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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

PROVINCIAL EMERGENCY PROGRAM

PRELIMINARY DEBRIS FLOW HAZARD ASSESSMENT OF FIELD, CARRATT, ENG, MCNAB AND DALE CREEKS, HATZIC VALLEY

FINAL REPORT

PROJECT NO: 0378-001
DATE: February 16, 2004

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March 1, 2004

Project No. 0378-001

Jim Whyte
Provincial Emergency Program
PO Box 9201
Stn. Prov. Govt.
Victoria, BC
V8W 9J1

Dear Mr. Whyte:

**Re: Preliminary Debris Flow Hazard Assessment of Field, Carratt, Eng, McNab and
Dale Creeks, Hatzic Valley**

Please find attached four copies of our above referenced final report dated March 1, 2004.

We appreciate the opportunity of having worked on such an interesting and challenging project and look forward to working with you in the future.

Sincerely,
BGC ENGINEERING INC.
per:

A handwritten signature in black ink, appearing to read 'Matthias Jakob', is written over a horizontal line.

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

Enc.

MJ/ph

EXECUTIVE SUMMARY

On October 16 and 17, 2003, prolonged and intensive rainfall triggered debris flows on Field, Carratt and Eng creeks on the eastern slopes of the Hatzic Valley. A road embankment failure on Sylvester Road at the Dale Creek crossing caused localized flooding and sedimentation. Debris floods were observed at McNab, Saporano, and Pattison creeks.

No individuals were physically harmed by the debris flow and debris flood events but property damage was sustained due to sediment deposition, scour and flooding. Several residents were evacuated, as it was not considered safe for them to remain in their homes.

The primary objective of this study is to evaluate the hazard and risk of debris flows at the subject creeks. A large body of previous reports, memos, maps and notes is reviewed to gain insight of the history of hazardous events in the area. This study investigates the causes, frequencies, magnitudes and consequences of debris flows and develops maps to delineate areas of varying hazards on the creek fan for a hypothetical 500-year return period debris flow. This information is then synthesized in a preliminary risk assessment for all the subject creeks.

At Carratt Creek, Eng Creek and McNab Creek, past logging and road building practices have likely increased the magnitude and may also be responsible for an elevated frequency of observed debris flows. The debris flow at Field Creek was due to natural causes while the avulsion and debris deposition at Dale Creek resulted from the partial impounding of the creek due to an embankment failure of Sylvester Road.

The 500-year return period debris flow volumes at Field, Carratt, Eng, McNab and Dale creeks were determined to range in size between 30,000 and 100,000 m³ and their respective discharges were between 500 and 1500 m³/s.

Debris flow frequencies for the subject creeks range between 5 and some 50 years. Debris flows of this size would be harmful to property and life along the flow path and in the runout zone for all five creeks. Risk for the 500-year return period event is considered medium for all the subject creeks and ranges between medium and high for the 100 to 500-year return period event.

At the present time, there are no structural debris flow mitigation measures in place at any of the subject creeks. Emergency measures that include stream channel excavation and piling of debris along the channel sidewalls will be short-lived in their effectiveness. Rapid infilling during subsequent flooding events can be expected.

Apart from property acquisition, a number of structural debris flow mitigation measures are proposed to alleviate future debris flow risk. The majority of these measures may approach or exceed existing property assets and are therefore not cost effective. Detailed hazard and risk studies for the subject creeks are recommended to allocate funds for debris flow mitigation towards the highest risk areas.

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LIMITATIONS OF REPORT

BGC Engineering Inc. (BGC) prepared this report for the Provincial Emergency Program (PEP). The material in it reflects the judgement 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 are the responsibility of such Third Parties. BGC accepts no responsibility for any damages suffered by any Third Party as a result of decisions made or actions based on this report.

As a mutual protection to our client, the public, and ourselves, all reports and drawings are submitted for the confidential information of our client for a specific project and authorization for use and/or publication of data, statements, conclusions or abstracts from or regarding our reports and drawings is reserved pending our written approval.

It is important to understand that this report is a preliminary study, which should be used to gain a better understanding and appreciation of debris flow hazards and risks in the study area and to recognize the approximate areas affected by debris flows. Reported debris flow return periods and magnitudes (debris flow volume and peak discharge) are approximate and need to be refined for the design of site-specific or creek-specific structural mitigation measures or for exact land use zoning.

Fan boundaries and hazard zones as delineated on maps presented in this report are also approximate and should be used to obtain a general sense of the areas that may be affected during a 500-year return period debris flow. The hazard zones are too inaccurate to be incorporated in site-specific land use decisions as the boundaries may change with a more detailed assessment that includes a number of field techniques and computer modelling of debris flows. Also, hazard zones may change gradually or abruptly if renewed debris flow activity or earth works change the fan morphology.

The study identifies some structural mitigation alternatives such as debris basins, debris barriers and deflection berms. The conceptual details provided here are not suitable for construction. Before this can be considered, pre-design studies will have to be carried out to identify location, size, design, infrastructure and cost of structural debris flow counter measures.

BGC understands that further debris movements occurred in the last week of January of 2004 (pers. comm. Jim White, PEP) which are not included in the analysis and reporting of this study as no work was authorized to include these in the present study. BGC assumes no responsibilities for any changes in hazard or risk that these debris movements may have created beyond those detailed in this report.

BGC does not assume any responsibility for any decreases or increases in property values that may result from this technical study.

1.0 INTRODUCTION

During a heavy rainstorm on October 16 and 17, 2003, debris flows occurred on Field Creek, Carratt Creek, and Eng Creek on the east side of the Hatzic Valley (Figure 1-1). Floods with high sediment loads (debris floods) also occurred on many neighbouring streams including McNab Creek, Saporano Creek, Pattison Creek and Dale Creek. None of the existing houses were severely damaged by the events, however, some minor boulder impacts were recorded and liquid debris after-flow and floodwaters caused flooding and extensive deposition of large organic debris, gravel and sand size sediment. Figure 1-2 shows the topography of four of the five study basins and the approximate fan boundaries.

The Fraser Valley Regional District (FVRD) consulted Thurber Engineering Ltd. (Thurber) for an emergency assessment. The results of its work is summarized in an October 31, 2003 letter report, a letter report of November 7, 2003, and an addendum to the latter report dated November 10 as well as a memorandum dated November 25, 2003.

The Provincial Emergency Program (PEP) sought further assistance from BGC Engineering Inc. (BGC) in quantifying the existing hazard and risk. Work was authorized on December 2, 2003. The objectives of this work were outlined in Schedule A (Services) of the contract received by BGC on January 30, 2004 and are summarized below:

- assess the risk of further debris flow activity on five creeks in the Hatzic Valley region of the Lower Mainland. These creeks are Eng, Carratt, McNab, Dale and Field Creek;
- review the work of Thurber Engineering Ltd. (Thurber) in their report to the Fraser Valley Regional District and historical records at the Ministry of Water, Land and Air Protection;
- in conjunction with staff of the Ministry of Water, Land and Air Protection, conduct aerial inspections of Hatzic Valley watersheds;
- interview residents, response staff of the Ministry of Transportation, the Ministry of Water, Land and Air Protection and roads maintenance contractors as required;
- provide a report which:
 - quantifies the risk of further debris flow activity on the creeks;
 - quantifies the risk to the existing homes on creek fans being impacted by further debris flows;
 - suggests whether or not the risk of debris flow impacts on the homes has increased as a result of the October event; and
 - recommends appropriate solutions to reduce the risk of loss of life, injury or structural damage to the homeowners and homes identified in the Thurber report.

A memorandum was issued to PEP on December 12, 2003 to provide a quick response to

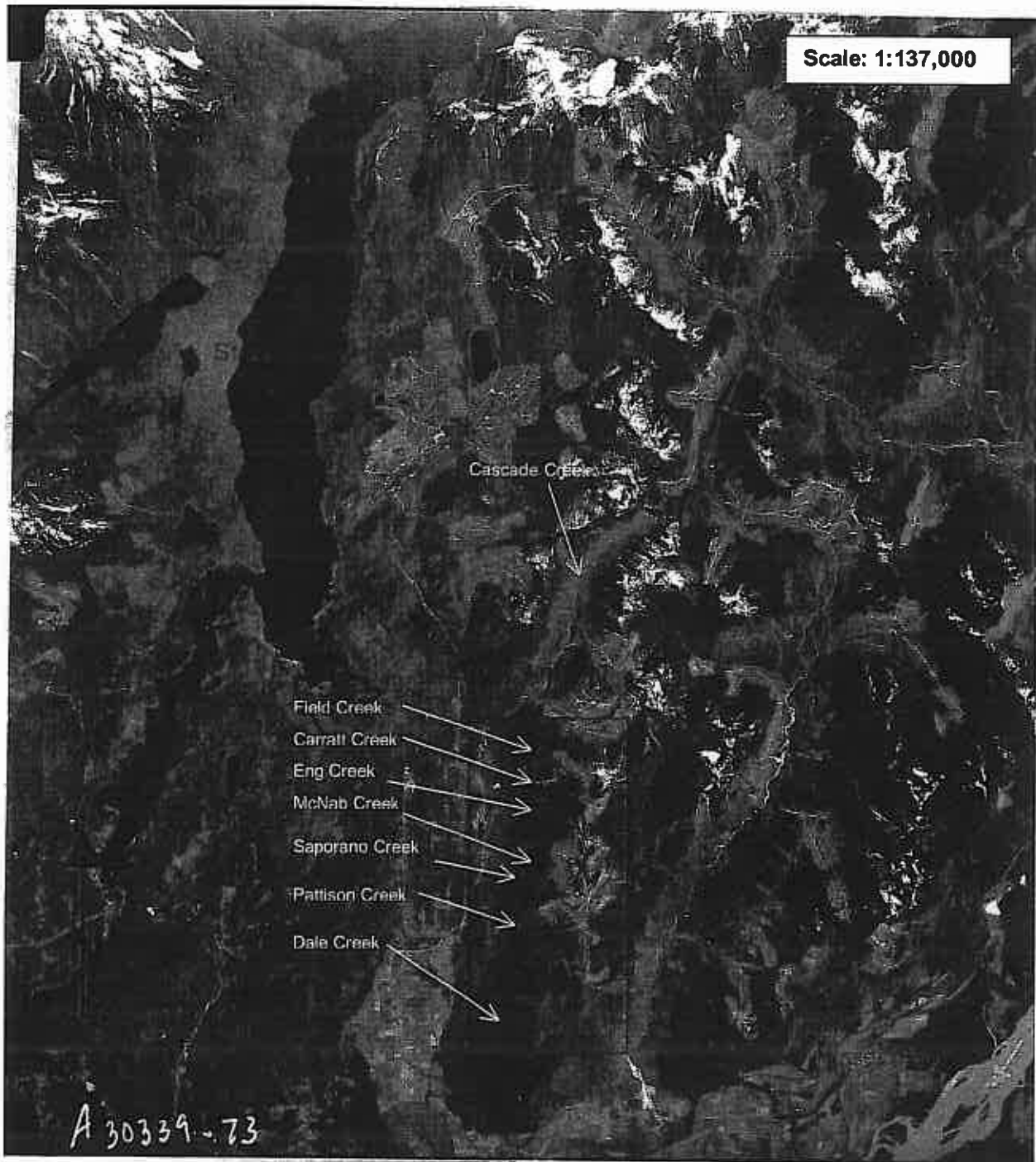
the above questions on which preliminary management strategies could be based.

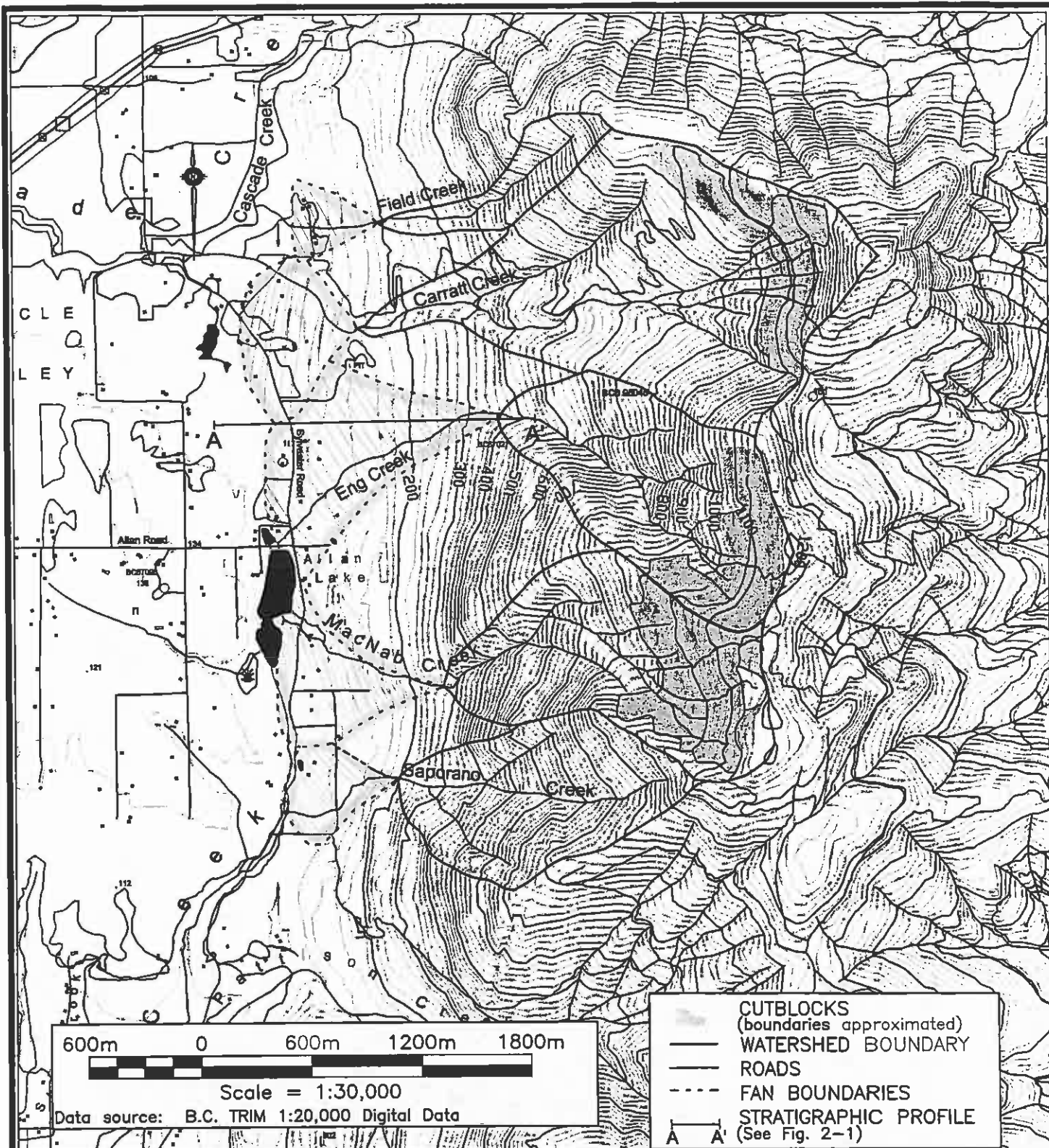
This report expands on the December 12, 2003 memo and provides information relevant to understanding debris flow behaviour in the watersheds and to manage their risk.

The report is organized in nine main sections: The introduction contains a review of previous work followed by eyewitness accounts of the debris flows. Section 2 describes the subject watersheds, while sections 3, 4, 5, 6 and 7 address debris flow frequency and magnitude, potential consequences, risk mitigation alternatives, emergency creek measures, and the potential impact of climate change on debris flow occurrence respectively. The report ends with a set of recommendations and a summary.

Three appendices are added to the report. Appendix I provides some background knowledge on debris flows which are often misnamed by the media as "mudslides". Appendix II describes the meteorology of the mid October storm and provides details from radar and satellite images of the study area. This section illustrates the magnitude of the storm and allows an appreciation of the return period of such climatic events. Appendix III is a collection of annotated photographs by BGC and Thurber showing the watersheds of the study creeks, damage done by the October 2003 debris flows and recent creek works conducted by the B.C. Ministry of Transportation.

Figure 1-1 - Study Area (photo RSA 30339, 1971, National Air Photo Library, Ottawa)





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PROJECT

PRELIMINARY DEBRIS-FLOW HAZARD
AND RISK ASSESSMENT

TITLE

STUDY AREA
(EXCLUDING DALE CREEK)

CLIENT:

PROVINCIAL EMERGENCY PROGRAM

PROJECT No.

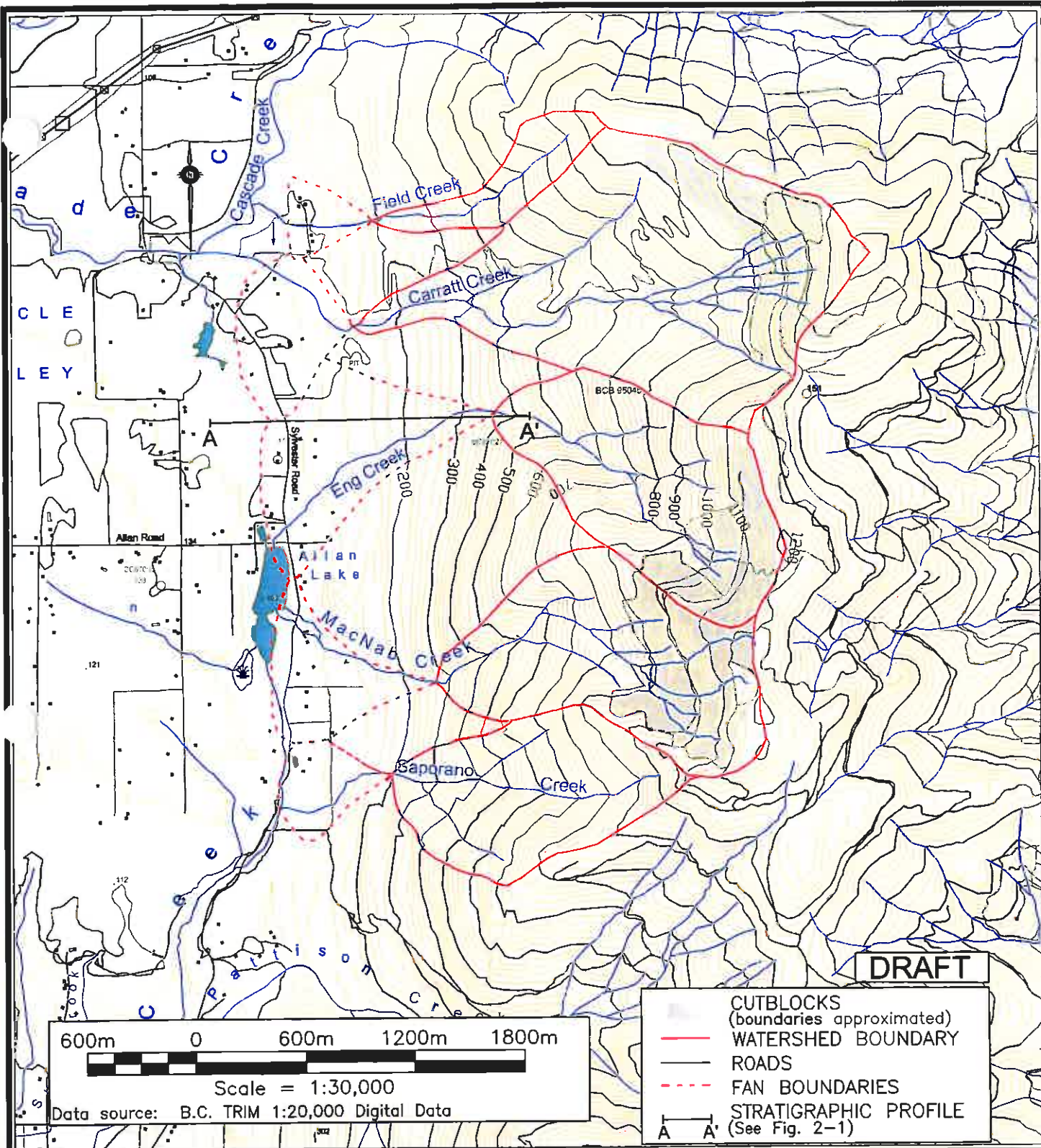
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1.1 Previous Work

The area under investigation was examined by Thurber following the mid-October rainstorm. The following documents resulted from this investigation:

- October 31, 2003: Letter report;
- November 7, 2003: Letter report;
- November 10, 2003: Addendum to letter report of November 7, 2003;
- November 25, 2003: Memorandum

In addition, we review observations, data and reports compiled over the past 25 years by:

- Dewdney Area Improvement District – Lagace Creek Flooding – December 1979 – Preliminary Report by the BC Ministry of Environment, Inventory and Engineering Branch, 1980.
- Pattison/Lagace Sediment Basin by the Ministry of Environment, Water Management Branch, 1981.
- Cascade/Carratt Creek Flood Control Outline Report by the Ministry of Environment, Water Management Branch for the Dewdney-Alloette Regional District in 1983.
- Memorandum on the Pattison/Lagace Sediment Basin by the Ministry of Environment to Mr. J. Wester, Water Management Branch, September 1981.
- Investigation of Sedimentation and Flood Control on Lagace Creek – Final Report. Prepared for the Ministry of Environment by Northwest Hydraulics Consultants, 1985.
- Flooding and debris flow hazard assessment for proposed dwelling, Strata Lot 12, 36264 Hartley Road, Mission, BC for Eszter Csutkai, Architect, by SRK-Robinson Inc. Vancouver, B.C., June 1993.
- Norrish Creek – Cascade Landslide Inventory by D.E. Howes, 1985.
- Pattison Creek Risk Assessment, prepared by Thurber for the BC Ministry of Environment, 1990.
- Terrain Classification, Terrain Stability, and Sedimentation Potential of Durieu Ridge Map Area. Prepared for the Chilliwack Forest District, Rosedale, BC by Denny Maynard and Associates Ltd., 1993.

- Engineering Study of the Cascade/Carratt Creek Flood Protection Works for the Fraser Valley Regional District, prepared by Sigma Engineering, 1999.
- Literature Review, Hatzic Prairie Watershed by M. Hogan, 2001.
- Cascade/Carratt Creek Flood Mitigation Works – Operation and Maintenance Manual, prepared by FVRD, Chilliwack, BC, 2001.

The following summarizes important observations from the above documents.

Thurber Letter Report of October 31, 2003

Thurber was retained by the FVRD to identify dwellings where landslide and flood hazards persist and where residents may be exposed to an increased level of risk. The study area was inspected by helicopter on October 27, 2003, followed by field investigations on October 27 and 28, 2003. The final recommendations resulting from this work can be summarized as follows:

- the five residences should remain vacated until a more detailed investigation is completed and the creek channels, culverts and flood ways return to conditions that will allow passage of winter discharges; and,
- forestry works (roads, culverts etc.) in the upper watersheds of McNab Creek, Carratt Creek, and Eng Creek should be inspected and the need for road deactivation and land reclamation should be assessed.

BGC considers the recommended evacuation at the time of the report by Thurber conservative and prudent in light of the uncertainty of present channel conditions and future storms. A geomorphologically and meteorologically-based climatic threshold for landslide initiation could provide better guidance for future decisions of this kind but no such threshold has been established for the FVRD to date.

Thurber Letter Report of November 7, 2003

Thurber responded to a request by the FVRD to investigate recent debris activity at Dale Creek and to determine if a residence at 35900 Dale Road is exposed to continuing flood and debris hazards. The conclusions of this investigation can be summarized as follows:

- the subject residence is in an inappropriate location with respect to flood hazards and debris flow hazards;
- hydraulic investigations of the creek and clean-out of the channel are urgently needed to

protect the subject property; and

- the subject residence should remain vacated until a more detailed hazard and risk assessment has been carried out and the creek channel and flood ways are restored.

BGC agrees with the first two recommendations. The decision whether the subject residence should remain vacated or not, in BGC's opinion, should lie with the local government agency (FVRD) after having been advised by the consultant as to the existing hazard and risk.

Thurber Letter Report of November 25, 2003

In the afternoon of November 17 and early in the morning of November 18, flooding was reported in Hatzik Valley. Thurber conducted a helicopter inspection. The following points summarize their findings:

- at Eng Creek, flood water remobilized much of the recently deposited debris causing extensive scour;
- no major changes occurred in the Pattison Creek watershed;
- heavy debris loads were observed in many creeks and ditches of the Allan Lake – Lagace Creek system which require re-opening; and
- At Dale Creek, no major changes occurred since the mid-October 2003 events but the drainage works need to be evaluated.

Furthermore, Thurber recommended a detailed engineering investigation before the onset of winter and pointed out that residents may have to be informed that they may not be able to return to their homes for some time to come.

Norrish – Cascade Landslide – Inventory (D.E. Howes, August 1984)

This 1:20,000 scale map was produced based on air photograph analysis from 1940, 1962, 1968, 1979, and 1981. The main features on this map with regard to this study are:

- Carratt Creek: A large debris flow deposit on the fan and seven shallow debris slides in the upper watershed.
- Eng Creek: A large rockslide on the north side of the creek that had descended to Sylvester road. Anecdotal evidence dates this event to the 1930s. Note that the author of the present report (M. Jakob) is not convinced whether this event was indeed a

rockslide or a debris avalanche (surficial materials).

- Dale Creek: A slump in unconsolidated materials north of Dale Creek. Note that the location of Dale Creek on the 1:20,000 scale map is in error. The creek flows well to the south of the mapped creek location on the fan of Dale Creek.

Mapping by Howes did not include Field, McNab, Saporano or Pattison creeks.

Literature Review, Hatzic Prairie Watershed by M. Hogan, 2001

This review summarizes work conducted by a number of studies in the Hatzic Prairie Watershed. The information is gleaned from the literature review by M. Hogan and supplemented with additional information obtained from the Ministry of Water, Land and Air Protection. The following reports and memos are listed in chronological order.

- In 1980, a study by A. A. McPherson was completed for the BC Ministry of Environment on Lagace Creek flooding of December 1979. The report discussed the damage caused by the flood and recommended repair of a channel breach.
- In 1981, A. A. McPherson completed a study for the Ministry of Environment on the Pattison/Lagace sediment basin. It was noted that beginning around 1953, numerous landslides occurred in the Pattison Creek watershed which added substantial amounts of material to its bedload. The process was forecast to continue in the future. The construction of a sediment basin to decrease bedload in Pattison Creek was recommended.
- In 1983, A. A. McPherson studied the Cascade and Carratt Creek flood controls by the BC Ministry of Environment for the Dewdney-Allouette Regional District. The work addressed the impacts of logging roads and high voltage transmission lines above Carratt and Cascade creeks and attempted to determine if flooding has resulted from this infrastructure. Logging in the Carratt Creek watershed was noted and recommendations were made for flood control along the creeks that included channel excavation, setback dykes to the limits of existing property and channel widening near bridges to increase flow capacity.
- In 1985, Northwest Hydraulic Consultants prepared a report for the Ministry of Environment in which they investigated sedimentation and flood control on Lagace Creek. It was concluded that long-term channel instabilities and sedimentation problems on Lagace Creek would depend on sediment volumes supplied from Pattison Creek. Those, in turn, would be governed by future extreme rainfall, landsliding and surface erosion. A 30,000 m³ debris basin was proposed but it was noted that the basin could induce upstream degradation and bank collapse due to localized channel steepening. It

was estimated that the basin would trap, on average, 10,000 m³ of gravel and sand per year. Furthermore, it was noted that landsliding in abnormally thick glacial till deposits in Pattison Creek could largely be attributed to logging and logging road construction.

- In 1990, a risk assessment was carried out for Pattison Creek by Thurber for the Ministry of Environment (now the Ministry of Water, Land and Air Protection). This report detailed the effects of a debris flow in November of 1990. It was noted that debris flows likely occurred before logging began in the 1950s. The November 1990 event began at a logging road crossing the upper reaches of a steep gully. It was concluded that further debris flow activity was likely and that the probability of further debris flow activity was not affected by the November 1990 event. The 1990 event increased the probability of avulsions and heavy property damage was predicted during avulsions with some risk to loss of life. Channel excavation or dyke building was listed as possible solutions to protect against flooding.
- In 1992, a comprehensive study on Hatzic Prairie drainage was conducted by Associated Engineering Ltd. that included an investigation of flooding and sedimentation issues on the tributaries of Lagace Creek. With respect to these tributaries, the study states that logging in the area had not caused a significant increase in the magnitude of debris flows in the lower river system, but can be associated with debris slides and surface erosion which has increased sediment load in Lagace Creek.
- In 1993, a comprehensive terrain classification, terrain stability analysis and sedimentation potential were carried out by Denny Maynard, P.Geo. of Denny Maynard & Associates Ltd. This study provides a comprehensive account of the surficial geology and Quaternary history of the area and describes the glacial deposits in the Pattison Creek watershed and adjacent watersheds. The report points towards the massive glacial and glaciofluvial deposits along the Durieu Ridge, which also affect areas further north. A detailed terrain map at a scale of 1:20,000 was included in the report.
- In 1993, a study by Bruce Dagg, P.Eng. for Eszer Csutkai, Architect addressed a property (Strata Lot 12, 36264) on McNab Creek with respect to flooding and debris flow hazards. The study concluded that McNab Creek was debris flow prone. Two debris flows were recorded, one in 1984 and another in September of 1992. It was noted that logging had occurred in the upper watershed some 15 to 20 years earlier and that roots from logged areas had decayed. A point was made that the 1992 debris flow scoured most of the creek channel decreasing the likelihood of another debris flow in the following few years. In conclusion, the report noted that field evidence, logging activities and observed debris flow activity indicated that future debris flows were likely on McNab Creek and that the degree of hazard diminished downstream.

- In 1995, a terrain classification, terrain stability and sedimentation study was carried out at Durieu Ridge by Denny Maynard and Associates Ltd. The report identified major debris flow activity on Pattison Creek in 1960 and 1990 and noted that the threat of further activity remained. It was noted that poor logging practices during the 1960s are the cause of debris flows and landslides in this area. Specifically, it was noted that: "modifications [of the central headwater bowl of Pattison Creek] caused by clear cutting and road building probably further destabilized the gullied slopes leading to a number of major landslides which have caused extensive sedimentation into the Hatzic Prairie lowland [...]. All steep slopes bordering the main gully systems [of Pattison Creek]¹ are considered highly sensitive to forestry activity.
- In 1997, Robert Hudson, P.Geo., Research Hydrologist of the Vancouver Forest Region conducted a SBFEP risk assessment for proposed cutblocks in the Pattison Creek basin. He concluded that the proposed cutblocks posed no risk to landsliding but noted that old logging roads cutting across gullied terrain in Pattison Creek and McNab Creek continued to have potential for future landsliding. Hudson also pointed out that rehabilitation and deactivation of all old logging roads in the bowl of Pattison Creek and McNab Creek were essential to minimize future landslide potential. Furthermore, he recommended landslide scarp rehabilitation by hydroseeding and hardwood planting.
- In 1999, a study was carried out by Sigma Engineering Ltd. for the FVRD dealing with flood protection on Cascade and Carratt creeks. A large flood was noted to have occurred in 1984. The beds of both creeks were found to be relatively low following extensive gravel removal in 1998. It was recommended that Carratt Creek be widened to reduce the likelihood of breach during high water. It was found that the creek cross-section was able to pass the 200-year return period flood but no mention was made of debris flows. It was also noted that Carratt Creek berms lacked erosion protection and would sustain erosion damage during large floods. Riprap placement or setback dykes were recommended.
- In 2001, a manual for operation and maintenance was issued by the FVRD for Carratt Creek. It recommended that annual inspections of the Carratt Creek training berms and riprap bank protection be carried out with reports submitted to the Dyke Inspector. Creek bed levels were to be monitored according to existing guidelines. Gravel was to be removed in accordance with guidelines and new riprap was to be placed on creek banks.

In summary, a large body of recent literature has been compiled on various aspects of flooding and landsliding on the eastern slopes of Durieu Ridge. The sheer number of these studies demonstrates that the study area has a rich history of flooding and sedimentation problems. Debris flows have been recognized and recorded in many reports but to date, no

¹ Brackets added by BGC for better understanding

detailed study has been carried out to quantify debris flow hazard and risk. Most studies agree that forestry activities have likely increased the likelihood of landsliding and some studies have called for road deactivation. It was found that the increased sediment yield in streams can in part be attributed to logging-related landslides and that streambed aggradation has led to flooding problems at Lagace Creek.

1.2 Forestry Activities

Forestry activities are reviewed briefly in this overview study because numerous studies have demonstrated that logging and road building can have detrimental effects on slope stability in a watershed and can increase the frequency and magnitude of shallow landslides and debris flows (e.g. Swanston and Swanson, 1976; Rood, 1984, 1990; Jakob, 2000, Brardinoni et al. 2002).

The upper watersheds of the study areas have been logged approximately 10 to 30 years ago (1970s through 1990s). The forest cover maps 92G.029 and 92G.03 provide the following age classes for forest polygons stratified by watershed and elevation.

Table 1 - Age of forest polygons in the study area

Watershed	Approx. Elevation Band	Age (yrs.)
Field Creek	< 300 m	81-100
	300 m to 750 m	141 to 250
	750 m to 900 m	121 to 140
Carratt Creek	< 200 m	41 to 80
	200 m to 300 m	61 to 80 (S)
	800 m to 1000 m	141 to 250 (N)
	> 1000 m	21 to 40
Eng Creek	< 200 m	> 141 yrs.
	200 m to 500 m	61 to 100
	500 m to 900	41 to 100
	900 m to 1000 m	41 to > 250
	> 1000 m	1 to 40
McNab Creek	< 200 m	> 250
	200 m to 500 m	81 to 100
	500 m to 800 m	41 to 250
	800 m to 1000 m	121 to > 250
	> 1000 m	21 to 40
Dale Creek	< 200 m	> 250
	200 m to 800 m	81 to 100
	> 800 m	100 to > 250
		21 to 40

Age classes are calibrated to the year 2001.

Table 1 shows that some of the lower watersheds were selectively logged at the turn of the 19th century, but the most significant logging (in terms of slope instability) has occurred in the last 20 to 40 years.

Level I Watershed Restoration Study – Chehalis Consulting Ltd.

A Level I Watershed Restoration Study was initiated in 2001 by Canadian Forest Products Ltd., under contract from Forest Renewal BC. The study was undertaken by Chehalis Consulting Ltd. (Chehalis) for the entire upper Cascade and Durieu Ridge drainage areas, including the upper watersheds of Carratt, Eng, McNab and Basil Creeks. The general scope of the assessment was to characterize the upper watersheds and inventory past and present areas of instability, relating them to past timber harvesting and/or road construction methods where cause could be established.

A risk rating was placed on each element to determine where detailed field studies were required. Preliminary results from this study suggested that natural instability existed in the area prior to timber harvesting development, which became either more pronounced or exacerbated in some cases by either timber harvesting practices or road construction practices of the past. As of the date of this assessment, roads remained deactivated and stability issues relating to old roads and old harvested areas in the upper watersheds were unresolved. With the abolishment of FRBC in 2002, the study was discontinued. According to Chehalis (written communication with Raveen Singh, P.Eng., of Chehalis, January 16, 2004), arrangements are being made to have the study completed with funding from outside sources and with assistance from Chehalis.

Impacts of Logging on Slope Stability

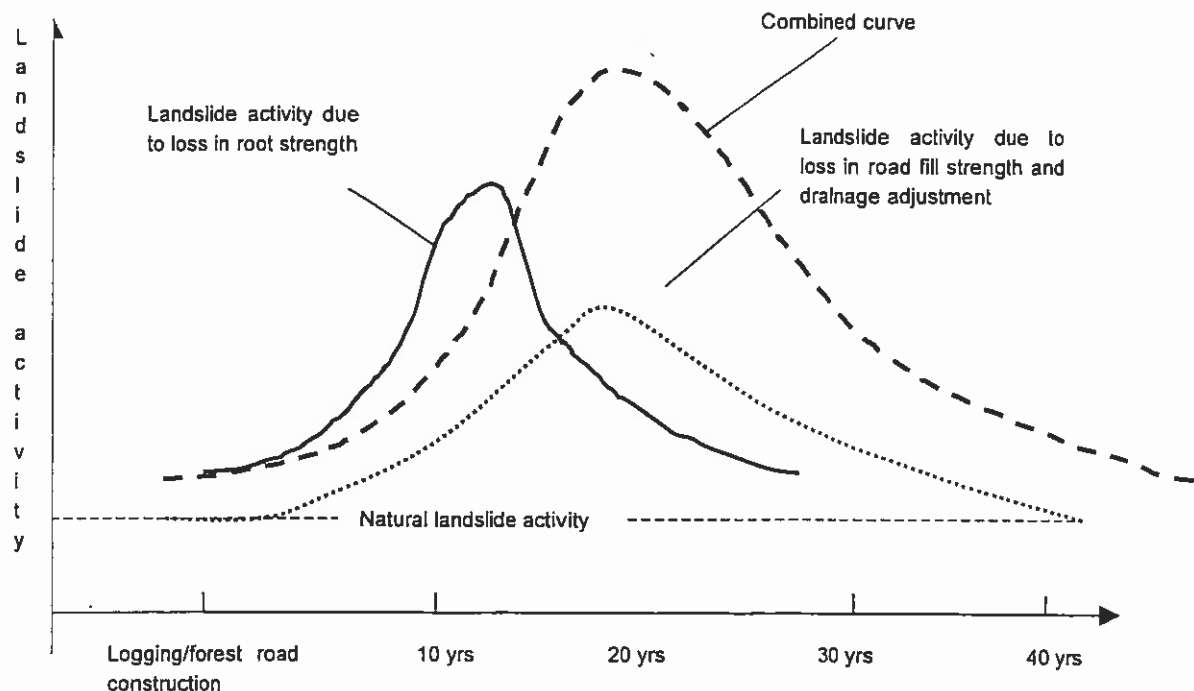
The age-of-logging review as well as the Level I Watershed Restoration Study quoted above show that the timing of logging in addition to non-deactivated roads likely contribute to the increase in probability and magnitude of mass movements. The time elapsed since logging is important for two principal reasons:

- Tree removal initiates root decomposition. Root strength is a very important factor in providing strength to shallow forest soils. Research has identified a time window between 7 and 15 years after logging during which the probability of landsliding is significantly elevated due to this process. After this period, the regrowth of roots from seedlings slowly helps to regain pre-logging root strength.
- Logging activities are usually associated with road construction (an exception is helicopter logging). Before the introduction of the Forest Practices Code of British Columbia in 1994, road-building standards were often poor and led to hillslope destabilization. Oversteepening through placement of road fill and removal of toe support

of the cutslope lead to an increasing probability of landsliding. Furthermore, drainage alterations along road ditches have been found to be responsible for numerous landslides in the Pacific Northwest. Last but not least, slow deterioration of stumps and logs in the fill of forest roads may lead to progressive destabilization. The latter process can remain active several decades after logging has ceased.

Figure 1-3 shows a conceptual graph of a postulated bi-modal increase of logging-related effects on slope instability based on a review of relevant literature discussed in Brardinoni et al. (2002). In the study area, logging occurred some 25 to 40 years ago, which implies that current landslide activity is mostly connected to road-related stability loss or drainage redirection. This hypothesis is substantiated by Photographs 7, 8, 13, 26 and 40, although fieldwork is needed to verify the landslide causes. Figure 1-3 also suggests that forestry-related disturbances should subside with time. This "healing process", however, may be significantly delayed by renewed slope destabilization such as that which occurred in October of 2003. This observation is typical for coastal watersheds as has been discussed by Brardinoni et al. (2002) who found that the recovery time after clearcut logging exceeds 20 years, but that continuous disturbance due to logging may extend the recovery time for watersheds well beyond 20 years.

Figure 1-3. Conceptual model of landslide response to inadequate logging practices, loss of root strength and poor forest road construction



Please note that while root strength deterioration over time is well recorded, logging road deterioration effects have received much less research attention. Figure 1-3 is conceptual and does not imply that forestry-related effects have vanished completely by 50 years after logging.

In summary, it can be stated that landslide activity is still elevated in the upper watersheds of the study area due to incomplete recovery from root strength loss (Photograph 6 at Carratt Creek and Photograph 26 at McNab Creek) and progressive weakening of road fill (Photograph 7 and 8 at Carratt Creek). The present landslide scars will supply sediments to the stream channels by ravelling and minor sliding for some years to come. This process will accelerate channel recharge and add to the volume of future debris flows.

1.3 The October 16 to 18, 2003 debris flows

1.3.1 Magnitude Estimates

In this report, debris flow magnitude is expressed as volume and peak discharge (see Section 3). A detailed reconstruction of the October 2003 debris flow magnitudes were not the prime objective of this study and are thus estimated rather than determined from detailed field surveys. Furthermore, volume estimates are much more reliable shortly after the event rather than two months later when much of the physical evidence has been removed by clean-up operations. Volume was estimated by determining the approximate area inundated by the debris flow and multiplying it with the assumed average deposition depth. Peak discharge was estimated by measuring flow at a cross-section near the fan apex and multiplying it by velocity estimates using the forced vortex equation and run-up equations.

Estimates for volume and peak discharge at Field Creek, Carratt Creek, and Eng Creek are summarized in Table 2.

Table 2. Estimates of volume and peak discharge of the October 2003 debris flows in Hatzic Valley

Creek	Volume (including error range) (m ³)	Peak Discharge (including error range) (m ³ /s)
Field Creek	5,000 (4000 to 6000)	150 (120 to 170)
Carratt Creek	30,000 (20,000 to 40,000)	500 (400 to 600)
Eng Creek	40,000 (30,000 to 50,000)	600 (500 to 700)

Total volume estimates include debris mobilized on the fan by scour and remobilization of previous deposits. Peak discharge is estimated at the respective fan apexes. McNab Creek and Dale Creek did not experience debris flows, only minor sediment movement.

1.3.2 Eye Witness Interviews

On October 16 to 18, 2003, a series of debris flows occurred on the east side of the Hatzic Valley. The following provides a description of the events as is inferred and interpreted from eyewitness accounts.

Field Creek

Interviewees	Description/Observations
Charlotte Virtue	On October 16, 2003 at about 8:00 PM, Danny and Charlotte Virtue heard very loud but distant rumbling sounds that lasted all night. By the morning they noted that water and sediment from Carratt Creek had spilled over the access road to their house and onto their property. Charlotte Virtue noted that Carratt Creek was dry at the time.
Photographs: 1, 2, 3, 4	On October 17, 2003 it was already dark (probably 6:00 PM to 8:00 PM) when the rainfall intensified again. Danny and Charlotte Virtue heard extremely loud crashing and banging sounds, which made them have to yell at short distance to make each other understandable. This time the sounds came from Field Creek. The Virtues left the property and over-nighted in a motel. By the morning they found debris all over their property and gravel-size material backed against the east side of their house.

Interpretation: The storm affecting the area had two peaks, one on October 16, 2003, at around 8:00 PM and another on October 17, 2003, some time between 6:00 PM and 8:00 PM. The first triggered the debris flow at Carratt Creek, while the second triggered the debris flow at Field Creek.

Eng Creek

Interviewees	Description/Observations
Marlin Ramaseder 36380 Allan Road	According to Marlin Ramaseder at 7:00 PM the power went out and at 8:30 PM her dog yelped. Ms. Ramaseder went outside and observed about 50 cm-deep mud streaming by the house at "running speed". Organic materials including large logs, some of which were cut, were deposited first, followed by mineral sediments. Tree trunks were piled up some 10 m high at Sylvester Road. There is extensive flooding damage on the property. Another flow reached the property in the evening of the 17th.
Photographs: 22, 25	
Rafael Hambalek 13710 Sylvester Road	On October 16, 2003, at about 10:00 PM, Mr. Hambalek reports that "the house was shaking" as if in an earthquake. On October 17, 2003, at about 5:00 PM, he again felt that the ground was shaking and he ran for his life. The debris flow deposited some 15 cm of mud and sandy debris on his property, damaging his pitch-and-put six-hole golf course and filling his workshop with sand.
Photographs: 25	
Marion Lund and Jim Lund	On October 16, 2003, at about 8:30 PM, Marion Lund heard a sound she described as a "freight train". The power was out and when her grandson checked outside with a flashlight and muddy water, silt, sand and organic material started pouring through their east (uphill) facing back door. Throughout the night, their son, David Lund, used a front-end loader to keep debris away from the house. On October 17, 2003, between 2:30 PM and 3:00 PM, muddy water broke through a pushed-up berm and again surrounded the building. At about 6:00 PM, Marion and Jim Lund noted ground shaking and left the building.
Photographs: 23, 25	

Interpretation: It appears that at least two debris flow surges descended down Eng Creek, one at about 8:30 pm on October 16, 2003 and another at 6:00 pm on October 17, 2003. The times provided by Marion Lund are likely to be accurate as she wrote those down immediately after the event took place. Similarly, Ms. Ramaseder's time estimate is likely accurate because she is used to feeding her dog at 9:00 pm and believed that the yelping of the dog was due to it wanting to be fed.

The fact that two debris flow surges occurred within two subsequent days is extremely important for future hazard response and creek management. It shows that emergency works may have to wait until a meteorologist with Environment Canada has been consulted to determine the likelihood of further high-intensity rainfall. Following this, a helicopter overview by a debris flow expert is needed to confirm that the area can be declared safe to proceed with emergency works. In this context, the use of a hydroclimatic threshold for

landslide initiation would be very helpful in preparing and alerting residents of when a critical threshold is being approached that could trigger debris flows and to allow emergency works to commence after a storm has passed.

Dale Creek

Interviewees	Description/Observations
Cathy Gravelle 35900 Dale Road Photographs: 36, 37, 38	<p>The debris event occurred between 5:00 and 6:00 PM on 17 October 2003. According to Cathy Gravelle, Dale Creek discharge increased throughout the afternoon of October 17 and the creek became increasingly muddier. The Gravelle's left to have their car repaired sometime between 5:00 and 6:00 PM. When they returned around 6:00 pm, mud, sand and gravel had spread over the property, largely as a consequence of the road embankment failure at Sylvester road above their property. The yard was covered by mud, sand and gravel up to 10 cm deep. Water flowed over the low berm on the downstream right side of the creek, around the house and through the carport.</p> <p>The Gravelle's had moved to the subject property in 1990 and reported that this was the first time that a debris event had occurred. The house, which they had purchased had been at the site for some 10 years prior to their occupancy. Their neighbours house-the Spoiler's Bluejay Farm house-was constructed in 1991.</p>

2.0 WATERSHED DESCRIPTION

This section provides a brief description of the main geomorphic and geologic characteristics of the study watersheds, which are necessary to understand debris flow processes and their hazard potential.

2.1 Bedrock Geology

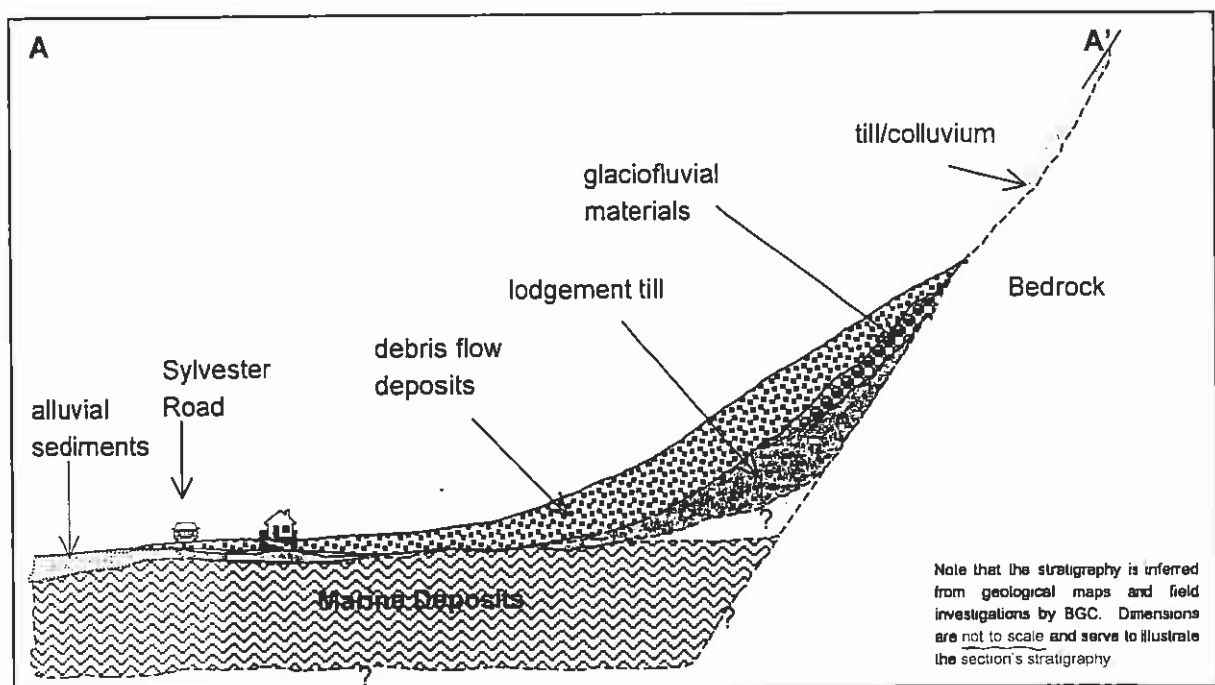
The research area is located north of the Fraser River between Hatzic Lake and Stave Lake on the western slope of Durieu Ridge north of Dewdney Peak (Fig. 1-1).

The middle and upper watershed areas of all study creeks are located within the Mount Jasper Pluton, which in the research area is characterized by early middle to late Jurassic quartz diorite. Tectonically, this pluton belongs to the Gambier Assemblage, which is wedged between the Wrangellia Island Arc outcropping to the west and the Cadwallader Terrane and the Cayoosh Assemblage to the east (Monger and Journeay, 1994).

2.2 Surficial Geology and Quaternary History

The research area is characterized by a complex set of surficial materials that will be described from south to north starting at Hatzic Lake. This description will be complemented by a sketch (Figure 2-1) illustrating the material stratigraphy along a hypothetical transect A-A' shown in Figure 1-2.

Figure 2-1. Stratigraphic sketch along transect A - A' as shown in Fig. 1-2



North of Hatzic Lake, Hatzic Slough meanders through postglacial alluvial deposits consisting of floodplain and over bank deposits up to 8 m thick as well as occasional Sumas outwash deposits consisting of coarse-textured, sandy loam and loamy sand. Some 3 km north of Hatzic Lake, these sediments are replaced by Salish sediments consisting of bog, swamp and shallow lake deposits, peaty organic silt loam and silty clay loam 0.3 to 10 m thick overlying Sumas outwash. Just north, an extensive alluvial fan from Pattison Creek that drains into Hatzic Slough overlies Sumas outwash and Salish sediments.

North of Pattison Creek, there is a sharp break in slope that demarcates the transition to sediments of the Fort Langley Formation consisting of glaciomarine deposits, marine sediments and till 8 to 100 m thick. In places it is overlain by lodgement and minor flow till 0.5 to 2 m thick from the Fraser Glaciation².

On the east side of the valley where all of the study creeks except Dale Creek are located, the lower slopes up to an elevation of approximately 150 m above sea level are mantled by thick colluvial slope deposits consisting of debris flow sediments and rock slide deposits of Holocene age overlying the Fort Langley Formation near the valley bottom. Interspersed on high points between the colluvial fans are Pleistocene recessional ice contact deposits containing till lenses and clasts of the Fort Langley glaciomarine sediments (Armstrong, 1976).

The area has likely undergone an interesting succession of events throughout the Quaternary period. During receding phases of the last (Fraser) glaciation, a large valley glacier occupied the Fraser Valley. At this time, the Stave glacier had receded, leaving ice-free land in the area north of Hatzic Lake and south of Stave Lake. As the ice retreated or down-wasted, the sea reoccupied land during the early deglacial period. Debris flow activity commenced as soon as the valley slopes were ice-free and began to form colluvial fans. As the land gradually rebounded from losing its ice load, the glaciomarine sediments were lifted above sea level and became subject to sub-aerial erosion processes. Deeply incised gullies on the southern limit of the Fort Langley Formation provide evidence for the erosion that followed isostatic rebound. Following this, it is believed that the Stave glacier re-advanced, overrode and consolidated sediment of the Fort Langley Formation and colluvial fans. Photo 21 taken near the fan apex of Eng Creek shows glacially over-consolidated debris flow deposits and possibly ice-margin sediments that provide evidence for this re-advancement as well as the recessional ice contact deposits directly overlying the Fort Langley Formation in the valley bottom.

The Quaternary history has significance for debris flow occurrence and hazards because extensive and repeated mantling of glacial deposits along the eastern slopes of Hatzic Valley created a large source of sediments that are now being eroded by debris flows.

² Fraser Glaciation is the local name for the last major glacial advance during the Quaternary period.

2.3 Watershed Morphometry

The watersheds are 0.3 to 2.5 km² in size and are characterized by steep channels with gradients between 17° and 28° between the fan apex and the highest mapped channel elevation. Fan gradients range between 2° and 13°. Table 3 summarizes morphometric data and Figure 2-2 shows longitudinal creek profiles for the study creeks. The creek profiles are concave indicating a long history of mass movements since orographic uplift. The watersheds themselves resemble erosional amphitheatres drained by a number of small tributaries.

The watershed shape (morphometry) allows for rapid debris recharge because of its natural landslide activity. It also suggests that during storms with very low return periods a number of simultaneous landslides could be initiated. This consideration is very important in determining the design magnitude for the 500-year return period event (see Chapter 3).

Because of a lack of flat reaches of the channels draining the subject watersheds, it can be expected that each debris flow, once initiated, will sustain momentum at least to their respective fan apexes. Premature deposition is also hindered by flow confinement, which is the case for all study creeks upstream of their fan apexes.

Table 3 – Morphometric parameters

Creek	A _w (km ²)	A _f (km ²)	S _T (°)	S _w (°)	S _f (°)	R _w (m)	R _{A-P} (m)	L _{TC} (m)	L _F (m)	L _w (m)
Field Ck.	0.34	0.1	20	25	9	630	710	2180	740	1450
Carratt Ck.	2.50	0.4	13	17	2	910	860	5330	1010	2920
Eng Ck.	1.35	0.7	16	22	8	990	750	5180	1590	1940
McNab Ck.	1.34	0.4	18	23	9	1040	880	5760	1080	2350
Dale Ck.	1.20	0.3	22	28	13	810	620	3250	840	1300

where A_w is the watershed area, A_f is the fan area; S_T is the average slope from the valley fl to the highest watershed elevation. S_w is the average watershed slope, S_f is the average fan slope, R_w is the total watershed relief, R_{A-P} is the relief from the fan apex to the highest watershed elevation, L_{TC} is the total channel length with all tributaries and includes the fan stream channel, L_F is the fan stream channel length, and L_w is the total watershed stream channel length. The data for this table were obtained from topographic maps at a 1:20,000 scale obtained from the FVRD and are considered reliable at the reported precision.

2.4 Land Use

Land use in the upper watersheds is limited to timber extraction that began in the 1960s and ceased in the late 1970s. Over the past 30 years or so, increasing development has infringed on the lower fans with residential use and livestock. East of Sylvester Road there are no significant agricultural activities. A large horse riding and stable facility south of Carratt Creek is now also used as a studio by feature film producers.

3.0 DEBRIS FLOW PROBABILITY AND MAGNITUDE

3.1 Introduction

This section provides a semi-quantitative hazard analysis related to debris flow hazards and risks in the study area. The overall risk is defined as a combination of hazard and consequence, where:

- *hazard* represents the occurrence of creek events, expressed in terms of probability and magnitude; and
- *consequence* represents the elements at risk and their vulnerability to damage during an event.

The level of risk, and therefore the need to consider the implementation of mitigation measures, depends on both the degree of hazard and the potential consequence.

3.2 Debris Flow Probability

Debris flows occur in irregular intervals. The time period of observation (usually determined by historical information or absolute dating methods) divided by the total number of debris flows in this period is referred to as the *return period*. For example, if there is documentation of six debris flows in 90 years, the return period is 15 years. The *frequency* or *annual probability* of a debris flow is defined as the inverse of the return period or, in this example, $1/15$, which equals 0.067. The latter number can be interpreted as a 6.7 or rounded up to 7% chance of a debris flow occurring in any given year. It is important to emphasize that these numbers are probabilities which do not preclude the possibility of debris flows occurring in subsequent years or even two or more debris flows on the same channel in the same year.

Debris flow probability is also controlled by the watershed type (i.e. the amount of sediment available for transport). Watersheds with a quasi-infinite amount of stored debris (referred to as supply-unlimited watersheds) respond more readily with debris flow occurrences to hydroclimatic events and have a large range of debris flow magnitudes. They also occur more frequently than their supply-limited counterparts. Carratt Creek, Eng Creek, and McNab Creek belong to this type, primarily because of post-logging effects, which have significantly destabilized the watershed and large amounts of glacial sediments mantling bedrock in the watershed.

Watersheds with a limited amount of stored debris have to recharge after each significant event (referred to as supply-limited watersheds), and hence the event volume at any given time is more limited. Field Creek belongs to this type, which implies that the probability of another debris flow in the near future of the same or greater magnitude of the last one is low.

Debris flow probabilities can be classified as exemplified in Table 3 below.

Table 4 - Debris flow probability classes (after Hungr, 1997)

Return Period (years)	Qualitative Probability Classification	Probability of at Least One Occurrence in 50 Years	Significance of Probability
< 20	High	more than 90%	The hazard is imminent, and very likely to occur within the lifetime of a person or structure. There will generally be clear and relatively fresh signs of disturbance.
20 to 100	Medium	40% to 90%	The hazard is likely to happen within the lifetime of a person or structure. Disturbances are clearly identifiable from deposits and vegetation, but may not appear fresh.
100 to 500	Low	10% to 40%	The hazard occurrence within a given lifetime is possible. Signs of disturbance such as vegetation damage may not be easily noted. The BC Ministry of Transportation uses a probability of 10% in 50 years (475-year return period) as a design standard for natural hazards.

To determine the probability of debris flows in the Hatzic Valley, three methods were applied: Air photo interpretation, historical information from the BC Ministry Water Land and Air Protection and eye-witness accounts of local residents. These data provide some preliminary insights in the probability of debris flows but should be complimented by dendrochronologic³ dating and radiocarbon dating to construct reliable frequency-magnitude relationships. These relationships, which form the basis for decision making and the choice of structural or land use measures to minimize or avoid debris flow related damage, are beyond the scope of this preliminary study.

3.2.1 Air Photograph Interpretation

Table 5 summarizes information from the interpretation of different years of photography spanning a 48-year period from 1947 to 1999. It should be noted that this assessment is incomplete in that only those photographs available at the Geographic Information Centre at the Geography Department at UBC were viewed. For detailed creek-specific studies, it is recommended to view all air photography flown at a large scale. This would require rigorous searches of private as well as Provincial and Federal Government airphoto libraries, which was beyond the scope of this study.

³ Dendrochronology is a dating method in which tree rings are used to decipher the age of an event. In this case, trees can be cored or samples of boulder-scarred trees be extracted via a chainsaw to determine the years of past events.

Table 5 - Interpretation of air photographs (1947 to 1994)

FIELD CREEK		
Date	Photo No.	Observations
1963	BC 5407 32/33	<ul style="list-style-type: none"> No signs of debris flow activity. All buildings currently exist except office the building north of main residence
1999	SRS 6064 343/344	<ul style="list-style-type: none"> No change
CARRATT CREEK		
1963	5407 32/33	<ul style="list-style-type: none"> Channel is in present position Multiple older channels cross fan Berm built across fan perpendicular to flow direction Secondary fan on south side of present channel Road built through the middle of the watershed with numerous failures originating from road Upper watershed recently clearcut
1968		<ul style="list-style-type: none"> Recent deposition on south side of fan onto Virtue property
1999	SRS 6064 343/344	<ul style="list-style-type: none"> The channel is very active The riding facility (film studio) built An aggrading channel has increased the likelihood that Carratt Creek will avulse towards the Virtue property or over the southern portions of the fan
ENG CREEK		
1963	5407 32/33	<ul style="list-style-type: none"> Very large fan with many potential debris flow routes on the far southeast side of the fan No recent debris flow activity Five buildings on the fan Fan on far south side of channel Signs of a very large landslide in the upper watershed (probably the one mapped by Howes in 1984)
1999	SRS 6064 343/344	<ul style="list-style-type: none"> Large landslide scar completely healed No debris flows in upper watershed Channel located on far south side of fan (also present location)
MCNAB CREEK		
1963	BC 5062 118/119	<ul style="list-style-type: none"> No signs of recent debris flow or flood activity (only lower watershed visible) Freshly constructed road in the upper watershed of Saporano Creek and fresh logging Several natural landslides in the mid-McNab basin Fresh, large failures in the upper Saporano watershed

1971	BC 5407	<ul style="list-style-type: none"> • Creek bed not visible • Large fan with many possible debris flow trajectories
1974	BC 5580 88/89	<ul style="list-style-type: none"> • No debris flow activity, deciduous trees on fan
1979	BC 79036 225/226	<ul style="list-style-type: none"> • No change
1993	BCB 93030	<ul style="list-style-type: none"> • Creek on the north side of the fan, easily visible with debris flow runout zone at fan apex
1999	SRS 6064 343/344	<ul style="list-style-type: none"> • Two debris avalanches/debris flows in upper watershed
DALE CREEK		
1963	BC 5063 73/74	<ul style="list-style-type: none"> • Road access in the lower watershed 100-m north of the road intersection with Sylvester Road • Extensive talus old landslides in upper watershed
1969	BC 5063 12/13	<ul style="list-style-type: none"> • No change
1971	BC 5406, 161	<ul style="list-style-type: none"> • No change
1974	BC 5574 268/269	<ul style="list-style-type: none"> • No change • House west of Sylvester Road constructed between 1971 and 1974
1979	BC 79036 225/226	<ul style="list-style-type: none"> • Creek can not be distinguished under deciduous tree cover
1993	BC 93030 25/26	<ul style="list-style-type: none"> • No sign of activity
1999	SRS 6064 309/310	<ul style="list-style-type: none"> • No change

Air photo evidence is inadequate to provide reliable estimates of debris flow volume since much of the debris deposition occurs under the dense coniferous tree canopy. Based on air photo evidence alone and the debris flows in 2003, Carratt, Eng, and McNab creeks produce debris flows at decadal (10-30 years) return periods, while debris flows on Field Creek and Dale Creek may occur at return periods between 30 and 60 years. Dendrochronologic investigations, which are beyond the scope of the present study, could provide a record of debris flows spanning a period of at least 150 years.

3.2.2 Historical Information

A large amount of previous information was located in the archives of the Fraser Valley Regional District and at the Surrey office of the Ministry of Water, Land and Air Protection. These data are summarized in Table 6.

Table 6 - Summary of debris flow dates from historical information

Creek Name	Event Dates	Comment/Source	Return Period
Field Creek	Oct. 17, 2003	Charlotte Virtue (pers. comm.)	50 years [#]
Carratt Creek	1963 – 1968 Dec. 26, 1980 Jan. 1983 Jan. 4, 1984 Nov. 1989 Nov. 1990 Oct. 16, 2003	Memo by N. Peters to J. McCracken (Ministry of Environment, MoE), Aug. 12, 1987 J. McInnes (pers. comm. 2004) J. McInnes (pers. comm. 2004) Flood (uncertain) Bland Engineering Ltd. Letter report to MoE Memo by N. Peters to J. McCracken (MoE), Aug. 12, 1987 Charlotte Virtue (pers. comm.)	5 – 10 years
Eng Creek	1960 – 1964 Dec. 26, 1980 Jan. 4, 1984 Nov. 20, 1986 Feb. 24, 1986 Oct. 16, 2003	Landslide (killed farmer), Thurber, 1997 Memo to file by M.V. Currie (MoE) Flood (?) Ms. Hambalek (resident) James Lund (letter to MoE, Nov. 25, 1986) Flood (?) Memo to file by M.V. Currie (MoE) J. Lund (pers. comm.)	5 – 12 years
McNab Creek	Dec. 26, 1980 Jan 4, 1984 Sept. 23, 1992	J. McInnes (pers. comm. 2004), originating from three separate slides in the upper watershed Dewdney – Allouette Regional District and MoT personnel N.J. Peters (Site Inspection Notes, Sep. 29, 1992)	8 – 15 years
Dale Creek	Nov. 10, 1990 Oct. 16, 2003	Unspecified debris movement Assoc. Eng. Hatzic Prairie Drainage Study, August 1992 C. Gravelle (pers. comm.)	10 – 20 years

[#] This return period is assumed based on limited field evidence

3.2.3 Discussion

The use of “averages”, which are implicit in using the term “return period”, may be misleading in an environment where logging activities have such a profound effect on slope stability and

thus on debris flow activity. As demonstrated in Figure 1-3, a decline in the frequency of debris flows can be expected in the future due to regeneration of forestlands. The assumption of a decrease in debris flow frequency is also based on the premise that hydroclimatic conditions do not change significantly in this time frame, which may not be the case as explained in Chapter 7.

3.3 Design Standard for Debris Flows

For development of debris flow mitigation measures, a *design debris flow event* is often selected. In British Columbia, there is increasing consensus⁴ that the *design debris flow* should be based on the 500-year return period, correlating to the upper level of the medium probability event (Table 4). The term "design debris flow" is avoided in the following section to clarify that the estimates presented in this report are not meant for the design of debris flow mitigation measures. Instead, the term 500-year return period debris flow will be used.

3.3.1 500-year Return Period Debris Flow Volume

The purpose of this sub-section is to estimate debris flow volumes with the data at hand. Note that volume estimates are preliminary and should be improved through detailed fieldwork in which channels are ascended over their full length and the amount of presently stored debris is measured. Only a detailed investigation in which volumes of past flows are determined through fan stratigraphy, dendrochronology and photogrammetry will allow the construction of frequency – magnitude relationships on which to base accurate volume estimates for the design event. The calculations below are approximations and may have errors of up to 50%. The following estimates are prepared to obtain an understanding of the approximate magnitude of debris flows. They lack precision required for the design of debris flow mitigation structures or land use zoning.

Total debris flow volume mobilized in a debris flow (V_{total}) is calculated according to the following equation (Jakob, 2004):

$$V_{total} = \Sigma V_{ps} + \Sigma V_c + \Sigma V_{ss} + \Sigma V_f - \Sigma V_d \quad [1]$$

where ΣV_{ps} is the sum of all point sources that may contribute debris during an event, ΣV_c is the sum of the channel debris stored downstream of the debris flow initiation location(s), ΣV_{ss} is the total amount of debris added by progressive side slope failures, ΣV_f is the fan material entrained upstream of the area of interest, and ΣV_d is all debris deposited before reaching the site of interest.

⁴ This statement is based on the practice of the Ministry of Transportation to design for the 10% in 50 year probability event (475 year return period) for new subdivisions. The same standard has been used by the Ministry of Water, Land and Air Protection for hazard studies, and has been adopted by the District of North Vancouver as a design return period for debris flow mitigation. The 500-year return period is now also used by Whatcom County, Washington State for debris flow mitigation design.

Equation 1 is applied for all creeks in the study area to estimate V_{total} . An example is given for McNab Creek below and results are summarized in Table 6.

The October 2003 debris flows have shown that several debris avalanches may occur simultaneously in a given watershed. For a 500-year return period event, it is estimated that up to 10 individual debris avalanches may be initiated more or less simultaneously. Failure sizes may range between 300 m^3 and 5000 m^3 with an average of 2000 m^3 . Therefore, ΣV_{ps} is estimated to be $20,000 \text{ m}^3$. The total channel length of tributaries and the main channel that may support debris flows between the headwaters and the fan apex is approximately 6000 m. Channel yield rate (the amount of material stored per meter of channel length) can be averaged to $6 \text{ m}^3/\text{m}$ (depending on the time elapsed since the last debris flow). Therefore, ΣV_s can be estimated to $36,000 \text{ m}^3$ ($6 \text{ m}^3/\text{m}$ times 6000 m). For ΣV_t , an additional 5000 m^3 is estimated. For a 500-year return period event, it is estimated that all debris is transported to the fan apex, therefore ΣV_d is assumed to be zero. A total volume of $20,000 \text{ m}^3 + 36,000 \text{ m}^3 + 5000 \text{ m}^3 = 61,000 \text{ m}^3$ is calculated. At McNab Creek, an additional $20,000 \text{ m}^3$ could be entrained through deep scour in old fan deposits (ΣV_F) before significant deposition commences. Accordingly, the 500-year design volume at McNab Creek is estimated to be approximately $80,000 \text{ m}^3 \pm 20,000 \text{ m}^3$ (error estimated). Adding the error for reasons of geotechnical prudence, the preliminary volume estimate of a 500-year return period debris flow at McNab Creek is $100,000 \text{ m}^3$.

Table 7 - Estimated 500-year return period debris flow volumes at the study creeks

Creek Name	Estimated Volume Parameters (m^3)						V_{TOTAL}
	ΣV_{ps}	ΣV_c	ΣV_{ss}	ΣV_t	ΣV_d	Error	
Field Ck.	5,000	5,000	1000	10,000	0	10,000	30,000
Carratt Ck.	30,000	40,000	5000	5000	5000	$\pm 30,000$	100,000
Eng Ck.	20,000	30,000	5000	30,000	0	$\pm 20,000$	100,000
McNab Ck.	20,000	36,000	5000	20,000	0	$\pm 20,000$	100,000
Dale Ck.	15,000	15,000	1000	10,000	0	$\pm 10,000$	50,000

Total volumes are rounded to the nearest $10,000 \text{ m}^3$.

At this preliminary level, exact calculation of the above factors is not possible and assumptions have to be made that are based on judgement. To reflect this uncertainty, debris flow magnitude can be expressed in size classes as suggested by Jakob (2004).

3.3.2 500-year Return Period Debris Flow Peak Discharge

The second step in assessing debris flow magnitude is to estimate the peak discharge. Empirical relations between total debris flow volume and peak discharge have been derived by Jakob (1996) for bouldery and muddy debris flows in southwestern BC. To calculate the mean discharge of bouldery flows, Jakob (1996) suggested the following equation:

$$Q_p = (V_{\max}/28)^{0.9} \quad [2]$$

Where Q_p is the mean discharge derived from a regression line and $V_{\max}$ is the total volume of the debris flow. Using the above equation, peak discharges for all study creeks were calculated and are summarized in Table 9.

Table 8 - Size classifications for debris flows (simplified from Jakob, 2004b)

Size class	V, range (m ³)	Q _p , range (m ³ /s)	Potential consequences
1 (very small)	< 10 ²	< 5	Relatively harmless to people; sedimentation and flooding damage only
2 (small)	10 ² - 10 ³	5 - 30	Could bury a car, destroy a small wooden building, break trees, block culverts, derail trains
3 (moderate)	10 ³ - 10 ⁴	30 - 200	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines
4 (large)	10 ⁴ - 10 ⁵	200 - 1500	Could destroy parts of villages, destroy large sections of infrastructure corridors, could block creeks
5 (very large)	10 ⁵ - 10 ⁶	1500 - 12,000	Could destroy parts of towns, destroy forests of 2 km ² in area, could block creeks and small rivers
6 (extremely large)	> 10 ⁶	>12,000	Could destroy entire towns, obliterate valleys or fans of up to hundreds km ² in size, could block large rivers

V is the total volume; Q_p is the peak discharge for debris flows, respectively.

Note that the size classifications have changed from the Memorandum of December 12 after review of a draft paper by Jakob (2004a).

Table 9 – Summary of the 500-year return period debris flow magnitude parameters

Creek	Class	Volume (m ³)	Peak Discharge (m ³ /s)
Field Creek	4	30,000	500
Carratt Creek	5	100,000	1500
Eng Creek	5	100,000	1500
McNab Creek	5	100,000	1500
Dale Creek	4	50,000	800

Please note that these volume estimates are somewhat higher than previously reported in the Memorandum to PEP of December 12, 2003. The difference is explained by the added degree of detail in this preliminary study.

4.0 RISK ANALYSIS

4.1 Introduction

Risk is defined as the combination of the consequences of a hazard and the probability of a hazard. Risk analysis typically includes a determination of monetary loss and loss of life which is beyond the scope of this study. Instead, this chapter focuses on a semi-quantitative determination of debris flow risk by describing consequences and joining these with probabilities in a risk matrix.

4.2 Potential Consequences

This section focuses on possible consequences in the case of the 500-year return period debris flow occurring. As pointed out earlier, these are qualitative descriptions that require refinement once the magnitude estimates have been improved and the debris flow is modelled using computer software. The latter would require data on the exact topography of the fan areas as well as updated cadastral information including roads and buildings. The following lists possible consequences that may occur individually or in combination.

Field Creek

At Field Creek, the 500-year return period debris flow could mobilize approximately 30,000 m³ of debris. This amount is recruited from the initiating failure, mobilization of channel material and erosion on the fan surface. Damage to structures may vary considerably and depends on the trajectory of the principal debris flow paths, which, for the 500-year return period debris flow, are not predictable, as it is likely to avulse. In the instance of the 500-year return period debris flow avulsing from its channel and flowing south of its present alignment, complete destruction of the principal residence and the second building to the north is possible. The two log buildings approximately 50 to 100 m north of the Virtue residence could also be destroyed (see Photograph 1). The large barn south of the Virtue property would likely only be subject to sedimentation to an elevation of less than 0.5 m.

Carratt Creek

The 500-year return period debris flow at Carratt Creek could transport approximately 100,000 m³ of debris into the developed area. A debris flow of this magnitude would likely overwhelm the protective berms on either side of the creek and debris flow sediments would spill across the entire fan, which is well developed. Lot 3, 4, 5, 6 and 7 are located on the south side of the creek with at least seven buildings east of Sylvester Road. Lot 15 extends to both sides of the creek and includes the large horse riding facility. These buildings would likely suffer some structural damage but are unlikely to collapse. However, significant sediment deposition and flooding can be expected and there is the potential for loss of life

outside the buildings.

Eng Creek

The 500-year return period debris flow at Eng Creek could transport as much as 100,000 m³ of debris into the developed area. The 500-year return period debris flow may avulse near the fan apex and discharge onto the northern section of the fan, possibly as far north as Burns Creek. This debris flow could cause severe structural damage to homes on Lots 16, 17, 18 and 19 in R2 east of Sylvester Road as well as nuisance flooding damage in Lot 11, Plan 20912, LMP 570 in R1 and the property south extending to Allan Road. Furthermore, nuisance flooding can be expected in Lot 13, Plan 32533, Lot 11 Plan 31452 and Exp. 25688 as well as Lot 2, R2, 25374. Most of the lots east of Sylvester road are located in the orange hazard zone, which implies that the destruction of homes is unlikely, however, some structural damage may occur.

McNab Creek

It is estimated that the 500-year return period debris flow could transport as much as 100,000 m³ of debris past the fan apex. A debris flow of this size would likely avulse near the fan apex and allow debris to flow down the southern fan portions. The 500-year return period debris flow could cause severe structural damage on Lots 4 and 5, Plan 29900 and the northernmost section of Lot R2, BLK A. Nuisance flooding could be expected at S.L. 11 and S.L. 12 west of Sylvester Road.

Dale Creek

Dale Creek is believed to produce a 500-year return period debris flow of up to 50,000 m³, which could affect the developed area east of Sylvester Road. A debris flow of this size would likely avulse from the poorly incised channel and flow down the fan surface. It is not possible to predict which direction the flow would take at this preliminary level, but it is likely that eventually it will end in the deeply incised gully that is presently occupied by Dale Creek. A debris flow of this size would very likely cause severe structural damage to the two buildings south of Sylvester Road. Properties affected could include R-1, Lot 6 as well as Plan 66374 (Lot 4), the buildings on Plan 74515 west of Sylvester Road and the six buildings north of Dale Road. Impact may range between severe structural damage and minor nuisance flooding, depending on the trajectory of the debris flow.

4.3 Hazard Zones

The potential consequence from a debris flow depends on the degree of development located on the lower reaches of the creek. An area that is typically the most vulnerable is the creek fan, which is the cone-shaped depositional landform that develops as a result of repeated sediment delivery from the watershed above. The system used to classify debris

flow intensity and consequence in this study is shown in Table 10 and colour-coded on Figures 4-1 and 4-2 for the 500-year return period debris flow.

Table 10 - Classification of debris flow hazard zones

Class	v_{max} (m/s)	d_s (m)	D_b (m)	Description of Potential Consequences
High (Red)	> 5	> 2	> 1	Direct impact with potential for extensive structural damage. Severe erosion potential. Potential for loss of life inside and outside the building.
Medium (Orange)	2 - 5	0.5 - 2	0.3 - 1	Potential for some structural damage, but mostly sediment deposition and flooding. Some erosion potential. Persons inside the building are considered safe. Potential for loss of life outside of buildings.
Low (Yellow)	< 2	< 0.5	< 0.3	Minor potential for sediment deposition and flooding. Little erosion potential. Little potential for loss of life inside or outside of buildings.
v_{max} is maximum flow velocity, d_s is maximum flow depth, and D_b is the maximum boulder diameter transported				

Many other elements other than houses may be subject to damage. These may include infrastructure such as roads, bridges, telecommunication lines, hydroelectric lines, water supply conduits, storm sewers, and wastewater pipes. Creek hazards may also result in loss of agricultural land and damage to fish and wildlife habitat that are also not included in this analysis. The present preliminary assessment focuses on potential consequences on houses, as loss of life or injury is the most important aspect of risk analyses. Table 11 summarizes the risk for three different levels of hazard and consequence. Hazard probability is defined in Table 4, while the consequence rating is extracted from Table 10.

Table 11 - Risk matrix

HAZARD PROBABILITY	CONSEQUENCE		
	High	Medium	Low
High	High	High	Medium
Medium	High	Medium	Medium
Low	Medium	Medium	Low

4.4 Acceptable Level of Risk

Comparing an existing risk to an acceptable level of risk serves to quantify the relative degree of risk. It also helps to determine the scale of mitigative measures that are necessary to reduce the risk to an acceptable level.

Ultimately, the acceptable level of risk is decided by regulatory authorities in consideration of technical evaluations and public expectations. As of this time, there is no established acceptable level of risk for creek hazards in BC or Canada. Therefore, there is some latitude in the choice of protective measures or solutions to minimize the risk to public safety. It should be noted, however, that work by Cave (1991) on risk acceptance has been adopted by the Fraser Valley Regional District and in part by the B.C. Ministry of Transportation. In this context, a site has to be safe for its intended use for an event occurring with a 10% probability of at least one occurrence in 50 years (475-year return period), which corresponds, to a low hazard probability class (Table 4).

4.5 Hazard and Risk Tables

Field Creek

Field Creek has a watershed area of 0.34 km², an approximate fan area of 80,000 m², and an average channel angle between the fan apex and the watershed's peak elevation of 29°. Field Creek is considered to produce debris flow hazards and risks according to Table 12:

Table 12 - Debris flow hazard and risk assessment for Field Creek

Return Period (years)	Process	Size Class	Consequence to Virtue Property	Consequence Rating	Risk
< 20 (High)	Flood Flow	N/A	None	N/A	N/A
20 to 100 (Medium)	Debris Flow	3 (moderate)	Channel avulsion, direct impact of building. Potential for severe structural damage.	HIGH	HIGH
100 to 500 (Low)	Debris Flow	4 (large)	Channel avulsion, direct impact of buildings, deposition of over one metre of sediments at house sites. Severe structural damage expected.	HIGH	MEDIUM

The Virtue property is located at the fringe of an active debris flow fan where debris flows of return periods of less than 100 years pose a **high** hazard. Future debris flows could transport boulders of up to 1 m diameter against the house with estimated velocities of 3 m/s to 5 m/s. An event of this magnitude would likely cause severe structural damage and lead to loss of life if the premises are occupied at the time of the debris flow. Deepening of the

existing channel may temporarily lower the potential of avulsions on the fan; however, avulsions upstream could bypass the excavated channel section and impact the Virtue residence.

Carratt Creek

Carratt Creek has a watershed area of 2.5 km², an approximate fan area of 0.4 km², and an average stream angle between the fan apex and the peak elevation of its headwaters of 26°. Carratt Creek is considered to produce debris flow hazards and risks according to Table 13.

Table 13 - Debris flow hazard and risk assessment for Carratt Creek

Return Period (years)	Process	Size Class	Consequence to Fan Properties	Consequence Rating	Risk
< 20 (High)	Debris Flow	2 (small)	Debris flows would likely not overtop the southern dyke but would likely continue to flow towards the North and may affect the Virtue property.	LOW	MEDIUM
20 to 100 (Medium)	Debris Flow	3 (moderate)	Debris flows could overtop the southern dyke and affect large portions of the fan. Structural damage can be expected in the direct impact zone.	HIGH	HIGH
100 to 500 (Low)	Debris Flow	4 (large)	Multiple failures in the watershed would produce a large debris flow that would likely affect the majority of Carratt Creek fan. Complete destruction of houses on the fan is possible.	HIGH	MEDIUM

Eng Creek

Eng Creek has a watershed area of 1.35 km², an approximate fan area of 0.7 km², and an average stream angle between the fan apex and the peak elevation of 22°. Eng Creek is considered to produce debris flow hazards and risks according to Table 14:

Table 14 - Debris flow hazard and risk assessment for Eng Creek

Return Period (years)	Process	Size Class	Consequence to Subject Properties	Consequence Rating	Risk
< 20 (High)	Debris Flow	2 (small)	Fine-grained after-flow, water and organic debris can cause nuisance flooding	LOW	MEDIUM
20 to 100 (Medium)	Debris Flow	3- (moderate)	Channel avulsion likely. Debris flows may take new channel and affect different areas of the fan than during the October 2003 event. Distant runoff could cause some structural damage.	MEDIUM	MEDIUM
100 to 500 (Low)	Debris Flow	3+ (moderate)	Channel avulsion probable. Extensive debris deposition on lower fan with potential for direct impact of buildings. Severe structural damage is possible.	HIGH	MEDIUM
The + or - sign indicates that the debris flows are expected to be in the higher (+) or lower (-) range of the size class					

McNab Creek

McNab Creek has a watershed area of 1.34 km², an approximate fan area of 0.4 km², and an average stream angle between the fan apex and the peak elevation of 25°. McNab Creek is considered to produce debris flow hazards and risks according to Table 15.

Table 15 - Debris flow hazard and risk assessment for McNab Creek

Return Period (years)	Process	Size Class	Consequence to Subject Properties	Consequence Rating	Risk
< 20 (High)	Debris Flow	2 (small)	Fine-grained after-flow, water and organic debris can cause nuisance flooding	LOW	MEDIUM
20 to 100 (Medium)	Debris Flow	3- (moderate)	Channel avulsion likely. Debris flows may take new channel and affect different areas of the fan than during the October 2003 event. Distant runoff could cause some structural damage.	MEDIUM	MEDIUM
100 to 500 (Low)	Debris Flow	3+ (moderate)	Channel avulsion probable. Extensive debris deposition on lower fan with potential for direct impact of buildings. Severe structural damage is possible.	HIGH	MEDIUM
The + or - sign indicates that the debris flows are expected to be in the higher (+) or lower (-) range of the size class					

Dale Creek

Dale Creek has a watershed area of 1.2 km², an approximate fan area of 0.3 km², and an average stream angle between the fan apex and the peak elevation of 26°. Dale Creek is considered to produce debris flow hazards and risks according to Table 16.

Table 16 - Debris flow hazard and risk assessment for Dale Creek

Return Period (years)	Process	Size Class	Consequence to the 35900 Dale Road Property	Consequence Rating	Risk
< 20 (High)	Flood	N/A	A low return period flood may approach the capacity of the 1500 mm concrete culvert at the Sylvester Road crossing and may exceed the flume capacity downstream of the crossing. Flooding and deposition of sands and cobbles can be expected at the subject property	LOW	MEDIUM
20 to 100 (Medium)	Debris Flood	1- (very small)	Channel avulsion likely on the fan. High likelihood that the concrete culvert will be plugged and overtopped. Floodwater, sediment and organic debris will likely cause considerable damage to the subject property.	MEDIUM	MEDIUM
100 to 500 (Low)	Debris Flow	3 (moderate)	Channel avulsion probable. Debris deposition on lower fan possible with potential for direct impact of buildings. Structural damage is possible.	HIGH	MEDIUM
The + or - sign indicates that the debris flows are expected to be in the higher (+) or lower (-) range of the size class					

5.0 RISK MITIGATION ALTERNATIVES

5.1 Introduction

Based on the findings of Section 3 and 4, this section reviews alternative strategies that may be considered for risk mitigation at the subject creeks.

5.2 Identification of Alternative Approaches

There are two strategies for mitigating debris flow hazards:

- passive measures to avoid the hazard, such as land use planning; or
- active measures to mitigate the hazard occurrence.

Active measures are usually needed where a debris flow hazard affects a developed area. Passive measures can complement active measures to maximize safety in high hazard areas.

A zero solution (do nothing) with implementation of neither active nor passive measures implies full risk acceptance by decision-makers and / or residents.

5.3 Consideration of Mitigative Measures

The specific mitigative measures considered in this section for application are as follows:

- land use planning;
- warning systems;
- watershed management actions; and
- debris flow mitigation structures on the fan.

A preferred approach to risk mitigation is suggested at the end of each creek.

5.4 Land Use Planning and Development

Land use planning is the primary passive measure for natural hazard mitigation. In a case where a fan is already developed, such measures are generally limited in application and are best considered for implementation in conjunction with active measures to minimize future risks.

5.5 Zoning

In some cases, it is possible to delineate a fan into zones of varying hazards, either with or without mitigation measures. This may result in portions of the fan being designated as:

- suitable for land development;
- suitable for land development subject to conditions; or
- unsuitable for land development.

Appropriate land use planning measures can be implemented on the basis of such a zoning system. The hazard maps supplied in this report (Figure 4-1 and 4-2) provide some general guidelines for zones of high, moderate and low hazard. For site-specific zoning, these maps need to be refined by a combination of quantitative methods as described in the recommendations.

5.6 Land Development

Much of the land east and immediately west of Sylvester Road in the study area is privately owned. Further subdivision and building permits should only be issued after a detailed site-specific debris flow hazard assessment is completed which can make recommendations for flood or debris flow proofing of a building and the feasibility of such construction.

The hazard maps in Figures 4-1 and 4-2 can provide some initial guidance if the development is located in a hazardous zone.

5.7 Watershed Management Actions

Watershed stabilization activities can be considered to reduce the level of debris flow hazard. Such measures attempt to address slope stability problems at the source area where debris is generated. As discussed previously in this report, the upper watersheds were extensively logged in the 1960s and 1970s and are criss-crossed by logging roads. While, McNab and Eng creeks have been accessed via the east side of Durieu Ridge; Carratt and Pattison creeks have been accessed by a steep, winding road from Hatzic Valley.

To minimize the probability and size of future landslides, it is recommended that to roads susceptible to failure be deactivated, areas with low tree density be restocked and active landslide scarps be stabilized via a combination of bioengineering techniques and seeding. These measures will not eliminate debris flow hazards in the subject watershed but will provide more safety to the residents living in the hazardous areas below in the long term.

Because of the high consequences of debris flow impact, it is recommended that any proposed logging be preceded by a specialized terrain study beyond that currently mandated by the BC Forest and Range Practices Act and Regulations (2004) which took effect January 31, 2004.

5.8 Debris Flow Mitigation Structures

Several concepts can be considered that could be implemented individually or in combination to provide structural protection against debris flow impacts in developed areas at the subject creeks. It is important to realize that full mitigation of the debris flow hazard will entail large capital expenditure and will, in some cases, exceed the value of the assets to be protected. The structural alternatives listed in Tables 18 to 22 are not exhaustive but demonstrate some potential options that may be considered.

Debris Basin A debris basin is a constructed storage area in which the sediment and woody debris associated with the design debris flood volume is contained above a critical area. A debris basin includes a concrete/steel outlet structure that can be designed to allow passage of debris below a certain size.

*Debris Barrier,
Sorting Structure,*

Debris flow Nets A debris barrier consists of an open steel grillage or concrete slot structure that is anchored to bedrock in a confined section of a creek. Its function is to 'filter' large boulders and trees or root wads while allowing smaller debris to pass. Debris barriers are typically constructed at or upstream of the fan apex and therefore require road access. Maintenance is required after debris flows and debris floods, which involves access to the upstream side of the barrier. A debris flow breaker (large steel-reinforced concrete pillars) may be needed at Carratt Creek, Eng Creek or McNab Creek to sort out large boulders.

An alternative to an open grillage debris barrier could be an array of dynamic mesh wires such as those marketed by GeoBrugg. These nets have originally been designed for rockfall but have been tested for debris flows. They are much cheaper than a debris barrier and can easily be removed to excavate debris piled up behind it. At Carratt, Eng and McNab creeks, the tremendous impact forces of debris flows on these creeks would likely destroy such nets.

Deflection Berm A deflection berm (or training berm) diverts a debris flow from a critical area and allows it to deposit in an area where it will cause minimal damage. As opposed to channelization works, which are constructed in the channel, a deflection berm is constructed outside of the creek channel and results in less environmental impact. The main design consideration of deflection berms is the location of an appropriate runout area that does not provide the opportunity for risk transfer. At Carratt Creek, for example, an overflow channel could be designed in conjunction with a deflection berm to encourage debris deposition in the old gravel pit south of the present fan apex.

Field Creek

For the purposes of considering possible applications, an approximate volume of 30,000 m³ and a peak discharge of 500 m³/s are considered the 500-year return period debris flow at the fan apex of Field Creek. It is then very difficult to predict whether the debris flow will entrain additional material on the fan or begin deposition. A debris flow of this size would likely cover an area of up to 20,000 m².

To protect property at Field Creek, several structural mitigation alternatives can be considered which are listed in Table 18 below. Current value estimates for all creeks are approximate and will need to be refined by obtaining data from recent property assessments if structural debris flow mitigation is pursued.

Table 18 - Debris flow mitigation alternatives at Field Creek

Option	Advantages	Disadvantages
Debris Basin near the fan apex	<ul style="list-style-type: none"> Stores full debris flow above the Virtue Property. Hidden from view. 	<ul style="list-style-type: none"> Would far exceed the current value of the assets to be protected Would require additional channel works to guarantee channel stability Would require construction of an access road to the fan apex
Debris Barrier near the fan apex	<ul style="list-style-type: none"> Could catch most debris before reaching the fan apex Hidden from view 	<ul style="list-style-type: none"> High impact forces will require massive construction Would far exceed the current value of the assets to be protected Would require construction of an access road

Option	Advantages	Disadvantages
Debris Flow Netting	<ul style="list-style-type: none"> ▪ Cheaper than debris flow barrier or debris flow basin 	<ul style="list-style-type: none"> ▪ Would require several debris flow nets in sequence ▪ Would approach the current value of the property to be protected
Deflection Berm with Channel Works	<ul style="list-style-type: none"> ▪ Would direct the debris flow away from, or around, the Virtue residence to the north or encompassing the two buildings on both sides ▪ Could be constructed in an aesthetically pleasing manner 	<ul style="list-style-type: none"> ▪ Would have to be maintained after debris flow impact

Note that none of these options would prevent debris flow avulsions from Carratt Creek fan, which could also affect the Virtue property.

Judging from Table 18, the only cost-effective structural mitigation options are an engineered deflection berm or ring-berm to protect the Virtue residence or a series of debris flow nets installed near the fan apex.

Land use outside the ring-berm would have to be restricted. Relocation of the Virtue residence further to the west would significantly decrease the possibility of direct debris flow impact. However, this location may be subject to flooding or stream avulsion of Cascade Creek and may have to be addressed by raising the building over a specified elevation.

Carratt Creek

For the purposes of considering possible applications, an approximate volume of 100,000 m³ and a peak discharge of 1500 m³/s are considered the 500-year return period debris flow at the fan apex of Carratt Creek. Because of the low gradient of the lower fan, it is considered unlikely that the debris flow will entrain additional material on the fan and will likely begin deposition well upstream of the existing buildings. A debris flow of this size would likely cover an area of approximately 50,000 m². The horse riding facility at Carratt Creek has been constructed at a hazardous location.

To protect property at Carratt Creek, several structural mitigation alternatives can be considered and are listed in Table 19:

Table 19 - Debris Flow Mitigation Alternatives at Carratt Creek

Option	Advantages	Disadvantages
Debris Basin near the fan apex (use of the gravel pit)	<ul style="list-style-type: none"> Stores most debris flow above the existing development Hidden from view Could make use of the area excavated in the old gravel pit 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would have to be cleared after major debris flow events Would require the excavation and maintenance of an overflow channel and an outlet structure through the berm
Debris Barrier near the fan apex	<ul style="list-style-type: none"> Could catch most debris before reaching the fan apex Would significantly reduce channel aggradation rates downstream Hidden from view 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would need to be cleared out after debris flows and debris floods
Setback Dykes	<ul style="list-style-type: none"> Would allow a larger-than-existing area of deposition Could allow lower dyke heights 	<ul style="list-style-type: none"> Would have to be constructed on private property Would approach the current value of the assets to be protected Would have to extend to the fan apex
Improvement of existing dykes	<ul style="list-style-type: none"> Would funnel the debris between the Virtue properties and the horse riding facility on Lot 15 	<ul style="list-style-type: none"> Due to the low gradient of Carratt Creek through the lower fan, any confinement would lead to significant aggradation of the streambed during debris flows and floods. This would require sporadic maintenance The dykes would have to be high to account for several meters of event aggradation and would have to be riprapped with large, well anchored rock The existing dykes would have to be extended and riprapped (and in some cases grouted) up to the fan apex

At Carratt Creek, a combination between structural and land use measures may be advantageous. In this scheme, the right (northern) dyke could be dismantled and set back by several tens of meters. This would require acquisition of lands north of the existing berm. The dyke would also have to be extended to the fan apex and tied into high ground. Placement of large (> 1 m) riprap would be required along the entire dyke length and would have to be grouted at the upstream end. A wider floodplain would allow more aggradation to occur and lengthen the maintenance cycles. It would not, however, exclude the necessity of stream channel management after significant floods or debris flows. Improvements on the

southern dyke may also have to be implemented to protect from sudden debris aggradation events in the channel bend upstream of the development, which could cause avulsions into the southern fan sector.

Eng Creek

For the purposes of considering possible applications, an approximate volume of 100,000 m³ and a peak discharge of 1500 m³/s are considered the 500-year return period debris flow at the fan apex. At least in the upper fan area of Eng Creek there is evidence that material of previous debris flows and underlying glacial materials have been scoured during debris flow transport. It is therefore reasonable to assume that additional scour would occur during the 500-year return period debris flow. A debris flow of this size would likely cover an area of approximately 50,000 m².

Irrespective of the mitigation strategy being used, it is recommended that the lower channel (up to some 500 m upstream from the bridge at Sylvester Road) of Eng Creek be stabilized laterally by a combination of riprap placement and bioengineering techniques. This would decrease the amount of material eroded from the newly pushed-up sidewalls and decrease the rate of aggradation in the lower reaches. It would also improve channel aesthetics.

Table 20 - Debris Flow Mitigation Alternatives at Eng Creek

Option	Advantages	Disadvantages
Debris Basin near the fan apex	<ul style="list-style-type: none"> Stores full debris flow above the existing development Hidden from view 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would have to be cleared after major debris flow events Would require the construction of an access road
Debris Barrier near the fan apex	<ul style="list-style-type: none"> Could catch most debris before reaching the fan apex Hidden from view 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would require construction of an access road Would have to be cleared after major debris flow events
Deflection berms	<ul style="list-style-type: none"> Would funnel debris away from developed areas 	<ul style="list-style-type: none"> Would require a series of berms because of continuous development along the lower fringe of the fan Could create issues of risk transfer as there is little area for safe debris deposition
Debris berm paralleling the contours immediately upstream of existing properties	<ul style="list-style-type: none"> Would likely stop the debris before reaching the developed areas. Could be constructed for lower impact forces than structures near the fan apex Would protect all properties on the lower fan Material from subsequent debris flows could be used to improve the debris berm 	<ul style="list-style-type: none"> Would require major earthworks Would approach or exceed the current value of assets on the fan to be protected (~ \$ 1 million) Would have to be maintained and cleared upstream after major events Would require the construction of an outlet structure to prevent the debris flow from continuing down the main channel

Taking all pros and cons into account, a debris berm paralleling the contour upstream of the existing properties may be the least expensive solution to protect the development from the 500-year return period debris flow. Detailed costing of this alternative, however, may show that it would approach or exceed the current assets to be protected and property acquisition may be a more cost-effective alternative.

McNab Creek

For the purposes of considering possible applications, an approximate volume of 100,000 m³ and a peak discharge of 1500 m³/s are considered for the 500-year return period debris flow at the fan apex. At least in the upper fan area, there is evidence that material of previous debris flows and underlying glacial materials have been scoured during debris flow transport. It is therefore likely that additional scour would occur during the 500-year return period debris flow. A debris flow of this size would likely cover an area of approximately 50,000 m².

Table 21 - Debris Flow Mitigation Alternatives at McNab Creek

Option	Advantages	Disadvantages
Debris Basin near the fan apex	<ul style="list-style-type: none"> Stores full debris flow above the existing development Hidden from view 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would have to be cleared after major debris flow events Would require the construction of an access road
Debris Barrier near the fan apex	<ul style="list-style-type: none"> Could catch most debris before reaching the fan apex Hidden from view 	<ul style="list-style-type: none"> Would approach or exceed the current value of the assets to be protected Would require construction of an access road Would have to be cleared after major debris flow events
Deflection berms	<ul style="list-style-type: none"> Would funnel debris away from developed areas 	<ul style="list-style-type: none"> Could create issues of risk transfer
Debris berm paralleling the contours upstream of the existing properties	<ul style="list-style-type: none"> Would likely stop the debris before reaching the developed areas. Could be constructed for lower impact forces that structures near the fan apex Would protect all properties on the lower fan Material from subsequent debris flows could be used to improve the debris berm 	<ul style="list-style-type: none"> Would require major earthworks Would approach or exceed the current assets on the fan to be protected Would have to be maintained and cleared upstream after major events as the lower channel gradients are very low Would require the construction of an outlet structure to prevent the debris flow from continuing down the main channel

Considering the discussion above, a debris berm paralleling McNab Creek on the south side from the fan apex for approximately 500 m may be the most cost-effective solution to protect

Plan 29900, Lot 5 (north of Kussman Road), Lot 11, Plan 38134 and Blk A, R2 from debris flow impact. For this alternative, Lot 4 (Plan 29900) would have to be acquired and deposition in this area encouraged. A low berm would also have to be constructed paralleling Sylvester Road on the east side to prevent debris from reaching S.L. 11 and 12 (the lakeshore properties on the east shore of Allan Lake). Furthermore, a second deflection berm may need to be constructed to protect new development north of the Sylvester Road crossing of McNab Creek. Costing of this alternative may show that it would approach or exceed the assets to be protected. Alternatively, the deflection berm could be shorter (some 200 m from the fan apex), which would require property acquisition of Lot 4 and 5 (Plan 29900) as well as a protective berm along Sylvester Road to protect S.L. 11 and 12.

For all mitigation alternatives, it is recommended to replace the existing double corrugated steel pipes with a single-span bridge to minimize blockage and avulsion due to sediment accumulations. Furthermore, sediment accumulations could be greatly reduced if the lower reaches of McNab Creek were armoured with some riprap and bioengineering techniques were used to stabilize channel side slopes and improve the aesthetics of the lower channel.

Dale Creek

For the purposes of considering possible applications, an approximate volume of 50,000 m³ and a peak discharge of 800 m³/s are considered for the 500-year return period debris flow at the fan apex of Dale Creek. These estimates require significant debris entrainment on the fan, which will likely occur only at low return periods. A debris flow of this magnitude would likely cause severe structural damage to buildings on the fan west of Sylvester Road.

Table 22 - Debris Flow Mitigation Alternatives at Dale Creek

Option	Advantages	Disadvantages
Debris Barrier near the fan apex	<ul style="list-style-type: none">▪ Could catch most debris before reaching the fan apex▪ Hidden from view▪ Existing access road	<ul style="list-style-type: none">▪ High impact forces will require massive construction▪ Would far exceed the current value of the assets to be protected
Debris Flow Netting	<ul style="list-style-type: none">▪ Cheaper than debris flow barrier▪ Easy access via existing road	<ul style="list-style-type: none">▪ Would require several debris flow nets in sequence▪ May not prevent debris entrainment on the fan surface

At Dale Creek deflection berms are inadvisable because of a fully developed fan at the creek's mouth. Property acquisition or debris flow netting is the most cost-effective solutions at Dale Creek.

6.0 SHORT TERM CREEK MEASURES

Beginning shortly after the events in mid October, contractors were retained to remove debris from channels that had been affected by debris flows and flood flow. This section is added because the effects of these works will likely affect long-term hazard exposure.

Photographs 16, 17, 29, 30 and 31 show examples of channel works carried out on McNab and Eng creeks. Excavators have used the creeks' talwegs to access the channels. Accumulated channel material is excavated and placed on the channel sidewalls at slope angles between 20° and 40°. The side-casted material is neither consolidated nor armoured by riprap.

In the short-term (weeks to months), the following consequences can be expected from these works:

- decrease in debris flow hazard on the fan from existing (post event) condition due to higher channel conveyance;
- exposure of fine-grained material at the channel bottom and channel sidewalls;
- decrease in channel roughness due to removal of coarse clasts from the channel bottom and, therefore, an increase in water flow velocities which is likely partially offset by self-armouring of coarser clasts;
- undercutting of the channel sidewalls by fluvial erosion and steepening of the banks;
- retrogressive collapse of channel sidewalls where undercut;
- a sharp increase in sediment delivery to the creek channel;
- rapid aggradation in the affected lower gradient channel sections with an associated decrease in conveyance;
- infilling of culverts and bridge crossings; and
- increase in hazard to areas adjacent to the channel by a decrease in conveyance.

Furthermore, the creation of a well-defined channel on a debris flow fan may impede flow avulsion, which leads to spreading of debris and subsequent slowing of the debris mass. A channel will maintain a certain flow depth and cause the debris flow to travel further than it would have had the channel not been excavated.

The rate of the processes listed above will depend on the number and magnitude of floods in the next few months. A field check conducted on January 21, 2004 showed aggradation of 20 to 70 cm for fan channel reaches at Carratt, Eng and McNab creeks. For this reason, the channel works presently carried out at the affected creeks cannot provide sustainable protection to human development on the creek fans.

To decrease aggradation rates in the lower stream channels, channel side slope armouring with riprap and bioengineering techniques is recommended. This would also improve the aesthetics of the creek channels.

7.0 IMPACTS OF CLIMATE CHANGE

It is now well established that excess release of greenhouse gases by humans has altered the Earth's climate over the past 50 years (IPCC, 2001, King, 2004). This alteration is manifested by globally higher temperatures that lead to a number of secondary effects. In addition, for the west coast of Canada, climate models predict a more intensive hydrological cycle that will manifest itself in deeper low pressure systems, higher amounts of total rainfall and possibly higher rainfall intensities. While total rainfall amounts have increased by about 10% over the last century in southwestern British Columbia, evidence for higher rainfall intensities is sporadic and cannot be substantiated yet.

Given these predictions, a number of qualitative statements can be made with regard to debris flow occurrence in southwestern BC in general and at Hatzic Valley specifically.

- Higher average temperatures will lead to a general rise in freezing levels, and thus a rise in snowline. Snow depth will tend to decrease at lower elevations. Snowwater equivalents will likely rise as snow will fall increasingly wet. Snowline elevation and snow thickness are important variables in debris flow initiation because they affect soil saturation. Debris flows are less likely later in winter (February, March) when a thick snow cover persists at higher elevations which functions like a sponge in absorbing and buffering even high amounts and intensities of rainfall. However, at Hatzic Valley, a high proportion of the watersheds' area is below 1000 m where snow thickness decreases rapidly. An increase in the elevation of the snowline and a decrease in snow thickness will therefore increase the likelihood of debris flows by decreasing the snow "sponge" effect.
- Jakob and Weatherly (2003) developed a climatic threshold for landslide initiation on the North Shore Mountains of Vancouver. Their work showed that shallow landslides are most likely to occur when sufficient rain has fallen in the four weeks preceding a storm and a threshold for the 6-hour rainfall intensity is exceeded during a storm. More rain then, with all other factors being equal, would increase the frequency of reaching ground saturation thresholds. Consequently, the probability of debris flow initiation would increase. Similarly, if the intensity of rainstorms increases, the probability of debris flow initiation will increase.

In summary, predicted climatic change scenarios point toward a longer debris flow season and an increase in the probability of debris flow occurrence. Together, these factors may offset some of the effects of watershed stabilization due to slow tree re-growth and an increase in root strength. It is unclear whether predicted climate change will influence the magnitude of debris flows. Any future development in the study area should acknowledge the effects of climate change on debris flow occurrence as discussed in this section.

8.0 SUMMARY

A series of debris flows occurred in the evenings of October 16 and 17 on the western slopes of Hatzic Valley and descended Field Creek, Carratt Creek, and Eng Creek. Debris floods also occurred on McNab Creek, Saporano Creek, Pattison Creek and Dale Creek. The following points summarize the main findings of this report:

8.1 Debris Flow Initiation

1. At Field Creek, the debris flow was initiated by small channel side slope failures that quickly entrained material and evolved into a debris flow with approximately 200 m³/s near the fan apex and a total volume of approximately 5000 m³.
2. Carratt Creek debris flow of Oct. 16, 2003 had a total volume of 30,000 m³ and a peak discharge of 5000 m³/s while Eng Creek witnessed a debris flow with a total volume of 30,000 m³ and a peak discharge of 5000 m³/s.
3. At Carratt and Eng creeks, the debris flows originated from shallow debris avalanches in the upper watersheds that were logged in the 1960s and 1970s. Most landslides can be attributed to logging and poor forest road construction. Deterioration of root strength, collapse of old forests road fills and hydrologic disturbances along cutblock boundaries are believed to be the primary reasons for the initiation of debris flows. Although some failures did originate in old growth forest, logging-related landslides led to a significant increase in the magnitude and thus runout of the debris flows at Carratt and Eng creeks. The negative impact of logging practices on slope stability in the area has been recognized in numerous previous reports and memoranda.
4. At Dale Creek, most damage was caused by the overtopping of a small culvert draining the road ditch on the east side of Sylvester Road, which caused failure of the road embankment on the west side of Sylvester Road. There was significant debris movement at Dale Creek but it was confined to the higher fan reaches well upstream of the developed area.

8.2 Debris Flow Probabilities

Debris flow probabilities were estimated from air photograph interpretation and a review of previous reports and memos. These should be understood as minimum estimates (i.e. there were likely many more debris flows in the past centuries) and could be significantly improved by detailed dendrochronologic investigations.

1. According to hearsay, there has not been a debris flow for at least 80 years at Field Creek. Old impact scars on trees suggest that debris flows may have occurred in this

time period but were not recognized or documented.

2. Debris flows or debris floods occurred on Carratt Creek sometime between 1963 and 1968, in 1980, 1983, 1984, 1989, 1990 and 2003 resulting in a debris flow frequency between 5 and 10 years.
3. Debris flows or debris floods have occurred on Eng Creek in the early 1960s (there may have been a debris avalanche), 1980, 1984, 1986 and 2003 resulting in an average debris flow frequency of 5 to 15 years.
4. Debris flows on McNab Creek have occurred in 1980, 1984, 1992 and 2003 resulting in an average frequency of 6 years.
5. An unspecified debris movement occurred at Dale Creek in 1990. It is unclear if this was a debris flow. The recurrence of debris flows at Dale Creek is estimated to 10-20 years.

8.3 Debris Flow Magnitude of the 500-year Return Period Event

Total volume and peak discharge of the 500-year return period event (the design event) was estimated using empirical formulae and channel yield rates as determined from air photographs and limited fieldwork.

1. At Field Creek, the volume of the design event is estimated to 30,000 m³ with a corresponding peak discharge of 500 m³/s.
2. At Carratt Creek, the volume of the design event is estimated to 100,000 m³ with a corresponding peak discharge of 1500 m³/s.
3. At Eng Creek, the volume of the design event is estimated to 100,000 m³ with a corresponding peak discharge of 1500 m³/s.
4. At McNab Creek, the volume of the design event is estimated to 100,000 m³ with a corresponding peak discharge of 1500 m³/s.
5. At Dale Creek, the volume of the design event is estimated to 50,000 m³ with a corresponding peak discharge of 800 m³/s.

8.4 Debris Flow Consequences

Having evaluated the relative debris flow hazard at each subject creek, the consequences of the design event have to be evaluated qualitatively to gain an understanding of the risk for each creek. The consequences include damage to property and the potential for injury and

loss of life.

8.5 Debris Flow Risk

Debris flow risk is determined from a combination of debris flow hazard and consequences. Debris flow hazard is a function of the probability and magnitude of a debris flow. The LOW, MEDIUM, HIGH risk system used here is qualitative and does not suggest any specific land use strategies.

1. Debris flow risk at Field Creek is classified as HIGH for the medium return period events (20 to 100 year return period) and MEDIUM for the low return period event (100 to 500 year return period).
2. Debris flow risk at Carratt Creek is classified as HIGH for the medium return period events (20 to 100 year return period) and MEDIUM for the low return period event (100 to 500 year return period).
3. Debris flow risk at Eng Creek is classified as MEDIUM for the medium return period events (20 to 100 year return period) and MEDIUM for the low return period event (100 to 500 year return period).
4. Debris flow risk at McNab Creek is classified as MEDIUM for the medium return period events (20 to 100 year return period) and MEDIUM for the low return period event (100 to 500 year return period).
5. Debris flow risk at Dale Creek is classified as MEDIUM for the medium return period events (20 to 100 year return period) and MEDIUM for the low return period event (100 to 500 year return period).

8.6 Mitigation Alternatives

A number of structural mitigation alternatives were provided for the subject creeks including debris barriers, debris basins, deflection berms and channel armouring. In addition, property acquisitions were proposed.

1. At Field Creek, the two most cost-effective solutions would be a property acquisition or the construction of a deflection berm in an inverse V-shape around the two inhabited buildings on the south side of Field Creek. Alternatively, a series of debris flow nets could be erected near the fan apex.
2. At Carratt Creek, the most cost-effective alternative would likely be the construction of a setback dyke and channel works on the north side of the existing Carratt Creek. The

dyke would have to parallel the creek up to the fan apex and tie into higher ground. Upgrading of the southern berm may also be necessary.

3. At Eng Creek, the two most cost-effective solutions would entail property acquisition and / or the construction of a 2-3 m high berm paralleling the contours immediately upstream of the existing houses.
4. At McNab Creek, the most cost-effective solutions would be property acquisition or construction of deflection berms to direct debris into the undeveloped lower fan portion and protect areas west of Sylvester Road and north of the stream crossing.
5. At Dale Creek, the most cost-effective solution would be property acquisition or installation of debris flow netting at the fan apex.

9.0 RECOMMENDATIONS

This preliminary assessment has provided an understanding of the magnitude and severity of debris flows in the study area. However, the detail of the study is insufficient to provide a tool for site specific management of the debris flow risk. For this purpose, BGC recommends the following additional studies:

1. A detailed study of debris flow hazards and risks on the eastern slopes of Hatzic Valley between Dewdney and Cascade Creek. This study should include as a minimum the following creeks (from North to South):
 - Field Creek
 - Carratt Creek
 - Eng Creek
 - McNab Creek
 - Saporano Creek
 - Pattison Creek
 - North and South Herford Creek
 - Dale Creek
 - Storey Creek

Buildings exist in the debris flow runout zones of the above creeks. The costs of such detailed studies per creek would range between \$ 35,000 and \$ 70,000. The deliverables would include a set of comprehensive reports in which the magnitude and frequency of debris flows is determined, the design magnitudes calculated for each creek and the debris flow hazard modelled. A set of conceptual designs for debris flow mitigation alternatives could be presented and costed for each creek. Based on this work, local authorities could make decisions on how to manage debris flow risk in Hatzic Valley.

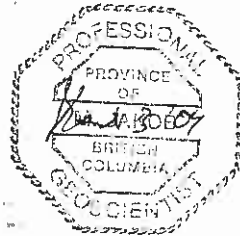
2. The discontinued Level 1 Watershed Study should be completed and reviewed by an expert on forestry-related landslides and debris flows.
3. A detailed forest road stability assessment should be initiated in which all forest roads in the upper watersheds of the above creeks are visited by qualified personnel and prescriptions are made to deactivate those road portions that pose the highest risk for failure;
4. A Coastal Watershed Assessment Procedure (CWAP) should be conducted and peer reviewed for all study watersheds and adjacent smaller drainages with downstream resources.

5. Slope stability experts should scrutinize all future logging plans in the study area watersheds and nearby creeks.
6. The bedrock failure in the upper watershed of Pattison Creek is investigated by a bedrock landslide specialist with reference to potential catastrophic failure and transformation into a rock avalanche, which could destroy development downstream.
7. A long-term management plan should be compiled on how to address recurrent debris flows and continuous streambed aggradation.
8. A hydroclimatic threshold for debris flow initiation should be developed for specific locations in the Fraser Valley, which could be used to develop an early warning system (i.e. a landslide advisory that can be issued over the radio or by calling residents in hazardous areas).
9. A public meeting should be held to advise affected and interested residents of the findings of this study.
10. Seek public input to any further hazard management strategies.
11. This report should be distributed to the Fraser Valley Regional District, the Department of Fisheries and Oceans as well as the Ministry of Water, Land and Air Protection, Water Management Branch at their Surrey office.
12. Ensure that all site-specific mitigation measures are incorporated into any land development approvals (building permits etc.) that are issued in the mapped hazard areas.
13. Consider the implementation of a hydroclimatic threshold advance warning system to alert residents when conditions become ripe during which debris flow initiation is likely.
14. If the decision is made not to proceed with further study it is recommended that periodic monitoring of the subject watersheds and channels be conducted to identify instabilities or channel changes that may warrant further public advisory or reconsideration of debris flow structures.

10.0 CLOSURE

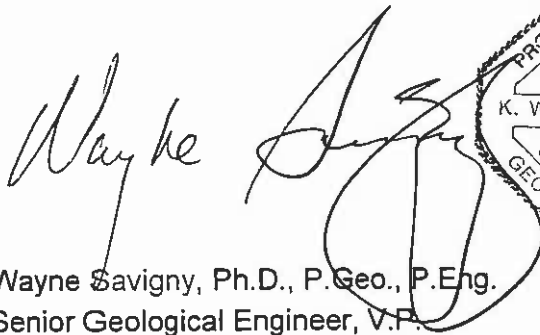
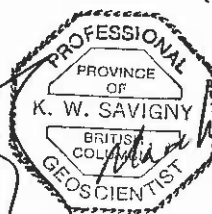
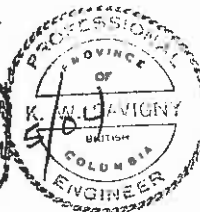
We trust the information provided in this brief report meets your current requirements. If you have any questions or comments, or if we can be of further assistance, please do not hesitate to contact the undersigned.

Sincerely,
BGC ENGINEERING INC.
per:



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

Reviewed by:



Wayne Savigny, Ph.D., P.Geo., P.Eng.
Senior Geological Engineer, V.P.

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APPENDIX I

Background Information On Debris Flows And Debris Floods

DEFINITION

Steep mountain creeks are typically subject to a spectrum of events, ranging from clearwater floods to debris flows to falls as shown by Figure A-1. Slides and falls are not confined to stream channels but can follow channels for part of their descent.

Debris flows are a form of rapid water-saturated channelized landslide. Velocities typically range between 5 and 10 m/s, but some fine-grained debris flows have been known to travel up to 20 m/s. They are most likely to occur on small, steep creeks that have abundant sources of debris. Debris flows are sometimes alternatively referred to as *debris torrents* where they are particularly coarse in nature and carry large amounts of organic debris or *mudflows* where they are particularly fine in nature. Volcanic debris flows are referred to as *lahars*.

Debris floods are a very rapid, surging flow of water, heavily charged with debris, in a steep channel (Hungar et al., 2001). The sediment may, furthermore, be transported in the form of massive surges, leaving sheets of poorly sorted debris ranging from sand to cobbles or small boulders. Sediment surges in a debris flood are propelled by the tractive forces of water overlying the debris and flow velocities are comparable to those of water floods. Discharges of debris floods are commonly 2 to 5 times higher than water floods of 100 to 200-year return periods (Jakob and Jordan, 2001).

OCCURRENCE

Debris flows and debris floods tend to occur in wet weather, but are not necessarily coincident with record rainfall or flood events. Recent research has shown that a complex interaction of antecedent moisture, total storm rainfall, rainfall intensity and snowmelt input has to exist for the initiation of shallow landslides and thus debris flows.

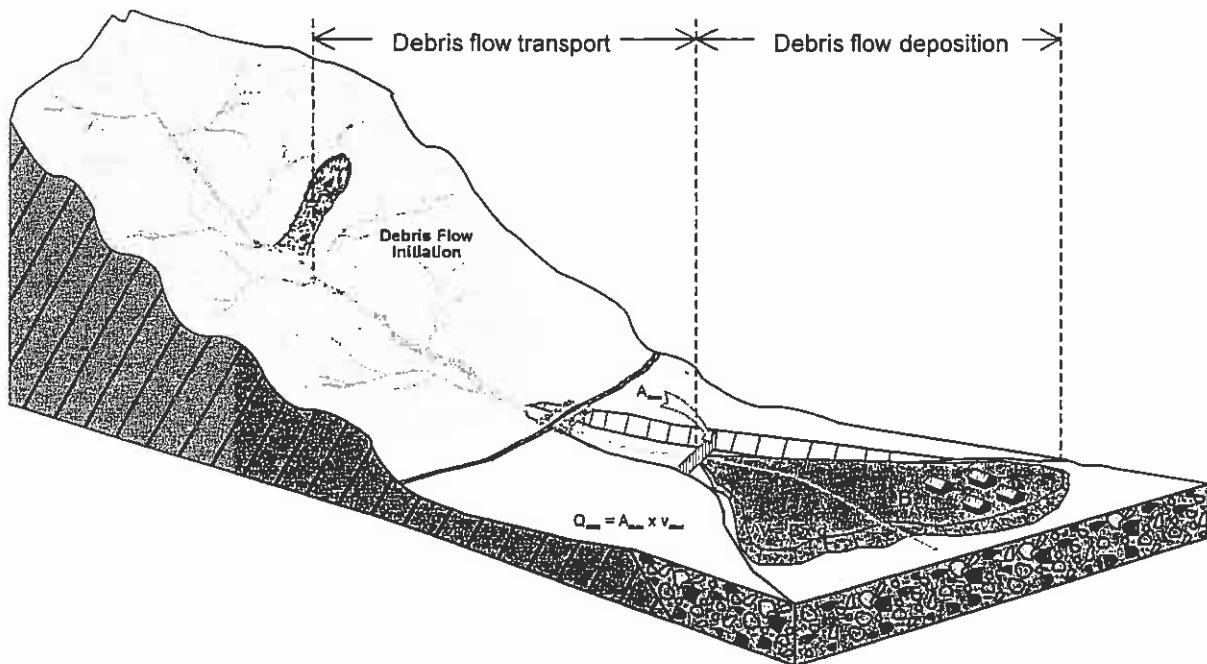
Debris flow and debris flood occurrence can be described by three consecutive processes as follows and shown in Figure A-1.

- *Initiation* where a mass movement is triggered at the source area in the creek headwaters. Possible trigger mechanisms include debris slides, logjam release, flood surges, and creek bed instability. Initiation may occur through direct momentum transfer from a failure or by temporary damming of the creek channel and subsequent dam outbreak flood.
- *Transport* of the debris flow down the creek channel. The transport zone is characterized by substantial bulking (increase in sediment volume and peak discharge by scour and debris entrainment). Channel yield rates (amount of material scoured by unit channel length) strongly depend on the time passed since the last debris flow, which allows

mineral and organic material to accumulate.

- *Deposition* where either the channel becomes laterally unconfined or the creek gradient flattens to the point that there is insufficient energy for continued movement. Depositional landforms are known as colluvial fans. The runout distance of debris depends on the debris flow volume, sediment concentration and composition, the geometry of the creek fan and the roughness of the fan surface (houses, trees, terrain undulations). Damage in creek fan areas during debris flow deposition can be catastrophic. The nature of the deposited material is highly variable, but typically covers a wide range from mud to boulders, and usually also includes a significant wood debris component. Debris flow deposition may also result in flooding of adjacent areas as a result of the creek channel avulsions.

Figure A-1 showing Debris flow initiation, transport and deposition zones



Q_{max} is the peak discharge of debris flows and B is the area inundated by debris flows.

DEBRIS FLOW AND DEBRIS FLOOD PROBABILITY

While significant floods occur virtually every year on a creek system, debris flows and debris floods are usually an intermittent occurrence. Typical debris flow and debris flood return periods range from 5 to 50 years, however, occurrences at lower or higher return periods have been recorded in the Pacific Northwest. Debris flow occurrence can be put into perspective by considering geomorphologic processes since the most recent glaciation about 10,000 years ago. In the first several hundred years following glaciation, the landscape was

unforested and littered with glacial debris. Debris flow activity is believed to have been considerably higher than today during the early Holocene epoch. As the landscape became forested and watersheds stabilized, debris production and debris flow activity gradually decreased. However, there is reason to believe that if the present trend of increasingly wetter conditions in coastal areas continues, debris flow occurrence will increase in frequency and possibly magnitude. Changes in land use such as forestry activities ski area development or mining can drastically change frequency-magnitude relationships. Similar changes can be caused by natural triggers such as massive windthrow or fire.

In general, the frequency of debris flows on a particular creek is a function of:

- availability of debris supply sources that contribute materials to the main creek channel and its tributaries (it is necessary to differentiate between material supply-limited vs. material supply-unlimited drainage basins)
- degree of instability and level of activity of the debris supply sources
- characteristics of the debris supply source (fine vs. coarse material, consolidated vs. unconsolidated)
- existence of potential triggers of debris flows (debris slides, rockfall, avalanches)
- capability of a creek channel to transport a debris flow (gradient, channel cross-section, longitudinal profile, channel roughness)
- frequency of hydroclimatic events that have the capability of triggering debris flows
- history of debris flows in the basin; and
- land use changes, massive windthrow and fire

As debris accumulates, a system gradually becomes "ripe" for a debris flow. The rate at which debris accumulates in a channel is a function of basin type, bedrock composition and distribution, land use, fire history and Quaternary history of the watershed.

BASIN TYPES

Recent research (Jakob, 1996) has identified two distinctly different basin types. One type, referred to as weathering-limited or supply-limited, is characterized by those basins that have a limited source of sediment and thus require recharge after a debris flow event for the next one to occur. In other words, even an exceptionally intensive storm will not trigger a debris flow if not enough sediment has accumulated to produce a debris flow. Because debris flow occurrence is thus time dependent (i.e. the timing and magnitude of a subsequent debris flow will depend on the time elapsed since the last event to allow sufficient channel recharge), encounter probabilities cannot be calculated as is commonly done using binomial or Poisson formulae (McClung, 2000). The other basin type is referred to as transport-limited or supply-

unlimited. In those basins, there is a quasi-infinite amount of sediment available for transport and a debris flow can be triggered as soon as a critical climatic threshold (rainfall, rain-on-snow) is exceeded.

From the above description, it is clear that transport-limited basins witness a higher frequency of debris flows than weathering-limited basins. Examples for transport-limited basins are young volcanic complexes that rapidly shed material into the channel system, or basins with massive Quaternary deposits in the source area of debris flows.

APPENDIX II

Meteorological Conditions of the October 2003 Debris Flows

INTRODUCTION

The major rainstorm that travelled over southwestern BC in October 2003 was an extraordinary event from a climatic perspective. The initial impulse of warm moist air originated in the southwest and generated record rainfalls over southern Vancouver Island and the Lower Mainland on October 16th and 17th. Greater Victoria and the Lower Mainland recorded a drop in rainfall amounts on the 18th but much of the South Coast continued to receive significant rains through the 21st. This appendix provides a meteorological overview of the initial phase of the rainstorm (16th and 17th) and focuses on the specific meteorological conditions in the Stave Lake area by examining radar imagery.

METEOROLOGICAL OVERVIEW

On the evening of October 15th, 2003, a westerly flow aloft drove a major Pacific frontal system onto the BC Coast (Fig. 1a). While an associated low-pressure system in the Gulf of Alaska deepened, the flow towards BC became increasingly southwesterly. This increased the supply of sub-tropical moisture as a "Pineapple Express" circulation became well established. A series of moist impulses surged along the frontal stream as it remained stalled across southwestern BC for the next several days. This sequence of events can be seen on the GOES Infrared Satellite imagery in Figures 1a,b, c and d.

Table 1 contains a summary of rainfall measurements taken between October 15th and the 21st, 2003, for a number of the meteorological service of Canada stations on the South Coast. Some of the heaviest rains occurred over southern Vancouver Island on October 16th. This was partly because southwesterly winds aloft avoided the Olympic Mountains and prevented the formation of a "rainshadow effect" which normally protects southern Vancouver Island from the full onslaught of Pacific storms. Port Renfrew reported the highest amounts of rain, with nearly 200 mm on the 16th. Victoria Airport established an all time daily precipitation record of 136 mm on the 16th (exceeding the previous record of 93 mm by 46%), and in one 6 hour period they received 51 mm which is 67% of the normal monthly total! The Lower Mainland also received extreme rainfalls. For example, during the 16th and 17th, Vancouver Airport established a new 48-hour rainfall record of 141 mm with an estimated return period of nearly 1000 years (such statistics must be used with caution because of the increasing uncertainty involved in long-term extrapolations). On the 18th, southerly winds aloft reformed the Olympic rainshadow effect and provided some respite to the Victoria area. However, another major impulse reached the coast on October 20th.

THE STAVE LAKE AREA

Debris flows in the Stave Lake area occurred during the heavy rains of October 16th and 17th. The closest Environment Canada Rain Gauge is located at Haney UBC Research Forestry Station, which reported 146 mm on the 16th and an additional 60 mm on the 17th.

Environment Canada's weather radar was employed to estimate the precipitation. Hourly precipitation estimates for the evening of October 16th are displayed in Figure 2a,b, c, and d while estimates for the evening of the 17th are contained in Figure 2e,f,g, and h. On the evening of the 16th, estimated radar rainfall rates of up to 7.5 mm/hr persisted in the Stave watershed with local rates of up to 15 mm per hour (orange). Because heavy rainfall can attenuate radar signals, the actual maximum rainfall rates in this case may have been as much as 3 times higher than estimated.

On the evening of the 17th the rainfall rates over Stave Lake of 2.5 to 7.5 mm per hour dropped off rapidly between 17:00 and 18:00 PST as the initial phase of the rainstorm began to subside.

Table 1
October 2003 Daily Precipitation Measurements [mm]
Environment Canada Climate Network (preliminary data)

Station	Oct 15	Oct 16	Oct 17	Oct 18	Oct 19	Oct 20	Oct 21	TOTAL
Port Renfrew	85.8	198.8	105.6	66.8	55.2	51.6	3.8	567.6
Squamish Airport	16.6	102.2	137.0	79.0	51.0	85.6	5.0	476.4
Cowichan Lake Forestry	62.4	117.8	98.8	44.2	36.4	50.6	4.2	414.4
Upper Squamish	30.4	117.1	103.5	66.8	11.8	67.6	0.8	398.0
Alberni Robertson Cr	39.8	67.8	112.0	69.6	37.4	15.6	2.7	344.9
Haney UBC Research Forestry	44.2	145.8	59.5	19.0	11.0	51.8	1.2	332.5
Port Alberni	7.6	77.2	66.8	122.6	1.4	50.2	0.4	326.2
Malahat	15.8	159.6	35.8	0.6	16.6	81.8	6.4	316.6
Agassiz CDA	3.6	99.0	86.6	0.2	17.4	69.4	31.4	307.6
Sheringham Point	13.8	140.0	46.6	4.8	24.4	52.8	11.0	293.4
Tofino Airport	60.4	72.4	89.8	43.0	16.6	4.6	1.6	288.4
Hope Airport	2.5	72.0	101.5	0.0	15.5	63.5	27.5	282.5
Victoria Int'l Airport	13.2	136.0	32.6	0.4	15.4	73.4	7.6	278.6
Pitt Meadows CS	12.2	136.6	73.8	0.4	15.2	21.6	14.8	274.6
Abbotsford Airport	12.4	93.8	73.6	0.0	11.8	50.6	25.0	267.2
Vancouver Harbour	0.0	141.8	77.8	2.0	7.4	29.4	3.0	261.4
White Rock CS	11.6	119.0	56.6	0.0	6.8	30.2	14.8	239.0
West Vancouver	2.8	97.8	88.4	4.6	9.0	27.6	1.0	231.2
Whistler	0.0	77.3	71.4	42.2	15.2	15.9	0.7	222.7
Tsawassen Beach	34.0	88.2	41.0	5.0	14.0	27.4	0.0	209.6
Estevan Point	11.4	74.2	43.8	51.8	0.6	18.2	0.2	200.2
Vancouver Int'l Airport	12.8	85.0	55.8	0.6	6.0	25.4	4.4	190.0
Nanaimo Airport	M	54.0	33.8	10.2	25.4	13.2	TR	136.6
Powell River	23.0	27.2	41.6	25.6	14.0	0.8	0.8	133.0
Campbell River Airport	32.4	22.0	28.0	17.4	26.4	1.8	1.0	129.0
Comox Airport	13.6	37.4	16.2	32.6	0.4	21.0	TR	121.2

Figure 3a. Cumulative rainfall data at the GVRD Maple Ridge Rainfall Gauge for October 16, 2003 showing Doppler Radar data and ground data. Note the strong deviation between predicted radar rainfall amounts and the data from the rain gauge. A steepening in slope of the red line indicates an increase in rainfall intensities. Therefore, highest intensities were recorded at the Maple Ridge station between 10 AM and 2 PM and again at around 5 PM on the 16th of October.

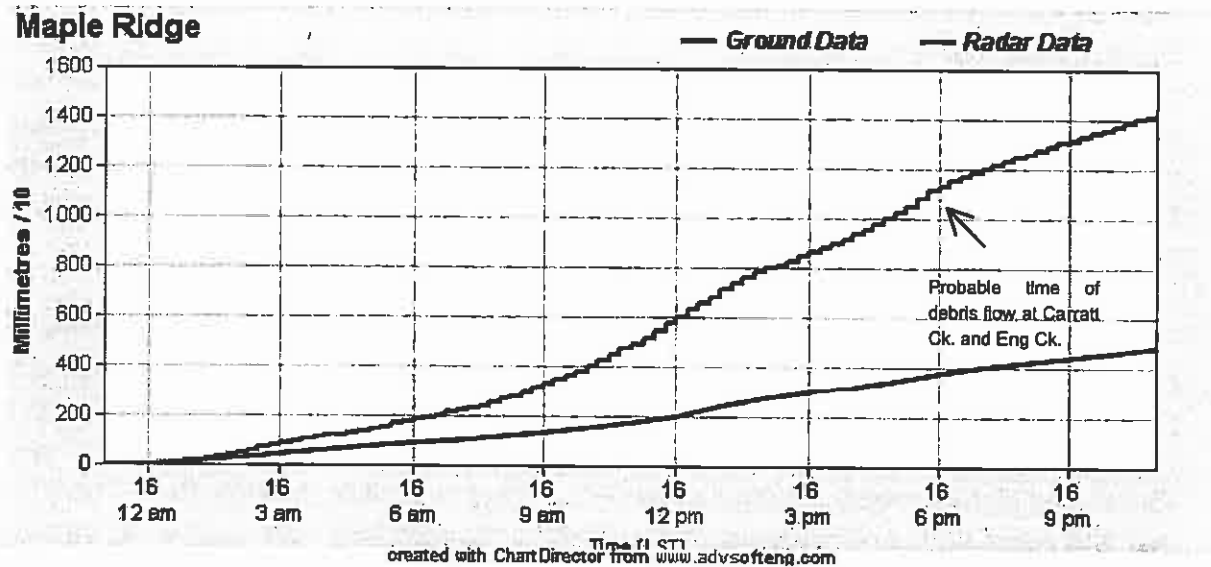
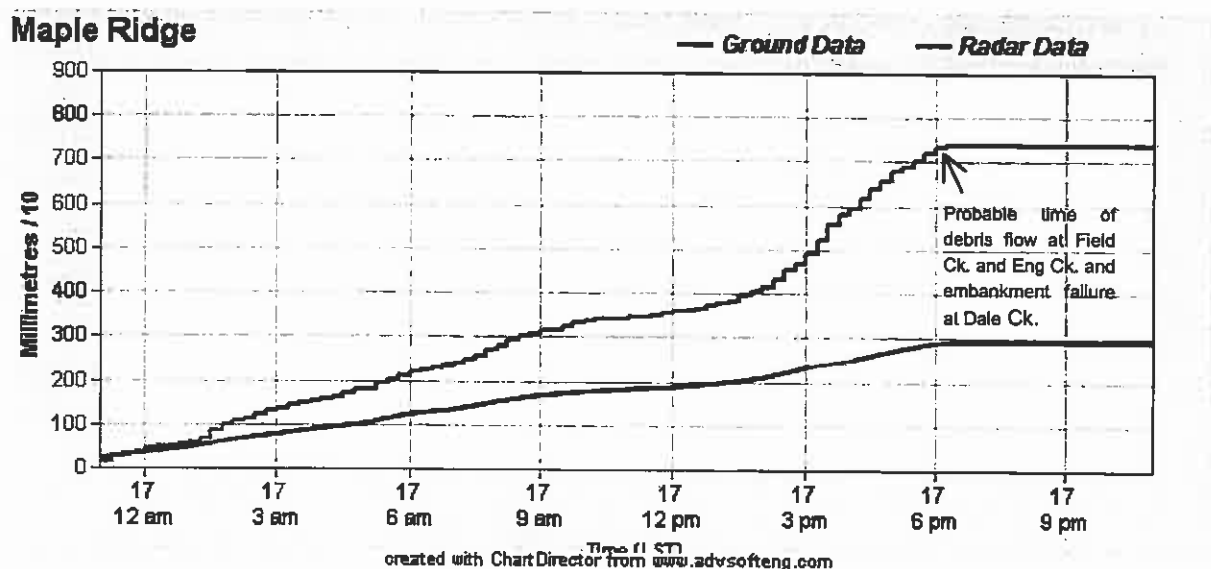


Figure 3b. Cumulative rainfall data at the GVRD Maple Ridge Rainfall Gauge for October 17, 2003 showing Doppler Radar data and ground data. Note the abrupt increase in rainfall intensity between about 2 PM and 6 PM at the Maple Ridge rainfall station. The debris flow at Field Creek and the second debris flow at Eng Creek coincide with the tail end of this increase.



DISCUSSION AND SUMMARY

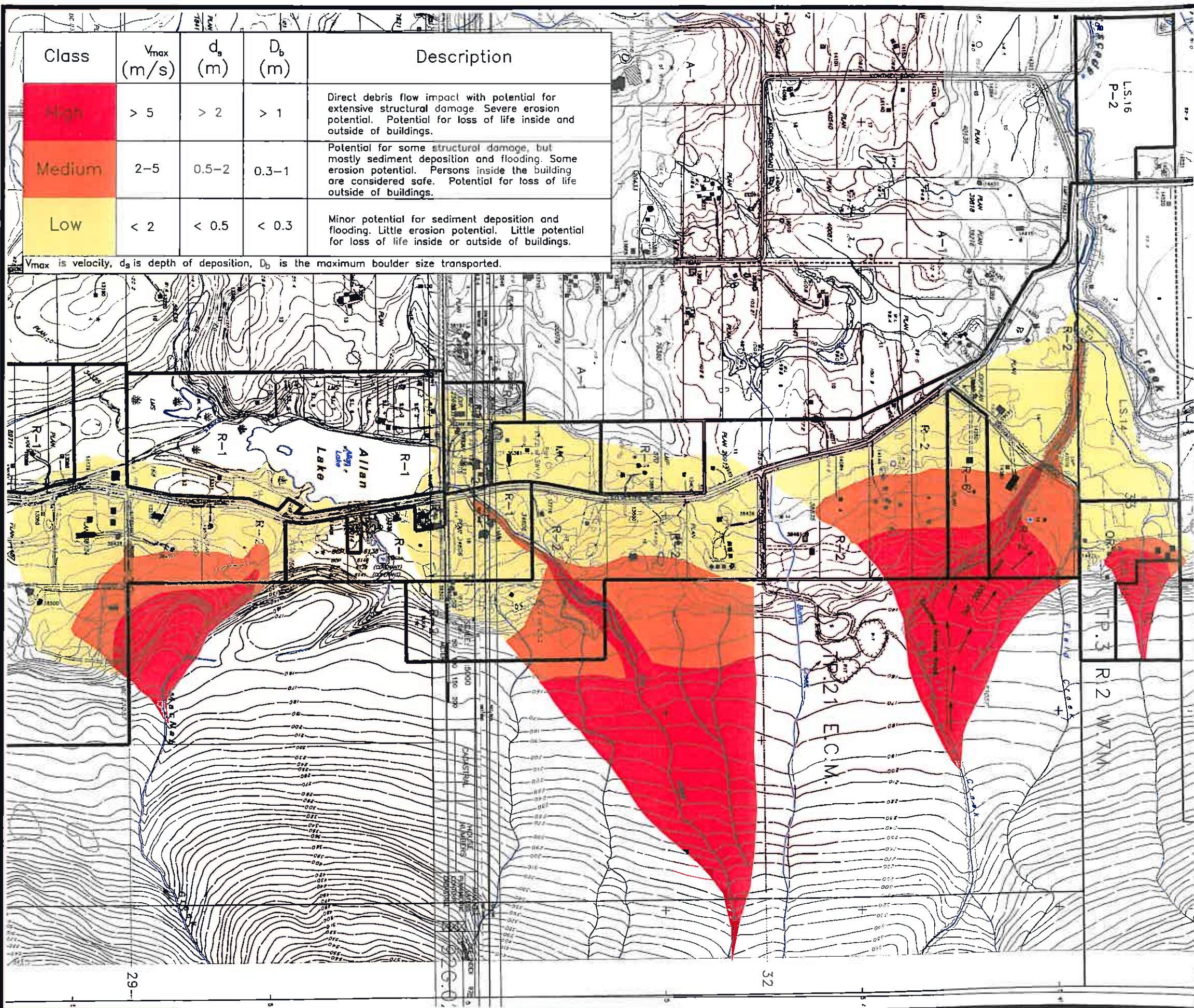
The storm of October 15 to 17, 2003 was unusual with respect to the vast amounts of rain that fell over short time periods over the Lower Mainland, exceeding previous records by percentages never observed before. This observation raises the question of why debris flows are not much more abundant in the Lower Mainland. Jakob and Weatherly (2003) have shown that the four-week cumulative rainfall prior to a significant rainstorm is highly significant in determining if a substantial rainstorm will trigger debris flows or not. BGC hypothesizes that had there been significant (> 150 mm) rainfall amounts from mid September to mid October (depending on the site, there were less than 50 mm cumulative rainfall), the October storm would have likely triggered tens if not hundreds of debris flows in the Lower Mainland. This observation emphasizes that if a similar storm pattern is observed in the future at times where antecedent rainfall amounts are high (typically in November to February), a regional landslide advisory could be issued.

The rains of October 15 through 16, 2003 gradually saturated forest soils that has been relatively dry from an extended drought in the summer of 2003. By the evening of the 16th, pore water pressures had decreased overall soil strength in the study area watersheds and disturbed areas (cutblocks, road fills) failed as debris avalanches lead to debris flows at Carratt and McNab creeks. Rainfall continued at lower intensities through the 17th until in the late afternoon, then early evening rainfall intensity dramatically increased once again and triggered debris flows at Field Creek and a second debris flow at Eng Creek. At this time, pore water pressures were high enough to trigger debris avalanches in undisturbed terrain. Rains quickly subsided after about 6 PM on October 17 and no further debris flows occurred.

This preliminary analysis has once again demonstrated the need for the establishment of a regional hydroclimatic threshold for landslide initiation. Advances in real-time monitoring by Environment Canada by means of satellite and radar imagery would allow this threshold to be combined with real-time meteorological observations to produce a realistic landslide advisory.

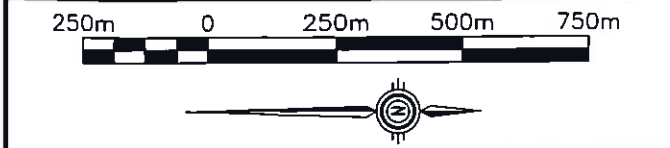
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High	> 5	> 2	> 1	Direct debris flow impact with potential for extensive structural damage. Severe erosion potential. Potential for loss of life inside and outside of buildings.
Medium	2-5	0.5-2	0.3-1	Potential for some structural damage, but mostly sediment deposition and flooding. Some erosion potential. Persons inside the building are considered safe. Potential for loss of life outside of buildings.
Low	< 2	< 0.5	< 0.3	Minor potential for sediment deposition and flooding. Little erosion potential. Little potential for loss of life inside or outside of buildings.

V_{max} is velocity, d_s is depth of deposition, D_b is the maximum boulder size transported.



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Notes:

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- The hazard areas are approximate and are based on judgement and limited field checking. This map is not intended for site-specific landuse decisions or for construction.
- Note that contours change at 50 m from a 2 m interval to a 10 m interval.
- This map is based on a hypothetical 500-year return period debris flow.
- Cadastral information was obtained from the Fraser Valley Regional District, and supplemented with field observations.
- Adjacent streams were not investigated as part of this study.
- This hazard map is a "snapshot" in time. Future debris flows or artificial alterations of the fan morphology may change the hazard zones.



Data Source: 1:5000 Data from Fraser Regional Valley District.

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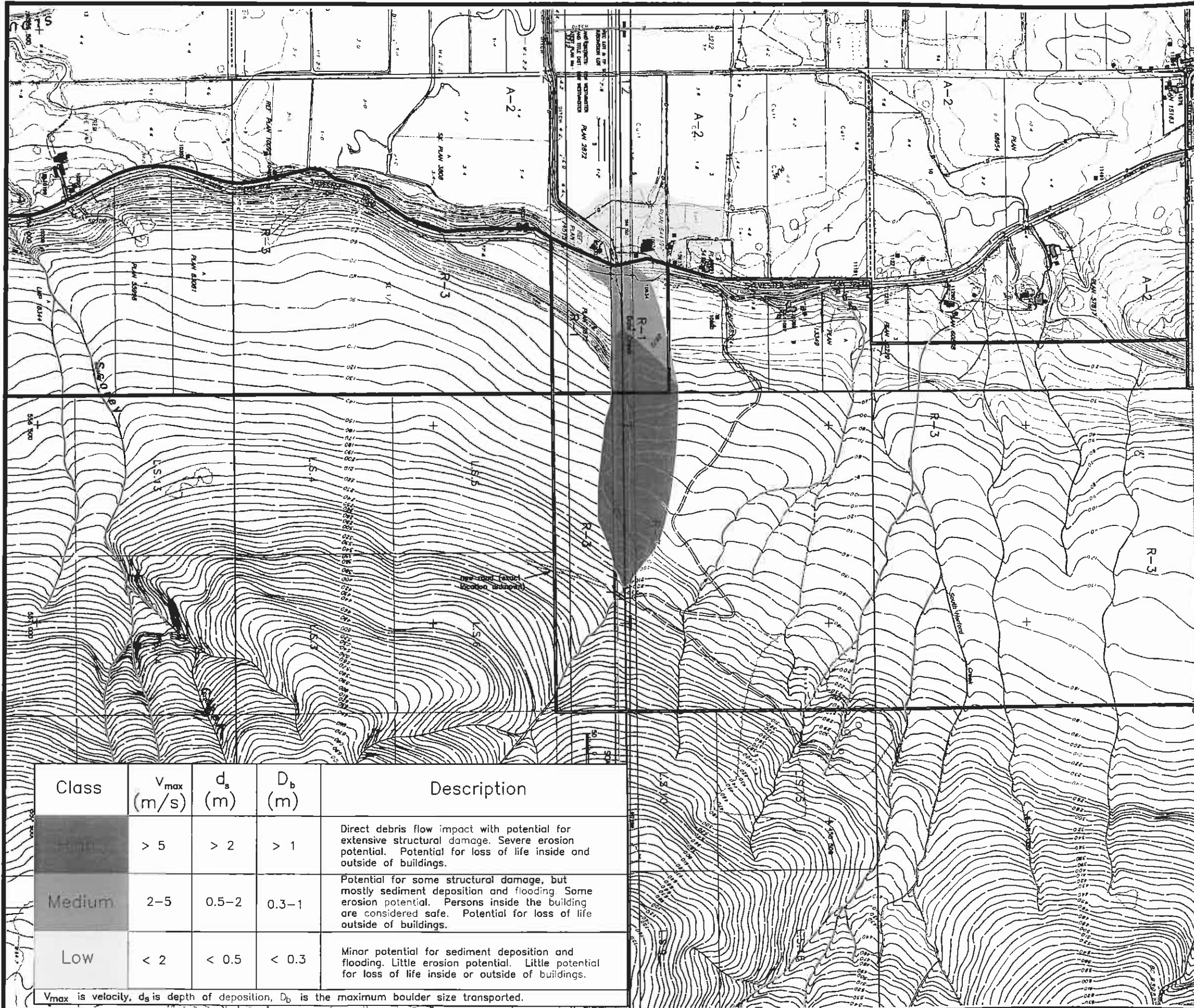
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REV.	DATE	REVISION NOTES	DRAWN	CHECKED	APPROVED

SCALE:	1:10,000
DATE:	JANUARY 2004
DRAWN:	GEJ
DESIGNED:	MJ
CHECKED:	MJ
APPROVED:	

PROJECT	PRELIMINARY DEBRIS-FLOW HAZARD AND RISK ASSESSMENT		
TITLE	PRELIMINARY DEBRIS FLOW HAZARD MAP AT FIELD, CARRATT, ENG AND MACNAB CREEKS FOR THE 500-YEAR RETRUN PERIOD DEBRIS FLOWS		
PROJECT No.	0378-001-01	FIGURE No.	4-1
REV.			0



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REV.	DATE	REVISION NOTES	DRAWN	CHECKED	APPROVED

SCALE:	1:10,000
DATE	JANUARY 2004
DRAWN:	GEJ
DESIGNED:	MJ
CHECKED:	MJ
APPROVED:	

PROJECT	PRELIMINARY DEBRIS-FLOW HAZARD AND RISK ASSESSMENT		
TITLE	PRELIMINARY DEBRIS FLOW HAZARD MAPS AT DALE CREEK FOR THE 500-YEAR RETURN PERIOD DEBRIS FLOW		
PROJECT No.	0378-001-01	FIGURE No.	4-2
REV.			0

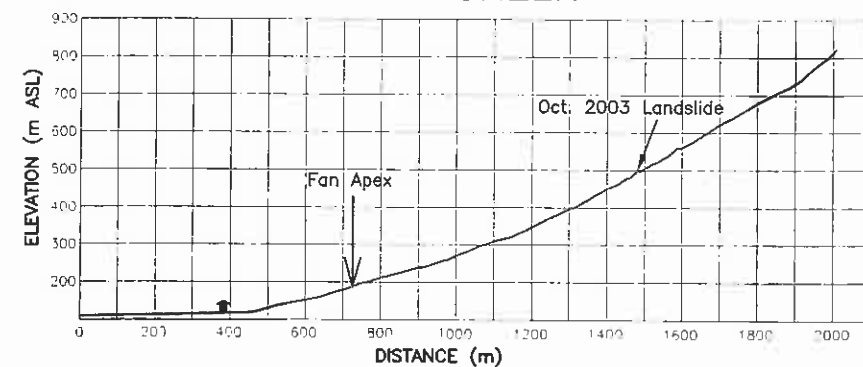
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High	> 5	> 2	> 1	Direct debris flow impact with potential for extensive structural damage. Severe erosion potential. Potential for loss of life inside and outside of buildings.
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v_{max} is velocity, d_s is depth of deposition, D_b is the maximum boulder size transported.

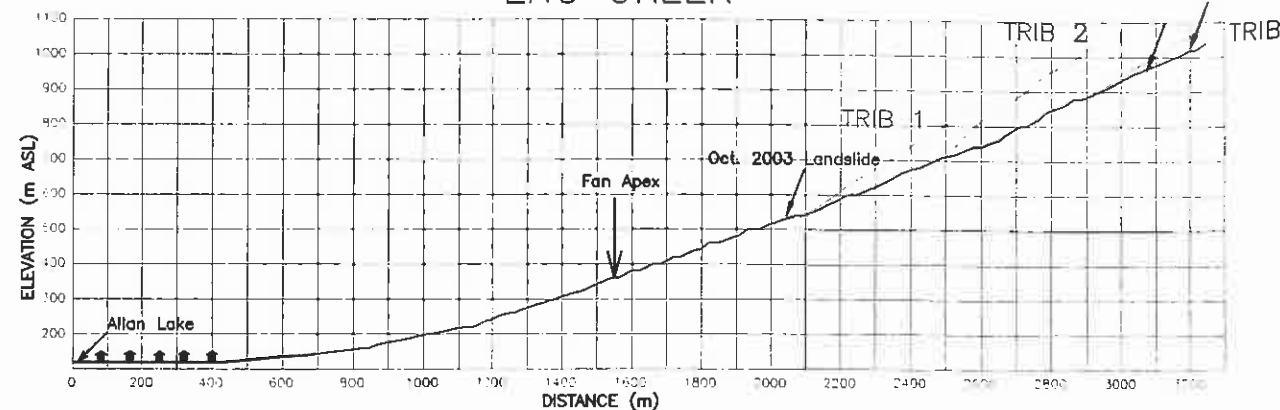


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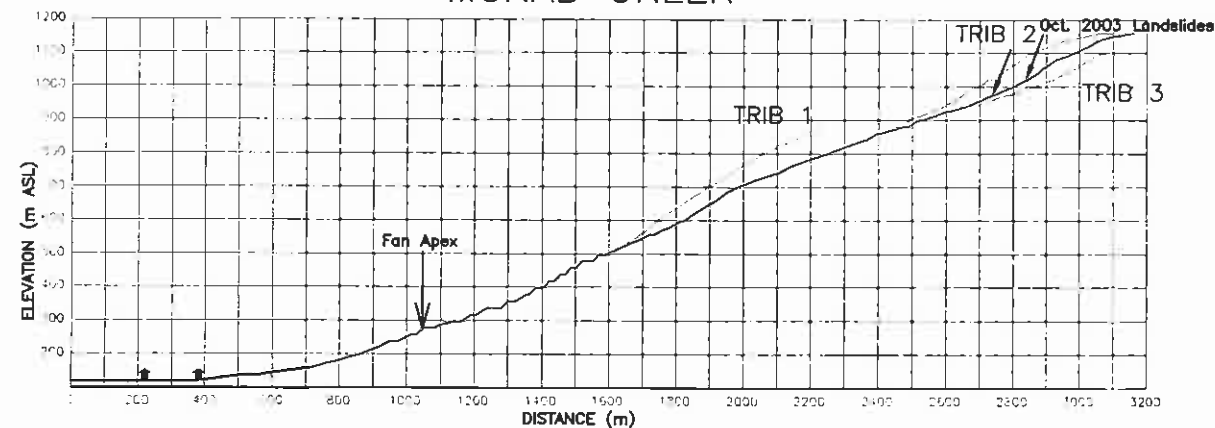
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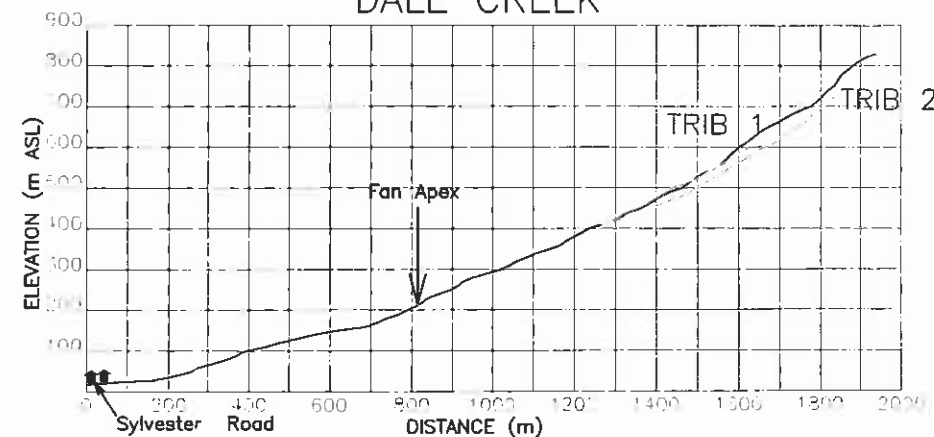
ENG CREEK



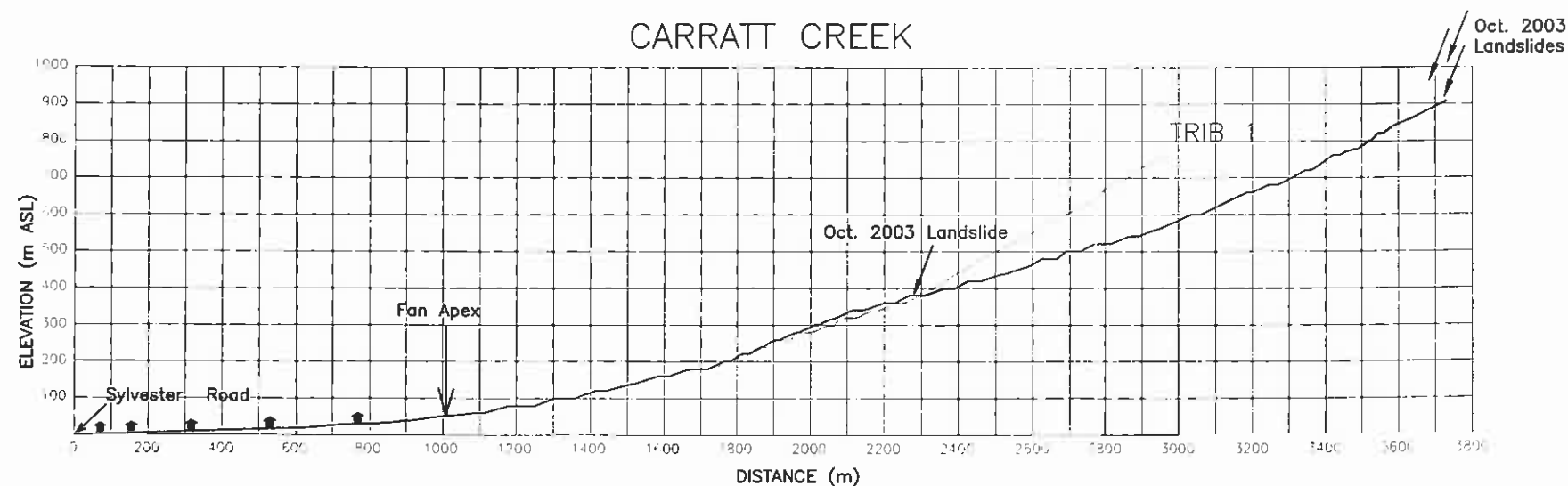
MCNAB CREEK



DALE CREEK



CARRATT CREEK



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Notes:

- Locations of houses, fan apices, roads and landslides are approximate.
- House locations are measured perpendicular to the creek alignment.

Data Source: 1:20,00 B.C. TRIM Data & 1:5,000 Data from Fraser Valley Regional District.

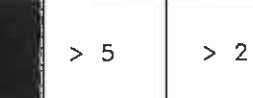
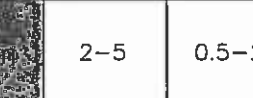
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REV	DATE	REVISION NOTES	DRAWN	CHECKED	APPROVED

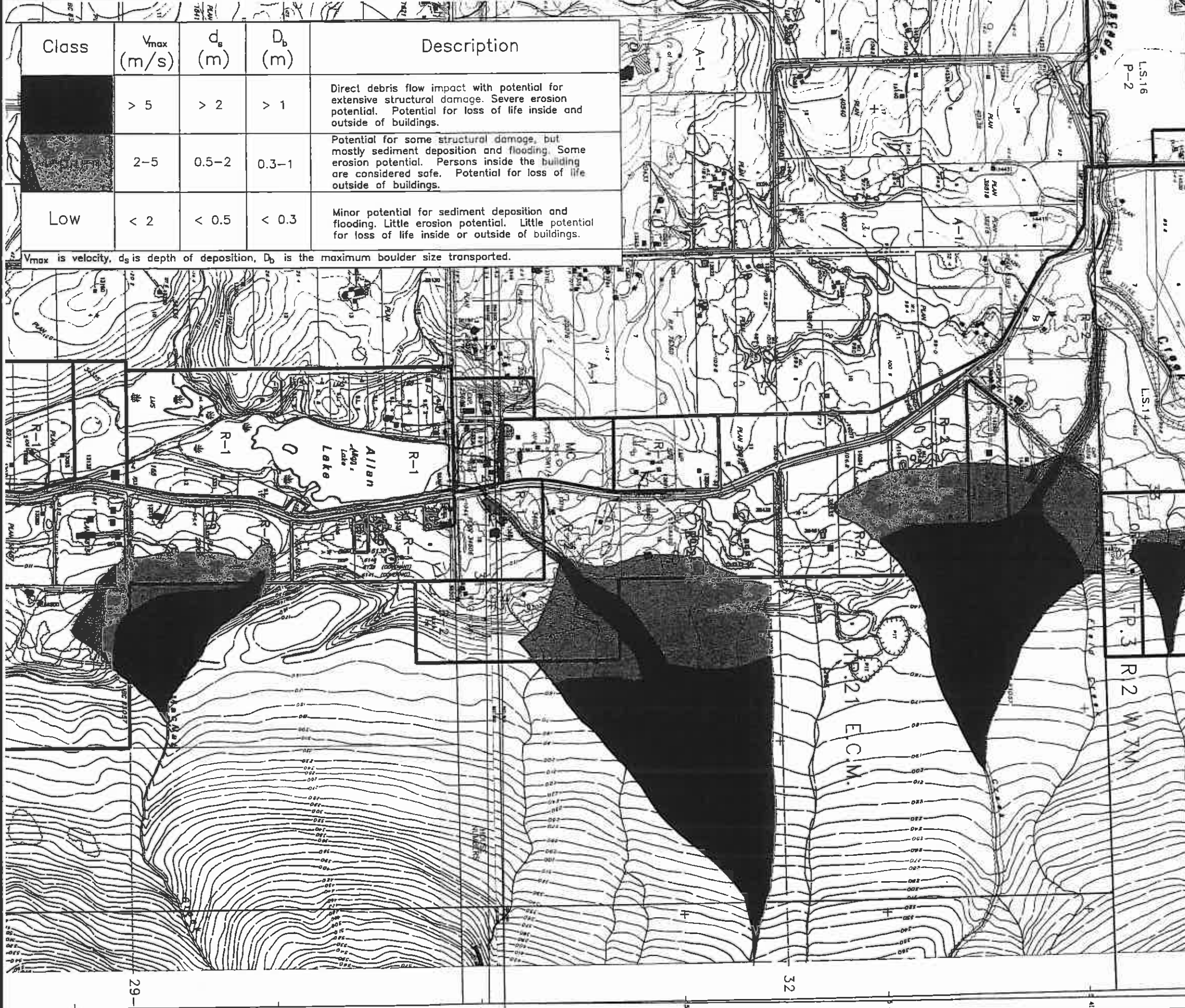
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DATE:	JANUARY 2004
DRAWN:	GEJ
DESIGNED:	MJ
CHECKED:	MJ
APPROVED:	

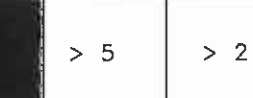
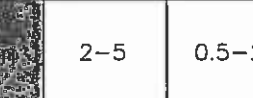
PROJECT	PRELIMINARY DEBRIS-FLOW HAZARD AND RISK ASSESSMENT	
TITLE	LONGITUDINAL CREEK PROFILES	
PROJECT No	FIGURE No.	REV
0378-001-01	2-2	0

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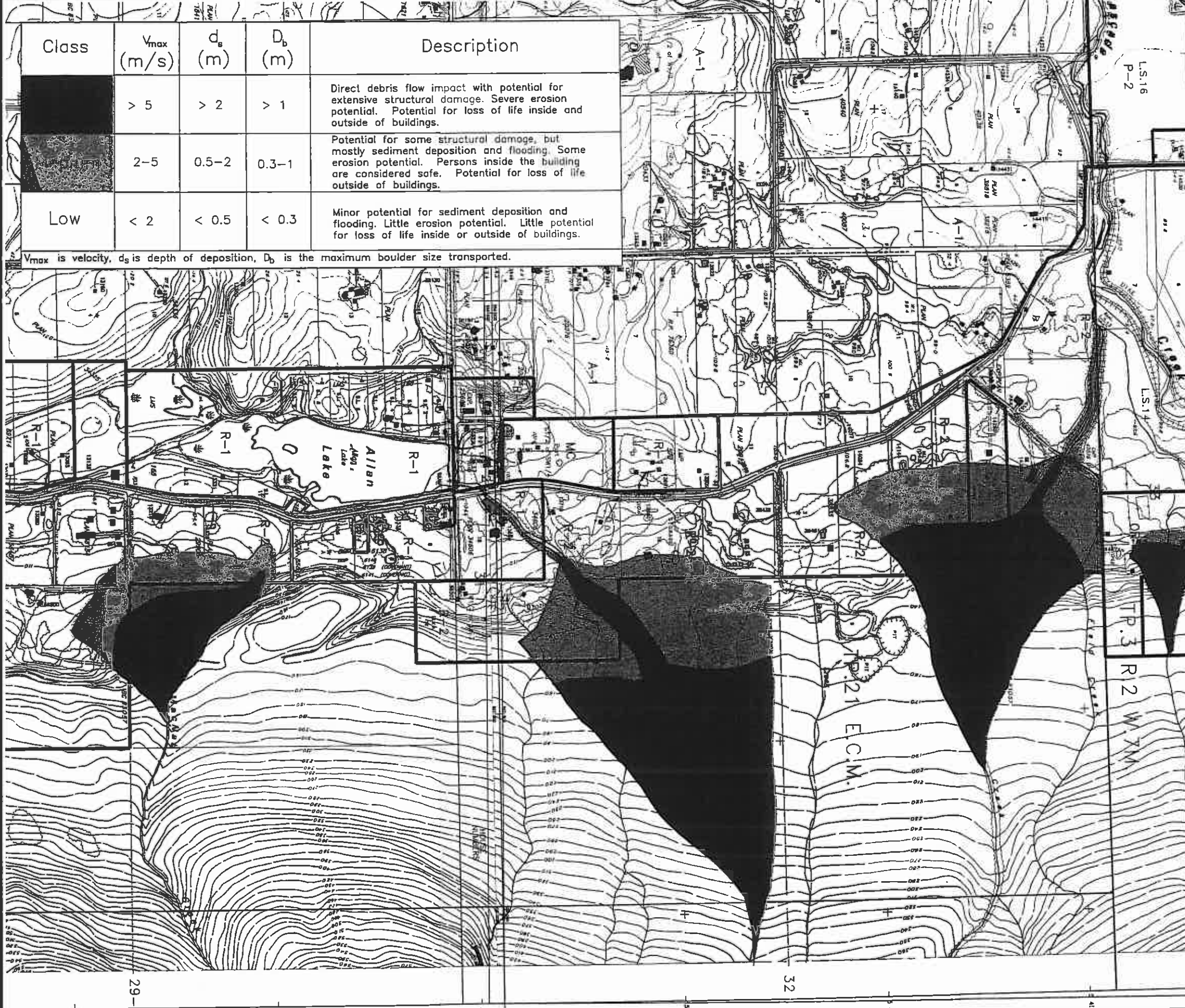
Class	V_{max} (m/s)	d_s (m)	D_b (m)	Description
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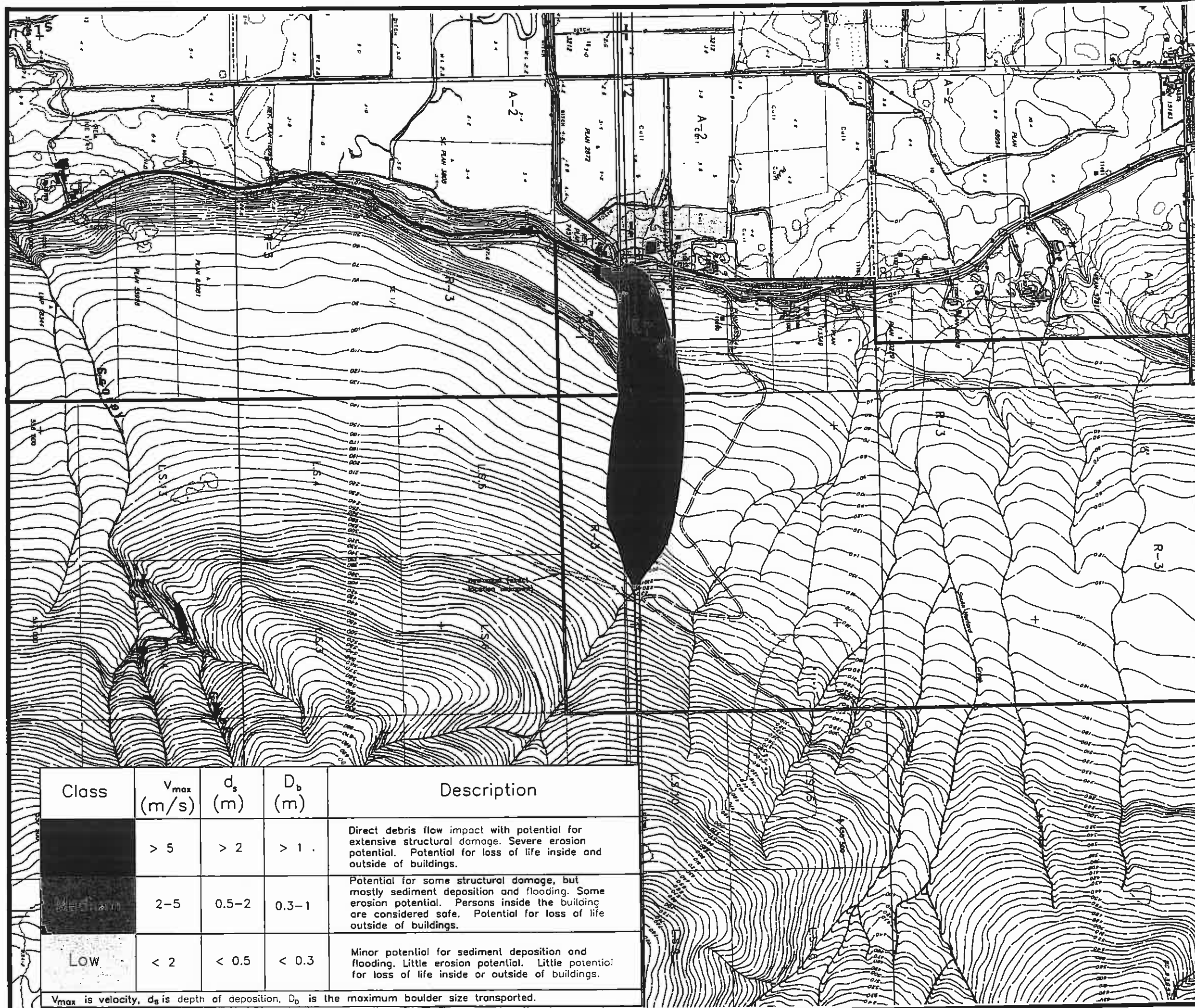
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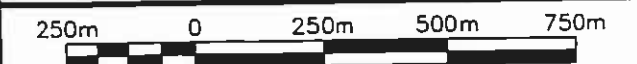
0378-001-01 002 DEBRIS FLOW HAZARD.dwg



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Data Source: 1:5000 Data from Fraser Regional Valley District.

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REV.	DATE	REVISION NOTES	DRAWN	CHECKED	APPROVED

SCALE: 1:10,000
DATE: JANUARY 2004
DRAWN: GEJ
DESIGNED: MJ
CHECKED: MJ
APPROVED:



PROJECT		
PRELIMINARY DEBRIS-FLOW HAZARD AND RISK ASSESSMENT		
TITLE		
PRELIMINARY DEBRIS FLOW HAZARD MAPS AT DALE CREEK FOR THE 500-YEAR RETURN PERIOD DEBRIS FLOW		
PROJECT No.	FIGURE No.	REV.
0378-001-01	4-2	0

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Photograph 29

Reaches of McNab Creek downstream of the fan apex. The channel has recently (December) been cleared of debris by an excavator that moved up the centre line of the creek and pushed debris onto both sides. Future debris flow events will likely entrain some of this loose material and redeposit it further downstream.

Photograph 30. Freshly excavated channel of McNab Creek 200 m upstream of Sylvester Road, December 8, 2003. The yellow lines show aggradation that was observed by BGC on Jan. 20, 2004.



Photograph 31

Lowermost 50 m of McNab Creek upstream of Sylvester Road. The channel has been freshly excavated into very loose material. Future streamflow will likely undercut the artificial creek banks and will cause rapid stream channel aggradation. Continued channel maintenance will be required to keep the channel cleared of debris and prevent plugging of the dual culverts.

APPENDIX III

Photographs

Photograph 32. Upper Dale Creek watershed. Note the extensive talus. High hydrologic conductivity will likely prevent frequent debris flows in this environment. Large, rare events, however, are conceivable.



Photograph: Kaurber Engineering, October, 2003



Photograph 33

Stream channel section on the Dale Creek fan, approximately 100 m downstream of the fan apex. This type of steep fan has the capability of rapid incision and entrainment of substantial amounts of fan material as has happened on Hope Creek in November of 1995. There has not been such an event recorded in recent history at Dale Creek.

Photograph 34. Panorama view from the fan apex of Dale Creek looking downstream. The fresh boulders in the foreground were deposited by high flood flow during the mid October 2003 storm.



Photograph 35

Glacial deposits upstream of Sylvester Road near the intersection with Dale Road. This photograph demonstrates that much of the Dale Creek fan is underlain by glacial deposits consisting mostly of basal till which is over-consolidated.

Photograph 36. Road fill repair at Dale Creek, where a malfunctioning culvert (the right) caused drainage avulsion across the road.



Photograph 37. Dale Creek downstream of the concrete culvert, which directs the creek below Sylvester Road. The cross-section at the point where the person is standing most likely will not contain the 200-year return period flood flow. The red dashed line delineates the area of the road fill that failed on October 17, 2003 due to culvert overtopping on the east side of Sylvester Road (shown by a red arrow on Photograph 36).



Photograph 38. Property north of the Dale Road – Sylvester Road junction. Here, a small berm has been built to prevent water and sediment from reaching the house (indicated by red arrow). The existence of this berm points towards previous flooding at this location.

Photograph 39. Upper watershed of Saporano Creek with McNab Creek watershed to the left (north) and Pattison watershed to the right (south). This watershed has not been logged and there are no recent landslide scarps visible.



Photograph: Thurber Engineering, October 2003

Photograph 40. Aerial photograph of Pattison Creek taken in 1993. Note the large debris flows (marked with red arrows) in the northern part of the watershed that were likely caused by logging road fill failures or drainage redirection. Also note the large deep-seated landslide delineated in red. The yellow lines approximate the watershed boundary. Source: Ministry of Sustainable Resource Management, 1993.

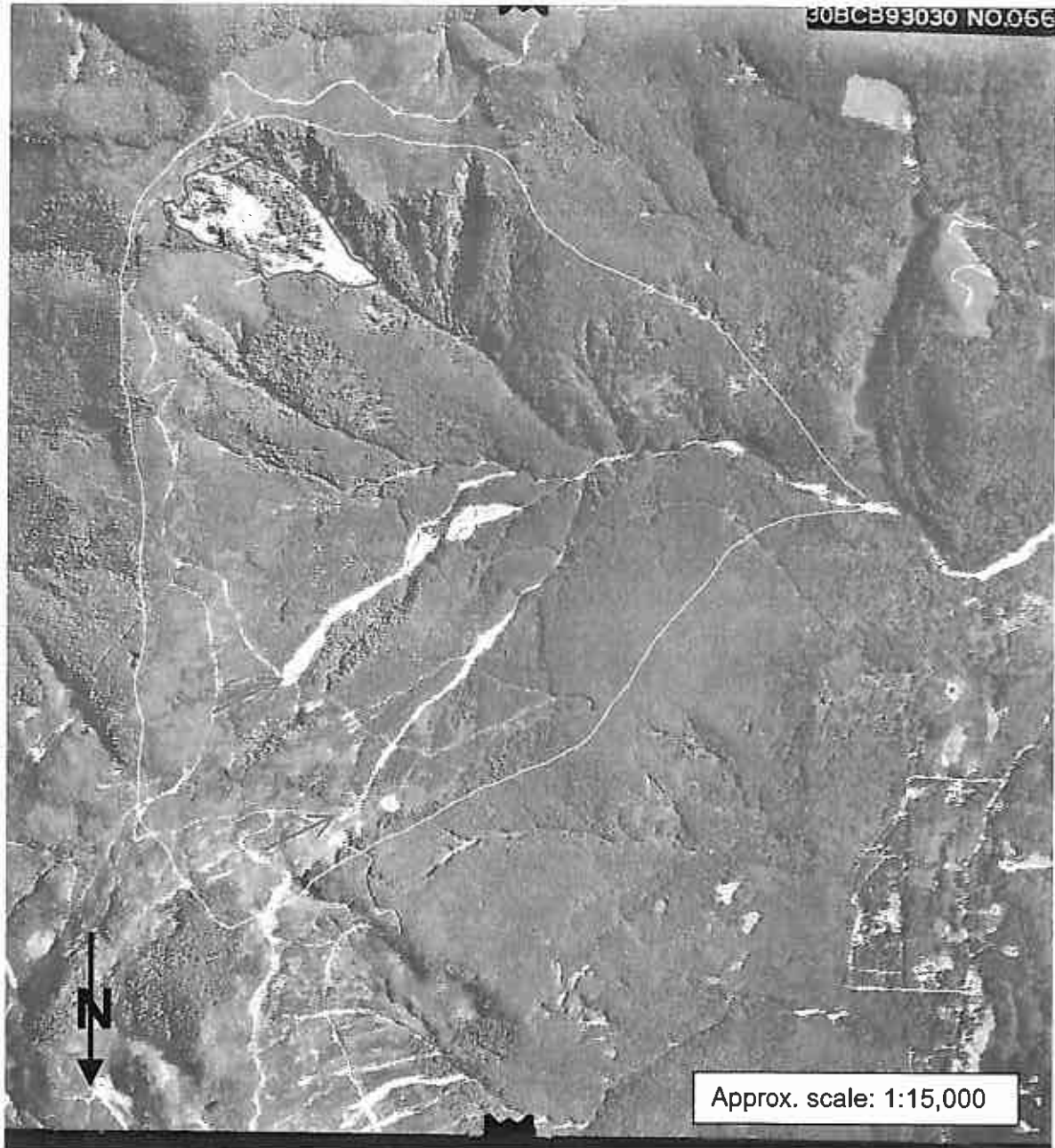




Figure 1a.

Infrared satellite image taken at 10 PM Pacific Standard Time (PST) on October 15, 2003. The front makes a landfall.



Figure 1b.

Infrared satellite image taken 10 PM PST Oct 16, 2003 at the height of the storm at Victoria Airport where 51 mm fell in 6 hours and 136 mm fell in 24 hours far exceeding previous records.



Figure 1c.

Infrared Satellite image taken 10 PM PST Oct 17, 2003. Flow more southerly, Olympic rain shadow strengthening Vancouver Airport received 141 mm in previous 48 hours exceeded previous record by 38 mm.



Figure 1d.

Infrared Satellite image taken 10 PM PST Oct 18, 2003. Southerly flow directs moisture into Howe Sound.

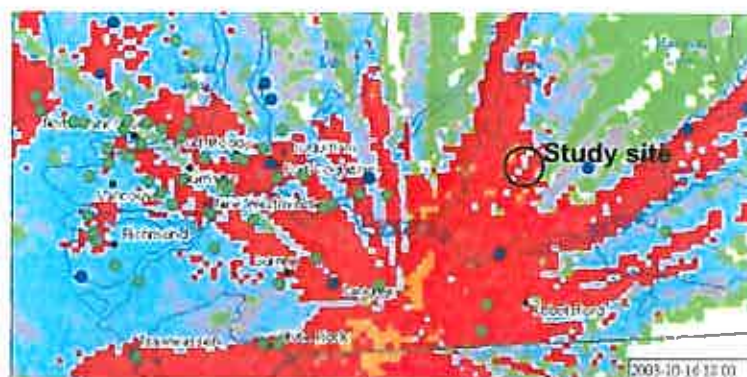


**FIGURE 2a Radar imagery
October 16th 2004, 18:00 PST**

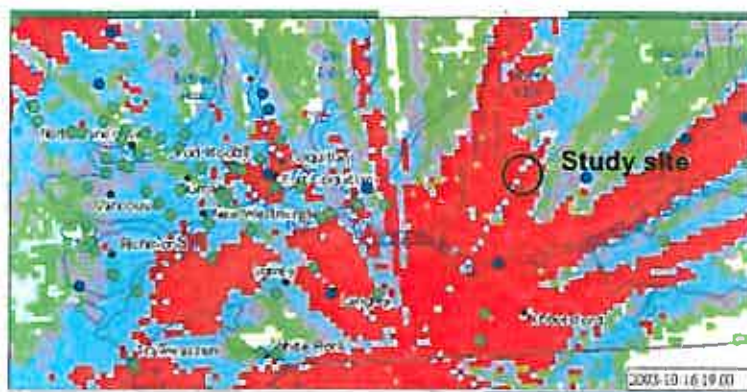


**FIGURE 2b Radar imagery
October 16th 2004, 19:00 PST**



**FIGURE 2c Radar imagery
October 16th 2004, 20:00 PST**



**FIGURE 2d Radar imagery
October 16th 2004, 21:00 PST**

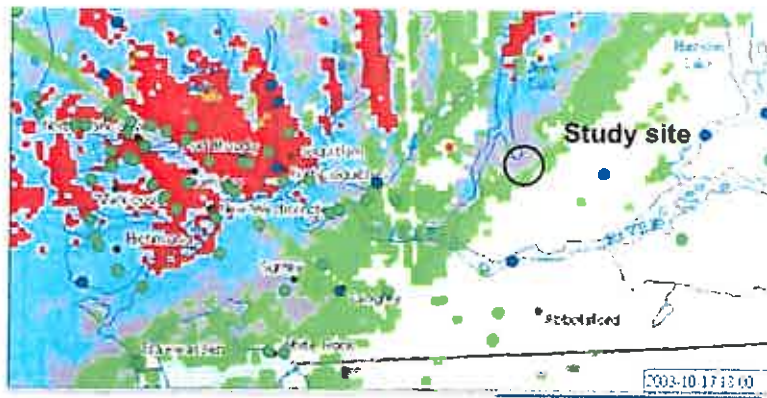


**FIGURE 2e Radar imagery
October 17th 2004, 17:00 PST**

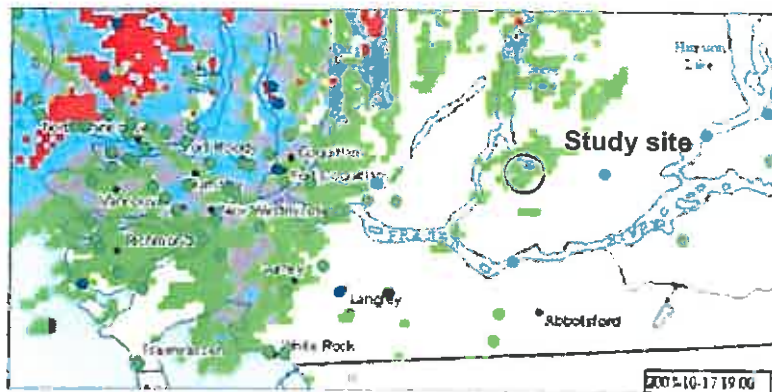


**FIGURE 2f Radar imagery
October 17th 2004, 18:00 PST**

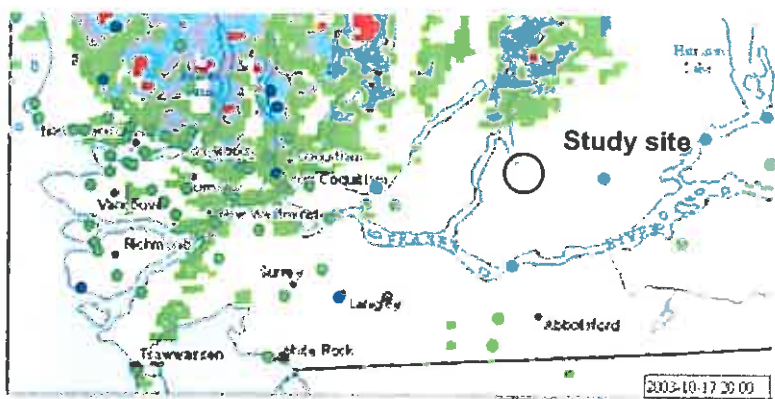


**FIGURE 2g Radar imagery
October 17th 2004, 19:00 PST**

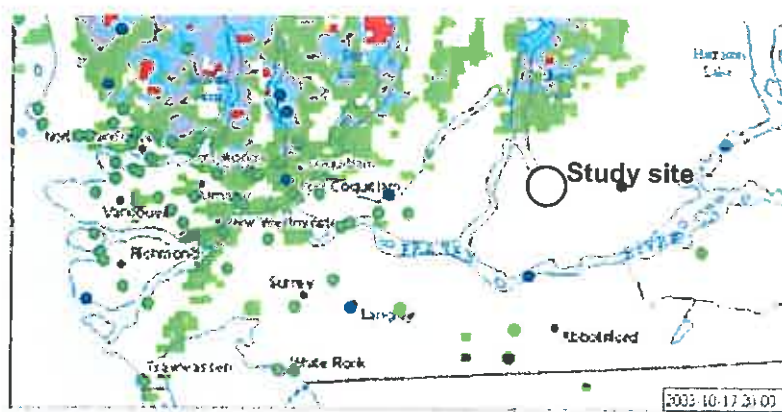


**FIGURE 2h Radar imagery
October 17th 2004, 20:00 PST**

Photograph 1. Field Creek debris flow. The red line approximates the outline of the modern debris flow fan.



Photograph 2. The Virtue residence with a fresh boulder lobe banking against the east side of the house.



Photograph 3. Channel section near the apex of Field Creek debris flow fan. The red line indicates

the approximate height of the flow as evidenced by bark and cambium scour of tree trunks. At this location the flow began losing confinement and began to spread.



Photograph 4. Channel section approximately 150 m upstream of the fan apex of Field Creek. The peak discharge back-calculated at this section was approximately $200 \text{ m}^3/\text{s}$.





Photograph 5

Upper Carratt Creek at an elevation of approximately 500 m. Two small debris slides in unlogged terrain likely contributed to the volume of the debris flow. It is possible that these debris slides were triggered by the main debris flow undercutting the slope, thus destabilizing the slide mass above.



Photograph 6

Several small debris slides that quickly transformed into debris flows. The two red arrows point towards debris slides in poorly regenerated clearcuts, and which were likely caused by progressive loss of root strength.

The yellow arrow points towards a debris avalanche that was triggered at the boundary between clearcut terrain and old-growth forest.

Photograph 7. Debris avalanches and debris flows in the upper watershed of Carratt Creek. Red arrows points towards the failures also shown on Photograph 6, blue arrows shown as vertical images on Photograph 8. The yellow dashed line indicates the location of the forest road.



Photograph 8

Two large debris avalanches (volume approx. 3000 m³ each) in the upper Carratt Creek watershed. The upper failure (far left on Photograph 7) initiated as a road-fill failure, while the lower debris avalanche initiated in a cutblock and then overran the logging road indicated by a double dashed yellow line. These failure scarps will provide fine materials into the channel systems below for some time to come before vegetation can be re-established. Further debris avalanches from this cutblock can be expected in the future.

Photograph 9. The riding and film studio south of Carratt Creek. The building is roughly at the same elevation as the creek bed at the present time (December 2003).



Photograph 10. Carratt Creek north of the horseback riding and stables facility. Freshly deposited debris has been pushed towards the north of the creek and is now being undercut by streamflow.





Photograph 11

Lower Carratt Creek with the horseback riding facility in the lower photograph. The red arrow indicates recent debris avulsion that caused bypassing of the right (northern) berm of Carratt Creek and flooding and sediment deposition on the Virtue residence. It is possible, that had this avulsion not occurred channel aggradation further downstream could have forced the flow into the southern sections of the fan as indicated by the yellow arrows. The yellow dashed line indicates the approximate location of berms paralleling Carratt Creek.



Photograph 12

Fan apex of Carratt Creek. Here the flow avulsed to the left (north), which caused flooding, and sediment deposition at the Virtue property. A gravel pit, which could be used as a debris basin is visible on the right, marked by a red arrow.

Photograph 13. Upper Eng Creek watershed. The fresh failure to the left indicated by a red arrow initiated approximately 50 m downstream of an old logging road and may have been associated with drainage redirection. An older failure (yellow arrow) can be seen to the right.



Photograph 14

A debris avalanche over bedrock in the lower section of Eng Creek. This event, which is not related to logging activities, likely added significant amounts of material to the debris flow. The sequence of events (i.e. if the debris flow from the upper watershed came first or the landslide shown on this photograph was initiated first) is unclear and can only be answered through detailed field studies.



Photograph 15

Fine-grained (mostly sand) runout of the debris flow on Eng Creek with Sylvester Road in the background. This type of inundation is classified as nuisance flooding.



Photograph 16

Fresh channel works at Eng Creek. Excavators went up the centre of the creek and pushed the sandy gravel to both sides creating a trapezoidal channel. It is expected that this channel will rapidly fill in with sediment during the winter months. December 2003



Photograph 17

Excavators working in the upper fan area of Eng Creek, attempting to return the channel to approximately pre-event topography. December 2003.



Photograph 18

Fan head entrenchment on Eng Creek near the fan apex. In this reach, the debris flow was able to scour through consolidated fluvio-glacial materials and glacial till thus adding to the material from the upper watershed. Explosive were used near this location in 1984 to clean out the channel. Disturbance by blasting could have created conditions favourable to deep scour.

Photograph 19. Scoured upper fan reaches of Eng Creek illustrating the possibility of additional channel scour in an area usually defined as the deposition area.



Photograph 21. Upper fan stratigraphy at Eng Creek with old debris flow deposits overlying fluvioglacial and glacial sediments.



Photograph 22. The Ramasteder residence. According to eyewitness accounts by Ms. Ramasteder, sandy debris piled up to 50 cm around the house.



Photograph 23. The Lund Residence where boulders up to 40 cm in size impacted the log home but did not cause structural damage. Much damage was likely avoided by the owners using a front-end loader to create a temporary berm, which directed water and debris away from the home.



Photograph 24. Lower reaches of Eng Creek before reaching Allen Lake. The Remester residence is the one with the red roof on the left side of the photograph.



Photograph 25. This image shows the lower fan of Eng Creek. The red arrow points towards the Lund residence, which is also shown in Photograph 23.



Photograph 26. The upper McNab Creek watershed. The photograph shows an older failure (yellow arrow) and a new debris avalanche (red arrow) that crossed a forest road and transformed into a debris flow.



Photograph: Thurber Engineering, October 2003



Photograph 27

The lower reaches of McNab Creek including Allan Lake. The reaches shown are at a gradient between 1 and 4 degrees and, therefore constitute an area of debris deposition. This area could be acquired and, in conjunction with a deflection berm be used to mitigate debris flow hazards on the McNab Creek fan.



Photograph 28

This photo was taken at the fan apex of McNab Creek where a large cedar has been impacted by previous debris flows. This tree would be well suited for dendrochronologic analysis. Also clearly visible are the large boulder levees to the right of the person. Some work has been done in the past at this location to prevent debris flows from avulsing on the southern fan margins.