*High*	*Very high*

TABLE 15 *Probability (likelihood) of occurrence of a hazardous gully failure, $P(H)_{GF}$*

$P(H)_{GF}$	**Logging history**	**Description of logging history**
Low likelihood	Unlogged	Gully situated in unlogged terrain or has been buffered by a leave area of standing timber
Moderate likelihood	Old logging	Gully with any portion logged before 1985
High likelihood	Recent logging	Gully with any portion logged since 1985

TABLE 16 *Qualitative partial risk matrix, $P(HA)_{GF}$*

$P(HA)_{GF}$, annual probability (likelihood) of occurrence of a hazardous gully failure and it reaching a fish stream and fish habitat $P(HA)_{GF} = P(H)_{GF} \times P(S:H)_{GSD}$		**$P(S:H)_{GSD}$ Probability (likelihood) that sediment from the gully failure will reach a fish stream and fish habitat**		
		Low likelihood (no connectivity to a fish stream)	**Moderate likelihood (indirect connectivity to a fish stream)**	**High likelihood (direct connectivity to a fish stream)**
$P(H)_{GF}$, Annual probability (likelihood) of occurrence of a hazardous gully failure	Low likelihood	*Very low*	*Low*	*Moderate*
	Moderate likelihood	*Low*	*Moderate*	*High*
	High likelihood	*Moderate*	*High*	*Very high*

TABLE 17 *Qualitative risk matrix for specific value of risk to fish habitat*

$R(SV)_{RL}$, $R(SV)_{SE}$, or $R(SV)_{GF}$ Specific value of risk, expressed as an expected annual relative dollar loss of fishery resource values		**Relative value of the fishery resource, E***		
		Poor relative worth = Low $ loss	**Fair relative worth = Moderate $ loss**	**Good relative worth = High $ loss**
$P(HA)_{RL}$, $P(HA)_{SE}$, or $P(HA)_{GF}$	Low	*Very low*	*Low*	*Moderate*
	Moderate	*Low*	*Moderate*	*High*
	High	*Moderate*	*High*	*Very high*

* Note: The risk component V(L:T) can be ignored in the estimates of $R(SV)_{RL}$, $R(SV)_{SE}$, and $R(SV)_{GF}$ since it is assumed that all fish and fish habitat would be lost with any amount of sedimentation delivered to the stream. In a quantitative analysis for this case, V(L:T) would be equal to 1.

Although not used in this case study, combining the specific value of risks, $R(SV)_{RL}$, $R(SV)_{SE}$, and $R(SV)_{GF}$ to obtain an R(M) (multiple risk) provides the overall specific value of risk to the fish habitat.

Risk evaluation and risk control From the specific value of risk analyses and the resulting multiple specific value of risk to fish habitat, opportunities for hillslope stabilization that could yield definite benefits to the downslope/downstream fishery resources were identified. Three types of hillslope stabilization projects were considered to have the potential to generate significant benefits. Road deactivation, landslide stabilization, and gully cleanout can significantly reduce the amount of sediment generated from hillslopes, and in turn reduce the potential for sediment to reach fish habitat. Both hillslope restoration by road fill and pullback (Figure 20) and water management with armoured cross-drains (Figure 21) were carried out for road deactiviation.

Where the specific value of risk to fish habitat from road-related landslide sedimentation $R(SV)_{RL}$ was *high* or *very high,* those roads were considered as candidates for deactivation. Where the specific value of risk to fish habitat from soil erosion originating from existing landslides $R(SV)_{SE}$ was *high* or *very high*, those landslides were considered for stabilization. Where the specific value of risk to fish habitat from

FIGURE 20 *Permanently deactivated road in the Williams Creek sub-basin (A. Chatterton photo).*

gully failures $R(SV)_{GF}$ was *high* or *very high,* debris cleanout was considered.

These hillslope stabilization strategies are common to the forest industry, and general costs for each are fairly well documented. Using available published information, it was possible to compare and evaluate the costs of specific project opportunities, and the benefits of carrying out the work, together with consideration of the relative worth of the fish habitat. After this qualitative comparison and evaluation of costs and benefits, it was possible to develop a ranked list of specific projects worthy of more detailed consideration.

On the basis of the specific project list, a series of detailed project plans for road deactivation, landslide stabilization, erosion control (Figure 22), and gully cleanout was developed by experienced consultants and contractors for the identified *high* and *very high* specific value of risk sites. In addition, some of the *moderate* specific value of risk sites that suggested an opportunity for relatively high benefit/cost also had detailed project plans developed. These detailed project plans more accurately determined the costs and benefits associated with each project, and by doing so, the final project priority list for hillslope stabilization projects was established for projects with detailed plans.

FIGURE 21 *Armoured cross-drain on a semi-permanently deactivated road in the Three Arm Creek sub-basin (A. Hasanen photo).*

The question of stabilizing natural (non-forestry related) landslide and gully failures arose. There was general consensus that natural landslides are integral to natural watershed processes and, as such, should be left in a natural condition. It was apparent, however, that stabilization of some natural failures identified by Chatterton (1998) could possibly yield a greater benefit to downslope fishery values than the stabilization of some of the harvesting- or road-related landslides.

In addition to the landslide and sediment risk control measures, several fish habitat enhancement projects, relating primarily to establishing access to previously inaccessible habitat and habitat complexing, were considered. Similar to the hillslope stabilization projects, the fish habitat enhancement projects underwent a similar process of comparing and evaluating costs and benefits. Subsequently, these fish habitat enhancement projects were merged with the hillslope stabilization project ranking list to form a comprehensive list of projects for risk control.

Action/Monitoring Specific projects with the potential to yield relatively high benefits to the San Juan River fishery resources relative to their cost were completed in accordance with the detailed project plans. The number of specific projects completed was

FIGURE 22 *Hydroseeding exposed road cutslopes in the Lens Creek sub-basin (A. Hasanen photo).*

largely determined by the total budget for the study. Table 18 summarizes the majority of the watershed restoration work completed in the San Juan River area.

The specific projects described in Table 18 were completed throughout the period 1996–2001. Because of the duration of the study, it was possible to monitor the effectiveness of many of the completed projects as work was continuing on other specific projects. By doing so, the specific activities in the watershed could be adjusted and modified to achieve the highest possible benefit. It was also possible to identify and take advantage of efficiencies and cost savings associated with simultaneously carrying out more than one project in a given area.

Several of the fish habitat enhancement projects had identified monitoring components that continued to the termination of the Agreement on December 31, 2001. The remaining projects were monitored on an informal basis during the life of the Agreement but there was no written documentation of this informal monitoring.

4.1.4 Concluding remarks

The comprehensive watershed study of the San Juan River Agreement identified several objectives and priorities for watershed restoration projects. This involved the implementation of a landslide risk management process to facilitate informed resource management decisions. As indicated at the outset, the San Juan River Agreement did not specifically outline a risk management decision-making framework. This process evolved as the overall study proceeded. It is anticipated that some efficiencies would have resulted if a detailed landslide risk management process had been established at the start of the study. In large part, the success of the project was the result of the planning structure that evolved throughout the study.

Overall, the study was a significant success for the fishery resources of the San Juan River watershed. Despite the magnitude and complexity of the comprehensive study undertaken for the Agreement, the stated objectives were, for the most part, achieved on time and within the overall budget. Two specific opportunities for improvement are evident. First, the time-limited nature of the study did not specify any effectiveness monitoring of the results beyond December 31, 2001. Such monitoring could have offered significant guidance to similar projects in the future. Second, there was no final retrospective report of the study to document the "lessons learned" to benefit future studies of a similar scope.

4.1.5 Acknowledgements

Bob Willington, PhD (TimberWest technical representative to the San Juan Watershed Agreement Steering Committee) and Steve Lorimer (Chair of the San Juan Watershed Agreement Steering Committee), both of TimberWest Forest Corporation Ltd., provided access to their project file information for the preparation of this case study. In addition, they provided a great deal of non-documented background information with respect to the project and edited drafts of the report with respect to technical aspects of the project. Jim Schwab, Research Geomorphologist with the B.C. Ministry of Forests, Smithers also reviewed a draft of this case study and provided helpful comments.

4.1.6 Dedication

This case study is dedicated to the memory of Bob Willington, PhD.

TABLE 18 *Specific project summary list*

Activity	Description
Road deactivation	Over 500 km of deactivated road (includes roads deactivated prior to the project)
Landslide stabilization	Over 100 ha of aerial hydroseeding of historic landslides and exposed soils
Gully cleanout	Approximately 20 gullies assessed for cleanout; however, none of these actually required cleanout
Fish habitat restoration	Approximately 30 in-stream fish habitat enhancement projects primarily related to access restoration and habitat complexing. Approximately 45 ha of riparian zone planting and stabilization

4.1.7 References

British Columbia Ministry of Forests and B.C. Environment. 1995a. Gully assessment procedure guidebook. Forest Practices Code of British Columbia, B.C. Forest Service and B.C. Environment, Victoria, B.C.

________. 1995b. Mapping and assessing terrain stability guidebook. Forest Practices Code of British Columbia, B.C. Forest Service and B.C. Environment, Victoria, B.C.

Chatterton, A.N. 1996. San Juan River watershed landslide gully and terrain assessment. Unpublished report prepared for the San Juan Watershed Agreement Steering Committee.

________. 1998. San Juan River watershed natural landslide rehabilitation. Unpublished report prepared for the San Juan Watershed Agreement Steering Committee.

Griffith, R.P. 1997. Assessment of fish production and restoration requirements in the San Juan River drainage. Unpublished report prepared for the San Juan Watershed Agreement Steering Committee.

Howes, D.E. and E. Kenk. 1988. Terrain classification for British Columbia. Recreational Fisheries Branch, B.C. Ministry of Environment and B.C. Ministry of Crown Lands, Victoria, B.C. MOE Manual 10.

Northwest Hydraulics Consultants Ltd. 1994. Impact of forest harvesting on terrain stability, stream channel morphology and fishery resources of the San Juan River watershed, Vancouver Island. Unpublished report prepared for the B.C. Ministry of Environment, Lands and Parks, Vancouver Island Region 1.

4.2 Qualitative Analysis of Partial Risk from a Proposed Cutblock: Oliver Creek Watershed, Columbia Mountains, British Columbia

TIMOTHY SMITH

Abstract

A qualitative partial risk analysis is presented that describes the risk from debris slides and debris flows to fish habitat in the adjacent Oliver Creek drainage, following proposed timber harvesting on steep mountainous terrain. The proposed cutblock was divided into four separate polygons and the partial risk was estimated for both debris slides and combined debris slide / debris flow events. This analysis includes estimates of the likelihood of occurrence of these landslide events and the spatial and temporal probabilities that the events would reach or affect Oliver Creek. The analysis showed that the P(HA) to fish habitat from a debris slide initiating on an open slope, entering the gullied reach of a fish stream, and triggering a debris flow event is very high. The proposed cutblock was modified to reduce this very high partial risk to an acceptable level.

4.2.1 Introduction

This case study describes the results of a qualitative analysis of partial landslide risk to the fishery resource from harvesting a proposed cutblock within the Oliver Creek watershed, in the interior of British Columbia. The analysis of risk to other elements, such as standing timber, productive growing sites, and future plantations, is not covered. Snow avalanche hazards are also briefly discussed. Several risk control options are identified.

This risk analysis forms part of a larger study that assessed the post-harvest landslide and snow avalanche hazards associated with this proposed cutblock. Because no terrain stability mapping was available for the area, the risk assessments were required as part of legislative requirements due to the natural landslide and snow avalanche activity in the area, and slope gradients within the cutblock that exceeded 60%.

4.2.2 Background information

General The Oliver Creek watershed is located southeast of Tumtum Lake in the upper Adams River watershed, in the interior of British Columbia (Figure 23). The watershed is in the Columbia Mountains, west of the Rocky Mountain Trench, and is characterized by high mountains and deep, steep-sided valleys. The valleys were intensely glaciated and, on retreat of the ice, a mantle of glacial drift was deposited, deeper on the valley bottoms than on the sides (Holland 1976).

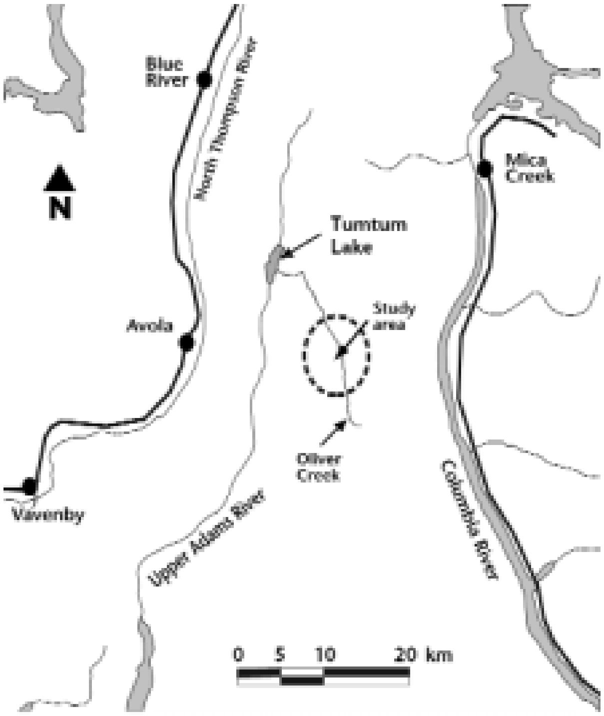


FIGURE 23 *The general location of the study area in the Oliver Creek watershed, to the southeast of Tumtum Lake.*

The Columbia Mountains are composed of Precambrian meta-sedimentary rocks and Paleozoic and Mesozoic sedimentary and volcanic formations, both intruded by granitic plutonic rocks. The bedrock in the Oliver Creek watershed forms part of the Shuswap Metamorphic Complex and is composed predominantly of micaceous quartzite, amphibolite, paragneiss, and cal-silicate rocks (Campbell 1963). The surficial materials within the watershed consist of morainal blankets (predominantly sandy, silty, gravelly till) in the valley bottoms and on the lower valley walls, and bedrock with scattered colluvial veneers on the steep mid- to upper valley walls (Fulton et al. 1986).

Proposed cutblock The British Columbia Ministry of Forests (MOF) commenced timber harvesting in the Oliver Creek watershed in 1990. The MOF proposed several cutblocks in this watershed for clearcut helicopter harvesting in 2004/2005, including cutblock A66213-4, discussed in this case study (Figure 24).

The proposed cutblock is located on northeasterly facing, moderately steep to very steep slopes to the southwest of Oliver Creek. It is situated on the lower to mid-slopes between elevations 1000 and 1280 m. The overall shape of the slope of the development area is concave, with 95–100% gradient slopes adjacent to the upper falling boundary and 20–25% gradient slopes to the northeast of the lower falling boundary. These 20–25% gradient slopes extend downslope approximately 175–200 m slope distance to the channel of Oliver Creek from Falling Corner 1 (FC 1).

Cutblock polygon descriptions For the purpose of this case study, the cutblock has been divided into four polygons (refer to Figure 24), and the terrain attributes of the polygons are described in Table 19. Based on field inspection, weathered colluvium generally overlies bedrock on the valley walls and morainal soils on the valley bottom. Bedrock out-

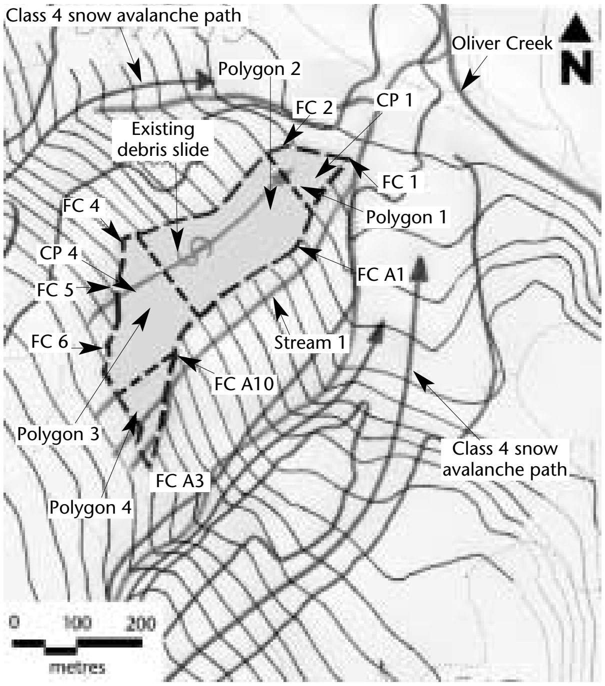


FIGURE 24 *The cutblock location map showing polygons and other features.*

TABLE 19 *Summary of polygon attributes in the proposed cutblock*

Polygon	Slope gradients	Surficial materials*	Slope configuration	Additional attributes and comments
1	20%–50%	Mb/Cv	Uniform and straight	FC 1 is approximately 175–200 m from Oliver Creek
2	50%–90%	Cv/Cb/R	Uniform and straight	Colluvium is rapidly drained and is clast supported; clast size varies from 0.5 to 3.0 m wide
3	90%–100%	Cv/R	Uniform and straight, to stepped (due to bedrock outcrops)	Colluvium is well to rapidly drained and varies from clast to matrix supported
4	90%–100%	Cv/R	Uniform and straight, to stepped (due to bedrock outcrops)	Colluvium is well to rapidly drained and varies from clast to matrix supported Considerable seepage present

* Terrain symbols from Howes and Kenk (1997).

crops are scattered across the upper slopes of the cutblock.

The weathered colluvium within the cutblock varies from clast supported on the lower to mid-valley walls, to matrix supported on the upper slopes. These predominantly coarse-grained materials consist of medium coarse to coarse, gravelly sand with some silt, to silty sand, and are well drained to rapidly drained. The gravelly and bouldery clasts in this colluvium range from angular to sub-rounded.

Observed geomorphic processes Naturally occurring debris slides, rockfalls, and snow avalanches are prevalent on the upper slopes and in the alpine areas within the Oliver Creek drainage. The debris slides and rockfalls have triggered debris flows where the event was confined to deeply incised gully systems. These events generally travelled to the valley bottom and in many cases have reached Oliver Creek.

No landslides were noted in the harvested cutblocks within this drainage; however, logging activities only commenced in this area in 1990. In addition, many of these logging activities were confined to the lower and lower mid-slope areas, where the slope gradients generally did not exceed 70%. Jordan (1995) found that landslide activity in harvested cutblocks in the southern interior of British Columbia generally increases with increasing slope, to a maximum of 40° (84%), where bedrock generally outcrops. An increase in post-harvest landslide activity was expected for the proposed cutblock, because the logging activities were to be conducted on steeper slopes.

A debris slide (estimated to be older than 100 years) is located within the proposed cutblock (Figure 24). The headscarp of this debris slide is situated on the very steep slopes (90–100%) upslope from Cruise Plot 4, outside the proposed cutblock. The surficial material exposed in the headscarp is composed of a veneer (<0.3 m) of weathered colluvium, overlying bedrock. Groundwater seepage was present in the headscarp of this landslide. Partial deposition (i.e., debris levees) is present on the moderately steep to steep slopes (50–75%) in Polygons 2 and 3, with most of the deposition occurring on the moderate to moderately steep slopes (35–50%) in Polygon 1, adjacent to Cruise Plot 1 (CP 1).

Several small, more recent debris slides (estimated to be older than 10 years) are present on the very steep slopes located in Polygon 4. The debris from these landslides travelled 15–25 m downslope. The surficial material in this polygon consists of a veneer (<0.3 m) of weathered colluvium, overlying bedrock. Considerable groundwater seepage was noted on these slopes.

Several older rockfall events have originated from the very steep bedrock bluffs within and upslope from Polygons 3 and 4. Some of the debris from these landslides has deposited on the moderately steep to very steep slopes within the cutblock.

A class S6 stream (Stream 1), having an average channel width of 1 m, originates from the seepage area on the very steep slopes upslope from Polygon 4 (Figure 24). This stream is gullied adjacent to FC A10 and is incised 4–5 m into the surficial materials on the surrounding moderately steep to steep slopes. The gullied reach parallels the southeastern falling boundary (outside the cutblock) down to FC 1. From FC 1 the gullied sidewalls diminish as the adjacent slope gradients decrease to 30–35%. At this location the stream turns northward to Oliver Creek. This lower reach, close to Oliver Creek, is a class S3 stream (fish bearing), having a stream width of 3–4 m. Debris levees and lobes adjacent to the channel of this stream extend from FC A1 to FC 1. This deposition zone is approximately 20–30 m wide.

Two large, natural snow avalanche paths, Size 4 or greater, are located northwest and southeast of the

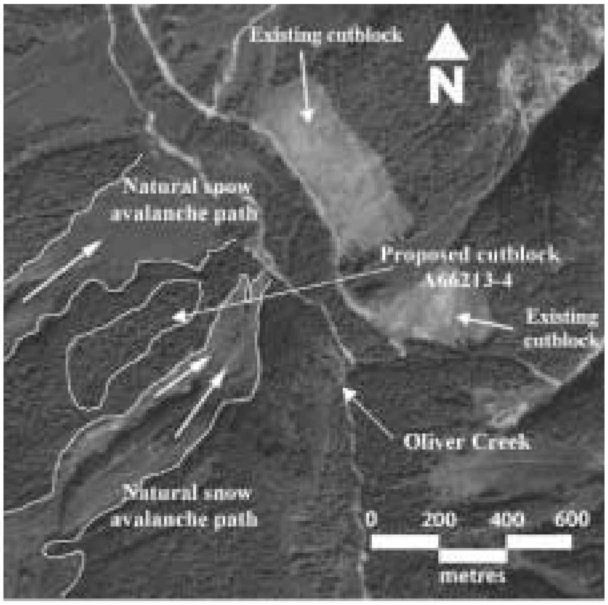


FIGURE 25 *A 2001 airphoto showing the approximate location of the proposed cutblock and adjacent geographic features. Airphoto reference: 30BCC 00050 No. 152.*

proposed cutblock (Figure 25). A Size 4 snow avalanche has impact pressures >500 KPa and can destroy a forest with an area of up to 4 ha (McClung and Scherer 1981). These snow avalanches have reached Oliver Creek. Wind damage to the limbs on the mature trees that flank these avalanche paths was noted. The northwestern falling boundary is located 70–80 m from the edge of the northern avalanche path, and the southeastern falling boundary is located 50–150 m from the edge of the southern avalanche path.

4.2.3 Landslide risk management

Landslide risk analysis Partial risk, P(HA), is the product of the probability of occurrence of a specific hazardous landslide and the probability of that landslide reaching or otherwise affecting the site occupied by a specific element. Partial risk is mathematically expressed as:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S)$$

In a qualitative partial risk analysis, P(H) refers to the likelihood of a landslide occurring, where likelihood is a qualitative description of probability or frequency (Australian Geomechanics Society 2000).

The sites of the fish-bearing streams are geographically fixed, and therefore the temporal probability, P(T:S), was estimated to be certain. In a quantitative analysis, the temporal probability P(T:S) would be equal to 1. Therefore, the expression for partial risk to the fishery resource in the streams reduces to $P(HA) = P(H) \times P(S{:}H)$.

Based upon work by Sidle and Wu (1999) in coastal watersheds in the Pacific Northwest, it is assumed that after 20 years the reinforcing effect to the composite shear strength from new root growth (from the re-planted trees) will have been regained. Experience suggests that the landslide likelihood ratings for this case study should be based on a 30-year time period following harvesting, due to the short growing season affected by the northeasterly aspect and the deep snowpack in this area.

When qualitative terms are used to describe probability of occurrence, P(H), they need to be defined. For this study, Table 20 describes the qualitative probability of occurrence ratings (likelihood of occurrence) over a 30-year period after harvesting.

Table 20 was modified from Table 2 in Chapter 3 to show an assumed relationship among qualitative likelihood of occurrence ratings, quantitative annual probability of occurrence, probability of occurrence over a 30-year time period after harvesting, and associated qualitative descriptions.

TABLE 20 *Definitions of qualitative ratings for P(H)*

Likelihood of occurrence, P(H), over a 30-year time period after harvesting	Annual probability of occurrence Pa	Long-term probability of occurrence, Px, over 30 years (rounded)	Qualitative description of site conditions*
Very low	<0.0002	<0.005	Likelihood of a landslide is very remote under the existing or assumed site conditions
Low	0.0002–0.001	0.005–0.03	Likelihood of a landslide is remote, although it is possible, given specific combinations of site conditions
Moderate	0.001–0.01	0.03–0.3	Landslide is not likely, but possible if there was a significant change to one or more of the assumed site conditions
High	0.01–0.1	0.3–0.96	Landslide is probable unless the site conditions are significantly better than assumed
Very high	>0.1	>0.96	Landslide is imminent regardless of reasonable changes in the assumed site conditions

*Site conditions refer to the geomorphic, hydrologic, and climatic conditions present.

The estimated likelihood of landslide occurrence within the four polygons is presented in Table 21, along with the supporting rationale.

P(S:H) is the likelihood of a landslide reaching the fish habitat within the class S3 reach of Stream 1 or Oliver Creek. In this study, the risk matrix shown in Table 22 was used to combine P(H) and P(S:H) to obtain P(HA).

P(H) and P(S:H) – Polygons 1, 2, and 3 For debris slides that initiate from Polygon 1, 2, or 3, the partial risk is simply the product of the likelihood of a landslide initiating within the area and the likelihood of the landslide reaching the fish habitat in the class S3 reach of Stream 1 or Oliver Creek (Table 23). As discussed, the existing debris slide, which originated upslope from Polygon 3, did not extend beyond the moderate to moderately steep slopes adjacent to Cruise Plot 1 (contained within Polygon 1). This plot is approximately 100 m from the channel of the class S3 reach of Stream 1 and is separated by 25–35% slopes. Thus, there is a *low* likelihood that a landslide originating from these polygons would reach the fishery habitat in this stream.

P(H) and P(S:H) – Polygon 4 For a debris slide that initiates within Polygon 4, two end members of possibilities were considered and analyzed.

The first possibility is that the debris slide would not extend beyond the slopes in this polygon, as supported by the recent events noted during the fieldwork. The P(S:H) for this possibility is the same as for Polygons 1, 2, or 3.

The second possibility is that the debris slide would be of a sufficient magnitude to enter the gullied reach of Stream 1, and trigger a debris flow. Strictly speaking, P(H) for this possibility is the product of the likelihood of debris slide initiation and the likelihood of debris flow initiation, given that the debris slide entered the gullied reach of Stream 1. For simplicity, and to be conservative, for this case study it was assumed that if a debris slide entered the gul-

TABLE 21 *The P(H) of each polygon and supporting rationale*

Polygon	P(H)	Rationale
1	Very low	Gentle to moderate slopes (30–50%)
2	Low	Rapidly drained and angular texture of the surficial materials; thickness of the surficial layer (>1 m)
3	Moderate	Rapidly drained and angular texture of the surficial materials; thickness of the surficial layer (<0.5 m); very steep slopes (i.e., 90–100%)
4	Very high	Recent landslides; thickness of the surficial layer (<0.5 m); considerable groundwater seepage; very steep slopes (i.e., 90–100%)

TABLE 22 *Qualitative partial risk matrix*

P(HA) = P(H) x P(S:H), likelihood of occurrence of a specific hazardous landslide and it reaching a fish stream over the 30-year time period after harvesting*		**P(S:H), likelihood that a landslide will reach a fish stream, given that the landslide occurs**		
		Low	**Moderate**	**High**
P(H), likelihood of occurrence of a specific hazardous landslide over a 30-year time period after harvesting	Very low	*Very low*	*Very low*	*Low*
	Low	*Very low*	*Low*	*Moderate*
	Moderate	*Low*	*Moderate*	*High*
	High	*Moderate*	*High*	*Very high*
	Very high	*High*	*Very high*	*Very high*

* In this case study, for simplicity, the resulting risk values in this table have been assigned symmetrically, diagonally across the central portion of the matrix. This assumes some form of linear relationship between the ratings on the two axes. This is not often the case.

TABLE 23 *Results of the qualitative partial risk analysis for the proposed cutblock*

Polygon	P(H) (from Table 21)	Estimated magnitude of landslide	P(S:H)	P(HA) from Table 22
1	Very low	100–250 m^3	Low	Very low
2	Low	250–1000 m^3	Low	Very low
3	Moderate	1000–2000 m^3	Low	Low
4 (1st possibility - a debris slide, but no debris flow)	High	25–50 m^3	Low	Moderate
4 (2nd possibility - a debris slide and a debris flow)	High	1000–2000 m^3	High (for the transport of fine-grained sediment to fish habitat)	Very high

lied reach of Stream 1, a debris flow would occur.

If initiated, the distance that a debris flow would travel in the gullied reach of Stream 1 depends on the characteristics of both the debris flow and the gully. For this case study, it was assumed that the majority of the coarse debris would travel approximately 300–400 m downslope, and would likely be deposited on the more moderate channel gradient adjacent to FC A1 and FC 1. Furthermore, it was assumed that the fine-grained sediment (sand size particles and smaller) from the debris flow would be carried in suspension to the fish-bearing reach of this stream and Oliver Creek.

Table 23 presents a summary of the results of the partial risk analyses for the four polygons within this cutblock.

Risk evaluation and control The P(HA)s for Polygons 1, 2, and 3 are *very low* to *low* (Table 23). The MOF determined that these levels of risk were acceptable and that no management strategies were required.

Table 23 shows that the P(HA) for Polygon 4 associated with the first possibility (*a debris slide, but no debris flow*) and the second possibility (*a debris slide and a debris flow*) is *moderate* and *very high,* respectively. To be conservative, it was decided that the risk reduction strategies should be based on the second and higher risk possibility. The most practical way to reduce the risk from a debris slide in Polygon 4 initiating a debris flow is to reduce the likelihood of occurrence of the debris slide. In consultation with the MOF, it was agreed that Polygon 4 would be removed from the area to be harvested.

4.2.4 Snow avalanche risk management

Because of the presence of the deep snowpack and frequent natural snow avalanches in the general area, the post-harvest snow avalanche potential was also analyzed. Based on this analysis, the probability of a Size 3 snow avalanche (impact pressures that range from 10 to 100 KPa) initiating from within the cutblock in the 10-year period after harvest was assessed as moderate. A 10-year period was selected because it takes at least 10 years for a new plantation to become sufficiently tall to reduce the avalanche risk to the pre-harvest conditions (assuming that a snow avalanche does not cause inordinate soil disturbance of new plantations in the interim).

Several methods were proposed to reduce the probability of snow avalanche initiation and to control the risk to the fish-bearing streams. These included:

- retention of logging slash and waste logs on >60% slopes;
- leaving high cut stumps (approximately 2 m high) on >60% slopes;
- retention of strategically placed timbered reserves on the >60% slopes surrounding the bedrock bluffs in this cutblock;
- creation of one or more timbered reserves to break the proposed cutblock into units of no more than 100 m long (slope distance); and
- avoidance of broadcast burning.

4.2.5 Concluding remarks

This qualitative partial landslide risk analysis illustrates a methodology for comparing risk levels to fisheries resources located downslope of a proposed cutblock and for assessing the reduction in risk when reviewing options for risk control. Qualitative slope hazard assessments rely on a sound understanding of the principles of slope stability, detailed site observations, and an empirical review of the stability of similar slope conditions in surrounding areas.

Forest resource managers operating within the steep, snow-dominated watersheds in British Columbia may have to evaluate the risk to non-forestry resources from both landslides and snow avalanches. These hazards, the associated risks, and the methods of risk reduction must be considered separately.

4.2.6 Acknowledgements

The author would like to recognize the request and support for this project by Martin Fennell of the MOF and the efforts during the fieldwork, the office analysis, and the report writing phases by the staff of EP Runtz and Associates Ltd. (Clearwater office). Peter Weir, PGeo, provided input into the section on snow avalanches. Jim Schwab, Research Geomorphologist with the B.C. Ministry of Forests (Smithers) also reviewed a draft of this case study and provided helpful comments.

4.2.7 References

Australian Geomechanics Society (AGS). 2000. Landslide risk management concepts and guidelines. Sub-committee on Landslide Risk Management, Australian Geomechanics, March 2000, pp. 49–92.

Campbell, R.B. 1963. Geology - Adams Lake (Seymour Arm, West Half), British Columbia. Geological Survey of Canada. Map 48 1963. Scale 1:253 440.

Fulton, R.J., N.F. Alley, and R.A. Achard. 1986. Surficial Geology – Seymour Arm, British Columbia. Geological Survey of Canada. Map 1609A. Scale 1:250 000.

Holland, S.S. 1976. Landforms of British Columbia, a physiographic outline. British Columbia Department of Mines and Petroleum Resources, Victoria, B.C.

Howes, D.E. and E. Kenk. 1997. Terrain Classification System for British Columbia (Version 2). B.C. Min. Environment and B.C. Min. Crown Lands, Victoria, B.C.

McClung, D.M. and P.A. Schaerer. 1981. Snow avalanche size classification. *In* Proc. Avalanche Workshop, Associate Committee on Geotechnical Research. National Research Council of Canada, Ottawa, Ont. Tech. Memo 133, pp. 12–27.

Sidle, R.C. and W. Wu. 1999. Simulating effects of timber harvesting on the temporal and spatial distribution of shallow landslides. Z. Geomorph. N. F. 43(2):185–201.

4.3 Quantitative Analysis of Partial Risk from Debris Flows and Debris Floods: Community of Swansea Point, Sicamous, British Columbia

NEIL SINGH

Abstract

A debris flow from the Hummingbird Creek watershed, one of the largest non-volcanic flows in recorded British Columbia history, affected the community of Swansea Point on Mara Lake in July 1997. It resulted in significant property damage, adverse environmental effects, disruption of traffic and utilities, and one death from a heart attack. A quantitative partial risk analysis was conducted to assess the risk to buildings on Swansea Point from debris flows and debris floods. This partial risk analysis includes an estimate of the probability of occurrence of hazardous debris flows and debris floods, and an estimate of the probability of those debris events affecting the sites occupied by residences and commercial buildings on Swansea Point. The analysis relied on physical evidence due to a lack of existing records—the 1997 event is the only verified record of a debris flow at this site. Physical evidence was used to prepare magnitude–frequency relationships for P(H). Estimates of debris flow and debris flood travel distance were used to obtain a probability of spatial effect P(S:H). Partial risk was estimated based on estimated values of P(H) and P(S:H).

4.3.1 Introduction

On July 11, 1997, one of the largest non-volcanic debris flows in recorded British Columbia history flowed through the community of Swansea Point, on the eastern shore of Mara Lake, south of Sicamous. Several residences were damaged or destroyed. There was one death, attributed to a heart attack. Highway 97A was closed for several days, and restoration of utilities, fish-bearing channels, landscaping, and water wells was required (Interagency Report 1997).

This case study provides the results of a quantitative analysis of partial risk to residences and commercial buildings from future debris flows and debris floods originating from either Hummingbird Creek or Mara Creek. It is based on a combination of field review and mapping, analysis of hydrologic data, and review of background and historical information. Data sources include historical newspaper accounts, personal anecdotes, a dendrochronologic study carried out on the fan (EBA/KWL 1998), terrain mapping (Terratech 1999), hydrologic data (B.C. Ministry of Water, Land and Air Protection 2003), sediment coring records in the lakeside delta front (Fuller 2001), water well records (MWLAP 2003), geologic studies, and costs (for emergency response, evaluation, and restoration) related to the 1997 debris flow. Previous studies include those by a provincial government interagency (Interagency Report 1997), EBA/KWL (1998), and Terratech (1999).

4.3.2 General site characteristics

The community of Swansea Point is built on the alluvial/colluvial fan of Hummingbird and Mara creeks on the east shore of Mara Lake, 10 km south of Sicamous on Highway 97A (Figure 26).

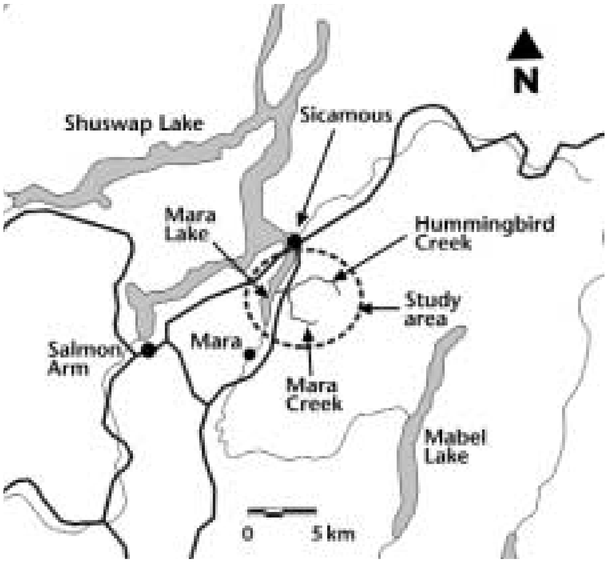


FIGURE 26 *Site location plan.*

Development at Swansea Point began in the early 1900s, and included a Japanese-Canadian internment camp in the 1940s. There are approximately 270 developed lots on Swansea Point, with residences ranging from mobile trailers to single-family homes, with small tourism-related commercial buildings (motel/restaurant). Site utilities include gas, power, cable, and telephone. The population of the community of Swansea Point is estimated between 500 and 600 including a seasonal summer peak, but there is a significant year-round population. Highway 97A crosses the eastern upslope portion of the fan and there is a well-developed system of local roads on the fan.

The fan gradient ranges from 18% at the apex to less than 5% near the lake. The fan's area is approximately 1.2 km^2, including the sub-aqueous portion of the fan. Based on water well records, the average thickness of the alluvial sequence is estimated to be 10–20 m near the apex, increasing to 70–80 m near the distal edge of the fan.

The fan has formed from colluvial and alluvial processes in the 10 000 years since the last major period of glaciation. The mix of processes has resulted in complex interlayers of materials, ranging from boulders, sand, and gravel, to silts, producing interlayers of materials of high and low permeability. Water well records show widely varying well yields across the fan at similar depths, and include annotations of boulders at depth. Interlayered bouldery lag deposits are noted in surficial exposures.

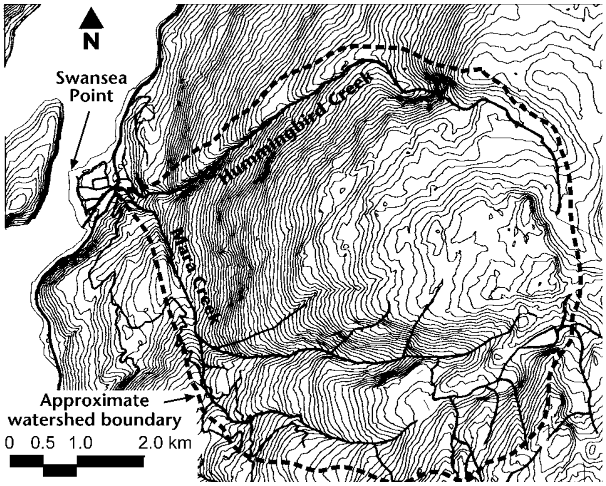


FIGURE 27 *Hummingbird and Mara creek watersheds.*

Current activities in the Hummingbird Creek and Mara Creek watersheds include forest harvesting and related road building, and additional harvesting of several cutblocks is planned (Terratech 1999). The creeks are each about 6 km long, with moderate to steep headwaters and transport reaches, and a coalesced, flatter alluvial/colluvial fan deposition area. The creeks have a combined catchment area of 39 km^2, of which Hummingbird is approximately 16 km^2 and Mara is approximately 23 km^2 (Figure 27). The creeks join just below the apex of the fan.

Regional bedrock includes plutonic and metamorphic units, characterized by foliations, jointing, folding, and faults, with several prominent lineations in the Hummingbird and Mara watersheds (Terratech 1999). Prominent lineations are particularly notable along the mid-section of Hummingbird Creek, where the creek channel has developed along a presumed fault line.

Surficial deposits within the watersheds include colluvial, fluvial, glaciofluvial, glaciolacustrine, and morainal materials with generally fluvial and colluvial deposits overlying the older, glacially derived deposits. Surficial soil textures are mixed but can be generally characterized as poorly drained silt to silty sand; they also include zones of well drained coarse talus rocky fragments. Terratech (1999) provides a terrain map (terrain survey intensity level C) for these watersheds. Geologic processes, including rockfall, rockslides, debris slides, debris flows, soil and rock slumps, and gully erosion, modify the landscape. Approximately 50% of the terrain polygons in the watersheds have some active geologic processes. Both natural and human influences have affected slope stability in the past and there are ongoing slope failures associated with Hummingbird and Mara creeks (Terratech 1999). The annual rate of sediment accumulation is estimated at 1000–2000 m^3 per creek (EBA/KWL 1998).

4.3.3 Past debris flows and debris floods

The 1997 debris flow began when a 25 000 m^3 debris slide entered Hummingbird Creek, and then scoured the creek for nearly 3 km before depositing an estimated 92 000 m^3 of soil and rock debris onto Swansea Point. The debris slide originated on a steep, saturated slope with colluvium overlying bedrock. Saturation occurred as a result of increased drainage concentration below a Forest Service road culvert following an 80-year return period rainfall event, shortly after the area above the road had been logged (Interagency Report 1997).

Several homes were damaged or destroyed. There was one death, attributed to a heart attack. Highway 97A was closed for several days, and restoration of utilities, fish-bearing channels, landscaping, and water wells was required. Costs for emergency response, evaluation, and restoration are estimated to exceed $3.5 million dollars in 2003 Canadian dollars, as compiled from data provided by MWLAP, B.C. Ministry of Transportation, and the B.C. Provincial Emergency Program.

Although the 1997 event is the only confirmed record of a debris flow in either Hummingbird or Mara creeks, there is anecdotal and scientific evidence that other debris flows or debris floods have occurred and reached the fan, including:

- an investigation of tree rings (dendrochronology) found evidence of possible debris flow or debris flood damage on average about once a decade since the early 1900s (EBA/KWL 1998);
- newspaper accounts of floods and anecdotal accounts of former residents indicated the possibility of a large debris flow in the mid 1930s (Fuller 2001);
- airphotos dating back to the 1920s indicate evidence of debris deposited on the fan between the 1930s and the 1940s, and four channel migrations since 1927;
- bouldery lag deposits have been mapped on the fan and in water well records—evidence of past debris events; and
- sediment coring of the submerged delta front indicates five to seven possible debris flow or debris flood events in the last 70 years (Fuller 2001).

In summary, there are five possible debris flow or debris flood events identified from lake sediment cores, seven possible events identified by tree ring damage, three events identified by anecdote or newspaper article, and two to four events identified by airphoto interpretation of debris on the fan.

Because of the nature of the evidence, it was not possible to distinguish between debris flows and debris floods. Therefore, the review identified a catalogue of events ranging from debris floods to debris flows, with assumptions made as to the volume of each event based on the specific physical evidence. By grouping evidence from similar time periods, it was possible to identify an estimated six to 10 individual hazardous debris flow or debris flood events in the last 75 years, or approximately eight to 13 events per century.

4.3.4 Risk analysis

Partial risk is the product of the probability of occurrence of a specific hazardous landslide and the probability of that landslide reaching or otherwise affecting the site occupied by a specific element; that is, the probability of a specific hazardous affecting landslide. For this case study, the specific hazardous landslide is a debris flow or debris flood large enough to leave the creek channel and therefore having a probability of affecting the residences and commercial buildings on Swansea Point. The vulnerability of the buildings was not considered. Other elements, such as the population, infrastructure, and the environment, were not considered.

Mathematically, partial risk is:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S)$$

Because the buildings on Swansea Point are permanent, $P(T{:}S) = 1$ and the above equation simplifies to:

$$P(HA) = P(H) \times P(S{:}H)$$

P(H) – Probability of occurrence of a specific hazardous debris flow or debris flood Magnitude–frequency relationships were prepared to determine P(H). Evidence of past debris flows and debris floods provided guidelines and mathematical bounds for the derivation of the magnitude–frequency relationship.

At first, it was assumed that debris flows or debris floods <1000 m^3 could be carried within the defined creek channels, and hence would be too small to register on airphoto, tree damage, or sediment core records. Thus, debris events for which physical evidence exists are likely >1000 m^3. There are probably many smaller events that have not been identified. The actual magnitudes of individual past events, except for the 1997 debris flow, are unknown.

A second assumption was that past annual average accumulation of sediment on the fan can be estimated by the ratio of the total estimated fan volume (approximately 20–40 million m^3) to the number of years of accumulation (approximately 10 000 years since the last glaciation), or approximately 2000–4000 m^3 per year. This correlates closely to the current estimated sedimentation rate in the creeks of 1000–2000 m^3 per year per creek (EBA 1998), but does not take into account past episodes of more rapid sedimentation, as often occurred in the early post-glacial time period. However, this assumption of a long-term average annual accumulation rate provides a rational check on the expected number and size of debris events.

The magnitude–frequency relationship covers a continuum of debris flows and debris floods from a magnitude <1000 m^3 to a maximum debris flow of 300 000 m^3. The maximum event size is estimated from physical and geometric constraints. Six magnitude classes (or Event States), were defined as follows:

- Event State 1 (ES1) 0–1000 m^3
- Event State 2 (ES2) 1001–10 000 m^3
- Event State 3 (ES3) 10 001–50 000 m^3
- Event State 4 (ES4) 50 001–100 000 m^3
- Event State 5 (ES5) 100 001–200 000 m^3
- Event State 6 (ES6) 200 000–300 000 m^3.

As indicated in the previous section (Past debris flows and debris floods), approximately eight to 13 events in the past 100 years were identified from physical evidence, each assumed to be greater than 1000 m^3; that is, within ES2 to ES6. Therefore the annual probability of an ES2 to ES6 debris flow or debris flood event was estimated to be 0.08–0.13. By corollary, the probability of an ES1 event (<1000 m^3) is 0.87–0.92 annually. ES1 events include regular stream flow, and water floods or possibly debris floods that are usually contained within the existing channels. These small events have a very low probability of causing physical damage to buildings, but do contribute a large amount of the sediment transported to the fan annually.

The third assumption was that the return period of an ES4 event (similar to the 1997 debris flow) ranges between 30 (EBA 1998) and 300 years (Terratech 1999), or an annual probability ranging between 0.033 and 0.0033.

Final magnitude–frequency relationships were developed using iterative regression analysis by varying the assumed annual return periods for each Event State, using the above three assumptions, then repeating the regression analysis until the coefficient of determination was >0.99. Figure 28 presents three magnitude–frequency relationships, constrained by available physical evidence. The three relationships address the uncertainty in the interpreted data by providing a range of probability of occurrence. From these curves, the probability of a debris flow or debris flood occurrence within a given magnitude range, P(H), can be estimated.

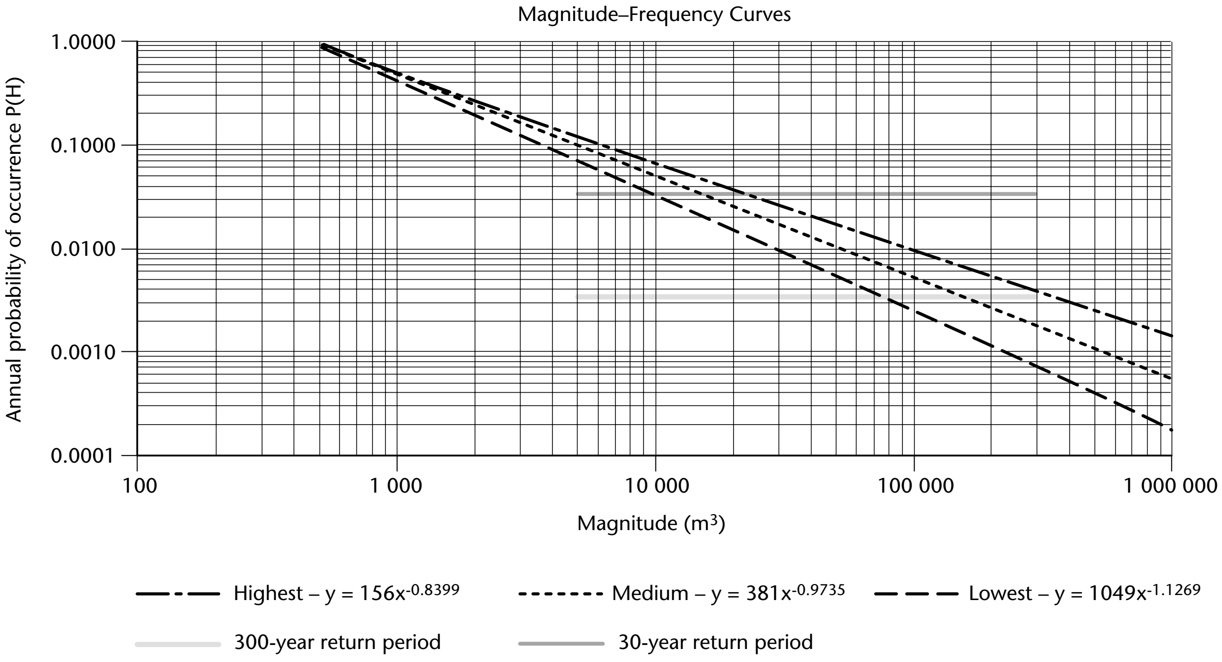


FIGURE 28 *Magnitude–frequency curves for debris flows and debris floods on Swansea Point.*

Future debris flows and debris floods may vary from these derived relationships, insofar as these derivations rely on available data that may be incomplete, and past geologic and climatic conditions. Also, future climatic conditions may be significantly different. For example, the rainfall trend-line has been increasing since 1900, and this trend is expected to increase through the 21st century, based on a review of local hydrologic data. Figure 29 presents 3- and 9-month precipitation totals over the last century, which has shown a steady increase. These intervals were selected to allow comparison against the 3- and 9-month precipitation that preceded the 1997 debris flow. Bruce (2003) projects climate changes to include a 15–20% increase in severe winter storm frequency and intensity due to a projected doubling of pre-industrial atmospheric levels of CO_2 equivalent by the latter half of the 21st century, and potentially a 20% increase in total precipitation by 2060. Whatever the cause of these long-term trends, increases in precipitation above current average levels can be expected, adding to soil saturation and to erosion rates. On this basis, and with ongoing harvesting and road construction within the watersheds, it is possible that the future frequency of debris flows and debris floods may increase.

P(S:H) – Probability of an event affecting a building site Given the occurrence of a debris flow or debris flood event, the probability of an event affecting a site occupied by a residence or commercial building, P(S:H), was estimated based on the probability that the debris flow or debris flood would reach or occupy the site containing such buildings. Initial estimates of runout distances on the fan were developed based on the computer program DAN (Hungr 1995) for the average magnitude within each of the six Event States. These distances were compared subjectively to actual deposition patterns of the 1997 debris flow, and checked using the model UBCDFLOW (Fannin and Wise 2001). Predicted runout zones on the fan were then derived based on the physical geometry and slope of the fan, using the 1997 debris flow event as a guide. Typical runout distances range from 200 to 1800 m below the confluence of Hummingbird and Mara creeks onto the fan (Figures 30a and 30b).

P(S:H) was estimated as the ratio of the number of residences and commercial buildings within a predicted runout zone to the total number of residences and commercial buildings on Swansea Point, using an exact count of structures within a predicted typical runout zone. This subjective probability estimate of a building being affected is based on the assumption that future debris events within a given Event State would follow a similar pattern to the estimated typical runout pathway. However, since the exact pathway cannot be accurately predicted, it is further assumed that all buildings on Swansea Point are equidistant apart. It is also assumed that no further building occurs. The estimated P(S:H) ranged from

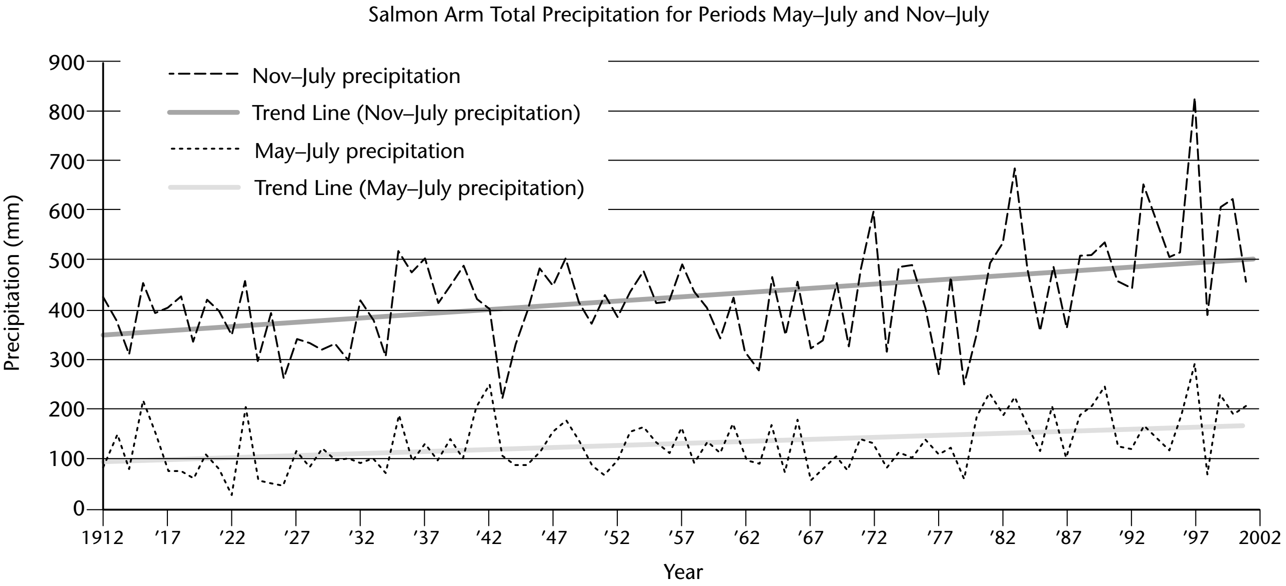


FIGURE 29 *Precipitation trend lines for Salmon Arm since 1900.*

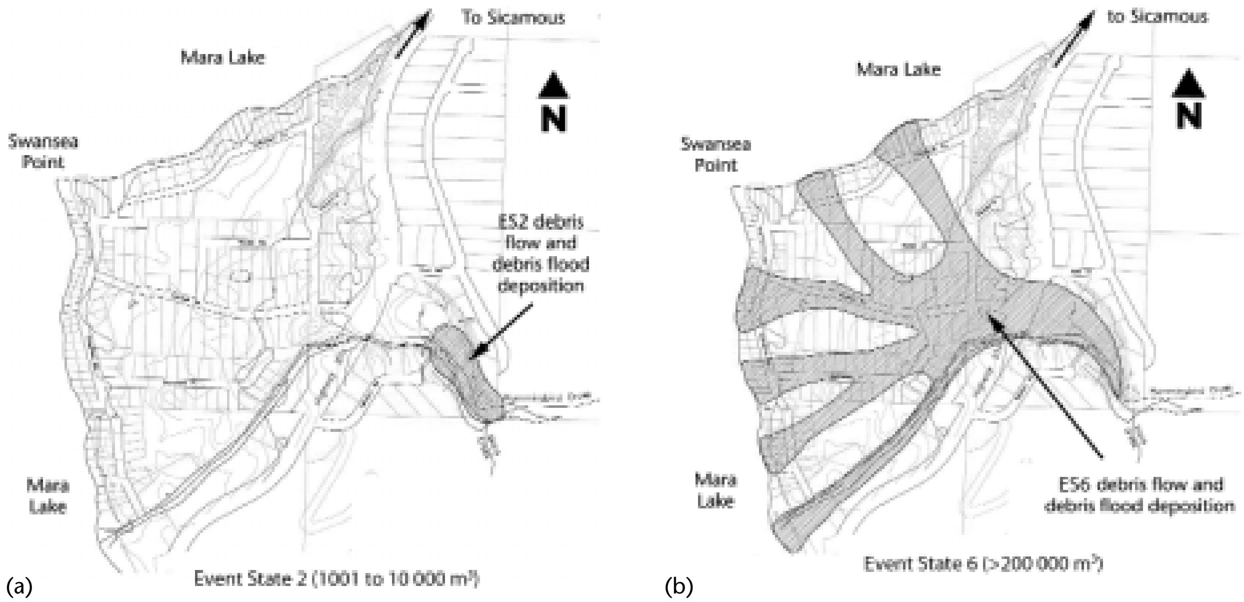


FIGURE 30 *Estimated runout zones for ES2 (a) and ES6 (b) debris flow and debris flood events.*

0.004 for ES1 debris events to 0.60 for ES6 debris events. Table 24 summarizes estimated runout zones for the different Event States, and estimated values of P(S:H).

A further, recommended, refinement to this assessment would be to ascertain the vulnerability and the estimated level of damage to buildings. For example, homes within the predicted runout zone, but closer to the distal edge of the fan, may be less vulnerable to damage from debris flows and debris floods because debris tends to deposit closer to the fan apex.

P(HA) – Analysis of partial risk to building sites

Partial risk, P(HA), is estimated as the product of P(H), derived from the magnitude–frequency relationships (Figure 28) and P(S:H) from the runout distance estimates (Table 24). Summation of the partial risk from each Event State then provides a quantitative measure of the overall partial risk to residences and commercial buildings on Swansea Point.

As a refinement, a value of P(HA) could be estimated for each of the three P(H) relationships shown in Figure 28, thus providing a range of partial risk consistent with the available physical evidence, and providing a measure of the confidence (or uncertainty) of the analysis.

Table 25 provides a typical calculation of P(HA) using typical calculated values of P(H) and P(S:H) for illustration of the risk analysis methodology. Some of the values presented have been purposely changed, for illustrative purposes, and do not represent actual partial risk values for buildings at Swansea Point.

TABLE 24 *Event State runout distance on the fan and probability of spatial effect*

Event State	Estimated runout distance (m)	Estimated P(S:H)
ES1	200	0.004
ES2	200	0.008
ES3	600	0.07
ES4	800	0.08
ES5	1000	0.20
ES6	1800	0.60

4.3.5 Concluding remarks

Recommended guidelines (Boyer 2002) suggest that the annual P(H) at subdivisions with protective works should be <0.002. Based on this case study, it is recommended that the above guidelines should reflect partial risk, by considering spatial probability associated with buildings or proposed buildings.

Quantitative partial risk analysis also allows comparison of alternative mitigative measures, each with differing costs and differing effectiveness. For example, some possible mitigative measures to control the debris event risk at Swansea Point would include (EBA 1998):

TABLE 25 *Sample partial risk analysis*

Event State	Average event magnitude (m^3)	Annual P(H) from Figure 28	P(S:H) from Table 24	P(HA)
ES1	500	0.869	0.004	0.0035
ES2	5 500	0.10	0.008	0.0008
ES3	30 000	0.02	0.07	0.0014
ES4	75 000	0.007	0.08	0.00056
ES5	150 000	0.003	0.20	0.0006
ES6	250 000	0.001	0.60	0.0006

- *channel widening improvements* to constrain small debris floods and debris flows to the stream channel and lessen the potential of events breaching the stream banks and affecting homes;
- *debris training berms* to constrain debris floods and small debris flows to the stream channel; and
- *debris basins* to contain and capture a portion of debris floods and debris flows and prevent debris from affecting homes by spatial impact.

The effectiveness of each measure depends on the size and type of debris event as well as the location and intrinsic design of the measure. Simply stated, a basin with a large catchment volume will be more effective than a small basin or a training berm. Evaluation of potential risk may indicate which mitigative measure is most cost-effective in providing the required risk reduction. Estimated values of P(S:H) can then be reduced to reflect the presumed effectiveness of each proposed measure, and the partial risk value following risk control can be calculated to compare the effectiveness of each mitigative measure.

4.3.6 Acknowledgements

The author would like to thank Klohn Crippen Ltd., the B.C. Ministry of Transportation, and the B.C. Ministry of Community, Aboriginal and Women's Services for assistance in preparation of this case study. Mr. Bryan Watts of Klohn Crippen Consultants Ltd., and several reviewers from the University of British Columbia, the B.C. Ministry of Forests, and the B.C. Ministry of Transportation, provided valuable review comments. Rick Rodman of Klohn Crippen Consultants Ltd. provided the hydrologic review. Bruce Thomson, Geomorphologist with the B.C. Ministry of Water, Land and Air Protection, Surrey also reviewed a draft of this case study and provided helpful comments.

4.3.7 References

Boyer, D. 2002. Recommended procedure for conducting studies in support of land development proposals on alluvial and debris torrent fans. Internal article for B.C. Min. Water, Land and Air Protection, Kootenay Region.

British Columbia Ministry of Water, Land and Air Protection. 2003. Website http://wlapwww.gov.bc.ca/wat/waterbot/gwell-out.html. Searchable database of British Columbia registered water wells.

Bruce, J.P. 2003. Implications of climate change for flood damage reduction in Canada. Proceedings of the 3rd Canadian conference on geotechnique and natural hazards, GeoHazards 2003, Edmonton, Alta. Geotechnical Society, pp. 29–34.

EBA Engineering Consultants Ltd. with Kerr Wood Leidal Associates Inc. (EBA/KWL). 1998. Stream restoration and restoration alternatives at Hummingbird Creek, Mara Lake, BC. Report for B.C. Min. Environ., Lands and Parks.

Fannin, R.J. and M.P. Wise. 2001. An empirical-statistical model for debris flow travel distance. Canadian Geotechnical Journal 38(5):982–994.

Fuller, T. 2001. Sediment coring at Swansea Point fan delta, Mara Lake, British Columbia – Application of a coring method to determine historical debris flow events. B.C. Min. Water, Land and Air Protection.

Hungr, O. 1995. A model for the runout analysis of rapid flow slides, debris flows and avalanches, Canadian Geotechnical Journal 32(4): 610–623.

Interagency Report. 1997. Hummingbird Creek debris event – July 11, 1997. B.C. Min. Environ., Lands and Parks, B.C. Min. For., B.C. Min. Transportation and Highways, and B.C. Min. Attorney General.

Jakob, M., D. Anderson, T. Fuller, O. Hungr, and D. Ayotte. 2000. An unusually large debris flow at Hummingbird Creek, Mara Lake, British Columbia, Canadian Geotechnical Journal 37:1109–1125.

Terratech Consulting Ltd. 1999. Detailed terrain stability mapping (TSIL C) Hummingbird Creek and Mara Creek watersheds. Report for Riverside Forest Products.

4.4 Quantitative Back-analysis of Partial Risk from a Harvested Cutblock: Jamieson Creek Watershed, Greater Vancouver Regional District, British Columbia

JONATHAN FANNIN, DEREK BONIN, AND DAVID DUNKLEY

Abstract

Storm precipitation during November 1990 caused a debris slide within a forest clearcut in the Jamieson Creek watershed. The debris slide progressed to a debris flow as it moved over the logged terrain, then entered and resulted in sedimentation of Jamieson Creek. Post-event analysis of the factor of safety of a potential failure plane at the point of origin in the cutblock suggests the probability of a specific hazardous landslide (in this case the debris slide) to be 0.26. The slope stability analysis is based on measured soil properties, interpretation of groundwater monitoring data, and some assumed geotechnical parameters. Attributes of the slope below the point of origin indicate the probability of the resulting debris flow entering Jamieson Creek to be certain (or 1), given the occurrence of the debris slide. The travel distance analysis is based on a consideration of slope angle, and a flow behaviour that was unconfined for most of the travel path. Accordingly, the post-harvesting back-analysis shows that the partial risk to Jamieson Creek from a debris slide initiating near the top of the cutblock and the resulting debris flow entering the creek to be 0.26.

4.4.1 Introduction and situation

The Seymour Watershed is one of three watersheds that supply drinking water to 1.8 million people in the Greater Vancouver Regional District (GVRD). During November 1990, nearly 1500 mm of precipitation fell in the Seymour Watershed, of which 970 mm fell up to November 22 and 376 mm fell on November 23. The antecedent conditions—intense precipitation and melting snow—caused many landslides to initiate, both on logged and unlogged terrain during the November 23rd storm.

Jamieson Creek is a tributary to Orchid Creek, which is a tributary to the upper Seymour River. Water quality is the primary objective of management plans for the watershed. Accordingly, the potential for landslide-induced stream sedimentation is a primary concern in land management decisions. The upper Seymour River is inaccessible to salmonids; however, high-quality aquatic habitat exists in the stream reaches downstream of the confluence of Jamieson Creek and Orchid Creek. A combination of landslide-induced stream sedimentation, streambank erosion, and shoreline erosion of the reservoir during the storm resulted in unacceptably high turbidity levels in the Seymour Reservoir (Thurber Engineering 1991). The GVRD responded by removing the reservoir, for a period of time, from the water supply system.

One significant landslide that occurred during the November 23rd storm originated in the Jamieson Creek watershed, a sub-drainage of the upper Seymour River (Figure 31). It initiated as a debris slide near the top of a cutblock (Figure 32). The path of the resulting debris flow crossed a logging road ap-

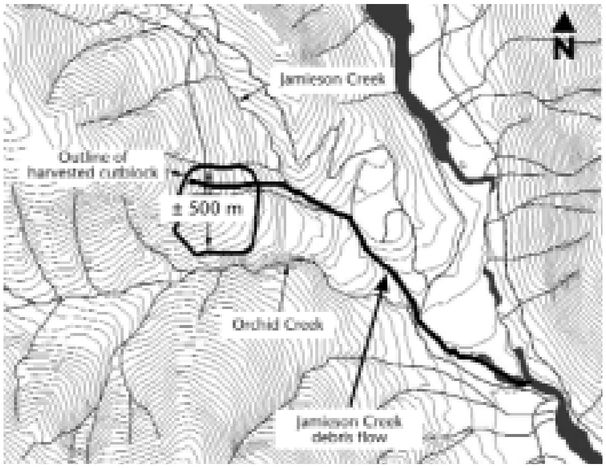


FIGURE 31 *Jamieson Creek debris flow—topographic details. Contour interval is 20 m.*

proximately 250 m (slope distance) below the headscarp, and continued for approximately 300 m (slope distance) before cutting through an unlogged streamside buffer and entering Jamieson Creek (Figure 33). The ground slope over which it travelled is steep, varying from approximately 31° (60%) above the logging road to 22° (40%) in the reach preceding entry to the creek. Entrainment of debris was the dominant process along the travel path. Indeed, the logging road presents the only flat ground encountered along the route, and experienced some deposition.

This case study presents a quantitative analysis of partial risk to Jamieson Creek from a debris flow originating within the clearcut and delivering sediment to the creek. The analysis uses data on soil strength and groundwater seepage that were acquired from field studies conducted after the failure. It makes use of modelling techniques, developed since the failure occurred, to back-analyze the debris slide initiation, and the debris flow travel distance.

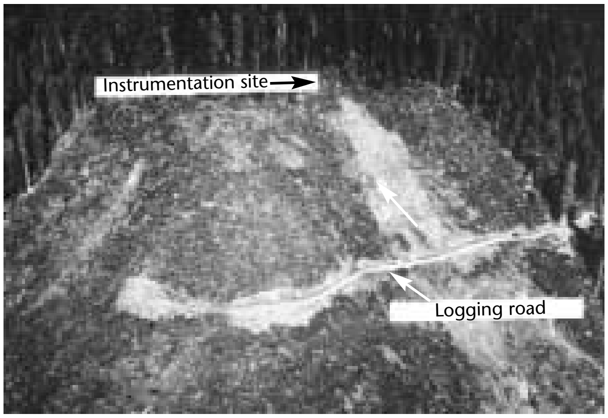


FIGURE 32 *Jamieson Creek debris flow—point of origin and initial portion of travel path.*

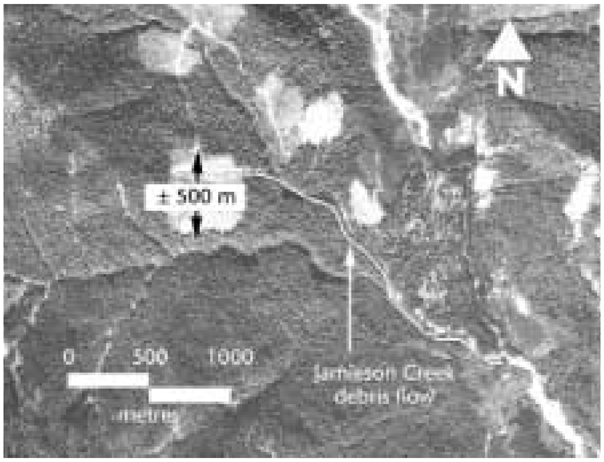


FIGURE 33 *Aerial ortho-photograph of the Jamieson Creek debris flow.*

4.4.2 General site characteristics

The Seymour Watershed, located north of Vancouver, lies within the Coast Mountain Range and is underlain primarily by quartz diorite (Roddick 1965). Landform development and geomorphoric processes during and since the end of the Fraser Glaciation, 10 000–12 000 years ago, have resulted in the present basin morphology and deposition of surficial sediments. On steep side slopes, the surficial soils overly bedrock and are relatively thin.

The cutblock at Jamieson Creek is located on a southeast- to east-facing slope. Its upper portion ranges from 740 to 785 m above sea level, in a transient snow zone, and is at the interface between the Coastal Western Hemlock submontane variant (vm1) and montane variant (vm2) boundary (Luttmerding et al. 1990). Prior to logging, the mature forest consisted of western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and amabilis fir (*Abies amabilis*). Data from a hydrometric station situated nearby, but at a lower elevation, on the Seymour River indicate a mean annual precipitation of approximately 3300 mm, with a maximum 24-hour precipitation >300 mm.

Indicators of pre-harvest slope instability, including several naturally occurring landslides adjacent to the proposed cutblock, were noted at the time of cutblock layout in 1982. In recognition of these indicators, the boundaries of the cutblock were amended. Road access was developed in 1983. During logging, in the fall of 1984, a small debris flow temporarily closed the logging road. Additional minor instability was noted following harvesting.

The debris flow of November 1990, some 6 years after harvesting, initiated as a debris slide on ground having a slope angle (TH) between 28 and 30° (53–58%). The steepest section on the locus of slip along the soil-bedrock surface exhibited a steeper angle (α) of 36° (73%) as a result of subtle undulations in the bedrock profile. Subsequent terrain stability mapping delineated the initiation zone as having a high likelihood of landslide initiation after harvesting. In the absence of any slope failures, however, a moderate likelihood of landslide initiation after harvesting would likely have been assigned based on the site attributes.

The surficial soils at the point of origin of the debris slide comprise a veneer to a blanket of highly weathered colluvium, overlying a discontinuous morainal deposit. The depth (D) of the surficial soils at the headscarp is between 1.0 and 1.5 m, with a mean value of 1.25 m. A dense root mat approximately 0.5 m thick overlies the mineral soils. Exposures along the slide and flow path indicate that the bedrock is relatively planar, with small undulations, and slightly weathered. Observations reveal that the root mat of the ground surface does not extend significantly into the colluvium, and does not intercept the locus of slip at the soil-bedrock interface. Accordingly, the apparent cohesion attributed to root strength (c_r), and root strength deterioration, are not believed to have been significant influences on stability of the slope (Thurber Engineering 1991). Given initiation within the clearcut, the soils were not subject to any tree surcharge (q_o) loading.

The colluvium comprises many sub-rounded to angular boulders and cobbles in a coarse-grained matrix. Visual observations, in test pits and along the headscarp, reveal that the cobbles and boulders are lodged individually within this matrix, and therefore the matrix of the colluvium is believed to control its mobilized shear strength along the locus of slip. Sieve analyses, on grab samples of the 25 mm minus fraction of the colluvium (Seymour watershed sites A and B), indicate that the matrix is gravelly sand with some silt and a trace of clay (Figure 34). Grain size curves for three other headscarp locations in coastal British Columbia (Figure 34) imply that the soil matrix is similar in grain size distribution. Field observations, and experience, were used to assign a range for moisture content (15–25%) and dry unit weight (15.7–17.3 kN/m^3), believed to be representative of the soil conditions at the point of origin.

In-situ direct shearbox tests were performed at the site in July 1994 (Wilkinson 1996; Fannin et al., in review). Results of five *in-situ* tests on moist undisturbed block samples of colluvium, and two additional laboratory tests on oven-dried reconstituted specimens of the 25 mm minus fraction of the colluvium, are shown in Figure 35. The curves reveal peak strengths at relatively small displacement that diminish to a constant value with further shearing action. The distinct second peak in sample B20712 is attributed to the influence of a root across the plane of shear. Several other shearbox tests were aborted or discarded because of such influences. The data indicate a mean angle of friction (φ) of 46° at large displacement. The relatively high value is attributed to the influence of a

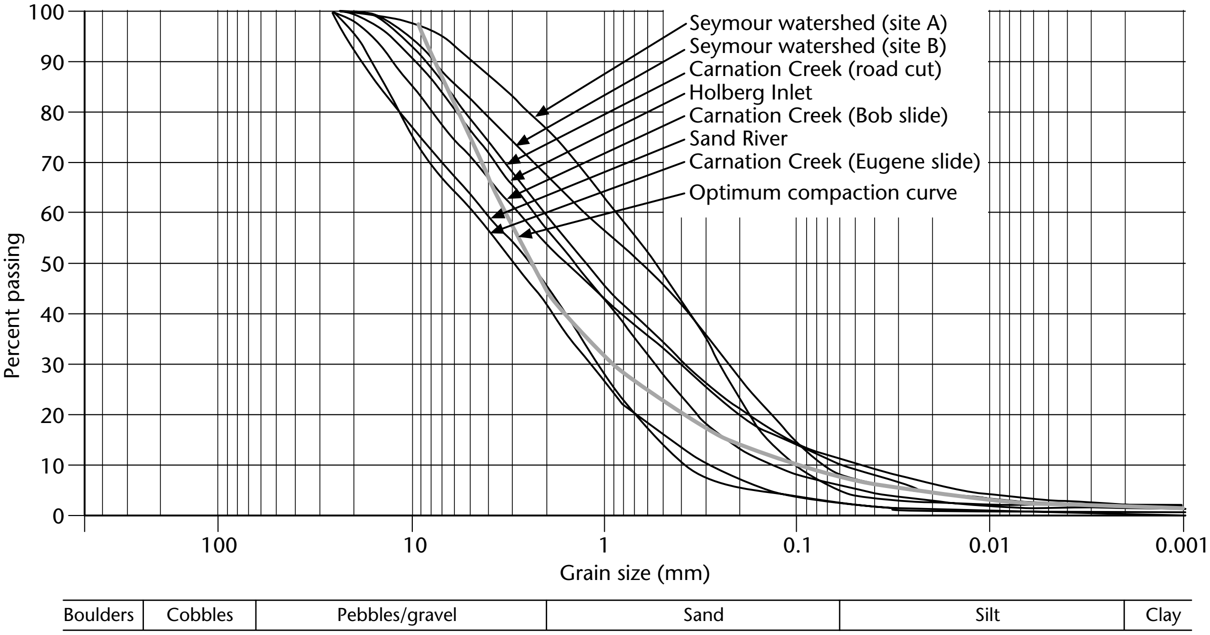


FIGURE 34 *Grain size distribution curves for the matrix of colluvium (after Wilkinson 1996).*

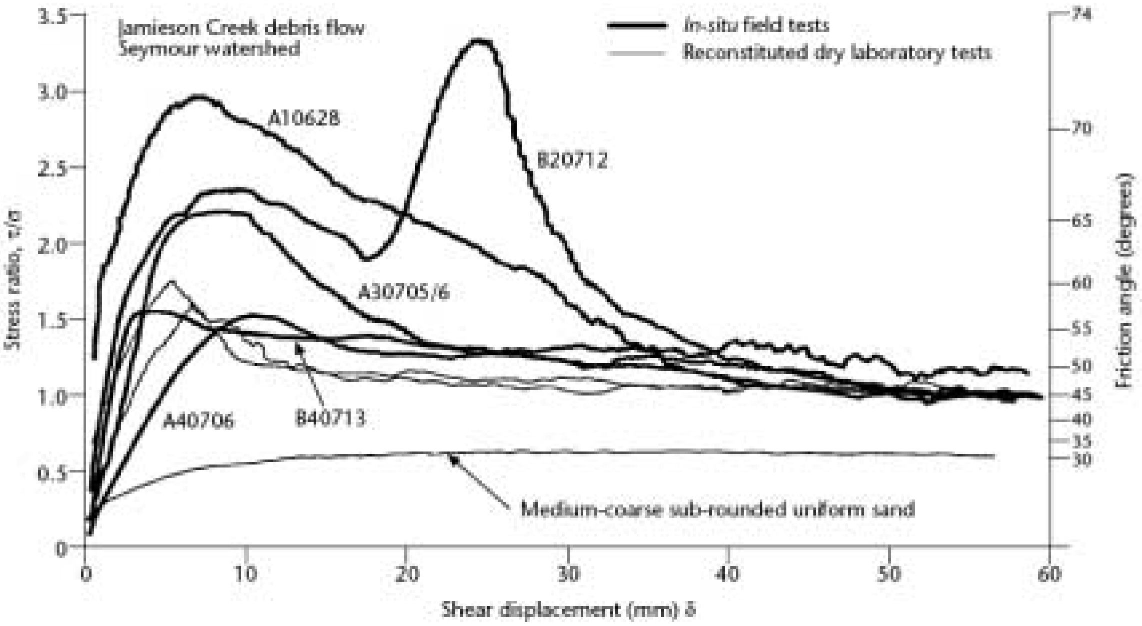


FIGURE 35 *Direct shearbox test results on colluvium (after Wilkinson 1996).*

broad gradation of particle size and low effective stress on mobilization of shear strength. The soils tested exhibited no cohesion (c_s).

In 1997, automated piezometers and tensiometers were installed at four instrumentation nests located between 3 and 6 m upslope of the headscarp of the 1990 debris slide (Figure 36), to monitor the post-failure groundwater seepage regime in the soil (Jaakkola 1998; Fannin and Jaakkola 1999). The instrumentation recorded positive and negative pore water pressures, respectively, from October 1997 to June 1998. A time series plot of hourly precipitation and groundwater response for the initial 2 months illustrates well the transition from moist to wet ground conditions with onset of winter storms (see Figure 37). Because the exposed seepage face at the headscarp may have influenced the response of the instrumentation, uncertainty exists as to how well the observed response to storm precipitation describes the site response before the failure.

The resulting data (Figure 37) show that most, but not all, of the responses were closely related to precipitation intensity. The onset of positive pore water pressures, and resulting peak values (of P1, P2, and P3), correlate generally with the onset of precipitation. However, a detailed comparison of maximum pore water pressures during a storm (e.g., that of

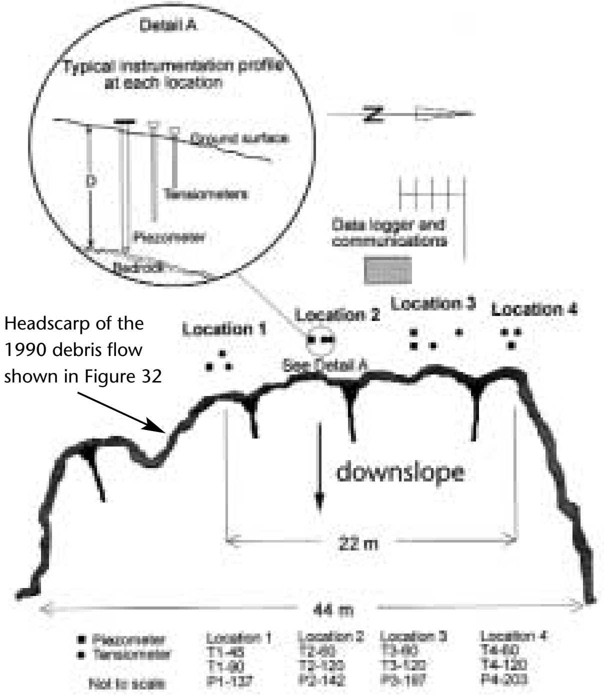


FIGURE 36 *Plan view arrangement of the instrumentation located upslope of the headscarp of the 1990 debris flow (after Fannin and Jaakkola 1999).*

29 October 1997) reveals a very localized response across the short 22-m section of apparently uniform hillslope. The piezometers did not respond in unison to the onset of precipitation. The localized response is attributed to the influence of preferential seepage paths in the surficial soils. The maximum pore water pressure, observed at P1, appears dependent on precipitation intensity and duration. Expressed as a dimensionless groundwater ratio, of pressure head to soil depth (D_w/D), it has a value of 0.7 for the monitoring period. The data confirm the groundwater seepage to be a highly variable parameter, both spatially and temporally. The occurrence of similar peak values of D_w/D in October and November 1997 (Figure 37) suggests that this hydrologic trigger to the debris slide has a short return period, and implies that the maximum value of D_w/D could be expected to occur annually.

4.4.3 Partial-risk analysis

Partial risk, P(HA), is the product of the probability of occurrence of a specific hazardous landslide **and** the probability of that landslide reaching or otherwise affecting the site occupied by a specific element. It is defined as:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S), \text{ where,}$$

- P(H) is the probability of occurrence of a specific hazardous landslide,
- P(S:H) is the probability of a spatial effect given that a hazardous landslide occurs, and
- P(T:S) is the probability of a temporal effect given that a spatial effect occurs.

For this case study, a quantitative partial-risk analysis was performed to account for the probability of occurrence of a debris slide at the point of origin,

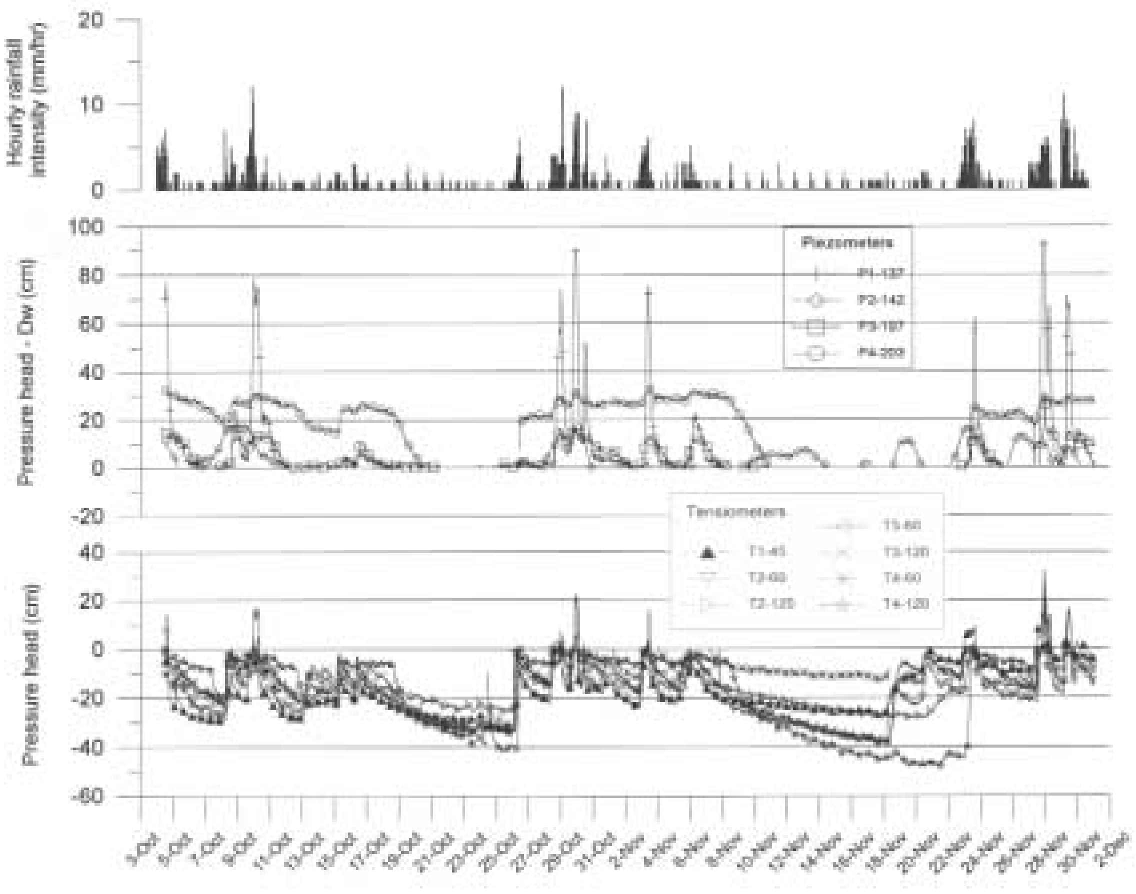
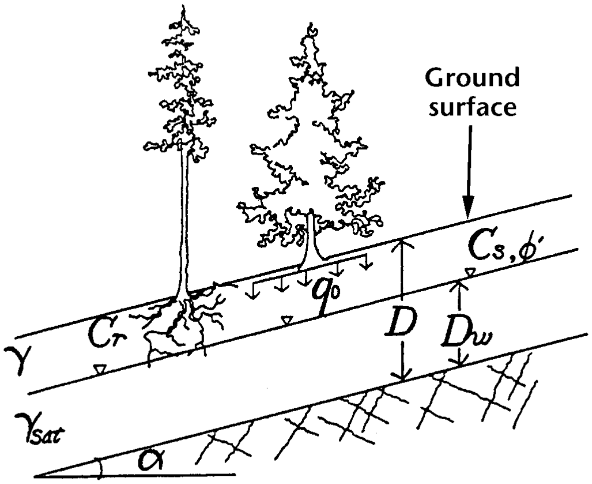


FIGURE 37 *Variation of pore water pressure and rainfall intensity during fall 1997 (after Fannin and Jaakkola 1999).*

and the probability of the travel distance of the resulting debris flow reaching, or causing an effect at, a point of interest on the slope below. Given the concern for landslide-induced stream sedimentation, the point of interest on the slope below is Jamieson Creek.

P(H) – Probability of occurrence of a specific landslide At the point of origin, the probability of occurrence, P(H), was estimated as the probability of the factor of safety (FS) being less than unity, P(FS ≤ 1), for an assumed translational slip. The FS was estimated using the infinite slope LISA model (Figure 38), developed by the U.S. Forest Service (Hammond et al. 1992). The LISA model assumes that both the plane of rupture and groundwater surface are parallel to the ground surface, and infinite in extent. LISA is a limit equilibrium analysis that is suitable for sites on planar slopes where the groundwater regime does not result in artesian groundwater pressures. The probability of the FS being less than or equal to one P(FS ≤ 1), was estimated from 1000 calculations of the FS; each calculation was made using random sampling of input parameters, given a user-defined distribution (constant, uniform, or triangular) for each parameter and its associated range in magnitude (Table 26).

As noted in the description of general site characteristics, the soil depth, ground slope, tree surcharge, friction angle, and soil cohesion values are based on field measurements. The groundwater values are based on limited field observations. The dry unit weight and moisture content are assumed values. A sensitivity analysis was conducted on the contribution of root strength. Three scenarios were examined for the influence of root cohesion: a significant contribution (3.5–7 kPa); a moderate contribution (0–7 kPa); and a nominal contribution (0–1.5 kPa). As discussed previously, the latter scenario is believe to be



$$FS = \frac{C_r + C'_s + \cos^2\alpha[q_0 + \gamma(D - D_w) + (\gamma_{sat} - \gamma_w)D_w]\tan\phi'}{\sin\alpha\cos\alpha[q_0 + \gamma(D - D_w) + \gamma_{sat}D_w]}$$

FIGURE 38 *LISA model—input parameters (after Hammond et al. 1992), refer to Table 26.*

TABLE 26 *LISA analysis—input parameters and probability of failure**

Parameter (see Figure 38)	**Distribution**	**Magnitude**		
Soil depth, D (m)	Uniform	1.0–1.5		
Ground slope, α (°)	Uniform	30–36		
Tree surcharge, q_o (kPa)	Constant	0		
Root cohesion, c_r (kPa)	Uniform	3.5–7	0–7	0–1.5
Friction angle, φ (°)	Triangular	45/46/47		
Soil cohesion, c_s (kPa)	Constant	0		
Dry unit weight, γ (kN/m^3)	Uniform	15.7–17.3		
Moisture content, w (%)	Uniform	15–25		
Groundwater (D_w/D)	Triangular	0.6/0.7/0.8		
Factor of safety (FS)	Minimum	0.97	0.88	0.86
	Maximum	1.50	1.50	1.29
	Mean	1.20	1.14	1.06
P(FS ≤ 1)		0.003	0.071	0.258

* Notes: Uniform distribution (min–max); Triangular distribution (min/apex/max), after Hammond et al. (1992).

most representative of the site characteristics, given that root strength and root strength deterioration are not believed to have exerted a significant influence on stability of the slope.

The output of the LISA analyses is also summarized in Table 26, with reference to the minimum, mean and maximum FS obtained in the three scenarios for contribution of root cohesion, together with the probability of the FS ≤ 1. The results show P(FS ≤ 1) to increase, from 0.003 to 0.258, with decreasing root cohesion.

Correspondingly, the mean factor of safety diminishes from 1.20 to 1.06. A mean FS = 1.06 implies a significant potential for instability, which is consistent with field observations noted at the time of cutblock layout in 1982, and which lends further credence to the belief that root strength and root strength deterioration had little significant influence on stability of the slope. Therefore, assuming a nominal contribution of root cohesion at the point of origin, and assuming that the groundwater values are representative of the hydrologic conditions in the slope at the time of failure, P(FS ≤ 1) = 0.258 is considered a reasonable estimate of the probability of occurrence of the specific landslide, P(H).

P(S:H) – Probability of spatial effect The probability of spatial effect is defined as the probability of the debris flow travel distance exceeding the slope distance from the point of origin to the point of entry at Jamieson Creek, using the UBCDFLOW model (Fannin and Wise 2001). A schematic diagram showing the UBCDFLOW model parameters is given in Figure 39. The model was developed from survey data on forest clearcuts in the Queen Charlotte Islands, British Columbia, using multiple regression analysis (Fannin and Wise 2001). Recent experience, however, suggests that the model may have potential for application to other regions (Eliadorani et al. 2003).

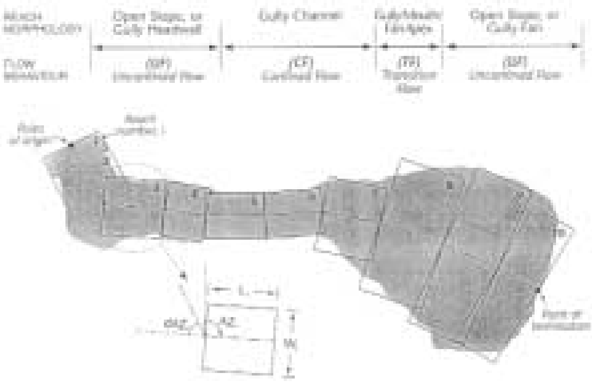


FIGURE 39 *Schematic plan view of a debris flow path (after Fannin and Wise 2001).*

To estimate travel distance using this model, it is assumed that, given an initial failure volume, the event magnitude changes as a result of entrainment and deposition of debris along the travel path, and therefore the point of termination can be established as the point at which the cumulative flow volume diminishes to zero. Hillslope morphology is used to assign three types of flow behaviour: unconfined (UF), confined (CF), and transition flow (TF). Flow behaviour and slope angle of the ground surface (TH) determine the occurrence of entrainment or deposition in all reaches of the event path (Table 27). The limits of TH shown in Table 27 are based on the observed flow behaviour of about 450 debris flow events (Fannin and Wise 2001).

Application of UBCDFLOW to the Jamieson Creek site implies that changes in event magnitude are dominated by one mode of flow, since the ground over which the debris flow travelled comprises a series of steep reaches (TH ≥ 22°). Accordingly, the model assigns entrainment in all but one reach (Figure 40). The exception is the nearly flat, unconfined reach (TH ≈ 2°) of the logging road, where deposition was assigned. The dominant modelled process was one of increasing cumulative flow volume along the travel path, which is consistent with field observations made shortly after the event. Those field observations suggested that about 5000 m^3 of debris was entrained above the logging road, of which about 1000 m^3 was deposited on the road, yielding 4000 m^3 that continued downslope to entrain about another 1500 m^3 of debris before entering Jamieson Creek (Thurber Engineering 1991). The model results (Figure 40) are in remarkably good agreement with the field observations. Since the modelled cumulative

TABLE 27 *Summary of flow behaviour and mode of flow, for ground slope angle (TH)*

Flow behavour	Mode of flow	UBCDFLOW range of ground slope angle (TH)
UF	Deposition	0°≤ TH ≤ 18°
	Entrainment	19°≤ TH ≤ 55°
CF	Entrainment	10°≤ TH ≤ 55°
TF	Deposition	0°≤ TH ≤ 20°

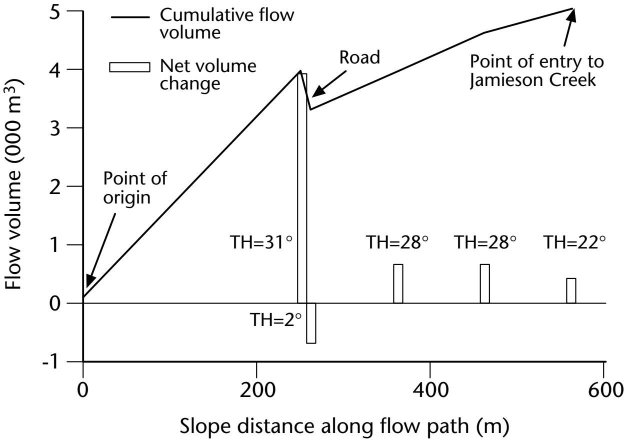


FIGURE 40 *Cumulative flow volume along travel path as calculated by UBCDFLOW.*

flow volume does not diminish to zero along the travel path, a certainty of the debris flow entering Jamieson Creek is implied. Therefore the UBCDFLOW analysis indicates that P(S:H) = 1.0.

P(T:S) – Probability of temporal effect The specific element at risk on the slope, below the point of origin, is Jamieson Creek. Since the creek is a permanent watercourse, the probability of a temporal effect given a spatial effect, P(T:S), defaults to 1.0.

P(HA) – Analysis of partial risk to Jamieson Creek The LISA model has been used to quantify the likelihood of debris slide initiation. The UBCDFLOW model has been used to quantify the likely travel distance of the resulting debris flow. Therefore, the partial risk of a debris slide initiating near the top of the cutblock, and the resulting debris flow having a travel distance of sufficient length to enter Jamieson Creek, is back-analyzed as the product of P(FS ≤ 1) × P(S:H) = 0.26 × 1.0 = 0.26. Given the nature of spatial and temporal variations in parameters governing both initiation and travel distance, and given assumptions of the models used to quantify the phenomena, P(HA) should be considered only an estimate.

4.4.4 Risk evaluation and risk control

The LISA model does not explicitly address probability over a specified period of time. Yet some of the input parameters, most notably D_W/D, vary temporally. Accordingly, the output variable of P(FS ≤ 1) reflects the time period over which the user-defined distribution for each input parameter, and its associated range in magnitude (Table 26), are believed to govern stability. Given the occurrence of similar peak values of D_W/D in October and November 1997 (Figure 37), which imply a short return period, and given that groundwater triggered the failure, the value of P(FS ≤ 1) is believed representative of an annual probability of debris slide initiation at this site.

A P(H) = 0.26 for debris slide initiation within the clearcut at Jamieson Creek is calculated with reference to site-specific data on the friction angle of the soil and the groundwater seepage regime. These site data provide for both confidence in the estimated value of P(H) and its interpretation as an annual probability. Field observations correlate a P(H) of this magnitude to indicators of pre-harvest slope instability, including a number of naturally occurring landslides adjacent to the proposed cutblock. In the absence of site-specific data for comparison, LISA could still be used to determine a P(FS ≤ 1); however, the results would be less certain and could differ from an annual probability. The spatial variation in the groundwater trigger to failure, D_W/D, observed at Jamieson Creek, confirms preferential seepage in surficial soils to be a critical factor governing the location of failure within terrain polygons.

The UBCDFLOW model was developed from field observations of debris flow travel distance on logged terrain. It is an empirical model, and therefore may be applied with reasonable confidence to logged terrain with attributes similar to those of the Queen Charlotte Islands. If the terrain over which the debris flow travels is unlogged, experience suggests that the travel distance is relatively shorter.

Recognizing that root strength and root strength deterioration are not believed to have exerted a significant influence on stability of the slope, the LISA analysis implies that, in the absence of logging, there was potential for a rainfall-induced failure to occur in the vicinity of the point of origin of the debris slide at Jamieson Creek. However, speculation would suggest that the volume of the failure would likely have been smaller, and the travel distance would likely have been shorter.

4.4.5 Concluding remarks

The landslide within the forest clearcut at Jamieson Creek initiated as a debris slide and progressed into a debris flow. Since the 1990 event, the site has been the focus of integrated geotechnical research studies that have yielded detailed information on soil properties, the hydrologic response of the soils to precipitation, the mechanism of failure, and attributes of the downslope travel path. Field monitoring shows groundwater seepage, which triggered the failure, to be a highly variable parameter, both spatially and temporally.

The debris slide initiation occurred as a translational slip, for which the factor of safety was calculated using the infinite slope LISA model. A sensitivity analysis confirms that root strength and root strength deterioration did not exert a significant influence on stability of the slope. The probability of FS ≤ 1 at the point of origin was estimated to be 0.26. Field observations correlate a P(H) of this magnitude to field indicators of pre-harvest slope instability, including a number of naturally occurring landslides adjacent to the proposed cutblock.

The travel distance of the resulting debris flow is governed by volumes of entrainment and deposition, and was estimated using the UBCDFLOW model. Attributes of the travel path below the point of origin indicate, with complete certainty, that the resulting debris flow would enter Jamieson Creek. The model results are in remarkably good agreement with field observations made shortly after the event regarding the volumes of flow.

The quantitative analysis of partial risk is based upon a combination of the probability of FS ≤ 1 at the point of origin, and the probability of the debris flow travel distance exceeding the slope distance from the point of origin to the point of entry at Jamieson Creek. Accordingly, the partial risk P(HA) to Jamieson Creek from a debris slide initiating near the top of the cutblock, and the resulting debris flow entering the creek, was back-analyzed to be 0.26. Given assumptions of the models used to quantify initiation and travel distance, this partial risk is considered an estimate.

4.4.6 Acknowledgements

Fieldwork at the Jamieson Creek cutblock was conducted with funding support from the Natural Sciences and Engineering Research Council of Canada, the Canadian Forest Service, the B.C. Ministry of Forests, and Forest Renewal British Columbia. Additional assistance was provided by the Greater Vancouver Regional District. Bruce Thomson, Geomorphologist with the B.C. Ministry of Water, Land and Air Protection, Surrey also reviewed a draft of this case study and provided helpful comments.

4.4.7 References

Eliadorani, A., R.J. Fannin and P. Jordan. 2003. Debris flows: Back analysis of travel distance at Blueberry Creek using UBCDFLOW. *In* Proc. 3rd Can. Conf. on Geotechnique and Natural Hazards, Edmonton, Alta., June 8–10, pp. 349–356.

Fannin, R.J., A. Eliadorani, and J.M.T. Wilkinson. Shear strength of cohesionless soils at low effective stress. Submitted to Geotechnique, Sept. 2003.

Fannin, R.J. and J. Jaakkola. 1999. Hydrological response of hillslope soils above a debris-slide headscarp. Canadian Geotechnical Journal 36(6):1481–1494.

Fannin, R.J. and M.P. Wise. 2001. An empirical-statistical model for debris flow travel distance. Canadian Geotechnical Journal 38(5):982–994.

Hammond, C., D. Hall, S. Miller, and P. Swetik. 1992. Level 1 Stability Analysis (LISA) documentation for Version 2.0. U.S. Dep. Agric. For. Serv., Intermountain Research Station, Gen. Tech. Rep. INT-285.

Jaakkola, J. 1998. Forest groundwater hydrology: implications for terrain stability in coastal British Columbia. M.Sc. thesis. Univ. British Columbia, Vancouver, B.C.

Luttmerding, H.A., D.A. Demarchi, E.C. Lea, D.V. Meidinger, and T. Vold (editors). 1990. Describing ecosystems in the field. 2nd ed. B.C. Min. Environment Manual 11, B.C. Min. Environment, Victoria, B.C.

Roddick, J.A. 1965. Vancouver North, Coquitlam, and Pitt Lake map-areas, British Columbia. Memoir 335, Geological Survey of Canada.

Thurber Engineering Ltd. 1991. Geotechnical assessment of 1990–1991 landslide events in Greater Vancouver Water District watersheds. Report to Greater Vancouver Water District.

Wilkinson, J.M.T. 1996. Landslide initiation: a unified geostatistical and probabilistic modeling technique for terrain stability assessment. M.Sc. thesis. Univ. British Columbia, Vancouver, B.C.

4.5 Quantitative Analysis of Partial Risk from a Proposed Cutblock: Northeast of Bamfield, Southwestern Vancouver Island, British Columbia

TOM MILLARD

Abstract

A proposed cutblock presents landslide risk to a fish stream. Quantitative partial risk analysis is used to estimate the risk, to identify where the risk is greatest, and therefore to identify where risk control would be most efficient. Partial risk is estimated for individual areas within the cutblock and these partial risks are combined to estimate the partial risk to the fish stream from the entire cutblock. The analysis shows that excluding 6% of the cutblock area would reduce the multiple partial risk to the fish stream by about 50%, and removal of 23% of the cutblock area would reduce the multiple partial risk to the fish stream by about 75%. Evaluation of the relative benefits of risk control options are facilitated by using quantitative risk analysis.

4.5.1 Introduction

Forest harvesting on steep slopes in coastal British Columbia often presents risks to fish streams. This case study is a partial risk analysis for a proposed cutblock on southwestern Vancouver Island. The study is quantitative, using estimates of landslide hazard and risk based on research conducted in the area surrounding the cutblock and similar areas of coastal British Columbia.

4.5.2 General site characteristics

The study area is located approximately 25 km northeast of Bamfield on southwestern Vancouver Island (Figure 41). The climate of the area is wet and mild. Bamfield has an average of 2870 mm annual precipitation, with more than 99% of this falling as rain (Environment Canada 2003). More precipitation is likely at this site due to the higher elevation (Marquis 2001), with a greater percentage falling as snow.

Bedrock is granodiorite of the Island Intrusions (Mueller 1976). Faults and shear zones are common in the area, with major gullies often following these bedrock discontinuities. Topography is rugged, with local valley bottoms at an elevation of less than 100 m and ridge tops at elevations of about 800–900 m.

The proposed cutblock is within the Coastal Western Hemlock biogeoclimatic zone, vm1 and vm2 variants (Nuszdorfer and Boetger 1994). Balsam fir and western hemlock are the dominant tree species within the cutblock, with some western redcedar present as well.

Southwestern Vancouver Island is subject to strong cyclonic storms from the Pacific Ocean. Winds from these storms are primarily from the southeast to southwest, but are subject to local topographic constraints. Additional winds from the north can also be strong. During site assessment of the cutblock, almost all windthrow was oriented towards the north, confirming that winds from the south are the dominant winds that could create windthrow problems.

Steep, deeply gullied slopes dominate the terrain in the vicinity of the cutblock. The cutblock is located on mostly open slopes between deep gullies. A fish stream is located about 300–400 m downslope of the cutblock. Forestry staff had identified concerns about

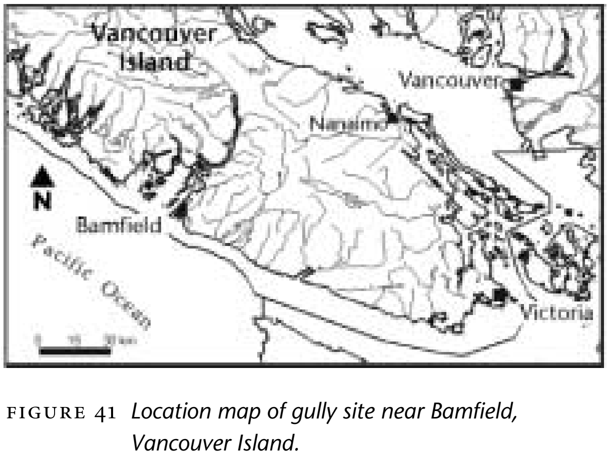


FIGURE 41 *Location map of gully site near Bamfield, Vancouver Island.*

post-logging landslide hazards and concerns that forest harvesting on this steep slope could pose a risk to fish and fish habitat.

Cutblock and terrain polygon descriptions The proposed cutblock is located on mid- to upper slopes with a northern aspect, and is bounded on either side by deep gullies that were previously excluded from the cutblock. The cutblock is composed of a West Unit and an East Unit, separated by a deep gully excluded from harvest. Only the West Unit is assessed in this case study (Figure 42). The West Unit has roads located on gentle to moderate midslopes, and these areas will be harvested with a grapple yarder. Upper slopes will be helicopter harvested.

Surficial materials within the West Unit are mostly till with some rock and occasional colluvium on steeper slopes. The till has a silty-sand matrix and is generally well drained. Lower portions of the cutblock are mantled in a thick blanket of till. As slope gradients and elevation increase, the till thins, with occasional rock exposures in the middle and upper portions of the block.

The West Unit of the cutblock is divided into small terrain polygons (Figure 42) based on surficial materials, slope gradient, and other attributes. Table 28 shows the attributes of each polygon. Polygons 4, 5, 9, and 10 are adjacent to, but outside, the West Unit and are included in Table 28, so that risk from potential windthrow-induced landslides may be evaluated. Column 5 in Table 28, "Probable landslide path," describes the landslide initiation slope morphology (open slope, gully sidewall, or gully headwall), which is an attribute of the polygon, and the slope morphology along the likely landslide path, which may include other polygons.

A small natural debris slide (about 5 × 75 m) recently initiated in Polygon 7 on a slope of 39° (80%), within the till veneer just below a rock bluff. The slide stopped on open slopes of about 17–19° (30–34%) within Polygon 8.

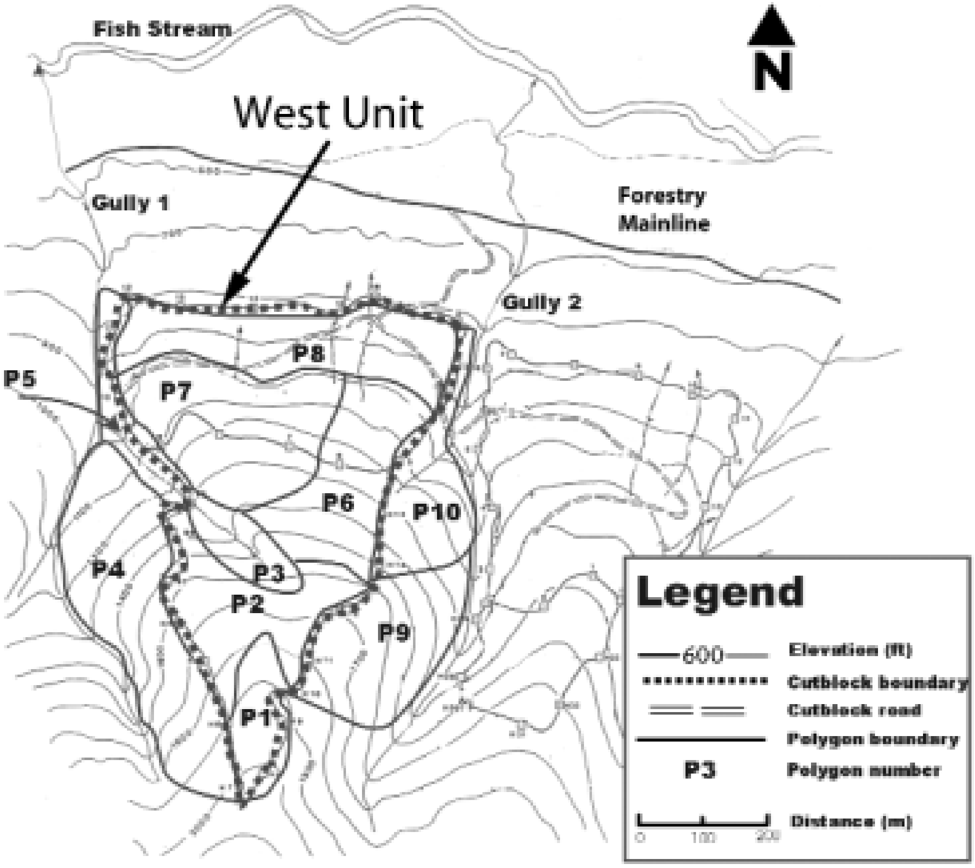


FIGURE 42 *West Unit of proposed cutblock.*

TABLE 28 *Summary of polygon terrain attributes*

Polygon	Area (ha)	Slope gradient (°)	Surficial materials*	Probable landslide path**	Additional attributes or comments
1	1.4	20–29	Mv/R	OS→GC	
2	3.8	31–37	Mv/R	OS→GC	
3	1.4	40–43	Mv/R	GH→GC or GS→GC	Headwall and sidewall gully area, creep present in headwall
4	7.8	35–42	Mv/R/Cv	GS→GC	Adjacent to the West Unit
5	1.3	35–40	Mv/R/Cv	GS→GC	Adjacent to the West Unit
6	4.3	31–35	Mv/R	OS→OS	Uniform hillslope configuration
7	5.9	31–39	Mv/R	OS→OS	Irregular hillslope configuration; moderate to imperfect drainage; small natural landslide present
8	5.7	17–30	Mb	OS→OS	Uniform hillslope configuration
9	4.6	35–42	Mv/R/Cv	GS→GC	Adjacent to the West Unit
10	3.0	35–40	Mv/R/Cv	GS→GC	Adjacent to the West Unit

* Terrain symbols from Howes and Kenk (1997).

** OS, GC, GH, and GS are slope morphologies. OS = open slope; GC = gully channel; GH = gully headwall; GS = gully sidewall. The arrow indicates the landslide path; for example, OS→GC = a landslide that initiates on an open slope and then enters a gully channel.

Landslide travel distance depends on whether a landslide is likely to enter into a gully and initiate a debris flow, or whether it will travel only on open slopes. Polygons 6, 7, and 8 are located on open slopes that do not lead to a gully channel. Polygons 1 and 2 are located on open slopes that lead into gullies. Polygons 3, 4, 5, 9, and 10 are gullies. Additional gully attributes are shown in Table 29.

4.5.3 Risk analysis

The geologic setting and geomorphology of the area indicate that debris slides and debris flows are the dominant landslide types, and only these types are considered in this case study. Only cutblock-related landslides are considered; potential landslides associated with roads are not considered.

Partial risk, P(HA), is the product of the probability of occurrence of a specific hazardous landslide and the probability of that landslide reaching or otherwise affecting the site occupied by a specific element. It is mathematically expressed as:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S)$$

In this case, since the fish stream is always present below the proposed cutblock, P(T:S) is assumed to equal 1.0 and the partial risk is:

$$P(HA) = P(H) \times P(S{:}H)$$

TABLE 29 *Summary of gully attributes*

Polygon	Surficial material depth (m)	Gully wall slope distance (GWSD, m)	Channel gradient (°)	Channel width (m)	Gully bottom width (m)	Channel sediment storage (m^3/m)*
3	0.3	8–15	26	<1	6–7	5
4	0.3	30	35–40	3–4	8	<1
5	0.3	30	14	4–5	10	<1
9	0.3	25	35	5	8	<1
10	0.3	25	15	5	10	<1

* The volume of sediment stored in the gully bottom per metre of gully length.

For open-slope landslides, $P(H)_{OS}$ is simply the probability of landslides initiating within an area, and P(S:H) is the probability of a landslide, once initiated, reaching the fish stream.

In gully areas, $P(H)_G$ is defined as the probability of a debris flow initiating. Almost all coastal British Columbia debris flows initiate from landslides that enter the gully channel after initiating on an open slope, gully sidewall, or gully headwall (Rollerson 1984; Rood 1990; Millard 1999). $P(H)_G$ can be expressed mathematically as:

> $P(H)_G = P(LI) \times P(DFI)$, where LI = landslide initiation and DFI = debris flow initiation.

Once a debris flow has initiated, it must travel the length of the gully to discharge into the fish stream. The distance a debris flow travels depends on the characteristics of both the debris flow and the gully, and therefore P(S:H) needs to account for both of these factors.

P(H) – Probability of landslide occurrence For this case study, probabilities of hazardous landslide occurrence are based on a terrain attribute study from southwestern Vancouver Island that identifies specific terrain types and the post-clearcut landslide rate associated with that terrain type (Rollerson et al. 2002). This case study uses one measure of landslide rates from Rollerson et al. (2002): "the percentage of sample polygons with landslides ≥ 500 m^2 (0.05 ha)." This measure applies only to landslides that occur within clearcut areas, and does not include landslides from the road cut or fill slope. The landslide rates reported by Rollerson et al. are for a period of about 15 years post-clearcutting, and therefore predicted landslide probabilities are for a 15-year post-clearcut period. Roberts (2001) detected little or no reduction in landslide rates when clearcut helicopter harvesting was used compared to conventional harvesting. Although some portions of the West Unit will be helicopter yarded and some areas will be conventionally yarded, no difference in landslide outcome is expected due to the different yarding methods.

These landslide rates can be used to predict the probability of landslide occurrence after clearcut logging by equating terrain types within the proposed cutblock with terrain types identified by Rollerson et al. (2002), and then using the landslide rate for that terrain type to predict future landslide probability. For example, if 20% of a specific terrain type has post-clearcut landslides, then it can be expected that future clearcut harvesting of that same terrain type will have a landslide probability of 0.20. Table 30 shows terrain types from Rollerson et al., their associated landslide rates, and, for each terrain category, the polygons from the West Unit that have similar terrain attributes.

TABLE 30 *Landslide rates for specific terrain categories based on data by Rollerson et al. (2002)*

Terrain category	**Significant terrain attributes**	**Percent of polygons with landslides >500 m^2**	**Polygons in or near the West Unit that are similar to the terrain category**
A	MSA* 21–33° NW - NE aspect	9	1, 8
B	MSA 33–40° Island Intrusions bedrock and Mv surficial material	13	2, 6, 7
C	MSA >40° Island Intrusions; surficial material <0.5 m thick	16	3, 4, 5, 9, 10
D	MSA >40° Island Intrusions; surficial material >0.5 m thick, gullied	40	3, 4, 5, 9, 10

* Maximum slope angle

Open slope polygons Table 31 shows the estimated $P(H)_{OS}$ for Polygons 6, 7, and 8. The probabilities in Table 31 are based on the observed landslide rates shown in Table 30. However, to account for specific site factors and other information presented by Rollerson et al. 2002, the values of $P(H)_{OS}$ for Polygons 7 and 8 were subjectively estimated to be higher and lower, respectively, than the observed landslide rates.

Gully-related polygons The gullied Polygons 3, 4, 5, 9, and 10 are similar to both Category C and Category D in Table 30. Terrain Category C has a landslide rate of 16% compared to 40% for Category D. A review of airphotos from the area surrounding the proposed cutblock found 10 of 26 recently clearcut gullies (38%) having landslides ≥ 500 m^2. Although the surficial material in the cutblock polygons is <0.5 m deep, the strong effect of gullies on landslide rates and local evidence supports the application of the Category D landslide rates when predicting landslide initiation probability for the gullied polygons. For Polygons 3, 4, 5, 9, and 10, P(LI) is estimated as 0.40.

Debris slides in Polygons 1 and 2 would likely enter Gully 1. Polygon 1 meets the criteria of Category A from Table 30 and Polygon 2 meets the criteria of Category B. Polygon 1 therefore has a landslide initiation probability, P(LI), of 0.09, and Polygon 2 has a landslide initiation probability of 0.13.

Millard (1999) uses terrain attributes, landslide attributes, and logistic regression to predict P(DFI) if a landslide enters the gully channel. For this case study, Millard's "Gully Best Model" was selected as most appropriate and uses the following attributes:

- geographic area (for this case study, the North Nitinat)
- channel gradient where the landslide enters the gully (Province of British Columbia 2001)
- gully wall slope distance (GWSD); inner gully wall slope distance used
- sidewall or headwall location
- landslide volume entering the gully channel.

Table 32 shows estimated volumes of debris that would enter the gully channel. The estimated length of the landslide is based on minimum and maximum distances from the polygon to the gully channel. Minimum and maximum debris slide widths of 10 and 20 m are assumed. Estimated depth of debris slide scour is 0.3 m—the approximate depth of surficial material in these polygons. Polygon 3 is gullied, and therefore the landslide volume estimate is based on a channel yield rate (Fannin and Rollerson 1993) of 5 m^3/m (Table 29) from Polygon 3 to Gully 1.

Table 33 shows the model parameters for each gully polygon, and the probability of a debris flow initiating within the gully channel.

For the gully polygons and polygons sloping into a gully, $P(H)_G = P(LI) \times P(DFI)$. Table 34 shows the calculated $P(H)_G$.

TABLE 32 *Estimated landslide volume entering the gully channels*

Polygon	Distance from initiation point to gully channel (m)	Landslide volume (m^3)
1	350–550	1000–3300
2	150–450	450–2700
3*	250–350	1250–1750
4	125–200	375–1200
5	10–30	30–180
9	25–225	75–1350
10	25–200	75–1200

* Distance to Gully 1.

TABLE 31 *Estimated probability of a hazardous landslide, $P(H)_{OS}$*

Polygon	$P(H)_{OS}$	Comments
6	0.13	$P(H)_{OS}$ estimated to be equivalent to observed landslide rate shown in Category B.
7	0.25	Considering the natural landslide in Polygon 7, $P(H)_{OS}$ estimated to be higher than observed landslide rate shown in Category B.
8	0.05	Mostly has slopes <25°; $P(H)_{OS}$ estimated to be lower than observed landslide rate shown in Category A.

TABLE 33 *Estimated debris flow initiation probability, P(DFI)*

Polygon	Channel gradient (°)	Gully wall slope distance (m)	Landslide entry location	Initial landslide volume (m^3) (Table 32)	P(DFI) range from the "Gully Best Model"	P(DFI) for use in Table 34
1	37	30	Sidewall	1000–3300	0.99	0.99
2	32	30	Sidewall	450–2700	0.97–0.99	0.98
3	26	30	Headwall	1500–1750	1.00	1.0
3	26	30	Sidewall	1250–1500	0.99	1.0
4	35	30	Sidewall	375–200	0.97–0.99	0.98
5	14	30	Sidewall	30–180	0.31–0.78	0.54
9	35	30	Sidewall	90–1350	0.79–0.99	0.90
10	14	30	Sidewall	90–1200	0.66–0.99	0.83

P(S:H) – Probability of a landslide entering the fish stream Predicting the probability of a landslide depositing debris into the fish stream requires predicting the path of the landslide. Polygons 6, 7, and 8 have fairly uniform open slopes below them, and it is likely that landslide paths will be unconfined and parallel to each other. Landslides in gullied polygons or polygons above gullies, if they travel far enough, will converge in the gully channel, and the path of the landslide is then well defined until deposition begins.

Open-slope polygons Open-slope, unconfined landslides tend to deposit on relatively steep slopes. Fannin and Rollerson (1993) found that landslides on open slopes stopped on slope gradients of about 15 ± 8° (average and standard deviation), with the length of the deposition area 41 ± 31 m. Hungr (1999) found that net deposition began on an average slope gradient of about 18° for events <3333 m^3.

The existing natural landslide from Polygon 7 was about 50–100 m^3 in volume and stopped on slopes of approximately 17–19°. This confirms that deposition will likely begin on open slopes of about 18°. Other landslides from the open-slope polygons may be larger and therefore travel farther; however, their volumes are still likely to be relatively small (<1000 m^3) and limited in their travel distance.

The slopes below the West Unit range between 12 and 18° for approximately 300–400 m. Below these slopes is a short steep escarpment directly above the fish stream. Based on the slope gradients and the long distance from the West Unit to the stream escarpment, the probability of a landslide from Polygons 6, 7, or 8 reaching the fish stream is estimated to be 0.1.

TABLE 34 *Estimated probability of a hazardous landslide, $P(H)_G$*

Polygon	P(LI) from Table 30	P(DFI) from Table 33	$P(H)_G$ = P(LI) × P(DFI)
1	0.09	0.99	0.09
2	0.13	0.98	0.13
3	0.40	1.0	0.40
4	0.40	0.98	0.39
5	0.40	0.54	0.22
9	0.40	0.90	0.36
10	0.40	0.83	0.33

Gully-related polygons Travel distance of gully debris flows depends on both the characteristics of the gully and the size of the debris flow. Larger debris flows tend to travel farther on less steep gradients (Hungr 1999). Gully 1 (Polygons 4 and 5) and Gully 2 (Polygons 9 and 10) have very little sediment stored within the bottom of the gully until the channel gradients are about 17° or less. Landslides that enter these channels are unlikely to increase in volume; however, the steep gradients in their upper reaches indicate that they are unlikely to decrease in volume until they enter the lower reaches, where channel gradients are less than 15°.

Below Polygon 5, Gully 1 is confined, with a gradient of about 15°, for about 350 m until it reaches the fish-stream escarpment, where the channel gradient increases until Gully 1 joins the fish stream. Below Polygon 10, Gully 2 is primarily confined, with channel gradients <15° from the bottom of the West Unit

TABLE 35 *Probability of a landslide reaching the fish stream from gully channels, P(S:H)*

Polygon	**Estimated landslide volume reaching a gully (m^3)**	**Sediment delivered to**	**Estimated P(S:H)**
1	1000–3300	Gully 1	0.9
2	450–2700	Gully 1	0.9
3	1250–1750	Gully 1	0.9
4	375–1200	Gully 1	0.9
5	30–180	Gully 1	0.2
9	75–1350	Gully 2	0.1
10	75–1200	Gully 2	0.1

to the top of the fish-stream escarpment. Gully 2 crosses a small mid-slope fan about 150 m in length, and is then confined until it reaches the fish stream, a distance of about 150 m.

Both gullies generally fit the *Type 3* description of Fannin and Rollerson (1993). Seventy percent of debris flows within this gully type continued past the bottom of the gully, despite an average channel gradient of only 10°. Debris flows composed of granitic bedrock types should result in greater deposition angles (Jordan 1994). For 15° unconfined slopes, approximately 10 m^3/m is deposited (Hungr 1999). This indicates that about 1500 m^3 is likely to be deposited on the fan surface of Gully 2.

Table 35 summarizes the estimated landslide volumes and shows the estimated probability of a landslide entering the fish stream. The estimates of spatial probabilities are based on the work of Fannin and Rollerson (1993), Jordan (1994), and Hungr (1999). The landslide volumes that reach the gully channel are used to assess whether the resulting debris flow is likely to stop before reaching the fish stream, or whether it is likely to have sufficient volume to reach the fish stream.

P(HA) – Partial risk to the fish stream from a landslide Table 36 shows the partial risk for each polygon, estimated from the P(H) and the P(S:H) in the previous section.

TABLE 36 *Partial risk to the fish stream, P(HA)*

Polygon	**P(H)***	**P(S:H)****	**P(HA)= P(H) x P(S:H)**
1	0.09	0.9	0.08
2	0.13	0.9	0.1
3	0.40	0.9	0.4
4	0.39	0.9	0.4
5	0.22	0.2	0.04
6	0.13	0.1	0.01
7	0.25	0.1	0.02
8	0.05	0.1	0.01
9	0.36	0.1	0.04
10	0.33	0.1	0.03

* P(H) is for the 15-year post-clearcut period, from Tables 31 and 34.

** P(S:H) is from the previous subsection (P(S:H) – Probability of a landslide entering the fish stream) and Table 35.

Overall, the West Unit presents a level of risk to the fish stream that is a combination of risks from all polygons. Landslides from one or several polygons may enter the fish stream, so it is easiest to calculate the probability of having no landslides enter the fish stream rather than calculate all possible combinations of polygons with landslides that enter the fish stream. Multiple partial risk for the entire cutblock can be calculated as:

$$P(HA)_{cutblock} = 1 - P(\text{no landslides reaching the fish stream from any cutblock polygon})$$
$$= 1 - \{[1\text{-}P(HA)_1] \text{ x } [1\text{-}P(HA)_2] \times \ldots \times [1\text{-}P(HA)_n]\}$$

Where 1, 2, …, n are all the polygons within the cutblock.

Multiple partial risk for the entire West Unit (Polygons 1, 2, 3, 6, 7, and 8) is 0.5. In other words, there is a 50% chance of at least one landslide from the West Unit entering the fish stream in the 15 years following harvest. Since Polygons 4, 5, 9, and 10 are outside the cutblock and will not be clearcut, they are not included in this calculation.

4.5.4 Risk evaluation

The West Unit of the cutblock as currently planned has a multiple P(HA) of 0.5 for the 15-year post-clearcut period. Table 2 in Chapter 3 indicates that this may be a relatively high degree of risk. It is prudent to consider developing the cutblock so that risk is reduced.

The total area of the West Unit is 22.5 ha. Polygons 3 and 2 are 1.4 ha and 3.8 ha in area, or about 6% and 17% of the proposed cutblock area, respectively. If Polygon 3 was excluded from the cutblock, the multiple P(HA) would decrease by about 50%, from 0.5 to

0.2. Similarly, if Polygons 2 and 3 were both excluded from the cutblock, the area to be harvested would be reduced by 23% of the proposed cutblock area, but the multiple P(HA) would decrease by about 75% (from 0.5 to 0.1).

4.5.5 Risk control

Risk control would be most effective by reducing the amount of risk presented by Polygon 3, and, secondly, by reducing risk presented by Polygon 2. Three options exist for reducing risk from Polygon 3.

1. The cutblock can be modified to exclude Polygon 3 so that the area will not be clearcut.
2. Partial harvesting of Polygon 3 could reduce the post-harvest probability of landslides. The reduction in landslide probability will increase with the percentage of trees retained, but for any percentage of retention, the degree of reduction in landslide probability is not currently known.
3. Polygon 3 can be harvested and a debris flow detention or deflection berm can be constructed so that a debris flow does not reach the fish stream. Although the lower slopes appear conducive to the construction of a berm, more investigation would be required to assess a berm's feasibility and cost-effectiveness.

Windthrow may become a significant issue if Polygon 3 is excluded from the cutblock or partially harvested. Excluding or partially harvesting only Polygon 3 from the cutblock will create a narrow buffer with a northwest–southeast alignment likely subject to windthrow from the southerly winds. If Polygon 3 is to be excluded, then additional upslope areas should be excluded as well, with windthrow treatments to minimize windthrow risks within Polygon 3. Exclusion of areas upslope of Polygon 3 will reduce risk from Polygon 2, as long as the area remains windfirm.

Recent experience in coastal British Columbia shows that landslides are associated with extensive windthrow on potentially unstable terrain (T. Rollerson, pers. comm., Dec. 2003). Polygon 4 is outside the block and, if clearcut, would have a partial risk similar to that of Polygon 3. The cutblock boundary along Polygon 4 is parallel or slightly windward to the dominant winds. If extensive windthrow occurs along this boundary, landslides may occur. Windthrow treatments should be considered for this section of the boundary to reduce the risk of landslides entering the fish stream. Other boundary edge polygons (Polygons 5, 9, and 10) have low partial risks and are not as exposed to southerly winds, so windthrow treatments in these areas would not significantly reduce partial risk to the fish stream.

An additional hazard, not formally considered in this study, is sedimentation of the fish stream through fluvial transport of sediment from a debris flow that deposits material in a gully before reaching the fish stream. Should a landslide deposit anywhere in Gullies 1 or 2, some sedimentation of the fish stream is almost certain.

4.5.6 Concluding remarks

The quantitative estimates of partial risk in this case study are useful for comparing risk levels within the cutblock and for assessing the reduction in risk with various options for risk control. Explicit evaluation of the costs and benefits of various harvest options is easier with quantitative estimates of risk.

Since these quantitative estimates are based on extrapolations from published studies, as well as rational subjective judgements, they are more scientifically defensible than subjective judgements alone. Although providing a quantitative estimate of partial landslide risk is possible, the demonstrated approach requires extensive research results on which to base the estimates. In this case study, the P(H) estimates are believed to be better estimates than the P(S:H) estimates because they are based on more extensive information, much of it derived from the area surrounding the proposed cutblock. More research in landslide travel distance could result in better P(S:H) estimates.

4.5.7 Acknowledgements

The author thanks the following individuals for their generous efforts. Terry Rollerson reviewed early drafts of this case study and provided valuable comment. Wendy Bergerud, Steve Chatwin, and Peter Ott also reviewed drafts of this case study.

4.5.8 References

British Columbia Ministry of Forests and B.C. Ministry of Environment. 2001. Gully assessment procedure guidebook, 4th ed. Forest Practices Code of British Columbia, B.C. Forest Service and B.C. Environment, Victoria, B.C.

Environment Canada. 2003. Website: http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html

Fannin, R.J. and T. Rollerson. 1993. Debris flows: Some physical characteristics and behaviour. Canadian Geotechnical Journal 30:71–81.

Howes, D.E. and E. Kenk. 1997. Terrain classification system for British Columbia (Version 2). B.C. Min. Environ. and B.C. Min. Crown Lands, Victoria, B.C.

Hungr, O. 1999. Landslide/debris flow runout prediction for risk assessment. FRBC final report. Department of Earth and Ocean Sciences, Univ. British Columbia, Vancouver, B.C.

Jordan, R.P. 1994. Debris flows in the southern Coast Mountains, British Columbia: Dynamic behaviour and physical properties. Ph.D thesis. Univ. British Columbia, Vancouver, B.C.

Marquis, P. 2001. How practical are precipitation shutdown guidelines? *In* Streamline watershed restoration technical bulletin. B.C. Min. Environ., Vancouver, B.C. Vol. 5, No.4., pp. 13–16.

Millard, T. 1999. Debris flow initiation in coastal British Columbia gullies. Forest Research technical report TR-002. Vancouver Forest Region, B.C. Forest Service, Nanaimo, B.C.

Mueller, J.E. 1976. Cape Flattery map-area (92C), British Columbia. Report of Activities, Part A. Geological Survey of Canada, Paper 76-1A, pp. 287–294.

Nuszdorfer, F.C. and R. Boetger (compilers and editors). 1994. Biogeoclimatic units of Vancouver Forest Region, Mapsheet 5 of 6, southern Vancouver Island and Sunshine Coast. B.C. Min. For., Res. Br., Victoria, B.C.

Roberts, W.B. 2001. A terrain attribute study of helicopter logging-related landslides in the southwest Coast Mountains of British Columbia. M.Sc. thesis. Simon Fraser Univ., Burnaby, B.C.

Rollerson, T. 1984. Terrain stability study–TFL 44. MacMillan Bloedel Ltd., Nanaimo, B.C.

Rollerson, T., T. Millard, and B. Thomson. 2002. Using terrain attributes to predict post-logging landslide likelihood on southwestern Vancouver Island. Vancouver Forest Region, B.C. Min. For., Nanaimo, B.C. Technical Report 15.

Rood, K.M. 1990. Site characteristics and landsliding in forested and clearcut terrain, Queen Charlotte Islands, B.C. Province of British Columbia, Victoria, B.C. Land Management Report 64.

4.6 Qualitative Analysis of Specific Risk from Road Route Alternatives: Tommy Creek Watershed, Lillooet, British Columbia

CALVIN VANBUSKIRK

Abstract

Many factors go into the selection of forest road alignments. These typically include location of timber resources, harvest methods, costs of road construction and harvesting, and stability of the terrain. This case study demonstrates how consideration of some of these factors, together with qualitative landslide risk analysis and geotechnical engineering, can be used in route selection, road design, and road construction. At the route selection stage, to access timber in the Tommy Creek watershed, an alternative alignment was identified that provided access to a larger area of potential forest development than did the original alignment, with significantly less landslide risk to the fish habitat in the creek. During road construction, the subsurface conditions were assessed and confirmed, and, where practicable, changes were made to the alignment, design, and construction technique. By involving terrain stability and geotechnical engineering professionals in the route selection, the design and construction of this challenging road saved the client an estimated $400 000 in road and bridge construction costs.

4.6.1 Introduction

In 1997, the British Columbia Ministry of Forests (MOF) noted that spruce bark beetles had infested the middle and upper portion of the previously undeveloped Tommy Creek valley, in the Lillooet Forest District. MOF started planning access to the area to salvage the timber. In 2000, Terratech Consulting Ltd. (TCL) was retained to review the terrain stability and geotechnical engineering aspects of the proposed Tommy Creek Mainline. This assignment included a review of plans and profiles, previous reports, airphotos, a terrain stability assessment and reconnaissance assessment of potential mainline options.

Site conditions The Tommy Creek watershed is located 50 km northwest of Lillooet, B.C , on the south side of Carpenter Lake. The bedrock geology in the area consists of Mississippian to Middle Jurassic, marine sedimentary and volcanic rocks of the Bridge River Complex (Fergusson Group). Intruded into these rocks and present in the upper watershed is Late Cretaceous to Early Tertiary granodiorite (Wordsworth 1977). In the mid- to upper-slope areas, the surficial geology consists of veneers and mantles of well-drained morainal and colluvial deposits overlying bedrock. The surficial geology of the lower slopes is quite variable and includes morainal, glaciofluvial, and colluvial deposits, as well as steeply sloping bedrock, talus, debris flow, and snow avalanche deposits. In general, the colluvial and morainal soils are poorly graded granular deposits.

An old mine exploration access road exists on the west side of Tommy Creek near the valley bottom. Grades on this road average between 14 and 16%, with some sections up to 22 %. This road includes sections built into the creek using log cribs, which are currently in an advanced state of decay. Debris flows, snow avalanches, stream erosion, and cutslope and fillslope instability have removed this road at several locations.

Proposed development Given the high percentage of spruce within the Tommy Creek valley, the original plan was to harvest as much of the beetle-infected forest as practicable within a 5-year period. There were no immediate plans for harvesting the lower (northern) portion of the valley, although harvesting opportunities exist.

Two potential mainline options were identified by MOF (Options 1 and 3) and one additional option was identified in the field (Option 2). These three options are shown in Figure 43. Option 1 starts at the

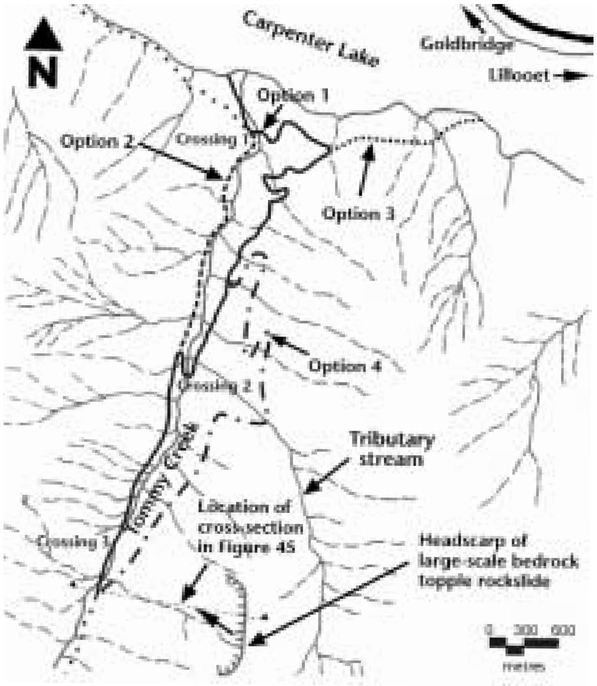


FIGURE 43 *Site plan of proposed mainline location options, Tommy Creek.*

Tommy Creek fan and crosses Tommy Creek three times before reaching the first proposed cutblock. Option 2 involves using the entire length of the old mine road on the west side of the valley. Option 2 would eliminate two crossings of Tommy Creek, one crossing of a tributary stream, and one difficult road switchback. However, this option was dropped due to significant concerns regarding the potential construction impacts on the creek, the length of road within the riparian reserve, and the extent of natural upslope hazards that would likely affect the road. Option 3 starts on the fan to the east of Tommy Creek and connects to Option 1. Option 3 offers improved barging opportunities and eliminates one crossing of Tommy Creek. However, the eastern fan is dominated by frequent debris flow activity.

Option 4 was identified by TCL during a review of airphotos, total chance plans, and topographic maps, and during a helicopter reconnaissance of the valley. It starts on the Tommy Creek fan, crosses the creek near the apex of the fan, and stays on the east side of the valley all the way to the first proposed cutblock. Option 4 has the immediate benefits of eliminating two crossings of Tommy Creek, one bridge crossing of a tributary stream, one difficult switchback, and all of the natural hazards associated with the west side of the valley.

For this case study, only Options 1 and 4 are considered.

4.6.2 Landslide risk analysis

P(H) is defined as the probability of occurrence of a specific hazardous landslide. Specific risk, R(S), is the risk of loss or damage to a specific element, resulting from a specific hazardous affecting landslide, and is expressed mathematically as:

$$R(S) = P(HA) \times V(L{:}T), \text{ or}$$
$$R(S) = P(H) \times P(S{:}H) \times P(T{:}S) \times V(L{:}T)$$

For this risk analysis it was assumed that, if a landslide occurs, it is certain to reach the site occupied by the specific elements (discussed below). Furthermore, it was assumed that the locations of all elements at risk are permanent. In a quantitative analysis, these assumptions are equivalent to saying that $P(S{:}H) = 1.0$ and $P(T{:}S) = 1.0$. Therefore, in this study, $P(H) = P(HA)$, and the expression for R(S) simplifies to:

$$R(S) = P(H) \times V(L{:}T)$$

where V(L:T) is the estimated proportion of loss or damage to a specific element, given a temporal effect.

When qualitative terms are used to describe probability (likelihood) of occurrence, P(H), the qualitative terms should be defined. Table 37 provides definitions for relative qualitative ratings of P(H) over the design life of the road.

The following elements were identified for Options 1 and 4:

- fish habitat in Tommy Creek
- forest road, once constructed
- timber resources (productive forestland).

It was assumed that that the probability of some loss or damage to fish habitat, forest road, or timber resources is certain should a landslide reach the site occupied by any one of these elements. Therefore, the vulnerability of these elements is simply the estimated proportion of loss or damage, and the vulnerability ratings are provided in Tables 38, 39, and 40, respectively.

TABLE 37 *Qualitative ratings for P(H)*

Qualitative rating of P(H) over the design life of the road	Qualitative description of site conditions*
Very low	There is a strong belief that a specific landslide event will not, or cannot, occur under the existing, or assumed, site conditions.
Low	It is believed that a landslide event will not occur, although it is possible, given specific combinations of site conditions.
Moderate	It is believed that a landslide event could occur; however, a significant change to one or more of the assumed site conditions would be required for a landslide event to occur.
High	It is believed that a landslide event will occur unless the site conditions are significantly better than assumed.
Very high	There is a strong belief that a landslide event will occur regardless of reasonable changes in the assumed site conditions. Landslide activity is likely to occur during road construction or within the first year following construction.

* Site conditions refer to the geomorphic, hydrologic, climatic, and anthropogenic conditions present, and include the influence of land use, inspections, maintenance, deactivation, and rehabilitation.

TABLE 38 *Vulnerability ratings for fish habitat in Tommy Creek**

Vulnerability rating	Description of Tommy Creek, V(L:T)
Moderate	Indirect effect of landslide on the creek via sediment transport by surface soil erosion or small-scale fluvial processes. Effect is limited to water quality, and is either short in duration and/or can be mitigated by drainage improvements and/or implementation of basic surface soil erosion control measures (grass-seeding).
High	Direct effect of landslide on the creek. Landslide debris is delivered directly into the stream.

* It is assumed that vulnerability of the creek is equal to the vulnerability of fish habitat. Accordingly, no vulnerability rating of "Low" was defined.

TABLE 39 *Vulnerability ratings for forest road once constructed*

Vulnerability rating	Description of forest road, V(L:T)
Very low	Minor obstruction of road by small slumps or slides from cutslope
Low	Temporary loss of road access, but practicably reparable
Moderate	Loss of road access, difficult to repair
High	Loss of bridge or total loss of road (reconstruction may not be practicable)

TABLE 40 *Vulnerability ratings for timber resources (productive forestland)*

Vulnerability rating	**Description of timber resource, V(L:T)***	
	Typical area influenced (ha)	**Typical site index****
Low	<0.5	<15
	<0.05	<20
Moderate	<0.05	>20
	0.05–0.5	15–20
	>0.5	<15
High	>0.5	>15
	>0.05	>20

* Assumes total loss of existing timber or plantation and significant damage to productive forestland.

** The typical site index values in this table were determined from a forest cover map for the area of interest. In this table, the site index is the total height in metres to which dominant trees of a given species will grow on a given site at an index age of 50 years. Site index is a tool to determine the relative productivity of a particular site or location. There is a close relationship between site index and timber yield.

Table 41 provides a simple qualitative risk matrix for specific risk used to estimate the risk to elements present within the study area.

Terrain stability assessment (TSA) of Option 1 Option 1 includes a significant section of the old mine exploration road, multiple crossings of Tommy Creek, some adverse end-haul, and a very difficult switchback proposed on 70% gradient slopes directly upslope of the creek. The results of the TSA are summarized as follows:

- The old mine road is located adjacent to Tommy Creek, mostly on moderately steep to steep slopes comprising glaciofluvial and morainal soils.
- Instability associated with the proposed road would likely affect the creek either directly or indirectly, via surface erosion and sedimentation.
- Cutslope instability would likely result in the need for significant road maintenance, and possible sedimentation of the creek.
- The road alignment is exposed to numerous geological hazards initiating upslope of the road, including debris flows, snow avalanches, rockfalls, rockslides, and flooding (in one area).
- There is significant potential for drainage diversions, possibly resulting in landslides and/or erosion and sedimentation that would adversely affect the road stability, timber resources, and the creek.

In summary, the likelihood of road-related landslides initiating and delivering material into Tommy Creek was judged to be *moderate* to *high* along many sections.

To analyze the landslide hazards and risks, the following criteria were considered for sections of the road with similar terrain:

- the likelihood that the road would result in or contribute to landslide activity (cutslope instability, fillslope instability, and instability from drainage diversions or concentrations downslope of the road).
- the potential for natural hazards upslope of the road to affect the road.

TABLE 41 *Qualitative risk matrix for specific risk, R(S)*

R(S), specific risk, expressed as an expected proportion of loss or damage over the design life of the road R(S) = P(H)* × V(L:T)		**V(L:T), vulnerability rating for the element, expressed qualitatively as a proportion of loss or damage, assuming that some loss or damage to the element is certain**		
		High (total loss or extensive damage)	**Moderate (some loss or damage)**	**Low (limited loss or damage)**
P(H),* likelihood of occurrence of a specific hazardous landslide over the design life of the road	Very high	*Extreme*	*Very high*	*High*
	High	*Very high*	*High*	*Moderate*
	Moderate	*High*	*Moderate*	*Low*
	Low	*Moderate*	*Low*	*Very low*
	Very low	*Low*	*Very low*	*Almost negligible*

* P(H) = P(HA) in this study, and therefore it is assumed that the specific hazardous landslide, given that it occurs, will have sufficient magnitude and mobility to reach or otherwise affect the site of the element.

Table 42 provides a summary of the qualitative specific risk analysis for Option 1. These specific risks were estimated assuming the proposed mitigation measures, such as full-bench cut and end-haul, engineered fills, and retaining walls, are in place.

From Table 42, of the proposed road length:

- 52% has a moderate or greater likelihood of contributing to landslide activity
- >34% represents a moderate or greater risk to the creek (36.1%), road (37.0%), and/or forest (34.3%)
- 30% is susceptible to debris flows
- 46% is susceptible to snow avalanches
- 5% is susceptible to flooding
- 18% is susceptible to rockfall/rockslide activity.

Terrain stability assessment (TSA) of Option 4 The results of the TSA for Option 4 are summarized as follows:

- most of the alignment is on relatively stable, gentle to moderately steep slopes well upslope of Tommy Creek
- instability associated with the proposed road would typically have a low likelihood of reaching or affecting Tommy Creek either directly or indirectly via surface erosion and sedimentation
- cutslope instability is typically expected to consist of ravelling and minor sloughing, which would have a low potential for affecting Tommy Creek in most areas
- portions of the alignment are exposed to snow avalanches and rockslides, which initiated upslope of the alignment
- a portion of the alignment crosses a significant bedrock toppling slope.

The key terrain stability challenge for Option 4 was the crossing of the steep slopes of a very large, bedrock topple (Figure 44). The proposed alignment was located just downslope of the junction between the bedrock and the talus slope. This location limited

FIGURE 44 *Looking south over the bedrock topple section of Option 4 (C. VanBuskirk photo).*

TABLE 42 *Summary of specific risks for Option 1, original alignment—total road length 3691 m*

Section						**Total length rated M, H, or VH (m)**	**% road length rated M, H, or VH**
From station	14801	15292	15484	15664	etc		
To station	15171	15324	15664	15698	etc		
Length (m)	370	32	180	34	etc		
Construction method*	FBCEH (Adverse)	FBCEH	C/F	FBCEH	etc		
Landslide likelihood, P(H)**	M	M	VL	M	etc	**1929**	**52.3**
Development-related landslide specific risk, R(S), to:							
Creek	N/A	M	N/A	H	etc	**1332**	**36.1**
Road	N/A	N/A	N/A	N/A	etc	**1366**	**37.0**
Forest	N/A	N/A	N/A	M	etc	**1235**	**34.3**
Specific Risk, R(S), to road from:							
Debris flow	N/A	N/A	M	N/A	etc	**1093**	**29.6**
Snow avalanche	N/A	N/A	N/A	N/A	etc	**1706**	**46.2**
Flooding	N/A	N/A	H	N/A	etc	**180**	**4.9**
Rockfall/rockslide	N/A	N/A	N/A	N/A	etc	**671**	**18.2**

* FBCEH – Full-bench cut and end-haul; C/F – Cut and fill.

** P(H) = P(HA) in this study, and therefore it is assumed that the specific hazardous landslide, given that it occurs, will have sufficient magnitude and mobility to reach or otherwise affect the site of the element.

the potential for extensive ravelling of the cutslope and the subsequent impact on road use and maintenance, limited the need to excavate dilated, unstable bedrock, and included a control point consisting of a relatively stable 35 m high bedrock bluff.

At TCL's recommendation, MOF retained BGC Engineering Ltd. to analyze the effect of the proposed road on the stability of the large bedrock topple. BGC's analysis supported the positive opinion of TCL (BGC 2001). Figure 45, from the BGC report, is a cross-section sketch of the large-scale toppling feature.

North of the bedrock topple feature the slopes were typically moderate to moderately steep and the terrain was generally stable. One exception was the crossing of the steep bedrock-controlled slopes of a major tributary drainage, which showed evidence of past landslide activity in the overlying colluvium and till.

Overall for Option 4, the likelihood of road-related landslides initiating and delivering material into Tommy Creek was judged to be moderate at a few locations. The landslide risks associated with Option 4 are tabulated in Table 43. These specific risks were estimated assuming that the proposed mitigation measures, such as full-bench cut and end-haul, engineered fills, and retaining walls, are in place.

From Table 43, of the proposed road length:

- 17% has a moderate or greater likelihood of contributing to landslide activity;
- about 2% has a moderate or greater risk to the creek, and 17% to the road; and
- 15% is susceptible to impacts from snow avalanches, rockfall, and rockslide activity.

Note that Option 4 is 1566 m longer than Option 1.

Comparison of specific risk – Options 1 and 4 Table 44 provides a comparison of the landslide risks between Option 1 and Option 4 based on their total length, and the differences in risks. A similar technique was used to compare the road construction costs associated with the various alignment options.

From Table 44, Option 4 when compared to Option 1 has significant reductions in the total length of road with P(H) rated *moderate, high,* or *very high,* in specific risk to the creek, the road, and the forest, and specific risk from debris flow, snow avalanche, and flooding hazards. The one exception is a 16% increase in the length of road exposed to rockfall and/or rockslide activity.

The potential for landslide risk reduction cannot be considered in isolation of recommendations for landslide risk mitigation. Table 45 provides a summary of the six basic recommendations for road design

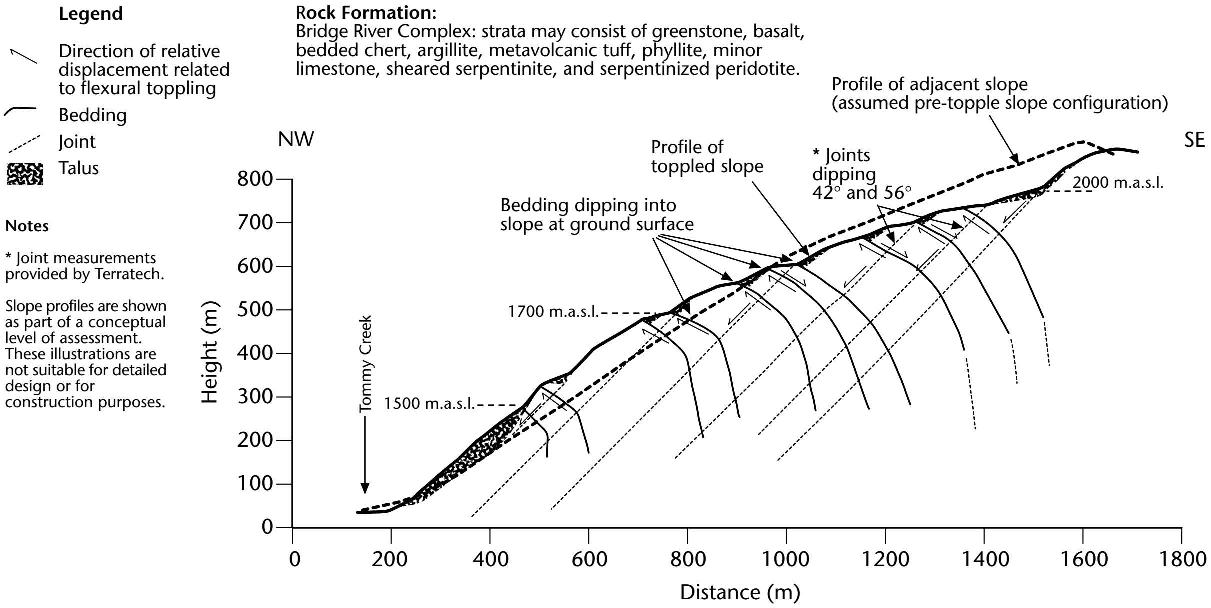


FIGURE 45 *Illustrated cross-section sketch of bedrock-toppling (BGC 2001).*

TABLE 43 *Summary of specific risks for Option 4 alignment—total road length 5257 m*

Section						**Total length rated M, H, or VH (m)**	**% Road length rated M, H, or VH**
From station	21	195	652	984	etc		
To station	66	213	733	140	etc		
Length (m)	45	18	81	418	etc		
Construction method*	Boulder stack embankment	FBCEH	FBCEH	¾BCEH	etc		
Landslide likelihood, P(H)**	L	L	L	L	etc	**887**	**16.9**
Development-related landslide specific risk, R(S), to:							
Creek	N/A	N/A	N/A	N/A	etc	**107**	**21**
Road	N/A	N/A	N/A	N/A	etc	**887**	**16.9**
Forest	N/A	N/A	N/A	N/A	etc	**0**	**0**
Specific Risk, R(S), to road from:							
Debris flow	N/A	N/A	N/A	N/A	etc	**0**	**0**
Snow avalanche	N/A	N/A	N/A	N/A	etc	**780**	**14.8**
Flooding	N/A	N/A	N/A	N/A	etc	**0**	**0**
Rockfall/rockslide	N/A	N/A	N/A	N/A	etc	**780**	**14.8**

* FBCEH – Full-bench cut and end-haul; 3/4 BCEH – 3/4 bench cut end haul.

** P(H) = P(HA) in this study, and therefore it is assumed that the specific hazardous landslide, given that it occurs, will have sufficient magnitude and mobility to reach or otherwise affect the site of the element.

TABLE 44 *Comparison of landslide hazards and risks for Options 1 and 4, based on total road length*

Landslide hazards and risks	**Option 1 (m)**	**Option 4 (m)**	**% difference Opt 4 – Opt 1**
Length of road with P(H) rated M, H or VH	1929	887	-54.0
Length of road contributing to specific risk, R(S), to:			
Creek	1332	107	-92.0
Road	1366	887	-35.1
Forest	1235	0	-100
Length of road subjected to specific risk, R(S), from:			
Debris flow	1093	0	-100
Snow avalanche	1706	780	-54.3
Flooding	180	0	-100
Rockfall/rockslide	671	780	+16.2

TABLE 45 *Comparison of construction types for Options 1 and 4, based on total road length*

Construction type	**Option 1 (m)**	**Option 4 (m)**	**Difference Opt 4 – Opt 1**
Full-bench cut and end-haul	690	585	-105
¾ Bench cut and end-haul	0	556	+556
Full-bench cut and sidecast	0	564	+564
Engineered walls	84	105	+21
Engineered fill	60	45	-15

proposed to manage the landslide hazards for Option 1 and Option 4.

There was a slight reduction (105 m) in the total length of full-bench cut and end-haul between Option 1 and Option 4; however, this was largely offset by an increase in the length of 3/4 bench cut and end-haul (556 m). The length of engineered retaining walls and fills remained essentially the same. Full-bench cut and sidecast (not prescribed in Option 1) was prescribed in Option 4 for 564 m. This prescription was a cost-effective technique for managing excess material on moderately steep to steep talus slopes and did not significantly affect the cost of road construction.

In addition to the apparent reduction in landslide hazard and risk, Option 4 had several other significant advantages from a forest development and road engineering perspective:

- Total Chance Planning for the northern end of the Tommy Creek drainage showed only four potential cutblocks on the west side of Tommy Creek compared to 24 potential cutblocks on the east side of Tommy Creek; therefore, Option 4 would provide the planned mainline access to 20 more cutblocks than Option 1.
- Option 4 eliminated three bridge crossings.
- Option 4 eliminated the need to construct a switchback on a 70% slope in talus material.

4.6.3 Risk evaluation and risk control

Based on the significant reduction in landslide risk, the increased utility of Option 4 with respect to future forest access requirements, and the reduction in the number of bridge crossings, Option 4 was selected as the desired alignment. Although Option 4 did represent a significant reduction in risk when compared to Option 1, the risks associated with construction and residual landslide risks associated with Option 4 required construction field reviews. This work was carried out during road construction that started in the fall of 2001 and ended in September 2002. The work also included post-construction field reviews in the summer of 2003.

Landslide hazard and risk ratings for proposed road construction in the forest sector rely on site conditions typically inferred from limited direct observations of the subsurface soil, bedrock, and groundwater conditions. Observations made during and following road construction play an important role in the management of landslide risk. Such reviews provide an opportunity to confirm that the subsurface conditions are similar to those that were assumed during the initial terrain stability assessment. Where conditions are different from expected, changes to the design, construction technique, or road location can be made to reduce landslide risk. In addition, other landslide risk mitigation measures could be developed to manage the risk. The following summarizes how construction field reviews were used to manage the landslide risk in this case study.

Construction field reviews were carried out on a regular basis during construction of retaining walls and the excavation of the large bedrock cut. During the reviews, observations of the bedrock condition were made. The observations included measurements of the strike, the dip and roughness of discontinuities (joints, fractures, faults), the strength of the bedrock, and the width and strength of materials infilling the discontinuities. These observations helped provide guidance to the contractor regarding drilling, blasting, and excavation procedures aimed at reducing the potential for cutslope and road surface instability, and determining the need for rock bolting and/or wire mesh.

Based on observations of the stability of the talus in the road cuts and the acceptance of a moderately higher road maintenance obligation (clearing the road of accumulated material from rockfall and ravelling) in some areas, a significant section of the road was re-aligned a short distance downslope. This change eliminated the requirement for two additional retaining walls.

The road construction across the steeply sloping talus consisted of a full-bench cut with sidecast spreading of waste material. This approach resulted in very little impact on the slopes beyond the road right-of-way. The validity of this construction technique and the associated landslide risk was confirmed in the field at the start of construction of this road section. Figure 46 provides an overview of the road following construction.

A post-construction review, including a drainage plan, was conducted to identify potential concerns about the road concentrating and/or diverting surface water flows. In addition, a follow-up review of the road was done in the summer of 2003 to assess the performance of the road following the freshet of 2003. This review concluded that the road had performed as expected, although some typical maintenance measures (such as clearing of accumulated rockfall material from the road) were required.

FIGURE 46 *Looking south at the critical section of Option 4 following construction (C. VanBuskirk photo).*

4.6.4 Concluding remarks

Geotechnical engineering and geoscience have always played an important role in the selection and evaluation of development sites and access corridors for roads, railways, pipelines, and other utilities. With the increased awareness of the effects of forest roads on the forest and other resources (such as water quality and fish habitat), and on other socio-economic values (such as wildlife, utilities, highways, and private property), geotechnical engineering and geoscience should play a fundamental role in the selection of forest road alignments. In this case study, the forest development manager realized significant benefits by having the landslide risk analyzed and by evaluating these risks in the context of both short-term and long-term development objectives.

The planning of the Tommy Creek Mainline demonstrates that evaluating alternative alignments requires both office reviews and fieldwork. Involving terrain stability and geotechnical engineering professionals in the route selection stage of development through challenging terrain permitted the location, assessment, design, and construction of this challenging road. The engineering input provided to this project saved the client an estimated $400 000 in road and bridge construction costs. These savings were made possible through clear communications among the client, the layout and design consultant, the road-building contractor, and the engineering consultant. In other words, it was a team approach.

4.6.5 Acknowledgements

The author would like to acknowledge the diligence, professionalism, skills, and conscientiousness of the following members of the project team: B.C. Ministry of Forests Small Business Forest Enterprise Program (now BC Timber Sales), Forsite Consultants, BGC Engineering Ltd., Cook Contracting, and Summit Drilling and Blasting. Kevin Turner, Geotechnical Engineer with the B.C. Ministry of Forests, Kamloops provided very helpful review comments.

4.6.6 References

BGC Engineering Ltd. 2001. Evaluation of proposed road alignment across a gravity displacement landform. Report prepared for the B.C. Ministry of Forests Small Business Forest Enterprise Program.

Wordsworth, G.J. 1979. Geology Pemberton (92J0 Map-Area – 1:250 000 scale), Geological Survey of Canada, Open File 482.

4.7 Quantitative Analysis of Specific Risk from a Debris Flow: Kitseguecla Debris Flow Fan, Smithers, British Columbia

DAVID WILFORD, MATT SAKALS, JOHN INNES, AND DAVE RIPMEESTER

Abstract

A specific risk analysis is described for forest development on a debris flow fan in west-central British Columbia. Evidence on the fan indicated that the small, steep watershed had produced seven debris flows in the past 100 years. Although strips of the forest on the fan had been destroyed by these past events, evidence in the standing timber demonstrated a much larger runout zone. Elements at risk included worker safety, road access, and future tree plantations. The forest development plan was altered to include a reserve encompassing the runout zone plus a special management zone. Seasonal constraints were also placed on harvesting activities. The case study demonstrates that information about geomorphic hazards on fans can be incorporated into a development plan through the use of specific risk analysis.

4.7.1 Introduction

The Kitseguecla fan is located 32 km northwest of Smithers, British Columbia (Figure 47). In 1999, the Pacific Inland Resources Division of West Fraser Inc. proposed to harvest the timber on the fan. Forestry staff were concerned that debris flow hazards on the fan could pose a risk to worker safety, road access, and future tree plantations. Furthermore, the licensee was concerned that timber removal within debris flow runout zones and possible post-harvesting instability of the fan could adversely affect its International Organization for Standardization (ISO) certification and future Sustainable Forest Initiative certification. In light of these considerations, the licensee wanted an analysis of hazards and risks to assist in the development of an appropriate harvesting plan.

This fan and its watershed were investigated as a part of a regional fan study (Wilford 2003), but the risks to specific elements associated with the proposed forest development plan were not previously studied.

4.7.2 Site characteristics

The Kitseguecla Creek watershed is located on the south side of Rocky Ridge, a steep and highly dissected ridge of andesitic, dacitic, and rhyolitic flows, tuffs, and breccias (Tipper and Richards 1976). The watershed draining onto the fan covers an area of 0.49 km^2 (49 ha), has basin relief of 550 m (1170–1720 m), and is 1.13 km long (Figure 48). Steeply sloping bedrock dominates the upper portions of the watershed, with moderately coarse colluvium on the lower slopes (Runka 1972; Madrone Consultants Ltd. 2000). Less than one-third of the watershed area is forested, and most of this area was mapped as unstable. Weathering of the bedrock, plus the unstable colluvi-

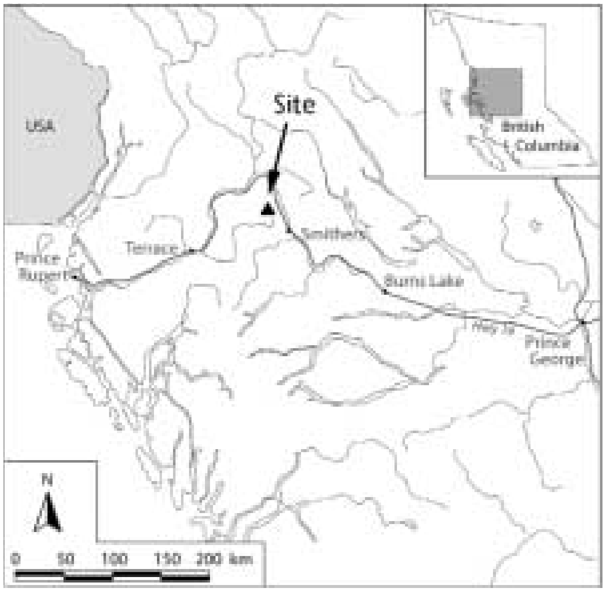


FIGURE 47 *Location of the Kitseguecla debris flow fan near Smithers, British Columbia.*

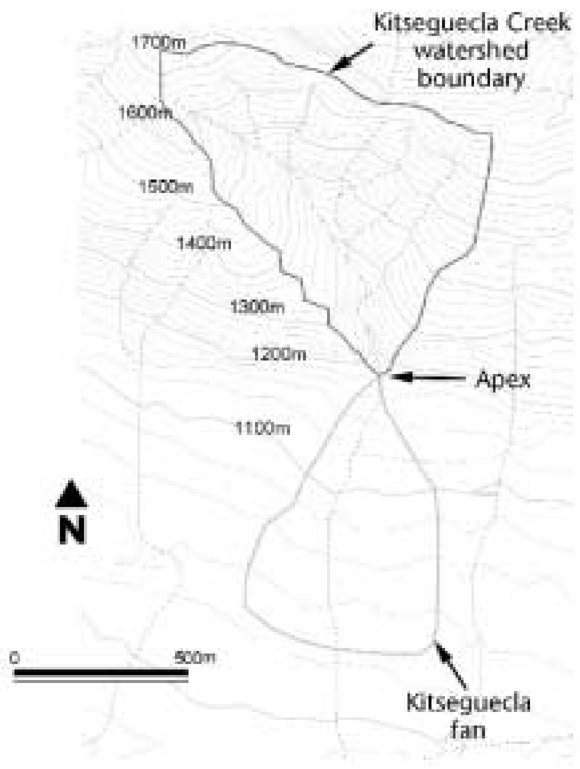


FIGURE 48 *Topographic map of the Kitseguecla fan and its watershed. The contour interval is 20 m.*

um, provides an abundant source of coarse and fine sediment to the stream channel draining onto the fan. Snow avalanches on the steep slopes also deliver sediment to the stream channel.

The southerly aspect of the watershed enhances early spring snowmelt. Steep gradients, exposed rock, and the coarse texture of colluvial materials all contribute to rapid runoff. Thus, fall rain-on-snow and spring snowmelt flood discharges are typically large.

The Melton ruggedness index (MR) is equal to basin relief divided by the square root of watershed area. The MR for this watershed is 0.78, combined with a watershed length of 1.13 (less than 2.7 km), indicating the potential for debris flows (see Table 46). Slope gradients on the fan range from 14° (25%) near the apex to 7° (12%) along the lower margins. As described in previous debris flow studies from elsewhere (e.g., Costa 1984; Kellerhals and Church 1990) the Kitseguecla fan similarly has abundant evidence of debris flow activity on the fan surface, such as levees, lobes, and scattered large boulders.

With the exception of a portion of the fan that was logged in 1993 (Figure 49a), the fan surface is forested with old-growth subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta* var. *latifolia*), and interior spruce (*Picea engelmannii* x *glauca*). The forest has a high level of insect attack from the western balsam bark beetle (*Dryocoetes confusus*) and spruce beetle (*Dendroctonus rufipennis*), resulting in a relatively low volume of merchantable timber (200 m^3/ha).

Dendroecology techniques, described by Strunk (1997), were used to date past debris flows: scars, abrupt changes in tree growth, and establishment of cohorts (groups of trees of similar ages established on sediment derived from events). Based on 31 dendroecology samples, seven debris flow events have occurred in the past 100 years (1900, 1942, 1953, 1970, 1980, 1985, and 1989).

Debris flow levees, much older than 100 years, confine the stream channel for approximately 190 m below the apex (Figure 49b). Immediately downstream of these levees the channel is unconfined and elevated above the adjacent fan surface. In the unconfined zone, recent debris flows have created multiple channels, which are commonly blocked by debris jams. At the time of the study, water was flowing toward the east side of the fan; however, during the last major debris flow most of the water and debris flowed toward the west side of the fan. Discontinuous debris flow levees extend to approximately 550 m below the fan apex.

Evidence of debris flow movement on the fan exists over 600 m from the fan apex to beyond the proposed spur road (Figure 49b). In the area of the spur road, debris flow-transported boulders, up to 1.4 m in diameter, are present on the fan surface. There are recent debris flow deposits in this area with 12-year-old conifer cohorts. Older conifer cohorts in

TABLE 46 *Basic watershed morphometrics for determining debris flow hazards*

Source	**Study area**	**MR and/or watershed length**
Jackson et al. 1987	Southern Rocky Mtns.	MR > 0.3 (includes debris floods and debris flows)
Bovis and Jakob 1999	Coastal Mtns.	MR > 0.53
Wilford et al. 2004	West-central B.C.	MR > 0.6 and watershed length < 2.7 km

FIGURE 49a *An oblique airphoto of the Kitseguecla fan looking in a northerly direction. The 1993 logging is shown on the right side (i.e., the east side) of the fan. The logging carried out in 2000–2001 based on the results of this risk analysis is shown on the left side of the fan. The forested reserve is the debris flow runout zone (D. Wilford photo).*

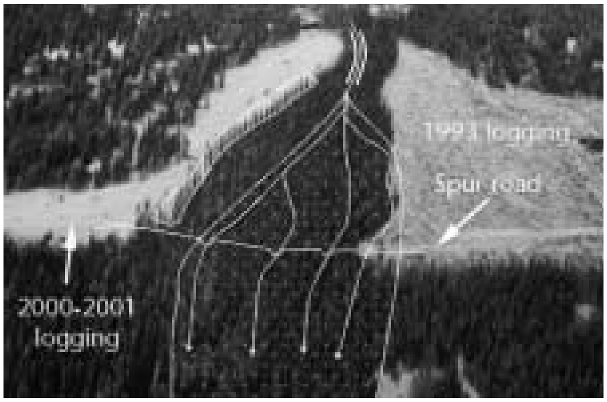


FIGURE 49b *Close-up photograph of the fan illustrating the much older debris flow levees (═), multiple stream channels (—►), zone of sediment deposition (xˣxˣ), spur road (‾◡‾), and special management area, which was the result of this case study (▥). For scale, the distance from the fan apex to the spur road is approximately 600 m and the width of the reserve at the spur road is approximately 150 m (D. Wilford photo).*

this area likely regenerated on older debris flow sediments. The total width of the area having been influenced by debris flows along the spur road is approximately 150 m. This length along the spur road also has multiple stream channels; however, only some of these channels carry water, and then only on a seasonal basis.

Trees play an important role in trapping debris flow materials downslope of the older levees. Sediment wedges formed behind downed logs (log steps) trap sediment to a height of up to 2 m (Figure 50). Individual standing trees hold back as much as 1 m thickness of sediment, including large boulders (up to 1 m diameter). When buried trees die and rot without subsequent sediment deposition, the result is a cylindrical "tree hole" in the ground. During this study, one such hole, 0.3 m wide and 1.8 m deep, was found along the proposed spur road.

The east half of the fan was logged in 1993, with a reserve along the stream (Figure 49a). This eastern reserve is not wide enough to contain avulsions or debris flows, and there is erosion along the fire break trail and sediment deposition into the block. The proposed logging plan called for harvesting the remaining timber on the fan, but leaving several small reserves along distributary channels. The proposed spur road, a westward extension of the 1993 logging road, was to be temporary, built to conventional specifications and not intended to extend beyond the proposed cutblock.

FIGURE 50 *An example of a 1.5 m high wedge of debris flow (D. Wilford photo).*

4.7.3 Debris flow risk analysis

The elements potentially at risk on this fan are worker safety, existing road access, and future plantations. The risk to worker safety and the risk of loss of road access are short-term risks (4 months), while the risk of damage to future plantations is a long-term risk (e.g., 100 years). Fish habitat is not at risk for this site.

The short-term specific risk to worker safety was reduced to an acceptable level by scheduling harvesting operations during the winter, when the probability of debris flow occurrence is estimated as very low.

The short-term specific risk to the spur road was reduced to an acceptable level by constructing a narrow winter road (i.e., use of snow and ice to build the road grade, temporarily placing logs in the dry stream channels) within a limited right-of-way width (Figure 51). The spur road was to be used only during logging and was to be fully deactivated prior to snowmelt.

A quantitative specific risk analysis was undertaken to determine the annual and long-term risk of damage from debris flows to future plantations on the fan. To decide on whether or not to harvest the timber on the fan, the licensee evaluated the results of the risk analysis against the costs associated with

- leaving timber in a reserve (lost revenues)
- establishing a plantation following harvesting, and
- possible negative implications to certification and public perception.

Specific risk is mathematically defined as:

$R(S) = P(H) \times P(S{:}H) \times P(T{:}S) \times V(L{:}T)$

The risk components are discussed below.

FIGURE 51 *A view of the spur road following 2001–2002 logging. Note the narrow width of the road and right-of-way (D. Wilford photo).*

P(H) – Probability of occurrence of a specific hazardous debris flow As discussed above, it was determined that seven debris flow events had occurred within the past 100 years; however, it was felt that four of these were too small to be hazardous. Therefore, based on three hazardous events in 100 years, the annual probability of occurrence was estimated as 0.03. In addition to the annual probability of occurrence, the probability of occurrence during three long-term periods were analyzed (0–33 years, 0–66 years, and 0–100 years) to reflect site changes such as the decay of large woody debris and regeneration up to the full rotation of the plantation. The long-term probabilities of occurrence were approximated using Equation 2 in Chapter 3, and are summarized in Table 47.

P(S:H) – Probability of a spatial effect The debris flow runout zone was estimated from field evidence: sedimentary features such as levees, lobes, scattered boulders, and sediment splays and forest indicators, including buried trees, tree holes, scars on stems, and cohorts. The debris flow runout zone extends from the downstream end of the old debris flow levees to the proposed location of the spur road, a distance of approximately 400 m. The zone is 20 m wide at the downstream end of the old levees and 150 m wide at the spur road, and has an average width of 85 m. For estimating purposes, this was rounded up to a width of 100 m. Therefore, the estimated runout zone occupies an equivalent rectangular area that is 400 m long and 100 m wide.

If the 400 m long and 100 m wide runout zone was clearcut, it would define the site of the plantation that could be affected by a debris flow. It was assumed that a hazardous debris flow occurrence in any of the three long-term periods (0–33 years, 0–66 years, and 0–100 years) would travel a distance of 400 m down the fan as far as the spur road. It was further assumed that the width of the deposition corridor of such a debris flow would depend on the resistance to lateral spread of the debris provided by the effects of stumps, large woody debris, and regenerating forest in each time period of the analysis. Therefore, P(S:H) was estimated as the ratio of the predicted width of the deposition corridor to the width of the estimated runout zone as follows:

- For the time period 0–33 years it was assumed that a debris flow event could result in a 20 m wide deposition corridor, giving a P(S:H) of 0.2. A 20 m width is similar to that estimated for the old-growth situation because even though the trees are removed by logging, the remaining stumps and large woody debris (natural and from logging) limit the spread of debris.

- For the time period 0–66 years it was anticipated that because of the decay of the large woody debris and the filling of available storage space, debris flows could extend further laterally. The regenerating forest could provide a degree of resistance to this lateral spread; however, the net effect was assumed to be that an event could result in a 25 m wide deposition corridor, giving a P(S:H) of 0.25.
- For the time period 0–100 years it was assumed that although much of the original large woody debris storage could be filled or not present, the regenerating forest would become relatively robust and some recruitment of large woody debris could occur. The net result would be that a debris flow event could result in a 25 m wide deposition corridor, giving a P(S:H) of 0.25, similar to that for the 0–66 year time period.

P(T:S) – Probability of a temporal effect The plantation location is fixed in the debris flow runout zone, and therefore the temporal probability remains constant at 1.0 for all assumed time periods.

V(L:T) – Vulnerability of the plantation In all time periods it was assumed that some loss or damage to the plantation within the debris flow deposition corridor would be a certainty. The proportion of the damage or loss to the plantation, however, was assumed to change with the age (size and robustness) of the second growth. Therefore, vulnerability of the plantation (i.e., proportion of plantation damaged or lost within the deposition corridor) was assumed to be 0.30 for the 0–33 year time period, decreasing to 0.25 for the 0–66-year time period, and decreasing further to 0.20 for the 0–100 year time period.

R(S) – Specific risk of damage or loss to the plantation Table 47 summarizes the results of the various risk components and the specific risks for the different time periods.

TABLE 47 *Specific risk analysis for the tree plantation on the Kitseguecla fan*

Time period of analysis	**Annual (Pa)[a] or long term (Px)[b]**	**P(H)**	**P(S:H)**	**P(T:S)**	**V(L:T)[c]**	**R(S)**
Annual for 0–33 yr	Pa	0.03	0.20	1.0	0.30	0.002
Annual for 0–66 yr	Pa	0.03	0.25	1.0	0.25	0.002
Annual for 0–100 yr	Pa	0.03	0.30	1.0	0.20	0.002
Long term 0–33 yr	Px; x = 33 yr	0.63	0.20	1.0	0.30	0.038
Long term 0–66 yr	Px; x = 66 yr	0.87	0.25	1.0	0.25	0.054
Long term 0–100 yr	Px; x = 100 yr	0.95	0.25	1.0	0.20	0.048

Assumptions:

[a] Annual probability of occurrence, (Pa) = 3/100 = 0.03, based on three potentially hazardous events in 100 years. Pa is assumed constant.

[b] Px is the long-term probability of occurrence that at least one landslide will occur within the time period. With certain limitations and as a first approximation, assume $Px = 1-(1-(Pa))^x$.

[c] V(L:T) is the estimated proportion of loss or damage to the plantation, assuming that the probability of some loss or damage to the plantation from a debris flow in all time periods is certain.

4.7.4 Risk evaluation, control, and action

The relatively low annual specific risks of 0.002 were not considered to be relevant because the forest licensee had a long-term commitment for the plantation.

As a result of the relatively high long-term specific risks of damage to the plantation of 0.038–0.054, and considering other risks to the environment, and potential economic loss, the licensee decided to establish a reserve on a portion of the fan. The reserve was to include the debris flow runout zone plus a buffer of 30 m on both sides. Beyond this reserve, a 50 m wide special management area was recommended for the west side of the reserve in which non-merchantable large woody debris was to be placed across the slope and high stumps (up to 3 m) were to be retained for large woody debris recruitment. The intent is that the reserve and special management area, shown on Figure 49b, will maintain the role of forest cover in storing sediment and will limit the expansion of the contemporary (i.e., within the last 100 years) debris flow runout zone (Irasawa et al. 1991; Wilford et al. 2002). In the zone of the much older debris flow levees, a 30 m wide forested reserve was left along each side of the stream to maintain the natural recruitment of large woody debris to the channel.

The plans to reduce the specific risk from a debris flow to a tolerable level were evaluated as satisfactory, and forest harvesting activities commenced in the winter of 2000.

4.7.5 Concluding remarks

The Kitseguecla fan had been mapped for terrain hazards using British Columbia Ministry of Forests mapping and assessing terrain stability guidelines (B.C. Ministry of Forests and B.C. Ministry of Environment 1999); however, potential effects on elements were not identified. Only the initiation zones of hazards (debris flows), with no information on runout, were identified on the maps. Although the licensee understood that there could be debris flow hazards associated with harvesting on the fan, the extent of these hazards was not fully appreciated. The licensee recognized the significance of the situation and fully participated in the risk analysis process, and modified the forest development plan by adding appropriate reserves and changing the design of the spur road.

On fans, geomorphic hazards such as debris flows, debris floods, and stream floods can be identified through sediment deposition features and past effects on forest stands. Such information is fundamental to undertaking specific risk analyses and promoting informed forest management decisions. Information on geomorphic hazards and risks can be included in both terrain mapping projects and incorporated into terrain stability assessments associated with forest development.

4.7.6 Acknowledgements

The authors acknowledge the initial request and subsequent strong support from Pacific Inland Resources Division of West Fraser Inc. Tyhee Forestry Consultants Ltd. undertook field layout of the reserve. The B.C. Ministry of Forests, Forestry Innovation Investment BC, and the University of British Columbia Faculty of Forestry supported this project. Tim Giles, Research Geomorphologist with the B.C. Ministry of Forests, Kamloops provided very helpful review comments.

4.7.7 References

Bovis, M.J. and M. Jakob. 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Process. Landforms 24:1039–1054.

British Columbia Ministry of Forests and B.C. Ministry of Environment. 1999. Mapping and assessing terrain stability guidebook. Forest Practices Code Guidebook.

Costa, J.E. 1984. Physical geomorphology of debris flows. *In* Developments and applications of geomorphology. J.E. Costa and J.P. Fleisher (editors.). Springer-Verlag. New York, N.Y. pp. 268–317.

Irasawa, M., Y. Ishikawa, A. Fukumoto, and T. Mizuyama. 1991. Control of debris flows by forested zones. *In* Proceedings of the Japan-U.S. workshop on snow avalanche, landslide, debris flow prediction and control. Sept. 30 – Oct. 2, 1991. Tsukuba, Japan. Science and Tech. Agency of Japanese Gov., pp. 543–550.

Jackson, L.E., R.A. Kostaschuk, and G.M. MacDonald 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *In* Debris flows/avalanches: Process, recognition, and mitigation. J.E. Costa and G.F. Wieczorek (editors.). Reviews in Eng. Geol. Vol. VII. Geol. Soc. Am., pp. 115–124.

Kellerhals, R. and M. Church. 1990. Hazard management on fans, with examples from British Columbia. *In* Alluvial fans: A field approach. A.H. Rachochi and M. Church (editors). John Wiley and Sons, New York, N.Y., pp. 335–354.

Madrone Consultants Ltd. 2000. Boulder and Kitseguecla terrain classification and terrain stability. Duncan, B.C.

Runka, G.G. 1974. Soil resources of the Smithers - Hazelton Area. Soil Survey Division, B.C. Dept. Agric., Kelowna, B.C.

Strunk, H. 1997. Dating of geomorphological processes using dendro-geomorphological methods. Catena 31:137–151.

Tipper, H.W. and T.A. Richards. 1976. Jurassic stratigraphy and history of north-central British Columbia. Geol. Survey of Can. Bulletin 270.

Wilford, D.J. 2003. Forest stand characteristics as indicators of hydrogeomorphic activity on fans. PhD thesis. University of British Columbia Faculty of Forestry, Vancouver, B.C.

Wilford, D.J., M.E. Sakals, and J.L. Innes. 2002. Forest management and restoration on fans. Watershed Restoration Tech. Bulletin Streamline 6(3):1–8.

Wilford, D.J., M.E. Sakals, J.L. Innes, R.C. Sidle, and W.A. Bergerud. 2004. Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides (in press).

4.8 Qualitative and Quantitative Analysis of Specific Value of Risk from a Road Repair Option: Nakusp, British Columbia

DOUG NICOL

Abstract

A debris slide that initiated from the Summit Lake Forest Service Road (FSR) removed a portion of the road and resulted in road closure. This landslide event also triggered a debris flow downslope of the FSR that damaged a highway, fish habitat, and a domestic water supply system, and narrowly missed a BC Hydro transmission line power pole. The road prism of the FSR required extensive repair, and an engineered fill consisting of welded wire mesh forms, geogrid, and rock drains was proposed. An analysis of specific value of risk from the road repair option was carried out to optimize the design. The risk analysis was quantitative for some of the elements at risk, including highway infrastructure, transmission line infrastructure, domestic water system infrastructure, and human safety, and qualitative for other elements, including fish habitat, public access, and power supply interruption. The results of the risk analysis were evaluated during the preliminary design, and options to mitigate and control the risk were integrated into the final design of the road repair.

4.8.1 Introduction

On June 4, 1999, a debris slide initiated within the road prism of the Summit Lake Forest Service Road (FSR). The debris slide triggered a debris flow within an unnamed creek below the FSR. The debris flow terminated on Highway 6 (see Figure 52), narrowly missing a BC Hydro transmission line power pole, and closed the highway for several days. The debris flow destroyed a domestic water intake used for a provincial campground, and transported sediment into Summit Lake—known trout habitat. This case study applies a specific value of risk analysis with respect to the repair of the Summit Lake FSR.

4.8.2 Site location and conditions

Summit Lake is located 15 km east of Nakusp, B.C. and is situated at the north end of the Valhalla Mountain Range within the Selkirk Mountains (see Figure 53). The FSR, located south of Summit Lake and Highway 6, starts at elevation 800 m, and after several switchbacks climbs to 1600 m.

The local bedrock consists of the Triassic Slocan Group (comprised of limestone, slate, siltstone, and argillite) with adjacent zones of Jurassic and Cretaceous Intrusives and Jurassic Volcanics (Read and Wheeler 1976). The limestone is indicative of local karst topography. Surficial soils include sandy till veneers and blankets, and local coarse colluvium deposits. The terrain ranges from gentle and moderately sloping (adjacent to Highway 6) to steeply sloping (upslope of Highway 6).

4.8.3 Description of the June 4, 1999 debris slide and debris flow

The debris slide initiated within the road prism of the FSR at approximately 1300 m elevation (Figure 54). The initial slide head scarp was approximately 30 by 30 m with an estimated slide volume of 600 m^3. An

FIGURE 52 *Debris being cleared from Highway 6, following June 4, 1999 debris flow (B. Ewings photo).*

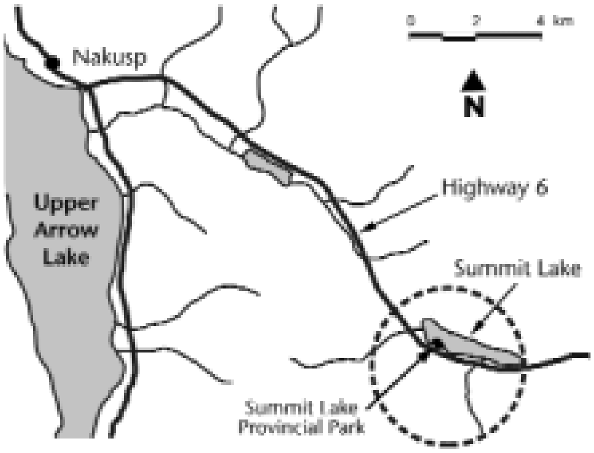


FIGURE 53 *Site location.*

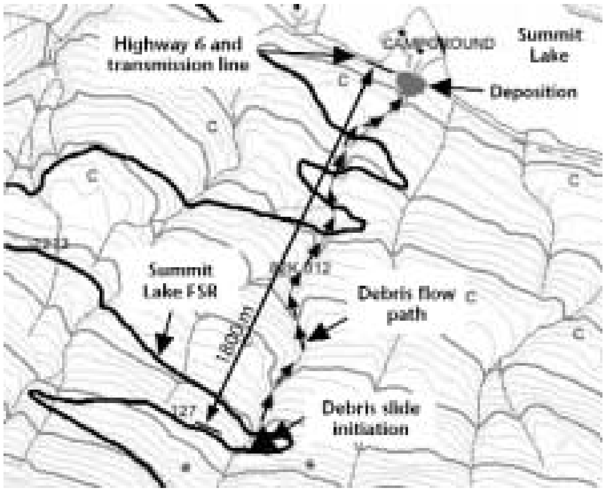


FIGURE 54 *Debris slide, debris flow, and deposition location.*

FIGURE 55 *Debris slide scarp (D. Nicol photo).*

S6 stream (non-fish stream, <3 m width) is located at the toe of the slide (Figure 55). The road was constructed as a cut and fill with a significant road fill volume adjacent to the stream. Pre-slide fill slope angles were estimated at >100%.

The debris slide initiated a debris flow when it reached the stream. The debris flow travelled 1800 m, destroyed four FSR metal culverts, and increased in volume to 2000 m^3. Channel gradients range from 65% (at 1250 m elevation) to 24% (800–1000 m elevation). A few hundred metres above Highway 6, the channel gradients decrease to <20%, with limited channel confinement. Some deposition occurred in these flatter, wider reaches. One hundred and fifty metres upslope of the highway, the debris flow completely in-filled the channel, and the flow avulsed, narrowly missing a BC Hydro transmission line power pole before depositing material on Highway 6.

Although some snow covered the FSR at the time of the debris slide, there was little snow cover in the adjacent forested areas. Significant seepage was observed on the scarp face, 5 m below the road grade, near the contact of fill and *in-situ* soil (Figure 56). This seepage, in combination with the steeply constructed roadfill, was the primary contributing factor of the debris slide.

The source of this seepage was not the road or ditchline. Surface flows, identified above the road, went subsurface 50 m east of the debris slide. Dye testing and a temporary redirection could not identify the source of the seepage on the scarp face. The weather was dry, with less than 6 mm of rain in the

FIGURE 56 *Seepage zone on headscarp of debris slide (D. Nicol photo).*

previous week, with warm daytime temperatures (>20°C). Local snow monitoring stations (Barnes Creek to the southwest and St. Leon Creek to the north) indicated that between June 1 and 4, 1999 the average snowmelt rate at 1600 m elevation was 35 mm/day snow water equivalent, with averages of 25 mm per day from the middle of May. At 1800 m elevation, the snowmelt rate was 17 mm per day. The snowpack in June of 1999 was at or above record levels for much of southern British Columbia, and at 1800 m elevation the snowpack was just starting to drop in early June. Given the lack of significant antecedent rain, the source for the seepage was likely snowmelt that was possibly feeding a local karst network.

4.8.4 Proposed FSR repair design

Since the source of the seepage on the scarp face could not be controlled, an engineering design of the FSR repair had to incorporate sufficient drainage measures. Road repair alternatives were limited, as there was not enough room to place a fill, including a steeply sloping rock fill, without encroaching into the stream. The road cutslope was steep (140%) and wet, and enlarging the cut to re-establish road width was not considered appropriate. As a result, a preliminary design was proposed consisting of an engineered fill with welded wire mesh forms, uniaxial and biaxial geogrid, rock drains, and offtake pipes (Figure 57). Considering all the elements at risk, a risk analysis was required to determine whether the residual risk was acceptable and appropriate given the benefit of the FSR, and, if required, whether improvements to the design were practical.

4.8.5 Risk management

P(H) – Probability of occurrence of failure of the engineered fill The first step in the risk analysis was to determine the probability of occurrence of failure of the engineered fill, P(H). To determine design sensitivities, a Limit Equilibrium Analysis (LEA) of the engineered fill was performed using *G-Slope* software and a design shear strength of 37° for local, well-graded sandy till and colluvium backfill. The shear strength was estimated from field classification of the soil and expected construction-compacted soil densities. The analysis assumed fully drained conditions. The minimum Factor of Safety (FS) was determined to be 1.7 (see Figure 58), which was consistent with active earth pressure and geogrid design calculations. An increase in the phreatic surface (water table) within the fill reduced the FS to 1.5 and 1.25 for pore pressure ratios, r_u, of 0.1 and 0.2, respectively.

An analysis of the global slope stability through the *in-situ* basal soil (Figure 59), using a nominal cohesion of 10 kPa and an assumed phreatic surface, resulted in a FS of 1.6. The FS dropped to 1.25 if the phreatic surface approached the base of the fill. Because of the relatively low stress associated with forest road cuts and fills, cohesion was considered significant relative to the total available strength. An LEA of global stability was run, assuming no cohesion, to verify the FS was greater than unity.

The stability analysis indicated that relatively small increases in the phreatic surface resulted in large reductions in the FS. Therefore, it was determined that if the fill did not drain, then either the *in-situ* glacial till foundation soil could fail due to saturation from the seepage site, or the fill itself could fail. Lack of adequate drainage was considered the most significant contributor to potential slope instability.

In order to ensure that the fill remained drained, the design utilized a rock drain with a slotted polyethylene offtake pipe. The annual probability of occurrence of drain failure was estimated, using subjective probability (Vick 1992, 2002), to range between 0.01 and 0.1. There is uncertainty in estimating the probability of a drain failure because of the many variables, such as excessive flows (drain capacity), drain crushing, and drain plugging. This uncertainty does not preclude a quantitative analysis as long as it is taken into consideration during the risk evaluation

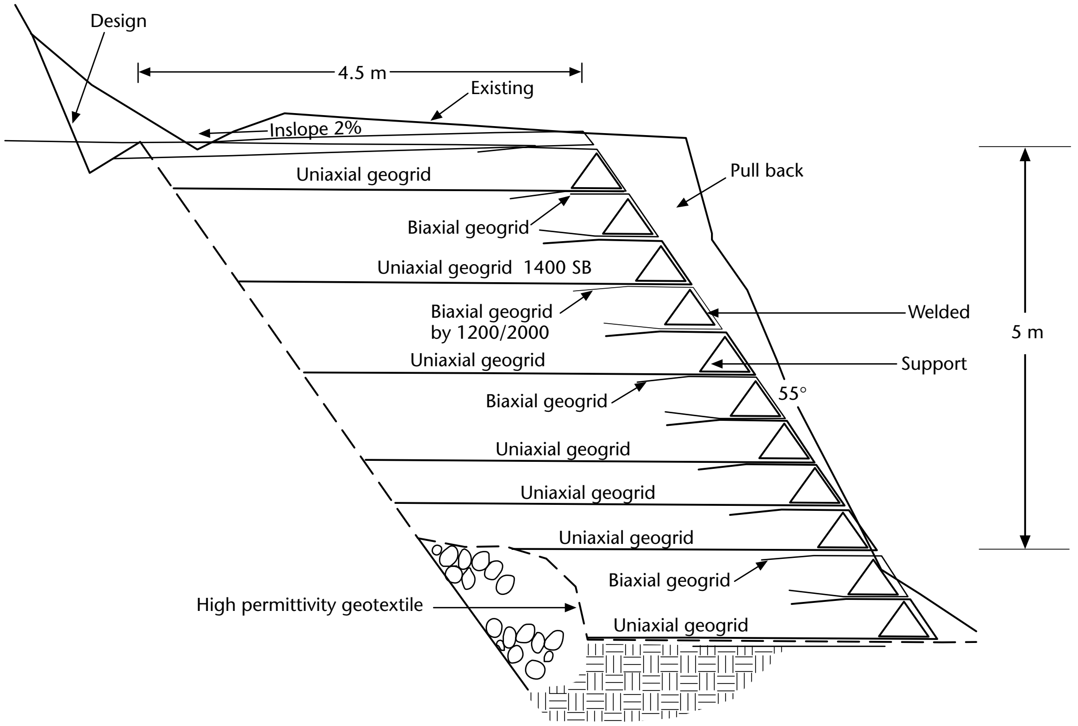


FIGURE 57 *Proposed road repair design.*

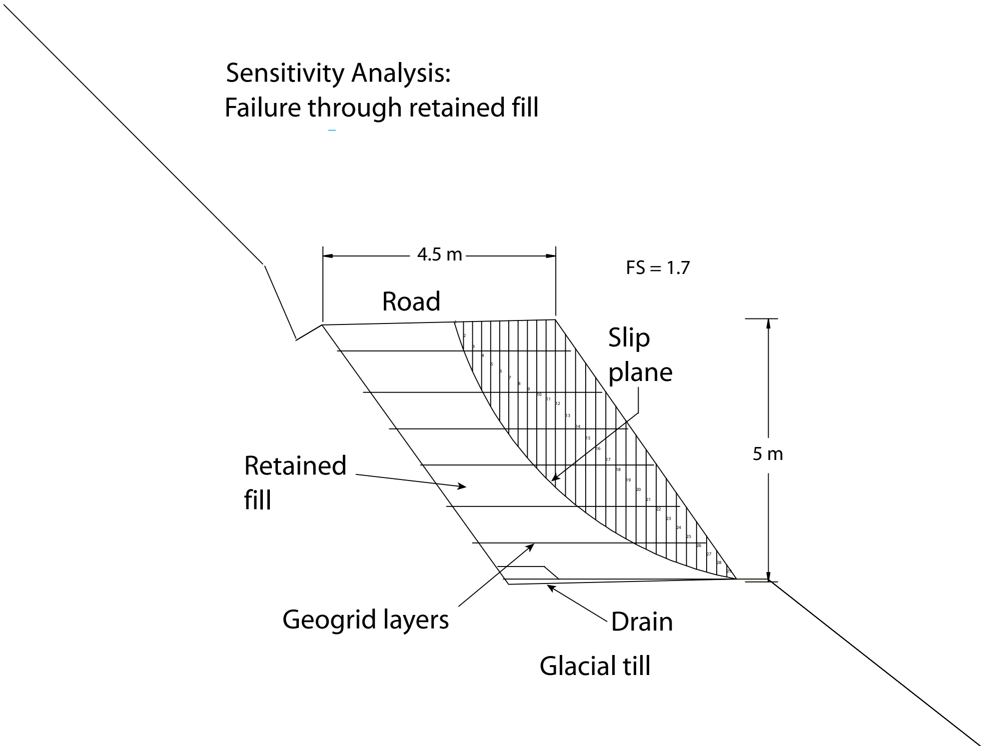


FIGURE 58 *Limit Equilibrium Analysis for retained fill.*

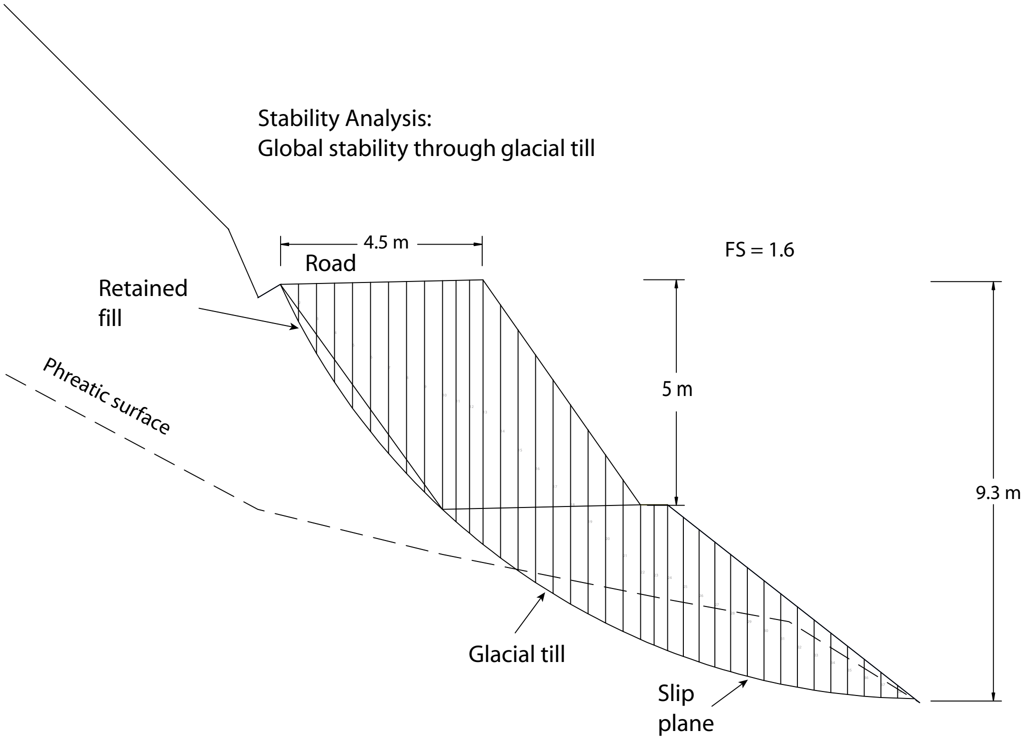


FIGURE 59 *Limit Equilibrium Analysis for global stability.*

stage. Using numerical probability ranges does not imply a better estimate, but rather it allows for a logical decomposition of the failure event, assists with communication of the hazard, allows for the application of subjective probabilities, and indicates the level of uncertainty.

Given a relatively impermeable retained fill, it was considered almost certain (probability = 0.9) that a drain failure would result in the phreatic surface rising significantly, and very probable (probability = 0.8) that a debris slide would result. Given a debris slide in the proposed backfill, with a high proportion of fines, debris flow initiation was considered very probable (probability = 0.8). Multiplying these probabilities (0.9 × 0.8 × 0.8) by the probability of occurrence of drain failure (0.01–0.1) resulted in an annual probability of occurrence of a hazardous debris flow event P(H) of 0.006–0.06. For ease of further analysis, P(H) was single-value–approximated to 0.02, although at the risk evaluation stage this range in uncertainty was considered further.

P(S:H) and P(T:S) – Estimates of spacial and temporal probabilities In order to determine partial risk, P(HA) = P(H) × P(S:H) × P(T:S), estimates of P(S:H) and P(T:S) were made for each element:

- P(S:H) for the highway was estimated at 0.5 since the stream channel gradient drops to 24% and less for the reach extending 500 m above the highway, and it was considered that there was an even chance that all of the debris would deposit before it reached the highway.
- P(S:H) for fish habitat in Summit Lake was estimated as 1.0 since it was considered that any event would produce some sedimentation, although it was felt that the vast majority of transported sediment would not enter the lake.
- P(S:H) for the water intakes was estimated to be 1.0 since they are located in a stream reach that would certainly be affected by an event.
- P(S:H) for the transmission line and power poles was estimated at <0.1 since an event would have to jump the stream channel (as was done in the 1999 event) and be directed towards and directly hit the powerpole.
- P(T:S) is 1.0 for the highway, fish habitat, water intakes, and transmission line since these elements have fixed locations.

P(HA) – Partial risk Multiplying P(H) × P(S:H) × P(T:S) resulted in estimates of P(HA) as: 0.01 for highway infrastructure, 0.02 for fish habitat, 0.02 for water intakes, and 0.002 for the transmission line.

In order to determine P(T:S) for highway users, the highway traffic volume, average driving speeds, stopping distances, reaction time, and site visibility were considered. The Average Annual Daily Traffic (AADT) for Highway 6 near Summit Lake is 1820 vehicles, while the Summer Average Daily Traffic (SADT) is 2200 vehicles. As it is likely that the debris flow would occur between April and June, 1850 vehicles per day was used to determine the average vehicle spacing. Using an average vehicle speed of 100 km/hour,[1] the average vehicle spacing is 2600 m in each lane. Therefore, assuming a 20 m wide impact zone, $P(T{:}S) = 2(L_1 + L_v)/L_d = 2(20\text{ m} + 5\text{ m})/2600\text{ m} = 0.019$ (after Hungr et al. 1999) where L_1 = debris slide corridor width, L_v = vehicle length, and L_d = average vehicle spacing in each lane.

Not only can a vehicle be hit directly by the debris flow crossing the highway, but once debris has deposited on the highway, vehicles can drive into the debris if they cannot stop in time. The total stopping distance[2] for a vehicle travelling at 100 km/hour was estimated at 154 m. The site distances (horizontal and vertical) were verified to ensure that there is at least 154 m at the likely zone of debris deposition. Therefore, it was assumed that any vehicle travelling within 154 m towards the deposition zone would either drive into the debris (indirect impact), or would veer off the highway. P(T:S) of an indirect impact (or avoidance accident) was estimated as $L_s/L_d * 2$ (2 lanes) = 154 m/2600 m*2 = 0.12, which is higher than P(T:S) for a direct impact and consistent with the results of Bunce et al. (1997).

Therefore, P(HA) for highway users was estimated as P(H) × P(S:H) × P(T:S) = 0.02 × 0.5 × (0.019 + 0.12) = 0.0014. This probability could have been increased to account for longer stopping distance at night.

R(S) – Specific risk To determine specific risk, R(S) = P(HA) × V(L:T), the vulnerability of each element must be considered. Quantitatively, vulnerability can be either the estimated probability of total loss or damage to a specific element between 0 and 1; or in the case where the probability of some loss or damage is assumed to be certain, it is the estimated proportion of loss or damage to a specific element between 0 and 1.

The vulnerability of the highway infrastructure to a future debris flow event, assuming that some loss or damage is certain, is the estimated proportion of loss or damage to the affected section of highway. For this study, it was assumed that the vulnerability of the highway infrastructure would be equal to the proportion of damage that occurred in the 1999 debris flow event. In that event, the direct cost of clearing debris from the highway surface and repairing the damaged infrastructure was $25 000. Based on the 1999 data, it was assumed that the $25 000 repair cost is a product of the vulnerability (estimated proportion of loss of the highway infrastructure) and the total direct replacement cost of the highway infrastructure over the affected section of highway (see Table 48).

The vulnerability of fish habitat in Summit Lake was difficult to quantify because total habitat loss is very unlikely. In addition, the highway would catch most of the debris, so for this element a qualitative analysis was considered more appropriate.

If the debris flow reached the water intake system, it was assumed that total loss would certainly occur. Therefore, V(L:T) was estimated as a 1.0 probability of total loss.

It is not certain that the powerpole would topple when hit by a debris flow, but it was assumed that if the pole did topple, total loss of the pole and power loss would occur. Therefore, V(L:T) for the transmission line and power pole was estimated as a 0.5 probability of total loss.

The vulnerability of a human life (an individual using the highway), $V(L{:}T)_{\text{human life}}$, was estimated as a 0.5 probability of loss of life given direct impact by a debris flow, and as a 0.25 probability of loss of life for an indirect impact or an avoidance accident (modified from Wong 1997).

---

[1] Although 100 km/hour was used for the purposes of illustrating the calculations, a range of speeds was considered to determine the sensitivity of P(T:S) with vehicle speed.

[2] The stopping distance was calculated by assuming mmgd=1/2mv2, where m = frictional resistance (tires to road surface) = 0.4 (wet conditions), and v = 100 km/hour (or 28 m/s). Including a reaction time of 2 seconds, an additional 56 m is required, resulting in a total stopping distance (Ls) of 154 m. Published MOT Stopping Sight Distance tables utilize slightly different coefficients of friction and slightly longer reaction times; however, for the purposes of this risk analysis the author attempted to reduce the effect of multiple layers of safety factors. In addition, various vehicle speeds were considered to determine their effect on P(HA).

TABLE 48 *Summary table of R(SV) based on annual probabilities*

Element	**P(H)**	**P(S:H)**	**P(T:S)**	**V(L:T) × E**		**R(SV)**
Highway infrastructure	0.02	0.5	1.0	$25 000		$250/year
Element	**P(H)**	**P(S:H)**	**P(T:S)**	**V(L:T)**	**E**	**R(SV)**
Fish habitat	0.02	1.0	1.0	Qualitative	N/A	N/A
Water intakes	0.02	1.0	1.0	1.0	$6 000	$120/year
Transmission line and power pole	0.02	0.1	1.0	0.5	$30 000	$30/year
Highway human life	0.02	0.5	0.14	0.28 (avg.)	N/A	N/A

R(SV) – Specific value of risk The Specific Value of Risk, $R(SV)_{property} = P(H) \times P(S:H) \times P(T:S) \times V(L:T) \times E$, to each element, excluding human life, was estimated and is summarized in Table 48. Table 48 also shows the Specific Risk (or Probability of Death of an Individual [PDI]) to individuals using the highway (highway human life).

A qualitative risk matrix table was used to estimate the specific value of risk for fish habitat (Table 49). Based on the values of P(H), P(S:H), and P(T:S) in Table 48, P(HA) for fish habitat was estimated to be 0.02 and is considered *high.* The estimated volume of sediment that could be transported into Summit Lake is small and therefore the estimated proportion of loss (vulnerability) to the fish habitat is *low.* However, the societal worth of the habitat is considered *high* (yearly stocking of 10 000–15 000 rainbow trout). The product of a *low* vulnerability, V(L:T), and a *high* worth, E, was assumed to equal a *moderate* societal value loss. From Table 49, the product of a *high* P(HA) and a *moderate* societal value loss resulted in a *high* $R(SV)_{\text{fish habitat}}$.

In addition to the direct infrastructure repair costs shown in Table 48, indirect costs were considered in the evaluation of the specific value of risk. These indirect costs include the cost and inconvenience of having the parks water systems down, the cost and inconvenience of having an extended power outage, and the cost and inconvenience of having the highway closed (for up to a day). These non-quantifiable costs were dealt with in a qualitative matrix (not shown), and the results were *moderate* with respect to water system usage, *high* with respect to power outage, and *high* with respect to highway usage.

Risk evaluation The combined $R(SV)_{annual}$ direct infrastructure costs (highway, water intakes, and power pole) was $400/year and appeared acceptable, considering that far more revenue would be generated from the use of the FSR. The R(SV) with respect to fish habitat was *high*, and the R(SV) with respect to the indirect cost associated with a power outage and highway closure was also considered *high.* When the $R(S)_{\text{human life}}$ (PDI) (estimated at 0.0004) was compared with published acceptability limits, it appeared to fall within either the "moderate risk range" (Hungr 1993) or within the "ALARP Zone"—As Low As Reasonably Practicable (Fell 1997). The ALARP principle implies that society may accept the risk as long as there are no practicable alternatives and that the benefits of accepting the risk are significant.

TABLE 49 *Qualitative risk matrix for $R(SV)_{\text{fish habitat}}$*

R(SV)fish habitat, specific value of risk to fish habitat, expressed as an expected annual relative societal loss of fish habitat value $R(SV)_{\text{fish habitat}} = P(HA) \times V(L:T) \times E$		**$V(L:T)_{\text{fish habitat}} \times E$**		
		High societal value loss	**Moderate societal value loss**	**Low societal value loss**
P(HA), annual probability (likelihood) of debris flow sediment reaching Summit Lake	Very high	*Very high*	*Very high*	*High*
	High	*Very high*	*High*	*Moderate*
	Moderate	*High*	*Moderate*	*Low*
	Low	*Moderate*	*Low*	*Very low*
	Very low	*Low*	*Very low*	*Very low*

Risk control Given the risk evaluation, and the uncertainty relating to the determination of P(H), it was determined that a further reduction in risk was desirable. The design to the FSR repair was reviewed and it was decided that backfill for the retained fill should consist of rock rather than local *in-situ* soil. In the event the drain should fail, the rock fill would likely continue to provide good drainage of the backfill, thereby reducing the potential for pore pressure build-up (both in the retained fill and in the foundation soils). In addition, the greater soil shear strength of the rock fill would increase the stability of the roadfill, reducing the likelihood of a debris slide and a debris flow. Thus $P(H)_{revised}$ = P(drain failure) × P(significant rise in phreatic surface) × P(debris slide initiation) x P(debris flow) = (0.1–0.01) × 0.1 × 0.5 x 0.3 = 0.0015–0.00015 (single-value–estimated at 5 × 10^{-4}), which is a 40-fold decrease in the $P(H)_{initial}$ of 0.02.

Note that P(H) of a failure through the foundation soils would not likely be reduced to the same degree as P(H) of a failure of the retained fill because the foundation soil type was not modified from the original design. However, it was considered that P(H) for a foundation failure approached that of a deactivated road segment at this location (given no internal drain) and thus the incremental P(H) for the site was largely a result of the potential for a retained fill failure.

If the design modification was adopted, $P(HA)_{revised}$ for highway infrastructure, fish habitat, water intakes, and transmission line and power pole would all be less than 5 x 10^{-5}. The yearly repair costs for the highway, water intakes, and power pole would decrease by a factor of 40, and the non-quantifiable costs with respect to water system, power outage, and highway usage would decrease to *very low, low*, and *low*, respectively. The resultant $R(SV)_{fish\ habitat}$ would decrease to *low,* while the $R(S)_{human\ life}$ (PDI) would decrease to 1 x 10^{-5} for a retained fill failure. The results of the PDI analyses are shown in an event tree in Figure 60.

Risk re-evaluation The revised specific risk to human life (PDI) is generally considered acceptable, as shown in Figure 61 (modified from Morgan 1992 and Fell 1997). Other comparisons were made to published risk acceptability criteria (Hungr 1993; Ho 2000) with the same conclusion that the revised PDI for the Summit Lake FSR was within a zone generally considered acceptable.

The resource managers for the project determined that the proposed revised design resulted in acceptable risks, and in comparing costs (repair and risk) to benefits (access) decided that the FSR should be repaired with the modified engineered fill. Figure 62 shows the final road repair.

4.8.6 Concluding remarks

This Summit Lake FSR repair case study provides an example of a specific value of risk analysis involving multiple elements, with some analyzed quantitatively

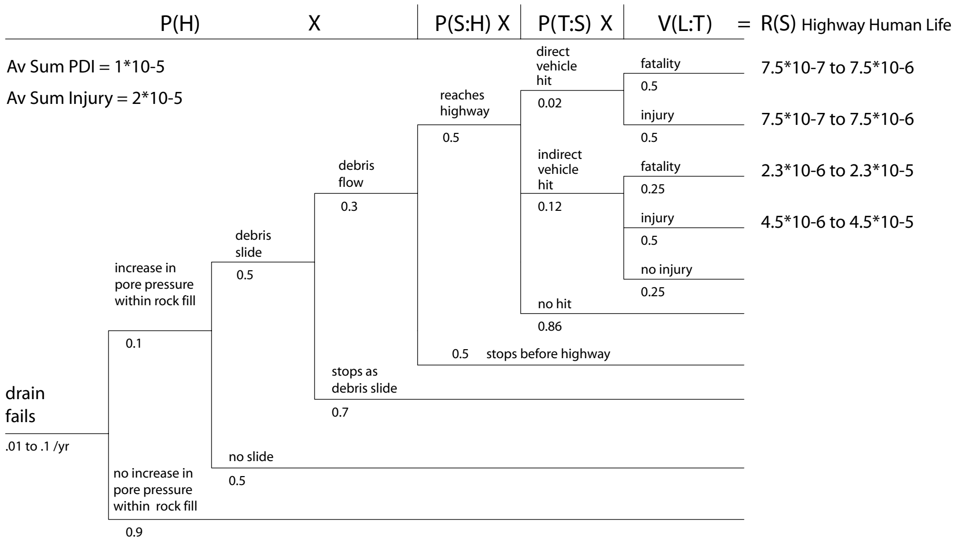


FIGURE 60 *Simplified event tree for Specific Risk to Human Life (PDI).*

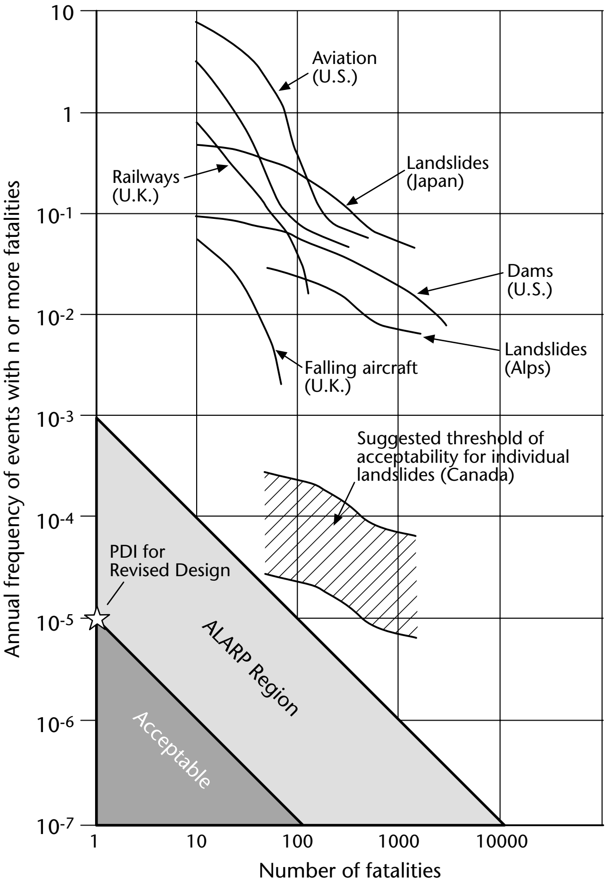


FIGURE 61 *F-N and f-N plot (modified from Morgan 1991 and Fell 1997).*

and others qualitatively. The analysis identified levels of risk to several elements that were considered unacceptable (highway safety and access, fish habitat, and power supply) and as a result the initial FSR repair design was modified, and re-analyzed, to estimate the likelihood of future landslides, and to verify that the risk would be reduced to acceptable levels. The decision to accept the residual risk for the FSR repair ultimately rested with the forest resource managers who considered the identified risks, the uncertainty levels associated with those risks, and the anticipated benefits of re-establishing FSR access.

A quantitative approach, for some of the elements, provided insights and comparisons that would not have been possible using a qualitative approach. The yearly "cost" to direct infrastructure was directly compared to anticipated yearly benefits, and the estimated specific risk to human life (PDI) was compared with published criteria for acceptability. These comparisons would not have been possible using a qualitative approach. At the same time, the uncertainty associated with the quantitative estimates must be communicated to the decision makers. A qualitative approach was more appropriate for some of the elements where values were difficult to quantify, such as loss or damage to fish habitat, power outage, and highway disruption.

FIGURE 62 *Repaired Summit Lake FSR (D. Nicol photo).*

The results of the risk analysis should be placed into a site-specific context to provide the perspective for resource managers to effectively evaluate the risk and compare those risks to the expected benefits. In this case study there was a relatively high degree of uncertainty in estimating the probability of failure, P(H), for the proposed retained fill for the FSR. However, even given this uncertainty, the analyses provided enough detail to highlight important design parameters and allow the decision makers to adequately evaluate the risks.

4.8.7 Acknowledgements

The author would like to thank Stephen Ngo, Kevin Turner, Hardy Bartle, and Brent Case for their review of this case study and for their many useful comments, Perry Lambkin for the drafting of Figure 61, and the staff of the Arrow/Boundary Forest District for their assistance with the field investigation. Tim Stokes with Terra Firma Geoscience Services also reviewed a draft of this case study and provided helpful comments.

4.8.8 References

British Columbia Ministry of Transportation. 1988. Minimum Stopping Sight Distance. Design Manual A.1–1.0.

————. 2001. Supplement to TAC Geometric Design Guide, pp. 1420–1422.

Bunce, C.M., D.M. Cruden, and N.R. Morgenstern. 1997. Assessment of the hazard from rock fall on a highway. Canadian Geotechnical Journal 34: 344–356

Fell, R. and D. Hartford 1997. Landslide risk management. *In* Proceedings of the International Workshop on landslide risk assessment, D. Cruden and R. Fell (editors); A.A. Balkema, Netherlands. Pp. 51–109.

Ho, K., E. Leroi, and B. Roberds. 2000. Quantitative risk assessment: application, myths and future direction. Keynote Proc. GeoEng 2000, pp. 269–312.

Hungr, O., J. Sobkowicz, and G.C. Morgan. 1993. How to economize on natural hazards. Geotechnical News 11(1):54–57.

Morgan, G.C. 1992. Quantification of risks from slope hazards. *In* Geological hazards in British Columbia, B.C. Geological Survey Brand, Open File 1992–15, pp. 57–70.

Read, P.B., and J.O. Wheeler. 1976. Geology Lardeau West-Half. Geological Survey of Canada. Open File 432.

Vick, S.G. 1992. Risk in geotechnical practice. *In* Proceedings Geotechnique and Natural Hazards Symposium, Canadian Geotechnical Society, Bi-Tech Publishers, Vancouver, B.C., pp. 41–62.

________, 2002. Degrees of belief, subjective probability and engineering judgement, ASCE Press, Reston, Va., p. 455.

CHAPTER 5 SUMMARY OF KEY ASPECTS OF LANDSLIDE RISK MANAGEMENT

MIKE WISE, GLENN MOORE, AND DOUG VANDINE

5.1 Conclusions from Case Studies

The case studies in Chapter 4 demonstrate that effective landslide risk assessment consists of both risk analysis and risk evaluation. It is important to select an appropriate type of landslide risk analysis for a given site. For example, a partial risk analysis requires the estimate of the probability of occurrence of a specific hazardous landslide, and an estimate of the spatial and temporal probabilities, to determine if that landslide will reach or otherwise affect the site occupied by a specific element. In a more complex specific value of risk analysis, the vulnerability and worth of an element must also be considered. Risk evaluation compares the risk analysis results to acceptable or tolerable thresholds of risk. If the level of risk is not acceptable or tolerable, risk controls may be needed to reduce the risk.

Terrain stability professionals usually carry out the analysis of landslide risk, while forest resource managers evaluate the risk and select options for risk control, often in consultation with terrain stability professionals. The case studies demonstrate that using the structured framework for landslide risk management, introduced in Chapter 2, provides a rational basis for informed, explicit, and defensible decisions during forest development. In addition, the application of this structured framework may help to support a due diligence defence in the event of a landslide.

The case studies also demonstrate that the common landslide risk terms and the methods of analysis, discussed in Chapters 2 and 3, can result in better estimates of landslide risk by terrain stability professionals, and more effective and consistent communication to forest resource managers. Better estimates and communication increase the potential for better decisions by forest resource managers. In light of these conclusions, the following sections summarize some key aspects about managing landslide risk that should be considered by forest resource managers and terrain stability professionals.

5.2 Key Aspects for Forest Resource Managers

Consider using a structured framework for the management of landslide risk. A structured framework helps to guide the process of a landslide risk management project. It separates the process into distinct steps and highlights the interdependent involvement of the terrain stability professional and the forest resource manager. A systematic analysis and evaluation of risk can also be used as a tool to prioritize proposed risk control work, as demonstrated by the need for watershed rehabilitation work in the San Juan watershed (Case Study 4.1).

Consider developing specific criteria that would initiate a landslide risk management project for typical or expected situations. Construction and operation of forest roads, and the harvesting of hillslope areas, can significantly contribute to the occurrence of landslides. Typically, a landslide risk management project should be initiated to address concerns about the effects of development on terrain stability, and the potential effects (short term and long term) of landslide runout on worker safety, forest resources, infrastructure, and people. For example, to show due diligence, it is important to establish criteria for triggering the initiation of a terrain stability assessment for forest planning and operations. The benefits of terrain stability assessments are demonstrated by the case studies for proposed harvesting of cutblocks in the Oliver Creek watershed (Case Study 4.2) and in the watershed near Bamfield (Case Study 4.5).

Consider evaluating the estimates of landslide risk using consistent thresholds for acceptable or tolerable risk. It is challenging to integrate differing, and perhaps ambiguous, legislative and corporate thresholds of risk into the evaluation of landslide risk. It is often beneficial to consider the context of the analysis along with the estimates. The risk analysis for Summit Lake (Case Study 4.8) provides a comparison of the risks to highway users, property, and fish habitat using established standards and discusses the importance of evaluating the risks to these elements separately.

Consider requesting more accurate analyses where warranted by higher-value elements at risk and the increased need for due diligence. The effort to analyze landslide risk must be appropriate to the value of the elements at risk, with more intensive studies typically resulting in better and more defensible estimates of risk. For example, landslide risk analyses were carried out for the alluvial fans on both Hummingbird Creek (Case Study 4.3) and Kitseguecla Creek (Case Study 4.7). Because the Hummingbird Creek fan is developed with residences, a more detailed risk analysis was appropriate to better estimate the risk to buildings.

5.3 Key Aspects for Terrain Stability Professionals

Consider using consistent terms and methods in landslide risk analysis to improve communication of results. Various combinations of risk components result in different types of risk analysis, such as partial risk, specific risk, and specific value of risk. The different types of analysis together with decomposition techniques, in which the risk components are further decomposed if necessary into a number of events, provide powerful tools for studying complex situations. The Tommy Creek road alignment study (Case Study 4.6) and the Summit Lake study (Case Study 4.8) demonstrate the use of some of these tools to effectively analyze landslide risk to multiple elements.

Consider the benefits of qualitative and quantitative techniques for landslide risk analysis, appropriate to the elements at risk and the scope of study. Various techniques are available for estimating landslide risks. For example, these techniques can range from:

- qualitative estimates in Case Studies 4.1 (San Juan watershed), 4.2 (Oliver Creek watershed) and 4.6 (Tommy Creek), and quantitative estimates in Case Study 4.7 (Kitseguecla Creek), based only on subjective probability;
- quantitative estimates in Case Study 4.5 (watershed near Bamfield), based on extrapolations from published statistical information, as well as subjective judgements; and
- quantitative estimates in Case Studies 4.3 (Hummingbird Creek), 4.4 (Jamieson Creek), and 4.8 (Summit Lake), based on detailed numerical analyses, as well as subjective judgements.

If necessary, consider providing recommendations for additional studies that can be carried out to more accurately estimate the risk, if considered necessary. In a phased approach to landslide risk management, reconnaissance-level techniques for risk analysis can be used at the initial stages of the project, progressing to more intense techniques of analysis during the later detailed phase (see Case Study 4.1, San Juan watershed). In other cases, it is appropriate to use more detailed analysis of landslide risk, such as estimating the vulnerability or worth of elements at risk.

Consider giving special consideration to studies with multiple hazards or multiple elements. Where an element may be at risk from multiple potential landslide sites (watershed near Bamfield, Case Study 4.5) or multiple slope hazards (Tommy Creek, Case Study 4.6), or where multiple elements are involved (Summit Lake study, Case Study 4.8), each hazard and element should be considered separately. Combining risks for different elements is not necessarily a simple task, because it may lead to ambiguous results for risk evaluation by the forest resource manager, as discussed in the Summit Lake study (Case Study 4.8).

5.4 Final Remarks

The *Risk Management: Guidelines for Decision Makers* document developed by the Canadian Standards Association (CSA 1997) states:

> *The objective of risk management is to ensure that significant risks are identified and that appropriate action is taken to minimize these risks as much as is reasonably achievable. Such actions are determined based on a balance of risk control strategies, their effectiveness and cost, and the needs, issues, and concerns of stakeholders. Communication among stakeholders throughout the process is a critical element of this risk management process. Decisions made with respect to risk issues must balance the technical aspects of risk with the social and moral considerations that often accompany such issues.*

In forest development, better estimates of landslide risk alone do not lead to better forest management decisions. Better estimates, together with clear communication of risk analysis results, consistent evaluation of risk estimates, appropriate actions to control risk, and monitoring, are paramount to effective and efficient landslide risk management.

APPENDICES

The left-hand column of Table A1.1 summarizes the landslide background information that can be considered in landslide risk analyses and assessments. The right-hand column provides some examples of the information. Table A1.2 indicates the landslide information that should be considered in the various analyses and assessments.

Much of the background information has to be obtained from fieldwork. There are, however, many other different sources, including:

- recent airphotos at various scales
- historical airphotos
- topographic maps at various scales
- bedrock, surficial geology, terrain, and terrain stability maps
- terrain attribute studies
- floodplain maps
- water licence maps
- biological inventories, including fish and other wildlife
- forestry information such as timber inventories, cruise plots, and silviculture prescriptions
- forest road information such as road layout plans, profiles, and cross-sections
- forest cutblock layout information such as deflection lines, storm wind directions, and gully assessments
- watershed and channel assessment reports
- previous landslide inventories, analyses, assessments, and investigations
- other related research.

The quality and validity of all background data should be assessed before they are used.

TABLE A1.1 *Landslide site variables and examples*

Variable	Landslide site variable	Examples
a	Existing attributes, geological processes, and environmental conditions	existing terrain attributes • slope – gradient, position, aspect, morphology • material type and geotechnical properties – bedrock, debris, earth • hydrogeology including soil drainage • soil depth and vegetation • existence of natural or human-related landslides existing human-related attributes • roads/trails – cuts and fills, drainage controls, road gradient • logging – harvesting type, age since logging, reforestation • mining and quarrying • agriculture • urban, rural development • impounding of water (dam building) • existing geological processes and environmental conditions • weathering and erosion • climate; weather events

TABLE A1.1 *Continued*

Variable	Landslide site variable	Examples
b	Future human activities, changing geological processes and environmental conditions	future human activities • road building • logging and reforestation • mining and quarrying • impounding of water (dam building) • agriculture • urban, rural development • changing geological processes and environmental conditions • volcanism and seismicity • natural landslide dams • climate change
c	Type of movement or mechanism of failure	falls and topples slides – rotational and translational lateral spreads flows
d	Geographical dimensions	travel path, travel distance zone of depletion, depth within zone of depletion zone of accumulation, thickness within zone of accumulation
e	Character of landslide debris	activity velocity total displacement, differential displacement impact force, kinetic energy per unit area
f	Element or elements at risk	humans, property, the environment, and other things of social, environmental, and economic value
g	Spatial probability	related to the occurrence of a hazardous landslide dependent on geographical dimensions the element in spatial relation to the landslide
h	Temporal probability	related to spatial effects is the element in the area affected by the landslide, at the time of the landslide
I	Vulnerability	related to the temporal effects probability of loss or damage proportion of loss or damage
j	Direct and indirect worth of element	monetary and qualitative
k	Known or implied criteria for tolerable/acceptable risk to elements	relative qualitative thresholds or quantitative thresholds

TABLE A1.2 *Types of landslide risk analyses, risk assessments, and landslide site variables**

		Landslide site and risk variables the analysis/assessment may consider										
		Existing attributes, geological processes, and environmental conditions	Future human activities, changing geological processes and environmental conditions	Type of movement or mechanism of failure	Geographical dimensions	Character of landslide debris	Element or elements at risk	Spatial probability	Temporal probability	Vulnerability	Worth, direct and indirect, monetary and qualitative	Known or implied criteria for tolerable/acceptable risk to element(s)
Type of analysis and assessment	**Symbol**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**
		Refer to Table A1.1 for description and examples of landslide site variables										
Landslide analysis	P	yes	yes									
	P(SL)	yes	yes	yes	yes	yes						
Hazard analysis	P(H)	yes	yes	yes	yes	yes	yes					
Partial risk analysis	P(HA)	yes	yes	yes	yes	yes	yes	yes	yes			
Specific risk analysis (property)	R(S) property	yes	yes	yes	yes	yes	except human life	yes	yes	yes		
Specific risk analysis (human life)	R(S) human life	yes	yes	yes	yes	yes	human life	yes	yes	yes		
Specific value of risk analysis	R(SV)	yes	yes	yes	yes	yes	except human life	yes	yes	yes	yes	
Multiple risk analysis	R(M)	one or more	one or more	one or more	one or more	one or more	one or more	one or more	one or more	one or more	if applicable	
Total risk analysis	R(T)	all	all	all	all	all	all	all	all	all	if applicable	
Risk, hazard, and risk value assessment		one or more, or all	one or more, or all	one or more, or all	one or more, or all	one or more, or all	one or more, or all	one or more, or all	one or more, or all	one or more, or all	if applicable	yes

* Refer to Table A1.1 for description of terms.

Some British Columbia provincial and municipal government approval agencies ask geotechnical engineers and geoscientists to provide quantitative estimates of probabilities of landslide occurrence. These quantitative estimates are used by the approval agencies to help evaluate landslide risks for proposed residential development.

When residential development is planned in rural areas, it may be exposed to elevated probabilities of landslide occurrence from forestry operations, and terrain stability professionals may be asked to provide quantitative estimates of probability of landslide occurrence. Therefore, terrain stability professionals should be aware of the evolution of quantitative landslide risk evalutaion in this province.

In 1973, British Columbia Supreme Court Justice William Berger ruled that the possibilities of floods and landslides on the Rubble Creek debris fan, located between Squamish and Whistler, constituted an unacceptable risk to a then-existing residential development. He based his judgement in part on a flood and landslide return period of 10 000 years (Berger 1973). In 1978, a panel of geotechnical specialists (the Garibaldi Advisory Panel) confirmed the flood and landslide potential for the area (Garibaldi Advisory Panel 1978). The Berger ruling and the Garibaldi Advisory Panel findings introduced the concept of quantitative probability of landslide occurrence to the B.C. Ministry of Transportation (BCMOT) subdivision approval process.

About 1978, the BCMOT began to ask consulting geotechnical engineers, when investigating natural hazards ("landslips [landslides], erosion, rockfalls, snowslides and [snow] avalancehes") for proposed subdivisions, to think in terms of a 10% probability of a hazardous occurrence in 50 years (an annual probability of 1/475, approximately 1/500) (BCMOT 1993). BCMOT acknowledges the difficulty in estimating the probability of occurrence for some natural hazards.

In the early 1990s, Peter Cave, then Director of Planning for the Fraser Valley Regional District (FVRD), published probability (equivalent to P(H) in this Land Management Handbook 56) guidelines for various types of hazards (flood, debris flood, stream erosion or avulsion, snow avalanche, debris flow, small-scale landslide, small-scale rockfall, and major catastrophic landslide hazards) for that regional district. The guidelines, which are still current today, address a range of residential development (minor repair, major repair, reconstruction, extension, new building, subdivision, and a new community) from Cave et al. 1990, Cave 1992a, 1992b. Cave used three precedents to help calibrate the guidelines:

- the return period of 200 years for provincially sponsored flood-proofing,
- the BCMOT 10% probability of at least one hazard occurrence in 50 years, and
- the unacceptable return period of 10 000 years as ruled by Mr. Justice Berger.

The District of North Vancouver and the Corporation of Delta also use numeric probability of hazard occurrence guidelines in their building permit reviews.

Section 699 (2) of British Columbia's *Local Government Act* (Province of British Columbia 2003) covers the issuance of building permits in potential hazardous areas, including those "which may be subject to flooding, mudflows, debris flows, debris torrents, erosion, land slip (landslides), rockfalls, subsidence and avalanches." The Act allows a building inspector to instruct a landowner to provide a report prepared by a professional engineer with experience in geotechnical engineering stating that "the land may be used safely for the use intended." The Act does not define what is meant by the term "safely."

APPENDIX 3 Examples of published landslide risk analyses

TABLE A3.1 *Types of landslide risk analyses, and example references**

			Risk components considered, or terminology and symbols used in example reference**							
Type of analysis	**Symbol**	**Example references**	**P(H)**	**P(S:H)**	**P(T:S)**	**V(L:T) property**	**V(L:T) human life**	**E**	**Qualitative or Quantitative**	**Comments (terminology as used in example reference)**
Landslide analysis	P	Rollerson et al. 2002							Quantitative	Terrain Attribute Study; a probabilistic mapping method
		BCMOF 1999; BCRIC 1996							Qualitative	Detailed Terrain Stability Mapping (5 Class Mapping), a subjective, relative mapping method
		USDA 1994							Quantitative	LISA(Level I Stability Analysis); a stability (limiting equilibrium) calculation mapping method
	P(SL)									No examples provided
Hazard analysis	P(H)	BCMOF 2002	yes						Qualitative	Likelihood of a particular landslide, the landslide of significance, occurring
		BCMOF 1999	yes						Qualitative	Terrain Stability Field Assessment determines existing and potential landslide hazards
Partial risk analysis	P(HA)	BCMOF1999	yes	yes	yes				Qualitative	Terrain Stability Field Assessment determines existing and potential landslide hazards and risks
		BCMOF 2002	yes	yes	yes				Qualitative	Determines landslide of significance, the smallest landslide that could adversely affect the element at risk
Specific risk analysis (property, the environment, and other things of value)	R(S) property	BCMOF 2002	yes	yes	yes	yes			Qualitative	Determines landslide of significance, the smallest landslide that could adversely affect the element at risk
		BCMOF 1999	yes	yes	yes	yes			Qualitative	Terrain Stability Field Assessment determines existing and potential landslide hazards and downslope/ downstream elements at risk and consequences
		BCRIC 1996	Pa	Vs	Vt	Vl			Quantitative	Rs = Pa x V = Pa x Vs x Vt x Vl
Specific risk analysis (human life)	R(S) human life	AGS 2000	P(H)	P(S:H)	P(T:S)		V(D:T)		Quantitative	R(DI) = P(H) x P(S:H) x P(T:S) x V(D:T)
		Fell and Hartford 1997	P(H)	P(S|H)	P(T|S)		V(L|T)		Quantitative	R(DI) = P(H) x P(S|H) x P(T|S) x V(L|T)
		BCRIC 1996	Pa	Ps	Pt		Pl		Quantitative	PDI = Pa x Ps x Pt x Pl
		Morgan et al. 1992	P(H)	P(S:H)	P(T:S)		P(L:T)		Quantitative	PDI = P(H) x Severity = P(H) x P(S:H) x P(T:S) x P(L:T)

TABLE A3.1 *continued*

			Risk components considered, or terminology and symbols used in example reference**							
Type of analysis	**Symbol**	**Example references**	**P(H)**	**P(S:H)**	**P(T:S)**	**V(L:T) property**	**V(L:T) human life**	**E**	**Qualitative or Quantitative**	**Comments (terminology as used in example reference)**
Specific value of risk analysis	R(SV)	AGS 2000	P(H)	P(S:H)	P(T:S)	V(Prop:S)		E	Quantiative	R(Prop) = P(H) x P(S:H) x P(T:S) x V(Prop:S) x E
		Fell and Hartford 1997	P(H)	P(S|H)	P(T|S)	V(P|S)		E	Quantitative	R(PD) = P(H) x P(S|H) x P(T|S) x V(P|S) x E
Multiple risk analysis	R(M)	AGS 2000	P(H)	P(S:H)	P(T:S)		V(D:T)		Quantitative	Sum R(DI) = Sum [P(H) x P(S:H) x P(T:S) x V(D:T)]
		BCMOF 1999	yes	yes	yes	yes	yes		Qualitative	Terrain Stability Field Assessment determines existing and potential landslide hazards and downslope/downstream elements at risk and consequences
		Gerath 1995, BCRIC 1996	Pa	Vs	Vt	Vl		E	Quantitative	R = Sum (Pa x V x E) = Sum (Pa x Vs x Vt x Vl x E)
Total risk analysis	R(T)	AGS 2000	P(H)	P(S:H)	P(T:S)	V(Prop:S)		E	Quantiative	Sum R(Prop) = Sum [P(H) x P(S:H) x P(T:S) x V(Prop:S) x E]
		Fell and Hartford 1997	P(H)	P(S|H)	P(T|S)	V(L|T)		E	Quantitative	Rt = Sum (Rs x E) = Sum (P x V x E)

* Refer to text for description of terms.

** "Yes" indicates use in qualitative example.

As discussed in Section 3.1 of Chapter 3, probability of occurrence of a landslide, including P, P(SL), and P(H), should be expressed over a specified period of time, such as an *annual probability of occurrence* (Pa, where "a" indicates annual) or a *long-term probability of occurrence* (Px, where "x" is a given number of years).

For independent events, where multiple trials of "similar" experiments with equally possible outcomes, such as rolling the dice, are used to calculate a probability over a set number of trials, Pa and Px are related as follows:

$$Px = 1-(1-(Pa))^{x}$$

This equation assumes that the Pa for landslides at one location for one year is constant and does not depend on the occurrence of previous landslides. This equation, however, can be used as a first approximation for equating short- and long-term landslide probabilities. For example, the probability that at least one landslide will occur in a 50-year period given an annual probability of occurrence of 1 in 500 is:

$$\begin{aligned} P50 &= 1-(1-(1/500))^{50} \\ &= 0.095 \end{aligned}$$

The results of this equation must be viewed subjectively and adjusted to account for other factors influencing the probability.

Table A4.1 demonstrates the relationship of Px, Pa, and x.

Table A4.2 is an example of probability of occurrence ratings based on ranges of annual probability of occurrence (Pa). Note that the lines that divide the probability ratings are horizontal, indicating that the ratings are *independent of long-term probability of occurrence.* In the example, the divisions between ratings are arbitrary.

Table A4.3 is an example of probability of occurrence ratings based on ranges of long-term probability of occurrence (Px) (e.g., within the design life of the project). Note that the lines that divide the probability ratings are diagonal, indicating that the ratings are *dependent on the long-term probability of occurrence.* In the example, the divisions between ratings are arbitrary.

By comparing Tables A4.2 and A4.3 it is apparent that the decision on whether to base the probability of occurrence ratings on Pa or Px is important. By overlaying Tables A4.2 and A4.3 it can be determined whether or not one probability rating system is more or less conservative than the other.

TABLE A4.1 *Px (long-term probability of occurrence) related to Pa (annual probability of occurrence) and x (years)*

Pa annual prob	Px,* long-term probability of occurrence x = years (life of project)													
	1	2	5	10	20	25	50	100	200	250	500	1000	2000	2500
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1/2	0.50	0.75	0.97	1	1	1	1	1	1	1	1	1	1	1
1/5	0.20	0.36	0.67	0.89	0.99	1	1	1	1	1	1	1	1	1
1/10	0.10	0.19	0.41	0.65	0.88	0.93	0.99	1	1	1	1	1	1	1
1/20	0.05	0.10	0.23	0.40	0.64	0.72	0.92	0.99	1	1	1	1	1	1
1/50	0.02	0.04	0.10	0.18	0.33	0.40	0.64	0.87	0.98	0.99	1	1	1	1
1/100	0.01	0.02	0.05	0.10	0.18	0.22	0.39	0.63	0.87	0.92	0.99	1	1	1
1/200	0.01	0.01	0.02	0.05	0.10	0.12	0.22	0.39	0.63	0.71	0.92	0.99	1	1
1/250	0	0.01	0.02	0.04	0.08	0.10	0.18	0.33	0.55	0.63	0.87	0.98	1	1
1/500	0	0	0.01	0.02	0.04	0.05	0.10	0.18	0.33	0.39	0.63	0.86	0.98	0.99
1/1000	0	0	0	0.01	0.02	0.02	0.05	0.10	0.18	0.22	0.39	0.63	0.86	0.92
1/2000	0	0	0	0	0.01	0.01	0.02	0.05	0.10	0.12	0.22	0.39	0.63	0.71
1/2500	0	0	0	0	0.01	0.01	0.02	0.04	0.08	0.10	0.18	0.33	0.55	0.63
1/5000	0	0	0	0	0	0	0.01	0.02	0.04	0.05	0.10	0.18	0.33	0.39

* Zeros in the table indicate values that are less than 0.01, and ones indicate values that are greater than 0.99.

TABLE A4.2 *Example of probability of occurrence ratings related to Pa (annual probability of occurrence)*

Probability of occurrence rating	Pa annual prob	Px,* long-term probability of occurrence x = years (life of project)													
		1	2	5	10	20	25	50	100	200	250	500	1000	2000	2500
VH	1/1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	1/2	0.50	0.75	0.97	1	1	1	1	1	1	1	1	1	1	1
	1/5	0.20	0.36	0.67	0.89	0.99	1	1	1	1	1	1	1	1	1
	1/10	0.10	0.19	0.41	0.65	0.88	0.93	0.99	1	1	1	1	1	1	1
H	**1/20**	**0.05**	**0.10**	**0.23**	**0.40**	**0.64**	**0.72**	**0.92**	**0.99**	**1**	**1**	**1**	**1**	**1**	**1**
	1/50	**0.02**	**0.04**	**0.10**	**0.18**	**0.33**	**0.40**	**0.64**	**0.87**	**0.98**	**0.99**	**1**	**1**	**1**	**1**
	1/100	**0.01**	**0.02**	**0.05**	**0.10**	**0.18**	**0.22**	**0.39**	**0.63**	**0.87**	**0.92**	**0.99**	**1**	**1**	**1**
M	1/200	0.01	0.01	0.02	0.05	0.10	0.12	0.22	0.39	0.63	0.71	0.92	0.99	1	1
	1/250	0	0.01	0.02	0.04	0.08	0.10	0.18	0.33	0.55	0.63	0.87	0.98	1	1
	1/500	0	0	0.01	0.02	0.04	0.05	0.10	0.18	0.33	0.39	0.63	0.86	0.98	0.99
L	**1/1000**	**0**	**0**	**0**	**0.01**	**0.02**	**0.02**	**0.05**	**0.10**	**0.18**	**0.22**	**0.39**	**0.63**	**0.86**	**0.92**
	1/2000	**0**	**0**	**0**	**0**	**0.01**	**0.01**	**0.02**	**0.05**	**0.10**	**0.12**	**0.22**	**0.39**	**0.63**	**0.71**
	1/2500	**0**	**0**	**0**	**0**	**0.01**	**0.01**	**0.02**	**0.04**	**0.08**	**0.10**	**0.18**	**0.33**	**0.55**	**0.63**
VL	1/5000	0	0	0	0	0	0	0.01	0.02	0.04	0.05	0.10	0.18	0.33	0.39

* Zeros in the table indicate values that are less than 0.01, and ones indicate values that are greater than 0.99.

TABLE A4.3 *Example of probability ratings related to Px (long-term probability of occurrence)*

Pa annual prob	Px,* long-term probability of occurrence x = years (life of project)														Probability of occurrence rating
	1	2	5	10	20	25	50	100	200	250	500	1000	2000	2500	
1/11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
1/2	**0.50**	0.75	0.97	1	1	1	1	1	1	1	1	1	1	1	
1/5	**0.20**	**0.36**	0.67	0.89	0.99	1	1	1	1	1	1	1	1	1	
1/10	0.10	**0.19**	**0.41**	0.65	0.88	0.93	0.99	1	1	1	1	1	1	1	
1/20	0.05	0.10	**0.23**	**0.40**	**0.64**	0.72	0.92	0.99	1	1	1	1	1	1	
1/50	**0.02**	**0.04**	0.10	0.18	**0.33**	**0.40**	**0.64**	0.87	0.98	0.99	1	1	1	1	
1/100	**0.01**	**0.02**	0.05	0.10	0.18	**0.22**	**0.39**	**0.63**	0.87	0.92	0.99	1	1	1	
1/200	**0.01**	**0.01**	**0.02**	0.05	0.10	0.12	**0.22**	**0.39**	**0.63**	0.71	0.92	0.99	1	1	**VH**
1/250	0	**0.01**	**0.02**	**0.04**	0.08	0.10	0.18	**0.33**	**0.55**	**0.63**	0.87	0.98	1	1	
1/500	0	0	**0.01**	**0.02**	**0.04**	0.05	0.10	0.18	**0.33**	**0.39**	**0.63**	0.86	0.98	0.99	
1/1000	0	0	0	**0.01**	**0.02**	**0.02**	0.05	0.10	0.18	**0.22**	**0.39**	**0.63**	0.86	0.92	
1/2000	0	0	0	0	**0.01**	**0.01**	**0.02**	0.05	0.10	0.12	**0.22**	**0.39**	**0.63**	0.71	
1/2500	0	0	0	0	**0.01**	**0.01**	**0.02**	**0.04**	0.08	0.10	0.18	**0.33**	**0.55**	**0.63**	
1/5000	0	0	0	0	0	0	**0.01**	**0.02**	**0.04**	0.05	0.10	0.18	**0.33**	**0.39**	
				VL				**L**			**M**				**H**

* Zeros in the table indicate values that are less than 0.01, and ones indicate values that are greater than 0.99.

The following tables adapted from AGS (2000), provide examples of definitions of relative qualitative ratings, and their relation to quantitative estimates. Some other examples of relative qualitative vulnerability and consequence ratings, for a variety of elements, are provided in Appendix 10 of BCMOF (2002).

TABLE A5.1 *Qualitative measures of likelihood of occurrence*

Descriptor	**Description**	**Indicative annual probability ***
Almost certain	The event is expected to occur.	$>\sim10^{-1}$
Likely	The event will probably occur under adverse conditions.	$\sim10^{-2}$
Possible	The event could occur under adverse conditions.	$\sim10^{-3}$
Unlikely	The event might occur under very adverse conditions.	$\sim10^{-4}$
Rare	The event is conceivable but only under exceptional circumstances.	$\sim10^{-5}$
Not credible	The event is inconceivable or fanciful.	$<10^{-6}$

* ~ means that the indicative value may vary by ± one-half an order of magnitude.

TABLE A5.2 *Qualitative measures of consequences to property*

Descriptor	**Description***
Catastrophic	Structure completely destroyed or large-scale damage requiring major engineering works for stabilization.
Major	Extensive damage to most of structure, or extending beyond site boundaries requiring significant stabilization works.
Medium	Moderate damage to some of structure, or significant part of site requiring large stabilization works.
Minor	Limited damage to part of structure, or part of site requiring some reinstatement/stabilization works.
Insignificant	Little damage.

* "Description" may be edited to suit a particular case.

TABLE A5.3 *Qualitative risk analysis matrix—level of risk to property*

	Consequence to property				
Likelihood of occurrence	**Catastrophic**	**Major**	**Medium**	**Minor**	**Insignificant**
Almost certain	VH	VH	H	H	M
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not credible	VL	VL	VL	VL	VL

TABLE A5.4 *Risk rating and example implications for evaluation*

Risk rating*		**Example implications for evaluation****
VH	Very high risk	Extensive detailed investigation, and research, planning, and implementation of treatment options essential to reduce risk to acceptable levels; may be too expensive and not practical
H	High risk	Detailed investigation, planning, and implementation of treatment options required to reduce risk to acceptable levels
M	Moderate risk	Tolerable, provided that treatment plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options.
L	Low risk	Usually accepted. Treatment requirements and responsibility to be defined to maintain or reduce risk.
VL	Very low risk	Acceptable. Manage by normal slope maintenance procedures.

* Use of dual descriptors for likelihood, consequence, and risk reflect uncertainty of the estimate, and may be appropriate in some cases.

** Implications for a particular situation are to be determined by all stakeholders; these are examples only.

The most common method of classifying the ***type of landslide*** is by type of movement and type of material. Varnes (1978) and Cruden and Varnes (1996) describe the most widely used conventions for classifying type of movement, type of material, and type of landslide.

Size includes length, width, and depth of the zones of depletion and accumulation, travel path, and travel distance. From this information the area and/or the volume of the landslide—the ***magnitude***—can be estimated. Some landslides, such as debris flows, occur as a series of movements or pulses and therefore it is important to differentiate between the magnitude of the entire event from those of individual movements or pulses. Refer to Cruden and Varnes (1996) for further information on landslide dimensions.

Landslide magnitudes can be expressed quantitatively or qualitatively. Quantitative estimates are often derived from estimates of the area, with or without estimates of depth of depletion and thickness of accumulation, and are often expressed as ranges. *Small, medium,* and *large* are examples of relative qualitative ***magnitude rating***, but such terms must be defined. Table A6.1 shows an example of the relationship between magnitude ratings and quantitative ranges of landslide area and volume.

Character of the landslide includes activity, velocity, total and differential displacement, and impact force and kinetic energy per unit area. Refer to Cruden and Varnes (1996) for further information on describing activity and velocity. Hungr (1997) describes these parameters (with the exception of activity) as ***intensity***. Intensity varies spatially down and across the landslide path. These parameters may be expressed quantitatively, ideally using a spatial distribution function, or using relative qualitative ***intensity ratings*** such as *slow, moderate,* and *fast,* or *low, moderate*, and *high,* but again such terms must be defined.

TABLE A6.1 *Example of magnitude ratings and ranges of landslide area and volume*

	Quantitative range	
Magnitude rating	**Area affected (ha)***	**Minimum volume involved (m^3)****
Very large	> 5	50,000
Large	0.5–5	5,000–50,000
Medium	0.05–0.5	500–5,000
Small	0.005–0.05	50–500
Very small	< 0.005	< 50

* 1 ha = 10 000 m^2.
** Based on planimetric area and assumed depth/thickness of 1 m.

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC). 2003. Guidelines for Terrain Stability Assessments in the Forest Sector. Burnaby, B.C. October 2003.

Atkins, R.J., M.R. Leslie, D.F. Polster, M.P. Wise, and R.H. Wong. 2001. Best management practices handbook: Hillslope restoration in British Columbia. B.C. Ministry of Forests, Watershed Restoration Program, Resource Tenures and Engineering Branch, Victoria, B.C.

Australian Geomechanics Society (AGS). 2000. Landslide risk management concepts and guidelines. Sub-committee on landslide risk management, Australian Geomechanics March 2000, pp. 49–92.

Berger, T.B. 1973. Reasons for judgment of the Honourable Mr. Justice Berger on the matter of the *Land Registry Act* – and an application for approval of a proposed subdivision by Cleveland Holdings Ltd. Supreme Court of British Columbia.

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

________. 2002. Forest road engineering guidebook, 2nd ed. Forest Practices Code of British Columbia, Victoria, B.C.

British Columbia Ministry of Transportation (BCMOT). 1993. Subdivision policies and procedures manual. Previously published as Chapter 5 of manual of policy and procedures. App - 61: Geotechnical Study "If an initial study is needed…." (Dec. 1994).

British Columbia Resource Inventory Committee (BCRIC). 1996. Terrain stability mapping in British Columbia: A review and suggested methods for landslide hazard and risk mapping. Victoria, B.C. Publication 055.

Canadian Standards Association (CSA). 1991. Risk analysis requirements and guidelines. Toronto, Ont. CAN/CSA-Q634-91.

________. 1997. Risk management: Guideline for decision-makers; Etobicoke, Ont. CAN/CSA-Q850-97.

Cave, P.W. 1992a. Hazard acceptability thresholds for development approvals by local government. *In* Geological hazards in British Columbia, B.C. Geological Survey Branch, Open File 1992-15, pp. 15–26.

________. 1992b. Natural hazards, risk assessment and land use planning in British Columbia. *In* Proceedings Geotechnique and Natural Hazards Symposium, Canadian Geotechnical Society, Bi-Tech Publishers, Vancouver, B.C., pp. 1–11.

Cave, P.W., H. Sloan, and R.F. Gerath. 1990. Slope hazard evaluations in southwest British Columbia. *In* Proceedings of 43rd Canadian Geotechnical Conference, Quebec City, Que.

Chatwin, S.C., D.E. Howes, J.W. Schwab, and D.N. Swanston. 1994. A guide for management of landslide-prone terrain in the Pacific Northwest, B.C. Min. For., Land Manage. Handb. 18.

Cruden, D.M. 1991. A simple definition of a landslide. Bulletin of the International Association of Engineering Geology (43), pp. 27–29.

Cruden, D.M. and D.J. Varnes. 1996. Landslide types and processes. *In* Landslides investigation and mitigation. A.K. Turner and R.L. Schuster (editors). Special Report 247, Transportation Research Board, U.S. National Research Council, Washington, D.C., pp. 36–75.

Fell, R. 1994. Landslide risk assessment and acceptable risk. Canadian Geotechnical Journal (31):261–272.

Fell, R. and D. Hartford 1997. Landslide risk management. *In* Proceedings of the International Workshop on landslide risk assessment, D. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 51–109.

Garibaldi Advisory Panel. 1978. Report to B.C. Department of Highways. 3 volumes.

Gerath, R. 1995. Landslide hazards in BC's forests, the case for formal risk assessment; B.C. Professional Engineer, March 1995, pp. 10–13.

Hungr, O. 1997. Some methods of landslide hazard intensity mapping. *In* Proceedings of the International Workshop on Landslide Risk Assessment. D. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 215–226.

International Union of Geological Sciences Working Group on Landslides, Committee on Risk Assessment (IUGS). 1997. Quantitative risk assessment for slopes and landslides–The state of the art. *In* Proceedings of the International Workshop on Landslide Risk Assessment. D. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 3–12.

Montgomery, D.C., G.C. Runger, and A.G. Nairn. 2002. Applied statistics and probability for engineers. 3rd ed. Wiley & Sons, New York, N.Y.

Morgan, G.C., G.E. Rawlings, and J.C. Sobkowicz. 1992. Evaluating total risk to communities from large debris flows. *In* Proceedings Geotechnique and Natural Hazards Symposium Canadian Geotechnical Society, Bi-Tech Publishers, Vancouver, B.C., pp. 225–236.

Province of British Columbia. 2003. *Local Government Act* (RSBC 1996), Chapter 323.

Rollerson, T., T. Millard, and B. Thomson. 2002. Using terrain attributes to predict post-logging landslide likelihood on southwestern Vancouver Island. B.C. Min. For., Nanaimo, B.C. Technical Report TR-015 Geomorphology.

United States Department of Agriculture (USDA). 1994. Slope stability reference guide for National Forests in the United States. Forest Service document EM-7170-13.

VanDine, D.F. 1996. Debris flow control structures for forest engineering. B.C. Min. For., Working Paper 22/1996.

Varnes, D.J. 1978. Slope movement types and processes. *In* Landslides, analysis and control. R.L. Schuster and R.J. Krizek (editors). Special Report 176, National Academy of Sciences, National Research Council, Washington, D.C., pp. 11–33.

Vick, S.G. 2002. Degrees of belief, subjective probability and engineering judgement, ASCE Press, Reston, Va., p. 455.

Wise, M.P., M. Leslie, G. Horel, D. Collins, and W. Warttig. 2001. Road deactivation for hillslope restoration: Lessons learned on the Escalante Watershed Restoration Project. Proceedings 15th Vancouver Geotechnical Society Symposium on Land Reclamation Techniques, May 25, 2001, Vancouver, B.C.