BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

KERR WOOD LEIDAL ASSOCIATES

CHEEKEYE RIVER DEBRIS FLOW RISK ASSESSMENT

FINAL

PROJECT NO: 0464-001
DATE: October 21, 2008
DOCUMENT NO:

DISTRIBUTION:

RECIPIENT	5 copies
BGC	3 copies

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY
#500-1045 Howe Street
Vancouver, B.C.
Canada V6Z 2A9
Tel: 604.684.5900
Fax: 604.684.5909

October 21, 2008

Project No. 0464-001

Mr. M. Currie, P. Eng.
Kerr Wood Leidal Associates
Still Creek Road
Burnaby, BC
V5C 6G9

Dear Mr. Currie,

Re: Fan Debris Flow Study - Debris Flow Risk Assessment

Please find attached two copies of our above referenced draft report dated October 21, 2008.

Should you have any questions or comments, please do not hesitate to contact me at the number listed above.

Yours sincerely,

BGC ENGINEERING INC.
per:

Matthias Jakob, Ph.D., P.Geo.
Senior Geoscientist

Enc.

MJ/lb

EXECUTIVE SUMMARY

This report summarizes a risk analysis conducted to determine existing risk to loss of life from debris flow hazards on the Cheekeye River fan complex. The purpose of the risk analysis is to quantify the risk resulting from Cheekeye River debris flows under existing conditions, and to illustrate the degree of risk reduction that would be provided by a large debris barrier (roughly 1.4 Mm^3 volume upstream of the Highway 99 crossing).

This report analyses and evaluates risk for three principal aspects. The first is debris flow risk to Highway 99 users at the Cheekeye River bridge crossing. Risk is determined for the length of highway that could be affected by debris flow impact. Four scenarios are differentiated: Vehicles being caught by debris through direct impact; vehicles driving into the gap left if the highway bridge was to be destroyed by a debris flow; vehicles being stopped due to the debris on the road and following surges impacting the vehicles, and vehicles that are unable to stop in time and that drive into the debris mass.

Analysis demonstrates that the risk to individuals using Highway 99 is classified as acceptable when comparing the calculated risk values to international standards. The risk to groups is unacceptable when compared to international standards. If a large debris barrier is constructed, risk is reduced substantially but still exceeds the unacceptable threshold for N=2 or more fatalities.

An economic analysis was conducted by Stats B.C. for a scenario in which the Highway 99 bridge was severed. Resultant costs to the economy could be in the order of one million dollars per day.

The second focus of this report was the existing development at the Cheekeye subdivision near the Cheekeye River – Cheakamus River confluence. Risk to individuals is unacceptable using the 10^{-4} annual probability standard applied in the District of North Vancouver and elsewhere, and group risk falls into the unacceptable region for all return periods including and exceeding 50 years. If a large debris barrier is constructed, individual risk would be reduced to acceptable levels for all return periods.

The third area of focus is a potential development area on the southern portions of the fan. A hypothetical development area is used for this aspect of the risk analysis, but this is not intended to represent a specific development proposal. It was found that the risk to individuals in this area without mitigation is considered unacceptable for a large number of homes, but would be rendered acceptable for all homes if a large debris barrier is constructed. Group risk under the unmitigated scenario would be unacceptable, but would be moved into at least the ALARP zone with construction of the debris barrier. Additional risk mitigation strategies discussed in the text, such as construction of a berm south of the fan apex, would likely reduce risk fully into the acceptable region.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIMITATIONS OF REPORT

BGC prepared this report for the account of KWL and MacDonald Development Corporation (MDC). It presents the results of a risk assessment for debris flows on Cheekeye River. Other hydrologic and geomorphic processes, such as flooding, debris floods and bank erosion are not explicitly included in this study. Rock avalanches have been addressed in BGC's frequency-magnitude report issued in January 2008.

The material in this report reflects the judgment of BGC staff in light of the information available to BGC at the time of report preparation. Any use which a Third Party makes of this report or any reliance on decisions to be based on it is the responsibility of such Third Parties. BGC accepts no responsibility for damages, if any, suffered by any Third Party as a result of decisions made or actions based on this report. In particular, BGC accepts no responsibility for changes in real estate values that may occur as a consequence of this report.

This report does not quantify all conceivable risks due to debris flows on Cheekeye River. For example, risk to users of the Squamish Valley Road and other roads on the fan except from Highway 99 are not addressed in this report. Furthermore, risk to the airport, BC Hydro Substation and CN Rail has not been examined. The examples chosen in this report served to illustrate risk for an existing highway, bridge, and residential development, and the level of risk reduction that could be achieved by proposed mitigation strategies.

As a mutual protection to our clients, the public, and ourselves, this report is submitted for the confidential information of KWL and MDC. KWL and MDC are authorized to use this report for the purpose of the Cheekeye Fan project, and may distribute this report as reasonably required for evaluation, implementation and approval of the project. Authorization for any other use and/or publication of data, statements, conclusions or abstracts from or regarding this report and drawings is reserved pending BGC's written approval. If this report is issued in an electronic format, an original paper copy is on file at the BGC Vancouver office and that copy is the primary reference with precedence over any electronic copy of the document, or any extracts from our documents published by others.

Anyone outside KWL and MDC receiving a copy of this report ought to recognize that these documents represent an interim step in the risk management process as defined by Canadian Standards Association Guidelines.

1.0 INTRODUCTION

BGC Engineering Inc. (BGC) has been retained by Kerr Wood Leidal Associates (KWL) to conduct a risk analysis on Cheekeye fan, Squamish, B.C. This report has three primary objectives:

- Quantify and evaluate risk to Highway 99 users under existing conditions, and following construction of a large debris barrier upstream of the highway;
- Evaluate risk to existing development under existing conditions, and following construction of a large debris barrier; and
- Evaluate risk to a hypothetical future development located on the Cheekeye Fan, both under existing conditions and following construction of a large debris barrier.

For the purpose of the risk analysis, the referenced debris barrier comprises a large structure within the upstream Cheekeye Canyon reach, having a storage volume of roughly 1.4 Mm^3 (representing the 500-year return period debris flow event). The referenced hypothetical future development comprising a possible future residential development within the area depicted on Drawing 1 (772 buildings). This is not intended to represent any specific development proposal.

Risk in this report is quantified using standard methods. It is then evaluated by comparing the computed risk values to standards developed in Hong Kong and Australia, which have recently been adopted on an interim basis by the District of North Vancouver (BGC, 2006, Porter et al. 2007).

The input parameters to risk analysis are a combination of hazard attributes and their anticipated consequences. Hazard intensities and return periods have been documented in two previous BGC reports on frequency and magnitude (BGC, 2008) and debris flow simulations (BGC, 2007).

1.1. Risk Analysis Techniques

1.1.1. Background

The occurrence of natural hazards such as landslides, debris flows, floods, earthquakes and forest fires in an urban setting can have negative impacts including damage to public and private property, and potentially, loss of life. Risk is defined as the product of the likelihood of a hazard occurring and its anticipated consequence. Procedures for hazard identification and risk assessment are available to guide decision makers and the public on ways to minimise the risks from natural hazards; however, it is usually not possible to completely eliminate these risks. Where the consequences of a particular natural hazard are largely economic in nature, the risk management process is suited to risk-cost benefit analysis. Where the anticipated consequences may include the potential for loss of life, the decision-making process requires that risks be compared against risk tolerance criteria as one means of prioritising natural hazard risk management activities.

Tolerable risks are risks within a range that society lives with to secure certain benefits. It is a range of risk regarded as greater than negligible, to be kept under review and reduced further if practicable. The evaluation criteria for individual and societal risk are different, but some common general principles can be applied (Leroi et al. 2005):

- The incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life;
- The incremental risk from a hazard should be reduced wherever reasonably practicable, i.e. the As Low As Reasonably Practicable (ALARP)[1] principle should apply;
- If the possible number of lives lost from a landslide incident is high, the likelihood that the incident might actually occur should be low. This accounts for society's particular aversion to many simultaneous casualties, and is embodied in societal risk tolerance criteria;
- Higher risks are likely to be tolerated for existing developments and hazards than for planned or proposed projects;
- Tolerable risks may vary from country to country, and within countries, depending on historic exposure to natural hazards, and the system of ownership and control of slopes and other natural hazards.

Quantitative tolerable risk or risk acceptance criteria for landslides and other natural hazards have not been defined for British Columbia, the District of Squamish or for highway users by any governmental agency. That notwithstanding, quantitative risk assessment has been recommended as a useful approach for the evaluation of other proposed developments in British Columbia, such as offshore oil and gas development (Strong et. al 2002).

In risk analysis for loss of life, one distinguishes between:

- Risk of loss of life for the individual most at risk; and
- Risk of loss of life of groups ("societal risk).

This differentiation is made to account for both individuals exposed to a hazard and larger groups as society is especially reluctant to accept large numbers of people perishing as the consequence of one hazardous event.

Definitions of acceptable hazard or risk have previously been established for other fields of engineering and geoscience practice, such as dam safety (ANCOLD), flood hazards (numerous federal water resources agencies worldwide), and the construction of hazardous

---

[1] The ALARP principal is also know as ALARA, with the last letter standing for "achievable". Their use is interchangeable.

installations (e.g. nuclear power plants) (Kendall et al. 1977). Risk is routinely calculated by insurance underwriters, who determine their own standards of acceptable risk to provide adequate insurance coverage for their clients while aiming to accomplish a profit. However, only a few countries have quantified acceptable risk thresholds for naturally occurring geohazards, and examples of their application within residential developments are rare. With decreasing societal tolerance of risk to human safety and the environment, and the high public scrutiny commonly associated with new development, systematic application of thresholds for geohazard risk acceptability appears warranted.

The following text introduces the risk thresholds used by experienced government bodies for individuals and groups.

Tolerance Criteria for Risk to Individuals most at Risk

Governments in both Australia and New Zealand have adopted risk criteria for development. The Australian Geomechanics Society guidelines for landslide risk management suggest a tolerable limit of 10^{-4} per annum (0.01% annual probability) for individuals most at risk on existing slopes or developments, and a limit of 10^{-5} per annum (0.001% annual probability) for new developments. The Hong Kong Special Administrative Regional Government has adopted, on an interim basis, the same tolerable limits for landslides from natural slopes (Leroi et al. 2005). Though not specific to landslides, other jurisdictions such as the United Kingdom have adopted similar risk tolerability criteria for managing major natural and industrial accident hazards. For existing situations they have adopted a maximum tolerable risk of 10^{-4} per year, however, the requirements of ALARP allow authorities to demand much lower risks. In the Netherlands the acceptable risk criterion for existing situations are set to 10^{-5} annual probability and 10^{-6} for new developments (see Ale, 2005); however, due to differences in their legal system the ALARP principle does not apply in the Netherlands.

An annual probability of 10^{-4} implies that individuals most at risk have a 1 in 10,000 chance of fatality for each year they are exposed to the hazard. This increment of risk is generally less than other risks individuals are exposed to in everyday life.

The order of magnitude difference in risk tolerance between existing development and new development is justified on the basis that hazard and risk mitigation for new development is more flexible. For example, development can be avoided in hazardous locations, restrictive covenants can be implemented and mitigation can be planned. The 10^{-5} annual probability for loss of life is significantly less than what most individuals accept as involuntary risk on a daily basis.

Tolerance Criteria for Risk to Groups (Societal Risk)

Societal risk is often presented on F-N graphs showing the frequency of events leading to loss of life (F) and the expected number of lives lost (N). The societal risk tolerance criteria were developed by the Geotechnical Engineering Office of Hong Kong (Fell, et al., 2005) and are gaining acceptance in Australia, the United Kingdom, and North America. F-N graphs are subdivided into four zones:

- ***Unacceptable*** – where risks are generally considered unacceptable by society and require mitigation;
- ***ALARP*** – where the incremental risks from a hazard should, wherever reasonably practicable, be reduced;
- ***Broadly Acceptable*** – where incremental risks from a hazard are within the range that society can generally tolerate; and,
- ***Intense Scrutiny Region*** – where a low potential for large loss of life (> 1000) exists that requires careful consideration.

The Intense Scrutiny region is not further considered in this report as the expected number of fatalities does not reach this region for Highway 99 users or the existing Cheekeye subdivision considered here. Figure1-1 FN Graph shows the F-N graph without any risk data added.

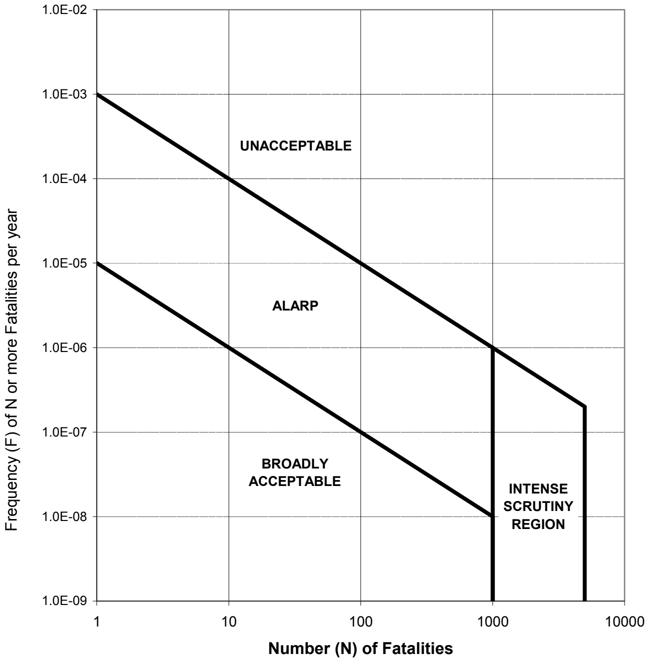


Figure 1-1 F-N Graph

Before documenting the results of the quantitative risk assessment (QRA), it is worthwhile reviewing how landslide risk acceptance is being addressed or guided by British Columbia law and various levels of governments, which is the topic of Section 2.

2.0 BACKGROUND

In previous work, BGC (2008) established a frequency-magnitude curve for debris flows on Cheekeye River. This curve yielded data that serve as input parameters for debris flow runout modelling. The frequency-magnitude input parameters are summarized in Table 2.1. Seven return period classes were chosen for analysis. The 20-year event was chosen as the lowest class because it is the minimum return period at which debris flows occur. An event of the magnitude may not impact the possible future development area, but was modelled to examine the risk to existing development, particularly in the Cheekeye subdivision south of the Cheekeye River's confluence with Cheakamus River. The 10,000-year event was chosen as the upper bound as it roughly encompasses the historic record since deglaciation. This analysis will provide information on the unmitigated debris flow risk and the effects on risk of proposed mitigation on existing development.

Table 2.1 Debris flow magnitude model input parameters

Return Period (yrs)	Annual Probability (1/yrs)	Size Class	Volume (Mm^3)	Peak Discharge (m^3/s)
20	0.05	5	0.2	700
50	0.02	5	0.4	1,500
100	0.01	5	0.6	2,500
200	0.005	5	0.8	3,400
500	0.002	6	1.4	6,700
2500	0.0004	6	2.4	12,600
10,000	0.00001	6	2.8	15,000

2.1. Risk Tolerance Criteria in British Columbia

Quantitative tolerable risk or risk acceptance criteria for landslides have not been defined for British Columbia or the District of Squamish. Instead, land-use decisions in areas with recognized geologic hazards have historically been made by considering hazard frequency only. The decisions have not been based on a consideration of consequences, which includes both hazard and consequences (see Fell et al. 2005).

Recently, following a fatal landslide in North Vancouver, a precedent has been set in landslide risk management in British Columbia. In this case, a recommendation was made by BGC Engineering Inc. (2006), summarized in Porter et al. (2007), and adopted on an interim basis by the District of North Vancouver that the thresholds for individual risk be set at an annual probability of 10^{-4} for existing development and 10^{-5} for new development. Societal risk or risk to groups is measured using the frequency of death/annum versus number of deaths (F/N) plot (Figure 1-1). In order to place the results of this study in perspective with British Columbia legal requirements, the legislative framework that currently restricts development in areas subject to landslide hazards is reviewed.

Residential development in British Columbia is governed by the Land Title Act, the Local Government Act, and the Community Charter. The Land Title Act contains provisions for refusing to approve a subdivision "if the approving officer considers the land subject, or reasonably be expected to be subject to flooding, erosion, I and slip or avalanche". In case the approving officer is doubtful, a report by a professional engineer or geoscientist experienced in geotechnical engineering will need to certify that "the land may be used safely for the use intended" subject to siting provisions, mitigative works and/or restrictive covenants. With respect to flood and debris flow hazards, professional practice is also guided by Flood Hazard Area Land Use Management Guidelines (Province of B.C., 2004).

Several issues arise that cast doubt as to the successful use of these provisions: First, the approving officer needs to be sufficiently skilled to identify that a report by a professional is needed. Second, since there is no official designation of a "geotechnical engineer" a large variety of engineers or geoscientists can claim experience or even expertise, even though their training may not be adequate for such assessment. Third, and most importantly, the adjective 'safe' is not defined and is therefore open to some interpretation. Similarly vague statements are made in the Local Government Act (Section 919.1 and 920) and the Community Charter (Section 56). In addition, there is little precedent in B.C. to differentiate between various types of land use (i.e. residential vs. commercial) with respect to natural hazard mitigation in view of the wording "for the use intended".

Specifically to debris flows, the Local Government Act (Section 910, Floodplain Bylaw Variances or Exemptions) states that although development should be discouraged in areas prone to debris flows, "consent to develop may be granted, with standard requirements as established for alluvial fan in Section 3.3 [of those guidelines], where there is no other land available, and where an assessment of the land by a suitably qualified professional indicates that development may occur safely."

In summary there are no quantitative risk acceptance criteria for landslides in any legal documents in British Columbia. The lack of a clear definition of 'safe' subjects all quoted legal documents to personal interpretation, but also allows a professional to provide a definition. This flexibility is undesirable as it will invariably result in non-comparable reports and a non-standard system of landslide risk evaluations, which may ultimately be addressed by courts when legal action follows a landslide disaster.

2.2. Geohazard Risk Tolerance by the B.C. Ministry of Transportation

Between 1978 and 1993, MoT asked qualified professionals carrying out landslide assessments for proposed subdivisions to evaluate acceptable hazard based on a risk standard of 10% probability in 50 years (or approximately a 500 year return period) (BC MoT, 1993). This guideline was abandoned in 2005, with the publication of the "Guide to Rural Subdivision Approval" (BC MoT, 2005, Section 2.3.1.07). This document states that a Professional Engineer should (i) determine if there is a hazard, (ii) determine the extent of any hazard, and (iii) identify building sites free from hazard, or where risk could be rendered acceptable through mitigation. The document does not provide levels of acceptable risk other than “free from hazard”, which in mountainous terrain is hardly achievable.

With regard to roads in British Columbia, MoT has not implemented landslide risk tolerance or risk acceptance standards. For rockfall, a systematic evaluation of rockfall hazards is being undertaken using a scoring system that had originally been designed in British Columbia and was later accepted by the Oregon State Department Transportation. Budgetary constraints will dictate how many sites are being mitigated every year according to the priority ranking that is derived from the rockfall hazard assessment. No such system exists for debris flows or other landslide types apart from those used to manage rockfall along CN and CP Rail’s mainline tracks.

In a landmark case in which a rockfall in 1982 killed a woman and disabled her father on Highway 99, the Supreme Court of Canada found that: *“The province owes a duty of care, which ordinarily extends to their reasonable maintenance, to those using its highways. The Department of Highways could readily foresee the risk that harm might befall users of a highway if it were not reasonably maintained. The maintenance could be found to extend to the prevention of injury from falling rock.”* (Cory and Sopinka, 1989). Consequently, while there is no accepted standard for the MoT against which risk can be compared, legal precedents suggest that a perceived or quantified hazard requires appropriate mitigation effort. Mitigation, however, will likely only proceed in a timely manner if the identified risk is high compared to other hazards and the mitigation works can thus be prioritized within budgetary constraints.

Fatalities resulting from debris flows are well documented in British Columbia (Table 2.2), and MoT is cognizant of debris flow hazards that may affect the Cheekeye River Bridge as well as its approaches. These issues have been pointed out in a previous report by Crippen Engineering (1974) and by Cordilleran Geoscience (2003). In a report on alternate route selections for Highway 99 (2001), MoT points out that the Cheekeye River has a history of “debris torrents”[2] with the most recent occurrences in the 1920s and 1958. MoT also verified debris flows in 1980 (December 26, 1980) and August 1991. The 1958 event likely destroyed the bridge that existed before the current bridge, which was constructed in the late 1960s. It is further conceded that the existing structure (the Cheekeye River bridge) “*may not have sufficient clearance beneath to accommodate an event of the magnitude of either of the most recent failures*” (BC MoT, 2001).

In summary, the B.C. Ministry of Transportation has no risk acceptance standards, nor is there a process to systematically address debris flow hazards along its highway system.

---

[2] Equivalent term for debris flows

Table 2.2 Fatalities resulting from debris flows on roads in British Columbia.

Date	Geographic Area	Nearest Town	Element Affected	Number of Deaths
1-Jun-1968	Monashee Mountains	Revelstoke	Road	4
5-Jun-1968	Camp Creek	Revelstoke	Road	4
28-Oct-1981	M Creek	Lions Bay	Bridge	9
4-Dec-1981	Charles Creek	Lions Bay	Road, Bridge	1
10-Nov-1987	Marine Drive	Port Alice	Road	1
14-Apr-2002	Summit Lake 25 km west of Revelstoke	Revelstoke	Road	1
18-October-2003	Rutherford Creek	Pemberton	Bridge	3
28-May-2007	Legate Creek	Terrace	Road	1
Unknown	Kicking Horse Pass	Field	Road	1
TOTAL				23

2.3. Subdivision Case Law

In August 1973, a historic decision was made with regard to a subdivision proposed in the Cheakamus River valley downstream of the Barrier (Supreme Court of British Columbia, 1973). This case is still viewed as an important precedent for future development and it has significantly influenced the development of hazard acceptance guidelines adopted by Fraser Valley Regional District. For this reason, it is reviewed here.

The Barrier is a vertical cliff of volcanic rock situated at the headwaters of Rubble Creek. A second phase subdivision consisting of 126 lots on Rubble Creek fan had been planned by Cleveland Holdings Ltd. (Cleveland). The senior approving office for the Province, Mr. Elston, refused to allow the deposition of the plan and thus no title was conveyed to the subdivision because he argued that the development of the subdivision would be against the public interest. Mr. Elston's decision rested on the potential of a catastrophic landslide originating at the Barrier to reach the development. Mr. Elston had previously approved Phase 1 of the development, which had 26 lots on which some residences had been built by the time he refused to allow title to Phase 2. Mr. Elston's decision was based on the recently acquired information that a large landslide had occurred in 1855 and that Mr. Farquharson, P.Eng. and Dr. W. Mathews (Geology professor at UBC) agreed upon the possibility of another catastrophic slide which would destroy the subdivision. An appeal was launched by Cleveland against this decision.

Judge Berger presided the proceedings and made some key conclusions, which are repeated here:

"*Dr. Mathews and Mr. Naismith both calculate the risk of a [catastrophic] slide on a time scale of thousands of years. They say there is a probability of a slide at the Barrier in the next 10,000 years. It may occur next year, it may occur in a thousand years, it may occur in 10,000 years. Yet for both of them the risk is real enough that neither would want to live in the subdivision. The risk is one they would prefer to avoid.*"

Contrasting these statements are those by others:

"*Dr. Dolmage, Dr. Stimpson and Mr. Brawner all said they would not have any misgivings about living in the subdivision. They felt there would be no risk at all*."

Judge Berger, clearly sided with Dr. Mathews view by stating: "*Can this Court say that Dr. Mathews was wrong? I have not heard any evidence which convinces me I ought to reject Dr. Mathews' theory. On the whole, I am inclined to prefer it*."

Then he continues by saying:

"However, there remains the question whether the risk is one that justifies refusal of the plan", clearly indicating that the level of risk was of central importance in Judge Berger's decision.

In his decision, Judge Berger again juxtaposes the opinion of the Counsel for Cleveland that the chance of a [catastrophic] slide is too remote to be included in the calculation of risk and that on a human time scale there is no risk with Dr. Mathews' and Mr. Naismith's opinion that on a human time scale there is a risk, that it is substantial even though it may not be immediate.

Furthermore, Judge Berger rejects the argument that flooding and landsliding can be compared as was advanced by the Counsel of Cleveland. He quotes a decision by Judge Dawson in Re: Land Registry Act, Subdivision Plan Kootenay District, in which he held that an approving office had no right to refuse to allow a subdivision to proceed simply because there was a danger of flooding.

Without actually calculating risk, in his decision Judge Berger follows the logic of a risk analysis. He argues that risk from landsliding is fundamentally different than that from flooding. In that he includes the notion of vulnerability, which is central to quantitative risk assessments. In addition, he carefully examines the meaning of frequency and identifies that the hazard and risk is quantifiable and real. His final judgement, therefore, may constitute the first (at least qualitative) risk-based court decision with regard to landslide hazards in British Columbia.

"*I uphold the Approving Officer's decision on the basis that there is a sufficient possibility of a catastrophic slide during the life of the community at Phase II to justify his refusal to approve the subdivision. He was not, in taking into account the possibility of a slide being "too paternalistic and unreal": The risk is there. I cannot say he was wrong in holding the development of Phase II would be "against the public interest*".

This case, later supported by the Garibaldi Advisory Panel (1978), demonstrates the reluctance of the judge to accept a risk, which at the time was poorly quantified. Given that a catastrophic failure had occurred in the past 200 years, he was not willing to allow development to proceed.

2.4. Hazard Acceptability Thresholds for Developments in the Fraser Valley Regional District

The first regional district to adopt hazard acceptance thresholds for a variety of geohazards was the Regional District of Fraser-Cheam (now part of the Fraser Valley Regional District). It is based on Peter Cave's work published in 1991 and updated with some major changes in 1993 (Cave 1993).

Cave's work differentiates between hazard types ranging from inundation by flood waters to catastrophic landslides. He uses five hazard-related responses to development approval applications:

- Approval without condition related to hazards
- Approval without siting conditions or protective works conditions, but with a covenant including "save harmless" conditions
- Approval, but with siting requirements to avoid the hazard, or with requirements for protective works to mitigate the hazard
- Approval as (3), but with covenant including "save harmless" conditions as well as siting conditions, protective works or both
- Not approved.

In addition, Cave distinguishes between different types of development in the evaluation of acceptability to reflect increases in exposure to risk. The seven types are: minor repair, major repair, reconstruction, extension, new building and subdivision, and major rezoning and community plan amendment.

Cave cites hazard acceptance precedents such as the provincial 1:200-year flood probability design standard, the 10% probability in 50 year standard used by MoT until 2005 as well as the landmark decision by Judge Berger that was discussed in Section 2.1.4. The latter, however, appears to have been misquoted because Cave writes: "…which (the Berger decision) found a site exposed to a very low probability of landslide occurrence (1:10,000) to be unsuitable for development. Cave notes that the 1:10,000 probability may be the best practical definition of "safe". As quoted above, this is not what Judge Berger actually said. Instead Berger expressed that it was irrelevant for his final decision if the hazard was to occur in the next year, the next 1000 or 10,000 years.

Cave's work then produces a series of eight matrices (one for each hazard type) that juxtaposes development type with return period classes. Applied to the possible future development area on Cheekeye fan (debris flow) and using rezoning as the type of proposed development, Cave's work would suggest a 5 (not approved) for the 1:1000 to 1:10,000 class but a 1 (approval without conditions related to hazard) for return periods exceeding 10,000 years. This example illustrates a shortcoming of Cave's risk matrix. It implies that (if such detailed probabilities could be calculated) a 1:10,100 year debris flow frequency would allow rezoning, but a 1:10,000 year event would not. This very sharp boundary is artificial and would, in practice, lead to extensive debates as to the “true” encounter probability of a debris flow. Even more striking is the suggestion that a major catastrophic landslide would lead to a non-approval even for return periods exceeding 10,000 years, while it would yield unconditional approval for subdivision extensions for the same return period class. Completely ruling out catastrophic landsliding in the form of rock avalanches as suggested by this method is very difficult to achieve and would pose severe limitations to the development of mountainous portions of British Columbia.

Hazard assessments as suggested by Cave’s work are useful for residential permitting because they are easily grasped by permitting officials and clients. Their application promotes considerations of hazard magnitudes and hazard avoidance. They are also less expensive and less subject to debate than QRAs, which may be unaffordable for small land owners.

3.0 RISK FROM VOLCANISM AND EARTHQUAKES

The risk analysis summarized in this report is limited to debris flows originating in the Cheekeye River basin and does not include any other geohazards to which the proposed subdivision may be subjected. Risk posed by rock avalanches has been addressed in the frequency-magnitude report (BGC, 2008) and will thus not be reiterated here. This section addresses two additional geohazards (volcanic eruptions and earthquakes) that could occur in the region. The reason for their inclusion is to put the calculated risk for debris flow impact into perspective to other risks posed from geohazards.

3.1. Risk from Volcanic Eruptions

Mount Garibaldi is a dormant stratovolcano with an eruptive history that involved an initial period of volcanism (200,000 - 300,000 years ago) followed by a period of quiescence. Renewed activity in the last 50,000 years has rebuilt the edifice in a series of eruptions. The most recent period of activity occurred shortly after the disappearance of the glacial ice filling the valley, 10,700 to 9300 years ago, and ended with the eruption of the Ring Creek lava flow from Opal cone, on Garibaldi's southeastern flank.

Mount Garibaldi has a dacitic volcanic centre that can erupt explosively and could be prone to very large (> 1Mm^3) lahars (syn-eruptive volcanic debris flows) in the event of volcanic unrest, regardless of hydrothermal alteration. Hot-rock-snow-ice interactions can lead to sudden release of water from Cheekeye Glacier high on the volcano. Lahars easily entrain sediments that would likely travel to the Cheakamus confluence. In this case pyroclastic flows, and lava flows damming rivers may be similarly or more hazardous to the population on the Cheekeye fan, adjacent Brackendale and Squamish.

The volcanic activity in the entire Garibaldi volcanic belt (mainly Mount Garibaldi, Mount Cayley and Mount Meager) has been estimated by Stasiuk et al. (2003) to 1/2000 per annum for all types of eruptions and 1/5000 per annum for dominantly explosive eruptions. Lacking better dating control, one can estimate the frequency of volcanic eruptions by multiplying the number of volcanoes with the frequency of explosive volcanism to arrive at an estimate of likelihood at Mt. Garibaldi (1/15,000). A pyroclastic flow deposit that incorporated radically fractured volcanic clasts (rapid cooling of hot rock) was identified by P. Friele at the new Garibaldi Springs development, with a radiocarbon age of 10,000 years B.P. It has also been suggested that the most recent eruption of Mount Garibaldi was associated with crustal adjustments (isostatic rebound) following deglaciation. Given the large uncertainty with the volcanic history and the probability of explosive eruptions a return period estimate of for explosive eruptions of 10,000 to 30,000 years and a mean of 20,000 years may be more appropriate than the reported average return period of 15,000 years.

An analysis of shallow (< 6 km) volcanism-related seismic activity under the Garibaldi volcanic complex over the past 20 years demonstrates that such earthquakes are absent in the Cheekeye River watershed. A cluster was observed near the lower reaches of Rubble Creek. However, seismic activity as documented herein is not a signature of imminent eruption, which would likely be heralded by tens or hundreds of small shallow magmatic earthquakes per day. The earthquakes are more likely associated with minor crustal adjustments to the load of the edifice mass (Scott, pers. communication, June 2006).

The main difference between an explosive volcanic eruption and associated mass movement phenomena and debris flows *not* associated with eruptions is that the former are usually predictable and thus fatalities could be averted by evacuations. Since this study focuses exclusively on the loss of life aspect and given that evacuations are very likely in the case of a pending volcanic eruption, further quantification of vulnerabilities and risk does not appear to be warranted.

3.2. Risk from Earthquakes

Canada's west coast is seismically active, and to provide a suitable level of protection for buildings and their occupants the GSC provides estimates of ground shaking hazard that are included in the National Building Code of Canada (NBCC 2005). The hazard level chosen for the NBCC is that with an annual probability of exceedance of $4*10^{-4}$/annum. The seismic activity on the west coast is derived partly from the subduction of the Pacific plate beneath the North American plate. This plate motion occurs some distance off the west coast of Vancouver Island. In addition to earthquakes on this plate boundary, the relative plate motion gives rise to compressive forces in the shallow surface North American plate to the east of the subduction zone. This compression is the source of the random occurrence of earthquakes in the upper plate that makes up most of the ground shaking hazard described in the NBCC. There are no known active fault zones or zones of surface rupture caused by earthquakes in southern British Columbia, other than the offshore subduction trench and the Queen Charlotte fault, both of which are a considerable distance from the Cheekeye Fan. Therefore, there is no reason for the ground shaking hazard on the Cheekeye Fan to be different than anywhere else in the Squamish area, and the design values of ground motion provided in the NBCC are appropriate for use with any development of this site.

According to the NBCC (2005), the area at the head of Howe Sound falls into the following spectral acceleration zones at a probability of 2% in 50 years for firm ground conditions (NBCC soil class C, shear wave velocity: 360-750 m/s).

Table 3.1 Peak ground accelerations in the Squamish – Brackendale area.

Period (s)	Spectral acceleration (g)
0.5	0.51
1.0	0.29
2.0	0.16
PGA	0.32

4.0 METHODS: RISK TO HIGHWAY 99 USERS

This section details the methods, assumptions and results for the quantitative debris flow risk analysis for Highway 99 in the area of potential inundation near the Cheekeye River crossing. This analysis was conducted to compare existing risk to the level of reduced risk following construction of a large debris barrier.

4.1. Assumptions

This section describes the method used to estimate risk to individuals (Section 3.1) and risk to groups (Section 3.2) for seven return period categories, including 20, 50, 100, 200, 500, 2500, and 10,000-year events. The volumes of the respective return period debris flows have been calculated and documented in BGC (2008). Risk estimates for highway users were made using model results without avulsion at the fan apex for return period flows ≤500 years. For the 2,500-year and 10,000-year return period events, model results suggest that debris flows with or without avulsion at the fan apex impact a similar length of highway, and both scenarios were considered together when estimating the zone of impact. The dogleg avulsion scenario was not considered as it occurs downstream of the highway (see BGC, 2007).

The risk calculations herein are associated with a degree of uncertainty because they depend on factors that are not well known, such as the likelihood that vehicle operators will notice a debris flow and be able to avoid the hazard.

The mitigated scenario considered in this analysis includes a debris barrier in Cheekeye Canyon. No other measures are considered. We assume that the debris barrier stores up to and including the 500-year event (1.4 Mm^3 volume), and that smaller debris flows will thus not reach the development at all. Risk analysis for additional mitigation measures including berms and raised foundations for proposed buildings are provided under separate cover (BGC 2008b)

4.2. Event Scenarios

Drawing 3 shows an event tree summarizing the analysis approach and potential scenarios considered together for vehicles in both the north and southbound lanes, for each magnitude category, and a hazard “consultation zone” equal to the length of highway impacted by the modelled 10,000 year event (3800 m), plus an estimated 100 m braking distance. In summary, the following scenarios are considered for each return period category:

- Vehicles are impacted by debris;
- vehicles are impacted by driving into highway gap in the case that the debris flow has destroyed the highway bridge; and
- vehicles impact debris that has already deposited on the highway.

4.3. Risk Estimation

For each magnitude category, risk is estimated based on the product of the probabilities for each branch in the event tree (Drawing 3).

Risk to vehicles impacted by debris corresponds to:

$$\mathbf{R = P_H \times P_{T:H} \times P_{S:H} \times N}$$

where:

P is the probability of the debris flow event.

N = **V** x **E;**

V (vulnerability) is the the probability of death in case of debris flow impact;

E is the number of motorists within the consultation zone, estimated as 34 individuals in 17 vehicles, based on an average 8400 vehicles/day travelling 90 km/hour, with an average of two persons per vehicle;

$\mathbf{P_{T:S}}$ is the temporal probability of impact, estimated at 0.9, corresponding to the likelihood that motorists will be present within the consultation zone at the time of impact; and

$\mathbf{P_{S:H}}$ is the spatial probability of impact, corresponding to the proportion of the consultation zone width impacted by a given debris flow magnitude category.

Risk to vehicles driving into the void given bridge destruction corresponds to:

$$\mathbf{R = P_H \times (1-P_{T:H}) \times (1-P_{S:H}) \times P_{BH} \times P_V \times N}$$

where:

$\mathbf{P_{BH}}$ is the likelihood of bridge destruction; and

$\mathbf{P_V}$ is the likelihood of driving into the void, given bridge destruction. This value was estimated at 0.1, based on an estimated braking distance of 80 m and field experience with visibility at the site.

The likelihood of bridge destruction at a given return period was estimated by comparing the cross-sectional area under the existing bridge (143 m^2 calculated from a design-built cross-section provided by MoT) to estimate debris flow conveyance at a given return period category. Table 4.1 shows the estimated peak discharge, modelled flow velocity ranges and cross-section ranges used to calculate debris flow cross-sectional areas under the bridge, for different return period categories.

Table 4.1 Debris flow conveyance for different return periods at the Highway 99 Crossing

P_H (events/yr)	Peak Discharge (m^3/s)	V_{min} (m/s)	V_{max} (m/s)	Section (min) (m^2)	Section (max) (m^2)
0.05	700	4	9	120	275
0.02	1500	5	14	154	489
0.01	2500	5	19	151	577
0.005	3400	6	24	191	703
0.002	6700	6	21	403	1355
0.0004	12,600	12	28	484	1130
0.0001	15,000	19	34	437	785

Table 4.1 demonstrates that the existing cross-section of 143 m^2 falls only in the range of conveyance for the 20-year return period. The lowest return period at which debris flows occur at Cheekeye River has previously been determined to be 20 years. A bridge failure was noted in 1958, which destroyed the pre-existing bridge that had a lower cross-section (approximately 100 m^2) than the existing bridge. Further debris flows occurred in 1980 and 1991. Neither the 1980 nor 1991 debris flows destroyed the existing bridge, even though they damaged the SW corner of the abutment where riprap was washed out (Tom Cloutier, Assistant Manager Operations, Miller Capilano, 2007). According to Mr. Cloutier, the flows were approximately 5 m below the lowest bridge girder. These observations suggest that either the upper range of flow velocities is more likely or that peak discharge estimates may be conservative.

While hydraulic criteria suggest that the bridge clearance may be insufficient to convey flows equal to or in excess of 50 years, there is some uncertainty and error involved in the hydraulic calculations. This error cannot readily be quantified. However, a probabilistic statement can be attempted as to the likelihood of bridge overtopping or failure for different return period events given the data and considerations discussed above. Probabilistic estimates are summarized in Table 4.2.

Table 4.2 Assumed likelihood for bridge overtopping or failure for different return period events

Return Period (yrs)	Volume (Mm^3)	Peak Discharge (m^3/s)	Likelihood of overtopping or failure (%)
20	0.3	1100	10
50	0.5	2200	30
100	0.7	2900	90
200	1.0	4500	99
500	1.7	8400	99
2500	2.5	13,500	99
10,000	3.0	15,000	99

Risk to vehicles crashing into the flow corresponds to:

$$R = P_H \times (1-P_{T:H}) \times (1-P_{S:H}) \times (1-P_{BH}) \times P_C \times N$$

where:

P_C is the likelihood of crashing into the flow. This value was estimated at 0.1, based on an estimated braking distance of 80 m and field experience with visibility at the site.

4.4. Individual Risk Summaries

Estimated Individual risk is calculated as the sum of individual risk for all scenarios. The values are reported for highway users who drive through the hazard zone 1, 2, 20, 100, and 500 times per year on average. These travel frequencies are realistic and range from the one time tourist to those residents in Squamish that commute daily to and from Whistler. In each return period case, the risk value is a multiple of the number of times passing through the hazard zone.

4.5. Group Risk Summaries

Group risk is summarized on F-N curves as defined below.

F-N curves show the cumulative frequency of **N** or more fatalities. The y-axis, **F,** is calculated as:

$$F = \sum f$$

where f is the product of probabilities along each branch of the event tree shown in Drawing 3.

The x-axis, **N**, is calculated as:

$$N = V \times E$$

where:

V is the probability of death in case of impact.

E is the number of elements at risk.

Values on the F-N curve where N<1 were not plotted.

In addition to the F-N statistics, the Probable Loss of Life (PLL) is also calculated for each scenario and event probability, as:

$$\mathbf{PLL = f \times N}$$

This statistic provides a convenient measure to determine which scenario contained the highest risk. However, it is important to note that PLL is not the same as individual risk (probability of death to an individual, PDI). Accordingly, PLL values should **not** be compared to the thresholds used to determine standards for acceptable individual risk.

5.0 METHODS: RISK TO DEVELOPMENT

This section describes methods to quantify risk from debris flows to the existing and proposed developments shown in Drawing 1. Methods are also described to estimate risks to individuals and to groups and to compare existing risk with the level of reduced risk following construction of a large debris barrier.

5.1. Assumptions

Risk is estimated based on the same debris flow magnitude classes used for the Highway 99 analysis (Section 0). Three modelled scenarios are considered: ‘standard’ (no avulsion), avulsion at the fan apex, and avulsion at the dogleg, as described in BGC (2007). These scenarios are assumed to have an equal likelihood of occurrence.

5.2. Elements at Risk

A total of 44 existing and 772 possible future buildings (assumed to be residential) were included in this analysis (Drawing 1). The existing buildings included in the risk analysis are located in the vicinity of the Cheekeye subdivision and Indian Reserve 11. Buildings were mapped by digitizing building locations visible on 2006 aerial photographs (photographs taken concurrently with the LIDAR imagery). Future buildings were simulated by grid points spaced at 50 m intervals with the approximate possible future development area because at the time of writing this report, a development plan has not been produced.

It is important to acknowledge that the existing buildings used in this analysis do **not** represent the complete inventory of existing buildings subject to debris flow hazard on the Cheekeye fan. The building inventory was selected only to compare the relative change in risk prior to and following hazard mitigation. In addition, the number of future buildings that may be constructed is not currently known. Because risk levels will vary with the number of buildings constructed, analysis results should only be used as a relative comparison of the existing and mitigated cases. Therefore, the total risk may increase or decrease somewhat depending on the final development layout, type of development and development density.

For the existing development, estimates of the number of lives potentially at risk (E) in existing buildings were based on the assumption of two people in each of the Sunwolf Camp cabins located near the Cheekeye River confluence, and four people in all other houses. The average occupancy of the Sunwolf Camp coffee shop was assumed as four people. For the large mill to the south of Squamish Valley road, a total of ten workers was assumed and three for the small mill to the west of the road. The proposed buildings were assumed to have 4 occupants each, on average.

Risk analysis was conducted for three groups of buildings: existing, proposed, and combined existing and proposed.

5.3. Risk Estimation

Drawing 4 shows an event tree summarizing the analysis approach and potential scenarios considered for existing and proposed buildings. For each building and each debris flow return period, risk is estimated as follows:

$$\mathbf{R = P_H \times P_{S:H} \times P_{T:S} \times V \times E}$$

where

$\mathbf{P_H}$ is the annual event probability (1/return period);

$\mathbf{P_{S:H}}$ is the spatial probability of impact;

$\mathbf{P_{T:S}}$ is the temporal probability of impact;

V is vulnerability; and

E is the number of occupants of a building.

Values for P correspond to the 7 return period categories. The other variables are discussed below.

5.3.1. Spatial Probability $P_{S:H}$

The spatial probability of impact corresponds to the likelihood of a particular avulsion scenario multiplied by the spatial probability that the debris flow will reach the element at risk (the building). The likelihood of no avulsion ("standard avulsion scenario") is considered the most likely as it follows the existing channel, and was assigned a probability of 0.5. The dogleg and fan apex avulsion scenarios were each assigned a value of 0.25. For each element at risk, the likelihood that a debris flow would reach the element at risk was assigned based on Table 5.1.

Table 5.1 Description Matrix for Spatial Probability Estimates

Qualitative Descriptor	Probability ($P_{S:H1}$)	Definition
Virtually certain	0.99	Building is located within the area inundated by the modelled flow.
Moderately likely	0.50	Building is located outside the inundated area, but within 50 m of the flow for events ≤ 200 year return period, or within 100 m of the flow for events ≥ 500 year return period[1].
Very Unlikely	0.01	Building is located further than 50 m from the flow for events ≤ 200 year return period, or further than 100 m from the flow for events ≥ 500 year return period.

While this simple method of determining $\mathbf{P_{S:H}}$ is not without error, it allows a systematic approach to determining spatial probability and ensures that comparisons for existing risk and risk under a mitigated scenario are replicable.

5.3.2. Temporal Probability ($P_{S:T}$)

For assessment of risk to individuals, $P_{T:S}$ refers to the single occupant estimated to occupy a building for the largest proportion of each day (individual most at risk), estimated as 16 hours per day on average ($P_{T:S}$=0.67). For industrial buildings with care takers, it was assumed that one occupant would occupy the area for 20 hours/day (0.83) on average.

For assessment of risk to groups within each building, it was assumed that occupants of residential buildings would be present, on average, 12 hours/day, ($P_{T:S}$=0.5). The two local mills were assumed to be occupied 8 hours/day (0.3).

For the cabins at Sunwolf Camp, a one third (0.33) annual occupancy is assumed based on input from the camp's caretaker, as well as a 12 hours/day occupancy, which results in an average $P_{T:S}$ of 0.165 (0.33 x 0.5). The coffee shop that is part of the Sun Wolf development was assumed to be occupied only one third out of the year and eight hours per day resulting in a daily $P_{T:S}$ value of 0.11 (0.33 x 0.33).

5.3.3. Vulnerability (V)

Vulnerability (V) corresponds to the likelihood of death should a building be impacted directly by a debris flow. A large degree of uncertainty is associated with this estimate because vulnerability will be affected by parameters that are poorly known. For example, the location of individuals inside the building, the intensity of direct impact, and the ability of a building to withstand impact without suffering structural damage that could lead to death could all affect V_d. Given these uncertainties, in this study the likelihood of total building loss is estimated and considered equivalent to the likelihood of death.

The likelihood of total building loss depends on the magnitude of debris flow impact, related to factors such as flow velocity, maximum flow depth, size of boulder transported, and the potential for undercutting of building foundations. The basic premise is that faster events with larger boulders, higher flow depth and a higher probability of undercutting of foundations are more likely to result in fatalities.

Estimates for the likelihood of building loss due to direct debris flow impact are provided in Table 5.2, based on modelled values for maximum debris flow velocity and flow depth, with reference to estimated debris flow impact pressures and field observations of boulder sizes. Values of N = E x V were calculated separately for each building and then summed to obtain the total N for each group.

Table 5.2 Matrix to compute Vulnerability (V_d) due to direct debris flow impact

		Flow Depth d_F (m)		
	Variable	<0.3	0.3-1	>1
V_{max} (m/s)	< 2	0.01	0.1	0.5
	2 - 5	0.1	0.5	0.99
	> 5	0.5	0.99	0.99

Dynamic impact pressures used as a guide for values in Table 5.2 are shown in Table 5.3. Table 5.2 may not result in precise vulnerability numbers, but it is designed to ensure that results are directly comparable and replicable between the mitigated and unmitigated scenarios.

Table 5.3 Estimated debris flow impact pressures and due to direct debris flow impact

V_{max} (m/s)	P_d (N/m^2)	Description
< 2	8,000	Low likelihood of total building loss
2-5	8,000-50,000	Moderate likelihood of total building loss
>5	>50,000	High likelihood of total building loss

5.4. Individual Risk summaries

Individual risk was estimated for each building (existing or proposed) based on the individual-most-at-risk, as described in Section 5.3.2.

5.5. Group Risk Summaries

Group risk was summarized on F-N curves using the methodology described in Section 4.5.

6.0 RESULTS: RISK TO HIGHWAY USERS

Drawing 2 shows the sections of road potentially impacted by debris flow events for return periods from 20 to 10,000 years.

6.1. Individual Highway Risk

Table 6.1 shows individual risks summed for all scenarios, for drivers travelling 1, 2, 20, 100, and 500 times annually across Cheekeye Fan. No cases exceed the 10^{-4} threshold for acceptable risk used by jurisdictions that have adopted these risk acceptance criteria on an interim basis.

Table 6.1 Cumulative Individual risk, Scenarios 1-4

Individual Driver Trips Per Year	Cumulative Risk
1	5.9E-08
2	1.2E-07
20	1.2E-06
100	5.9E-06
500	3.0E-05

6.2. Group Highway Risk

Figure 6-1 shows the F-N curve for Highway 99 users. This curve plots the expected frequency of N or more fatalities, considering the sum of all risk scenarios, and allows comparison of the total estimated risk to standard thresholds of risk acceptance as established, for example, in Hong Kong, Australia, Great Britain and the District of North Vancouver.

For existing conditions, the curve exceeds the threshold considered as unacceptable risk. Following construction of an upstream debris barrier, risk is substantially reduced but still extends above the threshold considered as unacceptable risk for N=2 or more fatalities.

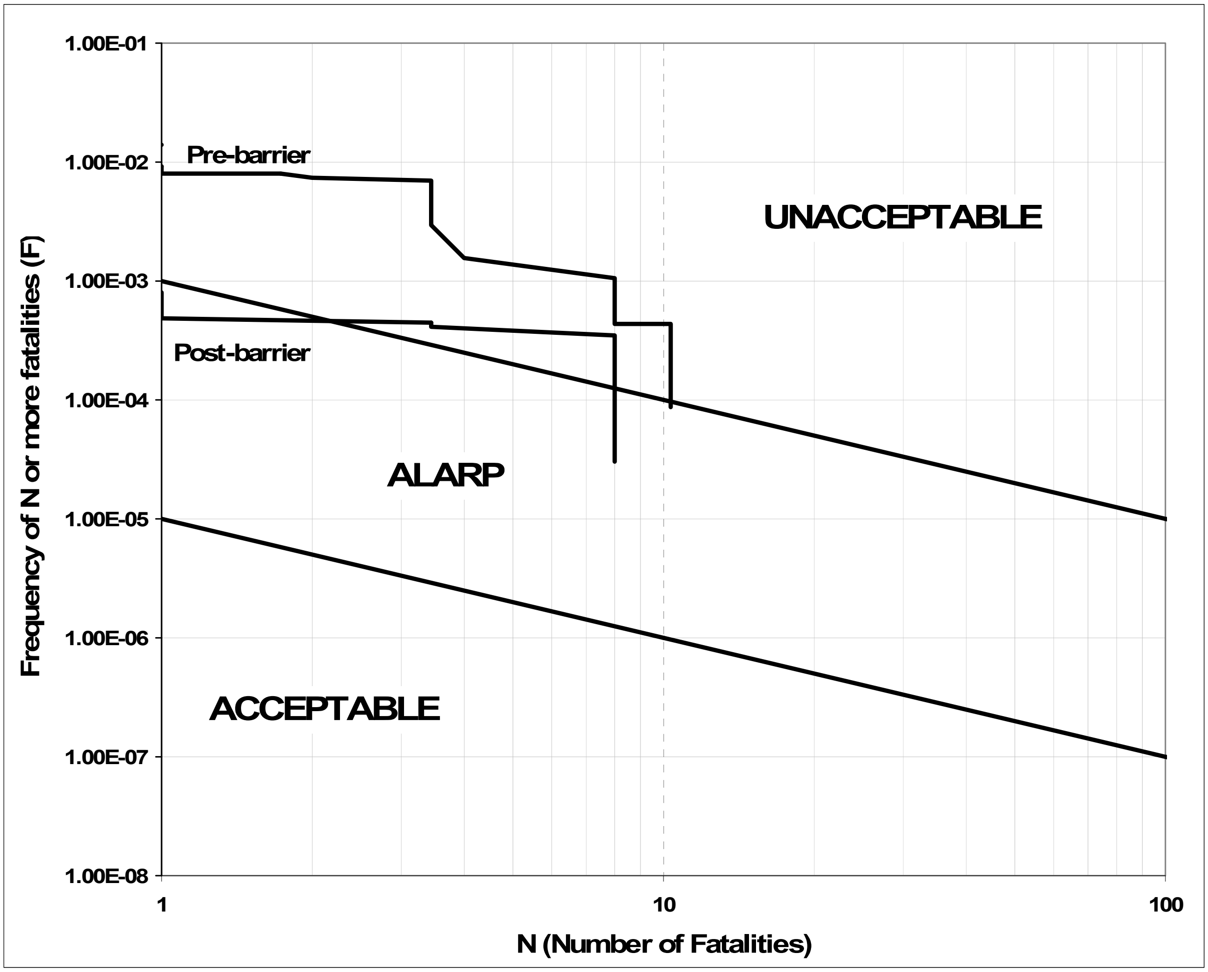


Figure 6-1 F-N curve for highway users

Table 6.2 summarizes PLL stratified by event probability and main scenario for the non-mitigated case. The table demonstrates that the highest risk scenario with respect to PLL corresponds to 100 to 500 year return period category events for cars impacted by debris flows, followed by the 100 year return period category event for cars driving into the former bridge location.

Table 6.2 PLL values for each main scenario and frequency class:

Type	Magnitude Class	PLL
Impacted by Flow	20	2.0E-04
Impacted by Flow	50	9.9E-04
Impacted by Flow	100	7.6E-03
Impacted by Flow	200	6.2E-03
Impacted by Flow	500	4.9E-03
Impacted by Flow	2500	3.6E-03
Impacted by Flow	10000	9.1E-04
Not Impacted, falls into Bridge Hole	20	8.9E-04
Not Impacted, falls into Bridge Hole	50	2.1E-03
Not Impacted, falls into Bridge Hole	100	4.9E-03
Not Impacted, falls into Bridge Hole	200	2.1E-05
Not Impacted, falls into Bridge Hole	500	3.1E-06
Not Impacted, falls into Bridge Hole	2500	1.1E-07
Not Impacted, falls into Bridge Hole	10000	1.8E-08
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	20	4.0E-03
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	50	1.2E-03
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	100	6.8E-05
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	200	2.7E-06
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	500	3.9E-07
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	2500	1.4E-08
Not Impacted, doesn't fall into Bridge Hole, Crashes into Flow	10000	3.5E-09

7.0 RESULTS: EXISTING AND POSSIBLE FUTURE DEVELOPMENT

7.1. Individual Risk Summaries

Individual risk is estimated as the total individual risk (sum of risk) for all return period categories. Risk was computed for individuals-most-at-risk within each building, but due to the large number they have not been reported individually here. Table 7.1 summarizes the number of buildings where values exceed the 10^{-4} or 10^{-5} thresholds.

Table 7.1 Number of buildings where estimated individual risk exceeds the 10^{-4} or 10^{-5} annual probability of death thresholds.

	10^{-4} probability threshold		10^{-5} probability threshold	
	Existing Conditions	With Debris Barrier	Existing Conditions	With Debris Barrier
Existing	20	0	31	6
Proposed	164	0	677	7

7.2. Group Risk

Table 7-1 shows F-N curves plotted for existing and possible future development. Six curves are plotted to compare risk values estimated for existing buildings, future buildings, and all buildings considered together.

In the existing conditions cases, risk exceeds the unacceptable threshold for both existing and proposed buildings. If a debris barrier is constructed (Section 4.1), estimated risk for all buildings move into the ALARP region.

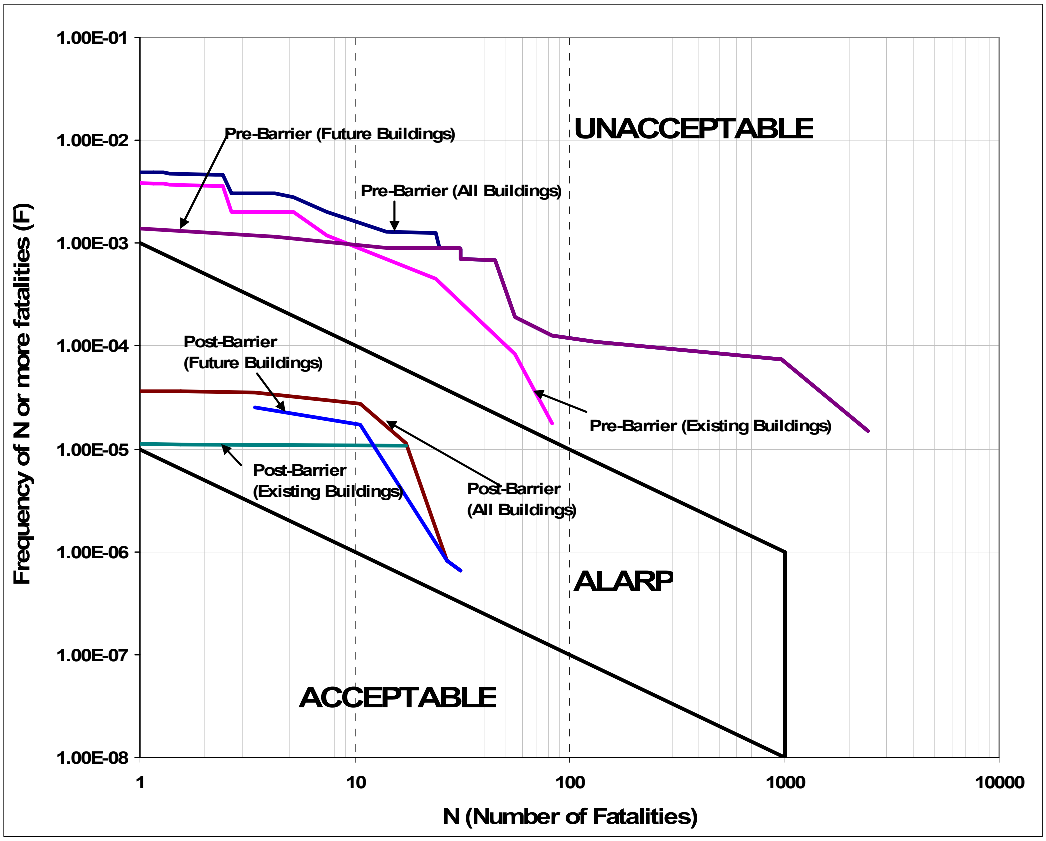


Figure 7-1 F-N curve, existing and future development

8.0 RISK-BASED DECISION MAKING FRAMEWORK

This report establishes that societal risk associated with existing development on the Cheekeye fan is unacceptable when compared to internationally accepted risk tolerance criteria. It also demonstrates that the risk to possible future development would be unacceptable without appropriate mitigation, but that the risk followign construction of a large debris barrier upstream of teh highway would reduce the risk to at least the ALARP area.

While the achievement of ALARP may be sufficient for existing development, it may be desirable to further reduce risk for future development by additional mitigation measures. For example, a berm could be constructed from the fan apex to Highway 99 and Highway 99 to the high ground west of the highway. The debris flow modelling and risk analysis could be updated to select a berm alignment and height that reduces the risk to the future development below the ALARP line, with consideration of additinoal supplemental measures if needed. Analysis of additional mitigation measures is provided under separate cover (BGC 2008b).

Using this approach, a defensible risk-based mitigation plan can be achieved. If the acceptable region on the F-N chart cannot be achieved by these measures, a discussion with local approving authorities could help in identifying whether the achieved level of risk is acceptable to them.

9.0 RISK REDUCTION BENEFITS

Mitigation measures in the form of a large debris barrier and possible additional works would yield significant risk reduction to a number of stakeholders. Identified beneficiaries of the risk reduction measures implemented are:

- The community of Brackendale (northern portions). Risk to loss of life will be reduced to near zero.
- The Cheekeye subdivision within Squamish. Risk will be substantially reduced.
  I.R. 11. Risk will be substantially reduced
- The Cheekeye Substation (BC Hydro). Existing risk is already low due to a natural shelter by a large bedrock bluff and an existing perimeter berm. Risk will be reduced to near zero.
- Lower transmission towers (BC Hydro). Risk to tower damage will be substantially reduced.
- Squamish Airport. Risk will be reduced to near zero.
- Squamish Garbage Dump. Risk to erosion or inundation will be significantly reduced.
- CN Rail. Risk to track washout or bridge loss over Cheekeye River will be significantly reduced.
- Brackendale high school and primary school. Risk with existing deflection berms will be reduced to almost zero.
- Users of Government Road and Squamish Valley Road. Risk will be substantially reduced.
- Users of Highway 99. Risk will be substantially reduced.
- Resort Municipality of Whistler and Village of Pemberton. Economic losses due to highway closure caused by bridge loss or highway erosion or sediment deposition will be significantly reduced.
- Terasen Gas. Risk of pipeline exposure by erosion will be significantly reduced.
- Aquatic habitat Cheekeye, Brohm, Cheakamus Rivers. The likelihood of extreme events destroying fish or spawning habitat will be signficiantly reduced.
- District of Squamish. Rates of fluvial sediment transport and aggradation in the Squamish River floodplain near Squamish will be reduced by reduction of debris flow sediment suppy into Cheakamus River.

This list demonstrates that the Cheekeye River and mitigation measures on Cheekeye River, particularly a large debris barrier would result in a broad spectrum of signficiant risk reduction benefits.

10.0 CLOSURE

We trust the information provided in this report meets your requirements. If you have any questions or comments, or if we can be of further assistance, please do not hesitate to contact the undersigned.

Yours sincerely,

BGC ENGINEERING INC.
per:

Matthias Jakob, Ph.D., P.Geo.	Kris Holm, M.Sc., P.Geo.
Senior Geoscientist	Project Geoscientist

Reviewed by:

Michael Porter, M.Eng. P.Eng.,
Vice President, Senior Geological Engineer

REFERENCES

Ale, B., 2005. Tolerable or Acceptable : a comparison of risk regulation in the United Kingdom and in the Netherlands. Risk Analysis, 25 (2), pp. 231-241.

BC Ministry of Transportation, 2006. Website showing traffic volumes, 2006 data. http://www.th.gov.bc.ca/trafficdata/tradas/tradas.asp?loc=P-15-3NS.

BC Ministry of Transportation and Highways (MOT) (1993). Subdivision Policy and Procedures Manual. Systems Planning Research Officer, Victoria BC.

BC Ministry of Transportation 2001. Alternative Routes Analysis and Corridor Improvements. [web]

BC Ministry of Transportation (MOT) 2005. Guide to Rural Subdivision Approvals, Sections 2.3.1.06 and 2.3.1.07. [web]

BGC 2006. Berkley Landslide Risk Management Phase 1 Risk Assessment. Report for the District of North Vancouver dated January 13, 2006. 44 pp.

BGC 2007. Cheekeye River debris flow simulations. Final report for Kerr Wood Leidal Associates and MacDonald Development Corporation dated December 14, 2007. 32 pp.

BGC 2008. Cheekeye River debris flow frequency and magnitude. Final report for Kerr Wood Leidal Associates and MacDonald Development Corporation dated January 10, 2008. 66 pp

BGC 2008b. Cheekeye Fan Debris Flow Study: Debris Flow Modelling and Risk Analysis for Mitigated Scenarios. Memorandum for Kerr Wood Leidal Associates and MacDonald Development Corporation dated May 16, 2008.

Cave (1991, revised 1993). Hazard acceptability thresholds for development approvals by local governments. In Proceedings of Geological Hazards Workshop, University of Victoria, B.C. February 20-21, 1991. BC Geological Survey Branch, Open File 1992-15, pp. 15-26.

Cordilleran Geoscience (2003). Email to Al Brown. May 8, 2003.

Cory, J., and Sopinka, J. 1989. John Just versus Her Majesty The Queen in right of the Province of British Columbia. Supreme Court Report, Vol. 2, pp. 1228-1258.

Garibaldi Advisory Panel, 1978. Report to the Deputy Minister, Department of Highways, Province of British Columbia, Parts I, II and III.

Jakob, M. 2005. A size classification for debris flows. Engineering Geology. 79: 151-161.

Jones, W.C. 1959. Cheekeye River mudflows. British Columbia Department of Mines, Victoria, BC, memorandum, 9p.

Kendall, H., Hubbard, R., Minor, G., Bryan, W., 1977. Union of Concerned Scientists, The Risks of Nuclear Power Reactors: a Review of the NRC Reactor Safety Study WASH-1400, Cambridge.

Crippen Engineering Ltd. 1974. Report on Geotechnical-Hydrological Investigation of The Cheekeye Fan. Report to B.C. Department of Housing, Victoria, BC.

Leroi, E., Bonnard, Ch., Fell, R., McInnes, R., 2005. Risk assessment and management. State of the Art Paper No.6., International Converence on Landslide Risk Management, Vancouver.

Porter, M., Jakob, M., Savigny, K., Fougere, S., and Morgenstern, N. 2007. Risk Management for Urban Flow Slides in North Vancouver, Canada. Proceedings of the 2007 Canadian Geotechnical Conference, Ottawa, Canada. October 21 – 24, 2007.

Province of British Columbia, 2004. Flood Hazard Area Land Use Management Guidelines. May 2004.

Supreme Court of British Columbia, 1973. In the matter of the Land Registry Act, R.S.B.C. 1960. Chapter 208 and amendments thereto and in the matter of an application for approval of a proposed subdivision by Cleveland Holdings Ltd.

Strong, D., Gallagher, P., Muggeridge, D., 2002. British Columbia offshore oil and gas development: report of the scientific review panel. Report prepared for the BC Ministry of Energy and Mines,

APPENDIX A

Estimates of Dynamic Impact Pressures

Estimates of Dynamic Impact Pressures

This appendix provides background on the methodology used to estimate the kinetic energy of a boulder transported by a debris flow, and dynamic pressures associated with debris flow impact to buildings. The calculations make simplifying assumptions of debris flow dynamics and terrain geometry, and results were used for reference only.

The kinetic energy, Ek, of an individual boulder transported by the flow can be approximated as:

$Ek = 0.5mv^2$

where m is the mass of the boulder, and v is boulder velocity.

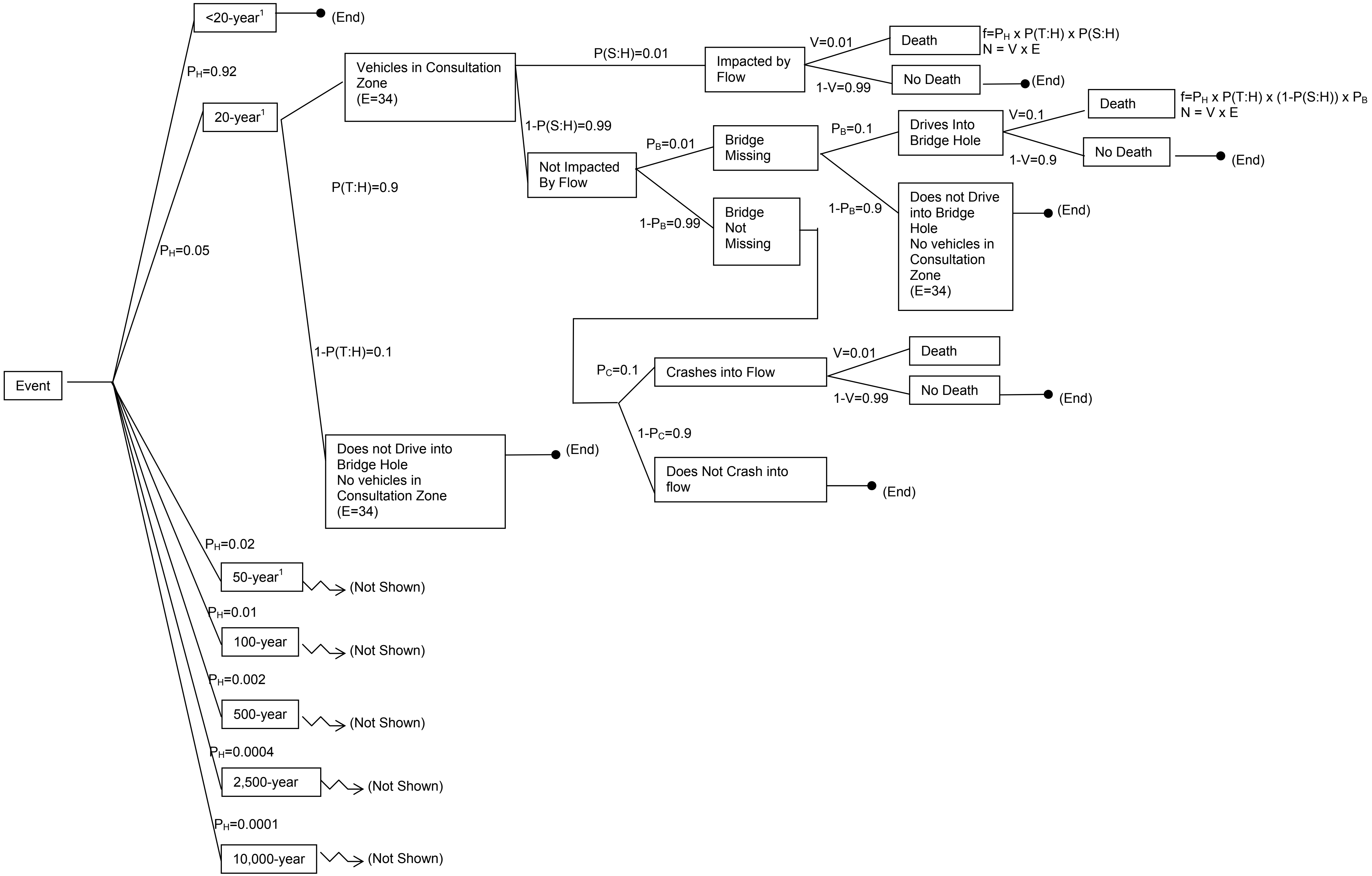
Assuming that the flow velocity profile is approximately uniform, the dynamic pressure, Pd, at any point on a barrier to flow (e.g. a building) can be approximated by:

$Pd = \rho v^2$

where ρ is bulk density (estimated as 2000 kg/m^3). Assuming that the bulk density is constant, the dynamic pressure distribution is rectangular in profile.

APPENDIX B

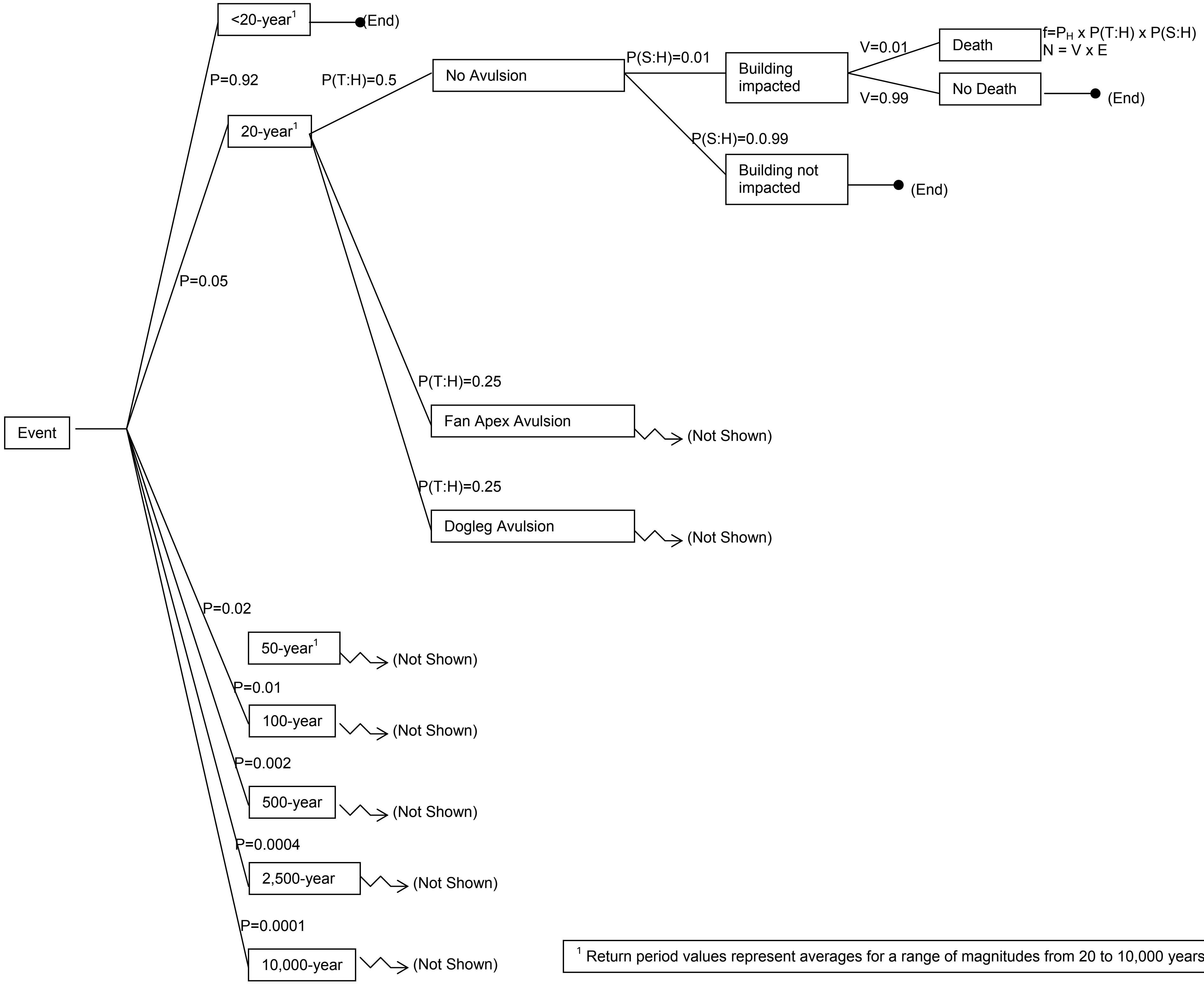
Risk Tree, Highway 99



[1] Return period values represent averages for a range of magnitudes from 20 to 10,000 years

APPENDIX C

Risk Tree, Buildings



[1] Return period values represent averages for a range of magnitudes from 20 to 10,000 years

DRAWINGS