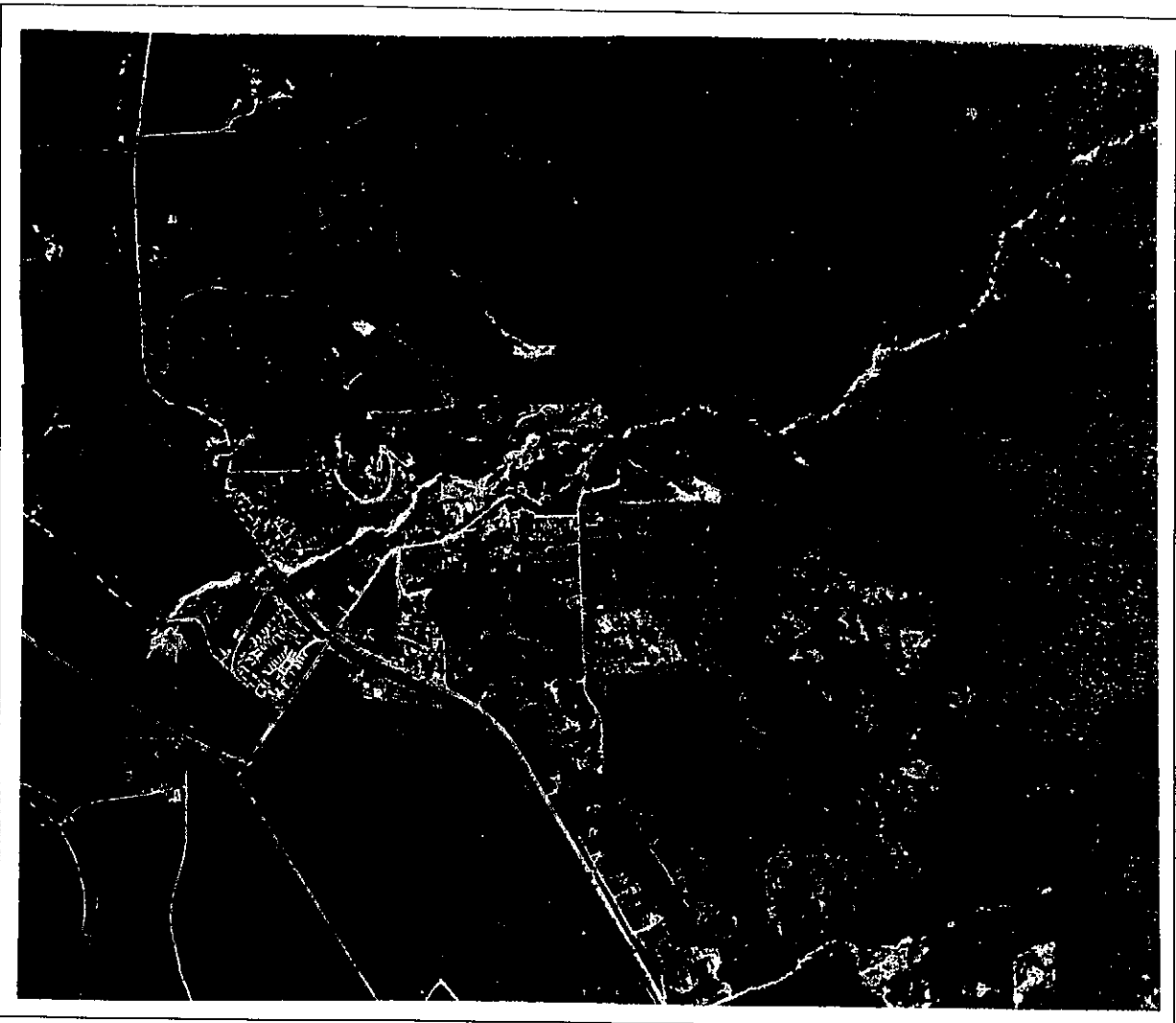

APPENDIX 1



***DEROCHE CREEK
DEBRIS FLOW AND DEBRIS FLOOD STUDY***



Deroche Creek Debris Flow and Debris Flood Study

February, 2000

Deroche Creek Debris Flow and Debris Flood Study

Prepared by:

**EBA ENGINEERING CONSULTANTS LTD.
Vancouver, B.C.**

Submitted To:

Hay & Company, Vancouver, B.C.

Project No. 0806-99-86217

February 2000

TABLE OF CONTENTS

1.0 INTRODUCTION AND OBJECTIVES	1
1.1 BACKGROUND	2
2.0 STUDY AREA	2
2.1 PHYSIOGRAPHY	2
2.2 BEDROCK GEOLOGY AND GEOMORPHOLOGICAL SIGNIFICANCE	3
2.3 QUATERNARY GEOLOGY	4
3.0 DEBRIS FLOW INVESTIGATION	5
3.1 DEFINITION	6
3.1.1 <i>Debris Flows</i>	6
3.1.2 <i>Debris Floods</i>	7
3.2 DEBRIS FLOW INITIATION LOCATIONS	7
3.3 DEBRIS FLOW PEAK DISCHARGE AND VOLUME	8
3.4 DEBRIS FLOW AND DEBRIS FLOOD FREQUENCY	9
3.4.1 <i>Air photo analysis</i>	9
3.4.2 <i>Resident Interviews</i>	10
3.5 DEBRIS FLOW RUNOUT	10
4.0 LOGGING IMPACTS	11
4.1 THE EFFECT OF LOGGING ON LANDSLIDE ACTIVITY	11
4.2 LOGGING HISTORY	14
4.2.1 <i>Potential debris flow source areas</i>	14
4.2.2 <i>Debris flow yield rate and probable volume</i>	14
4.2.3 <i>Debris flow runoff</i>	15
4.2.4 <i>Debris flow dam outbreak scenarios</i>	16
4.3 SEDIMENT LINKS AND SEDIMENT TRANSPORT	19
5.0 DEBRIS FLOW AND DEBRIS FLOOD MITIGATION MEASURES	19
5.1 ACTIVE MEASURES	19
5.1.1 <i>Channel improvements</i>	20
5.1.2 <i>In-stream debris barriers</i>	20
5.1.3 <i>Energy Dissipation Structures (EDS)</i>	20
5.1.4 <i>Erosion control in the upper Deroche Creek watershed</i>	21
5.1.5 <i>Debris Basins</i>	21
5.2 PASSIVE MEASURES	21
5.2.1 <i>Zoning</i>	22
5.2.2 <i>Covenants</i>	22
5.2.3 <i>Additional logging in the watershed</i>	22
6.0 CONCLUSIONS AND RECOMMENDATIONS	22
7.0 CLOSURE	24
REFERENCES	25

FIGURES

- Figure 1 Areas logged, recent landslides and areas of high likelihood for post-logging landsliding
- Figure 2 Surficial geology map of Deroche Creek fan
- Figure 3 Correlation between debris flow peak discharge and total volume
- Figure 4 Deroche Creek and tributary profile
- Figure 5 Probable landslide initiation locations and debris flow paths
- Figure 6 Sediment delivery linkages in the Deroche Creek watershed
- Figure 7 Examples of in-stream barriers

TABLES

- Table 1 Calculated Q_{200} and measured or back-calculated peak discharge of debris flows in small streams of southern British Columbia.
- Table 2 Landslide activity from natural and logging-related sources at Deroche Creek
- Table 3 Input parameters for debris flow runout calculation for T-4, T-5, T-6 and mainstem
- Table 4 Peak discharge estimates for dam outbreak scenario at T-4 confluence

PHOTOGRAPHS

- Photo 1 Densely jointed bedrock of the Harrison Lake Formation
- Photo 2 Interface between basal and weathered ablation till in the upper watershed
- Photo 3 Cross-section of older fan deposits along Morton Road
- Photo 4 Channel section adjacent to Mr. Gruenwald's property where v was calculated
- Photo 5 1970s failure in fluvio-glacial sediments triggered by redirected road drainage
- Photo 6 Fill slope failures from logging road in upper watershed
- Photo 7 Low-gradient fill slope failure due to redirected drainage in upper watershed
- Photo 8 Fill-slope failure that transformed into debris flow, upper watershed
- Photo 9 Extensive tension crack along upper road in upper western watershed
- Photo 10 Tension cracking and small fill slope slump along upper road
- Photo 11 1987/88 clearcutting along ridge crest of western sub-watershed
- Photo 12 Sediment wedge caused by debris flow in Deroche Creek mainstem
- Photo 13 Debris flow track and very large boulder upslope of Photo 12

1.0 INTRODUCTION AND OBJECTIVES

This study is part of a report by Hay & Company which addresses flood hazards and debris flows and their impact on Deroche Creek fan on which the community of Deroche is located. The study was commissioned because of a series of floods that necessitated mitigative measures. Significant floods occurred at Deroche Creek in 1962 or 1963, 1981, 1986, 1989, and 1990. A serious avulsion occurred upstream from Morton Road in 1989 resulting in channel clearing and restoration, which was funded by the Provincial Emergency Program (PEP).

Deroche Creek drains a 9 km² watershed on the southernmost slopes of the Coast Mountains east of Mission. Geomorphologically, the watershed has similar characteristics to other basins in this area. Deroche Creek basin has been logged numerous times during the past 50 years, and logging has led to an accelerated rate of mass movements particularly due to forest road drainage related failures.

The ultimate objective of this report was to quantify physical processes to an extent that a scientifically based judgement can be made as to the type and geometry and geotechnical characteristics of mitigation structures. The detailed objectives were:

- Assess the likelihood that debris flows will occur in the watershed;
- Determine the likely magnitude (volume and peak discharge) of potential debris flows;
- Assess the impact of debris flows on Deroche Creek fan, and
- Recommend mitigation structures against debris flows or debris floods

In addition, forest cover maps were reviewed to assess the likelihood of debris slide initiations from forest roads as well as open slope failures as a result of loss in root strength. The conclusions and recommendations of this report will be used in conjunction with the Hay & Company report to arrive at the most reliable estimates of peak discharge of floods and debris floods arriving at the fan apex of Deroche Creek.

In the mountainous regions of British Columbia, flat and hence developable land is often located on potentially hazardous locations such as floodplains, river deltas or alluvial fans. Particularly along picturesque lakes in the interior of British Columbia there is the desire to establish recreational sites and developments that are only possible on the flat alluvial fans. In contrast to the European Alps or the Japanese Alps, for example, there is limited historical experience and appreciation of natural hazards such as floods, debris flows, and rockfall in British Columbia. Only over the last 20 years or so have these hazards been addressed in case studies and a body of research emerged from the need to deal with threats to public safety. Nonetheless, there are numerous sites in B.C. where the hazard potential has not yet been identified due to the intermittent nature of the geomorphologic processes that created the landforms.

1.1 Background

Limited work has been done in the watershed of Deroche Creek. In 1988 British Columbia's first Integrated Watershed Management Plan (IWMF) was compiled for Norrish Creek, which is the large watershed north of Deroche Creek. As part of the IWMF, Deroche Creek was mapped according to guidelines set in the Terrain Evaluation Method for Predicting Terrain Susceptible to Post-Logging Landslide Activity (1987). The map shown in Figure 1 outlines all those areas that should not be logged (i.e. have a rating of 3:H or 4:H). The system consists of three elements. First it provides information on whether a mass movement has already occurred in a given polygon. Second, it includes a *Clearcut Landslide Rating* from 1-4 with detailed definitions for each class. The fourfold classification ranges from "very low likelihood of landsliding to "high likelihood" of landsliding following clearcutting. Third, the system consists of the *Potential Introduced Landslide Debris Rating*, which is a qualitative threefold rating (i.e. low, moderate and high) of the likelihood of clearcut landslide debris entering the stream system if a landslide should occur within a terrain polygon. The stream system includes stream order one and two channels, and gullies. The main conclusions of the terrain evaluation report compiled for the Norrish and Deroche Creek watersheds are summarized as follows:

- Terrain with the highest clearcut landslide rates within the study area includes till or till/colluvial mantles on slopes $>33^\circ$ and colluvial mantles on slopes $>36^\circ$, which are dissected by gullies, and escarpments of unconsolidated sediments with slopes $>33^\circ$.
- The clearcut landslide rate varies from 0.8 to 6.6 times the natural rate on different terrain types and the 1963-1981 clearcut landslide rate is 1.7 times the 1953-62 clearcut rate for clearcuts on steep slopes.
- The natural landslide rate has remained constant since 1940.
- The difference between the clearcut and natural landslide rates suggests that the removal of forest cover has strongly influenced the landslide rate by increased water inputs and soil moisture changes and/or the reduction of root reinforcement, aggravated by increasing wetter conditions from 1953-1981.

2.0 STUDY AREA

2.1 Physiography

Deroche Creek basin is situated on the north side of the Fraser Valley, some 20 km east of the township of Mission. The watershed lies between Nicomen Mountain (1224 m) to the west and Deroche Mountain (1419 m) to the east, and forms part of the southernmost boundary of the British Columbia Coast Mountains. The ridge system of which Deroche Creek basin is a part, extends north-eastward from the confluence of Norrish Creek and Nicomen Slough. The southern and south-eastern slopes of this ridge system are drained by a series of small ($<1\text{km}^2$) basins such as Pye, Barnes, Siddle and Holachten Creeks, as

well as larger ones such as Pennier Creek. Almost all of these creeks have debris flow potential; and some of them have witnessed debris flows in the past.

A good example is Pye Creek that drains the watershed immediately to the east of Deroche Creek. Here a large ($>20,000\text{m}^3$) debris flow deposited on the fan in 1962 or 1963. Since then three homes have been built in the runout zone of potential debris flows. In addition, further logging in the steep upper watershed has exacerbated the potential for debris flows.

Overall, the watershed is concave, having lost much of its original volume to mass movement processes and fluvial erosion. Since the last deglaciation that ended some 10,000 years ago, a large fan has formed on the Fraser River floodplain north of Nicomen Slough. The fan is probably interfingered with the Fraser River floodplain, given that periods of fan aggradation likely coincided with aggradation of Fraser River and its adjacent lands. It is also likely that in the past parts of the fan have been truncated by a Fraser River side arm (i.e. the modern Nicomen Slough) in the past. Therefore, the visible fan volume today does not represent the total fan volume, which can be an index of the relative geomorphic activity of the watershed. The most recent fan aggradation events occurred in 1962 or 1963 affecting most of the lower fan, and 1989, which affected an area close to the fan apex. There is evidence that clearcut logging has to some extent contributed to the sediment movement in Deroche Creek, and effects of logging on geomorphic activity and stream channel behaviour are still ongoing. An older fan surface, which has subsequently incised, has been identified and is delineated on Figure 2. The most active part of the fan is also delineated on Figure 2.

The drainage system is characterized by stream channel gradients of $8\text{-}10^\circ$ along its lower channel and then rising quickly to angles up to 40° in the upper watershed and along steep short tributaries of the lower channel. Landslides descending some of these tributaries are capable of temporarily damming Deroche Creek. Outbreak floods from those landslide dams may affect development on the fan, and in extreme cases may exceed the 200-year flood (Q_{200}) (Jakob and Jordan, 1999).

2.2 Bedrock Geology and Geomorphological Significance

In a geologic sense, Deroche Creek basin is anomalous compared to its neighbours (except for Pye Creek basin) which are located mostly in middle Jurassic quartz diorite of the Mount Jasper pluton. Deroche Creek runs for most of its path through the middle Jurassic Harrison Lake Formation consisting primarily of intermediate and felsic flows and pyroclastic rocks; local argillite, conglomerate, calcareous siltstone, shale and sandstone. An example of Harrison Lake Formation rock is shown on Photo 1 in the upper watershed. Lava flows include massive and columnar jointed dacite, rhyolite and dark green plagioclase andesite porphyry. Pyroclastic rocks include lapilli tuff, volcanic breccia, tuff and volcanic conglomerate.

The Harrison Lake Formation is part of the Harrison Terrane which was once an island arc that rafted on top of the Oceanic Plate across the Pacific Ocean and then collided with the continental margin. The terrane represents relics of a volcanic arc succession constructed either within or along the inboard margin of Wrangellia in early Jurassic time. Near Harrison Lake, the volcanic succession is unconformably overlain by Middle Jurassic shale and siltstone of the Mysterious Creek Formation and by Late Jurassic sandstone and volcanic rocks of the Billhood Creek Formation, both of which are part of the Gambier overlap assemblage.

In terms of its geomorphological significance, Harrison Lake Formation rocks will likely weather into fine grained materials such as silts and clays, more so than surrounding granodiorite and quartz diorites which weather into a more sandy soil matrix. A higher proportion of fines in the matrix of a debris flow aids its mobility, and prolongs its runoff distance and total runoff time. Fines can stem from eroded bedrock as well as from morainal material blanketing bedrock. A soil sample taken from glacial till in a road cut in the upper basin yielded a fines (silt and clay) content of 21%, which implies that if a debris slide starts in this area it will likely have high mobility even on gradients less than 30°. The abundance of glacial till will effectively shelter underlying bedrock from subaerial erosion (Photo 2). Tens of thousands of years are necessary to remove this till blanket or transform it into thick soils. Therefore, the control of bedrock and its significance for mass movement processes is limited to those limited sections (<10%) of the channel that are bare bedrock. In those reaches, however, it can be expected that erosion rates are higher compared to the more competent plutonic rock counterparts due to dense jointing which breaks in situ rock into smaller particles resulting in rapid gneusification (mineral weathering into sand-size particles) of the surface layer.

2.3 Quaternary Geology

The fan area of Deroche Creek has undergone significant changes over the last 12,000 years. Figure 2 shows a map of the Quaternary deposits and bedrock outcrops as mapped during fieldwork in October and November 1999. The Quaternary history can be summarized in the following stages:

1. Extensive mountain glaciation covering the highest elevations of the Deroche Creek watershed (approx. 18,000-12,000 yrs. BP).
2. At the same time, as the smaller watersheds were deglaciated by about 12,000 yrs. BP, a large valley glacier still persisted in the Fraser Valley, which was deglaciated between 16,300 and 14,100 yrs. BP (Clague et al., 1981). At this time Deroche Creek banked up against the ice of this glacier, forming a lake in which mostly clayey silts and later sandy silts were deposited in thin layers. The Fraser Valley Glacier advanced at least twice between 14,000 and 13,000 years ago (Sumas event), (Clague et al. 1997).
3. Following final deglaciation some 10,800 yrs ago, the base level for Deroche Creek dropped by approximately 50 m and streamflow transported stored sediment onto the Fraser River floodplain, which was then aggrading and pushing

- a delta towards the Straight of Georgia. A 2-3 m thick layer of deltaic sediments are evidence for the sediment transfer from Deroche Creek onto the Fraser River floodplain.
4. Some unknown time after deglaciation, a debris flow of substantial magnitude covered part of the fan of Deroche Creek. Evidence is in the form of 1.5 - 2 m large boulders in a non-stratified matrix that are overlying the deltaic deposits. Photo 3 shows the debris flow deposit superimposed on deltaic deposits.
 5. In later times, the amount of erodible material in Deroche Creek became less and the creek began to incise to its present level, creating a new active fan (Figure 2), which is at least partially flooded at intervals of approximately 30 years.

3.0 DEBRIS FLOW INVESTIGATION

Compared to floods, debris flows are the much more destructive mass movements. Table 1 shows a compilation of data on calculated Q_{200} and observed or back-calculated peak discharge from debris flows throughout British Columbia. From this table it becomes clear, that if there is a chance that a debris flow may occur at a creek with a return interval of 200 years or less the flood discharge is insignificant, and likely to be at least an order of magnitude lower than the expected debris flow peak discharge. Unlike floods, which are classified as a fluvial event with physics of motions distinctly separable to those of debris flows, the latter are classified as a landslide. This section will define debris flows and debris floods, pin-point the likely locations of debris flow initiation, as well as comment on their frequency and runoff. It must be noted in this context that debris flows are discrete and, compared to floods, rare events. Therefore statistical analyses such as used for flood frequency estimates cannot be used.

Table 1. Calculated Q_{200} and measured or back-calculated peak discharge of debris flows and outburst floods in small streams of southern British Columbia.

Site	Q_{200} (regional analyses) (m^3/s)	Q_{max} (observed/calculated) (m^3/s)	estimated return interval (years)	factor Q_{max}/Q_{200}
Hummingbird Ck.	20	1,000	60	50.0
Capricorn Ck.	40	2,000	20	50.0
Meager Ck.	350	70,000	50	200.0
Eagle Pass #2 Ck.	16	120	10	7.5
Eagle Pass #1.5 Ck.	3	40	15	13.3
Eagle Pass #1 Ck.	9	90	10	10.0
Victor Ck.	96	230	25	2.4
Clanwilliam Ck.	71	160	10	2.3
Eagle Summit Ck.	60	160	20	2.7
Tonkawalla Ck.	81	230	10	2.8
Mica Sawmill Ck.	14	90	10	6.4
Burner Ck.	36	90	10	2.5
M-Ck.	62	210	15	3.4
Charles Ck. 1969	20	120	10	6.0

Site	Q_{200} (regional analyses) (m^3/s)	Q_{max} (observed/calculated) (m^3/s)	estimated return interval (years)	factor Q_{max}/Q_{200}
Charles Ck. 1981	20	100	10	5.0
Charles Ck. 1983	20	340	10	17.0
Wahleach Ck.	23	566	15	24.6
Newman Ck.	20	85	15	4.3
No Good Ck.	10	500	5	50.0
Turbid Ck. 1984	25	4000	20	160.0
Turbid Ck. 1993	25	270	5	10.8
Densmore Ck.	4	100	10	25.0
Dakota Ck.	103	180	20	2
McNair Ck.	84	150	20	2
Deroche Ck.	63	250	30	4
Tastiquan Ck.	109	200	25	2
49-Ck.	2	100	10	50.0
Mackay Ck.	8	115	50	14.4
Average	43	3363	18	30.0
Range	2-350	40-70,000	5-60	2.0-200

3.1 Definition

3.1.1 Debris Flows

Debris flow is a channelized, highly fluid, landslide that usually starts as a debris slide at the head or along the sidewall of small streams in mountainous terrain. Debris flows contain rocks up to several cubic meters in size, gravel, sand, silt and clays, organic material such as tree wads, trees, branches, as well as water. They can travel as fast as 20 m/s but typically move with velocities between 3 and 10 m/s. Structures such as houses, hydroelectricity masts, bridges, piers and roads situated on the fan are often severely damaged by the high impact forces of debris flows. Typically, debris flows arrive with a bulging lobe with a high concentration of large rocks and organic material along its front followed by increasingly smaller grain sizes and more water. Although this first surge is usually the largest and determines the peak discharge, more surges are likely to follow the initial one. Apart from their destructive impact forces, debris flows can obliterate large parts of an alluvial fan with several metres of debris. Debris flows have significant erosive power, and are capable of entraining most of their sediment load through scour from channel sidewalls. Yield rates (rates of erosion per meter channel length during a debris flows), have been observed to range between 5-50 m^3/m . Typically, debris flows begin to deposit their load when the gradient of the channel flattens, and the channel loses confinement, which is commonly the case when the channel reaches the valley flats. Debris flow deposition commences around 12-14° for flows with a high boulder content, but may continue to flow at gradients lower than 5° for debris flows with a high clay

content. At Deroche Creek, the flow would largely be bouldary, but due to a relatively high fines content deposition would likely commence at around 10-12°.

3.1.2 Debris Floods

As opposed to debris flows, debris floods are water floods and not landslides. Debris floods have discharges 2-5 times higher than the calculated 200 year flood and are often due to geomorphic processes such as landslide damming in the creek, log dam outbreak, beaver dam failures, and others. Their sediment concentration is usually higher than that of a normal flood and there is a higher concentration of large organic materials such as trees, tree wads, branches etc. in the flowing water. Debris floods are capable to move keystones, which are clasts in the creek beds controlling the overall appearance and arrangement of so called stone nets in the creek bed. This implies that, other than during normal floods, a complete reorganization of the creek bed may occur during debris floods.

In many mountain creeks in British Columbia and elsewhere, there is a continuum from mass movement processes to floods. Debris slides transform into debris flows as they become channelized, and then transform again into debris floods as the channel gradient drops past a critical threshold combined often with an increase in channel width and a subsequent lowering of flow depth.

3.2 Debris flow initiation locations

Debris flows typically initiate as debris slides. Debris slides are translational movements of a layer of soil or rock along a distinct shear plane. In the mountain ranges of British Columbia, the shearing often occurs at the interface between weathered till and basal till, between till and bedrock, or between colluvium and bedrock. The initiation mechanisms are poorly understood in detail, but are almost always related to an abundance of water. Using basic principles of soil mechanics a steep slope with a thin surficial layer of permeable non-cohesive, or poorly cohesive, soil overlying an impermeable layer in a long a swale or longitudinal hollow is considered prone to debris slide initiation. In clearcut terrain, these factors may be significantly altered as explained below. The initial slide mass soon loses its structure and becomes chaotic along its descent. Since most hillsides are dissected by at least zero order ephemeral streams, debris slides commonly become channelized within the first 300-500 m of their descent. At the point of channelization debris slides become debris flows. The channelization is accompanied by an increase in flow depth that makes it more difficult for water to escape and aids the fluidization of the debris flow mass, thus adding to its mobility. Figure 5 shows the most likely areas of debris slide initiation on open slopes (not directly related to logging roads), and from road fill failures.

3.3 Debris flow peak discharge and volume

There are two variables that express the magnitude of a debris flow, peak discharge and total volume. Peak discharge is the area of a cross-section that will be filled by a debris flow multiplied by the peak velocity of the debris flow as it passes through the cross-section. For peak discharge it is important to calculate the cross-sectional area necessary to pass the debris flow. Any stream crossings (road and railway bridges) need to be designed so that they can accommodate the anticipated discharge. If the cross-section along the channel is insufficient to pass the peak flow, the debris flow or debris flood will likely avulse (leave the channel); particularly on the outside of channel bends, where the flow will superelevate (jump out of the curve). Total volume defines the sediment mass that is transported during the debris flow as one or multiple surges. The more liquid afterflow is included in this volume. The total volume is of great significance for development on the fan, because if the debris flow or debris flood leaves the channel it determines how much of the fan will be inundated and to what depth of deposition. As shown in Figure 3, there is a good correlation between peak discharge and total volume.

Usually, peak discharge and total volume are back-calculated from existing evidence. In the case of Deroche Creek, this is problematic since the last large flood which would allow this back-calculation dates back to 1962 or 1963. One cross-section was found approximately 100 m upstream of the Morton Road bridge alongside Mr. Gruenwald's property where the back-calculation of peak discharge of a debris flow or debris flood is possible due to a sharp channel bend of 100 degrees and a well defined bouldary deposit on the outside of the bend, as well as scarred wood on the inside (Photo 4). According to Mr. Gruenwald who was present during the cross-section measurements, water and debris overtopped the inside of the bend in 1989.

Velocity was back-calculated using the forced-vortex equation for superelevation to 8.0 m/s, and the cross-section was 42 m², resulting in a peak discharge of roughly 340 m³/s. The prerequisite for this number to be correct, is that the cross-section of the channel has not changed substantially since the event in 1989. This assumption, however, cannot be made in this alluvial channel section. Mr. Gruenwald noted that the channel bed was higher some years ago. Recalculating the peak discharge with a smaller cross-section of 25 - 30m² results in a peak discharge of approximately 200-240 m³/s, which is still 3-4 times as high as the calculated peak flow of 64 m³/s from regional analysis methods.

At 720 m upstream of the Morton Road bridge, another profile was taken in the alluvial channel. At this site the upper limit of sediment flow was determined by impact scars on trees on both sides of Deroche Creek. The cross-section area was calculated to be 26 m², which is close to the 25 m² assumed for the first cross-section. Assuming a flow velocity of 8m/s, this yields a peak discharge of about 210 m³/s at this site. Again, given that this section is an alluvial channel, the cross-section may have been larger or smaller at the time of debris flow/debris flood impact. Judging from the relative age of the scars, this event appears to coincide with the 1962 or 1963 flood.

3.4 Debris flow and debris flood frequency

Debris flow frequency is defined as the number of debris flows per year. A more meaningful measure of frequency is the return interval which is the inverse of debris flow frequency, signifying the average number of years between two debris flow events. Nothing is known about repeated debris flows on Deroche Creek fan, but debris flows have occurred in the upper basin. Since those were associated mostly with forestry activities, debris flow frequency in the upper basin will be addressed in Section 4.2.

3.4.1 Air photo analysis

Air photograph analysis has yielded the following information on sediment accumulation and the relative activity of Deroche Creek on the alluvial fan.

- 1963 BC 5062 and BC 5063 (April 28) *Major flood (either in 1962 or 1963)*
- Area east of North Deroche Road covered with recent flood debris
 - Wooded area of upper fan between bend in North Deroche Road and fan apex is covered with flood debris and dissected by at least three avulsion channels
 - One avulsion channel reaches Nicomen Slough approximately 200 m north of the Louheed Highway bridge across the Slough.

1969 BC 5095 (March 12) *No significant change*

- Channel of Deroche Creek is back in its original position
- Little evidence of 1962/63 flood remaining
- Extensive logging in the upper watershed

1971 BC 5406 (March 19) *No significant change*

1974 BC 5580 (March 21)

- Debris slide scar in upper basin originating from logging road
- Debris slide that transformed into a debris flow that traveled down T-5 and descended Deroche Creek for 50-100 m.

1979 BC 79036 and BC 79055 (June 9 and June 25)

- No changes on fan of Deroche Creek but increasing development
- No new logging in upper watershed and previous slide scars are mostly healed

1983 BC 83058 (Sept. 12) (*Minor flood*)

- Channel freshly scoured, but no major avulsion recognized

1988 BC 823

- No obvious flood damage or avulsions
- Trailer park built on fan
- Very active channel in upper watershed

1993 BCB 93030 (*July 1*)

- Channel very active, fresh scour
- Recent logging (1988/89) in headwaters of upper watershed, but no new landslide scars
- Channel very active upstream of T-4

1996 BCC 96083 and BCC 96083 (*July*),

- Several new failures in the upper watershed
- No significant changes in the lower channel

3.4.2 Resident Interviews

Mr. Norbert Gruenwald and Mr. Kauko Sokkanen were interviewed with respect to past flood damage on the fan of Deroche Creek. Mr. Gruenwald moved to Deroche Creek in 1995, whereas Mr. Sokkanen has been living near the fan apex since 1972. According to Mr. Gruenwald, one flood in 1989 affected part of his property, but his account is based on hearsay. Mr. Sokkanen who operated the town of Deroche's water works reported that there were three large historic floods, of which 1989 was the biggest. (EBA believes that the 1962/63 flood was of higher magnitude, and since Mr. Sokkanen did not live in the area at that time, he has no recollection of the event). According to him, the 1989 flood occurred on a Sunday in the first two weeks of December. When he went to the creek, he noticed that no water was flowing, despite a heavy rainstorm with high freezing levels at that time. Six to 10 hours passed during which he went to warn people downstream and in the trailer park of an impending disaster. Mr. Sokkanen had rightly deduced that landslide damming must have occurred in the upper watershed. As assumed, 6-10 hours after the stream stopped flowing, a large flood wave descended the channel which destroyed Morton Creek road and spilled logging debris onto the fan.

In addition to the 1989 flood, Mr. Sokkanen recollected that the large failure found in glacio-fluvial materials located some 400 m upstream of the fan apex on the east side of the creek was triggered at the logging road by incorrect redirection of drainage to a culvert, thus increasing the discharge onto the slopes below considerably (Photo 5).

3.5 Debris flow runoff

Debris flow runoff is defined as the distance of travel of continuous sheets of boulder size material in the debris flow slurry measured from the fan apex. It does not include reworked sediments beyond the limits of continuous debris coverage, or boulders transported in the creek channel by floodwaters during and after the debris flow.

Debris flow runoff on unconfined alluvial fans is of major geotechnical importance. It depends on the channel longitudinal profile, composition of the debris flow material, debris volume, debris velocity and flow depth. In general, the larger and faster a debris flow, and the more fine material it contains (particularly clay), the further it will travel on the fan.

Takahashi and Yoshida (1979) developed a frequently quoted runoff equation which is based on a granular flow model. Using this formula, a debris flow with a flow depth of 3 m arriving with a velocity of 8m/s at the fan apex would run out for about 100 m. This runoff, however, is defined as the area of direct impact, in which complete destruction can be expected. It is likely that a debris flow would travel further as more liquid afterflow, which can inundate areas and can cause severe scour. This was as observed at Hummingbird Creek on July 11, 1997 at Mara Lake near Sicamous (Jakob et al. 1998). The runoff of 100 m is limited to the fan, but a debris flow is expected to travel at least twice the distance in the channel.

4.0 LOGGING IMPACTS

Numerous studies in the Pacific Northwest including British Columbia have demonstrated that logging may have detrimental effects on slope stability. In this section an overview is presented of various logging impacts on slope stability, and then details the hazards stemming from debris slides and debris flows reaching Deroche Creek mainstem.

4.1 The effect of logging on landslide activity

Forestry operations can have a multitude of impacts on the stability of slopes. They can all be explained by the principals of soil mechanics expressed as the infinite slope equation by Mohr and Coulomb:

$$S = c' + c'' + (\Phi - u) \tan N'$$

where

S is the shear strength of the soil

c' is the cohesion of the soil

c'' is the cohesion due to root strength

Φ is the total normal stress

u is the pore water pressure, and

N' is the effective angle of shearing resistance

The main effects of logging on slope stability are:

- Decay of root systems after the trees are felled which causes a drop in root strength, c_r , that is not restored until the roots of the newly planted trees can match the loss in root strength. The critical time window in which the old roots have decayed to an extent where they have lost most of their cohesive force and the new roots have not regained substantial strength is between 7 and 15 years after clearcutting. In this period a slope is most susceptible to failure.
- Surcharging of slopes (cut and fill road construction) on the road fill slope side. In full bench or half bench road construction the material from the cutslope is simply placed onto the downslope side. This is one of the most frequent sources of landsliding in British Columbia's Pacific Ranges. The local steepening of the slope causes a decrease in slope stability. Although not obvious in the equation above, both normal stress and pore water pressure are a function of slope gradient β . Good examples for failures stemming from fillslopes and probably associated with redirected drainage are provided in Photos 6, 7, and 8.
- Organic material in fillslopes. It is often observed that organic material (trees, branches, root wads) are part of the fillslope. When these rot, water conducting asperities are created that will concentrate runoff and may lead to failure at the point where water is discharging into the slope. Tension cracks are usually the predecessor to failure of the fillslope section of logging roads as displayed on Photo 9 and 10. In addition, layers of organic material can serve as potential shear planes.
- Drainage diversion. Hillslopes are a very complex system of small surface and subsurface drainage channels, which are highly variable in both three dimensional space and time. Any interruption of the natural drainage system may lead to an excess of water in a system that operates at a sensitive dynamic equilibrium. Water concentration in swales that are not "used" to a substantial increase during rainstorms can lead to failure. A typical scenario is that a drainage ditch collects water from several small ephemeral streamlets and funnels it towards one culvert, which discharges the water onto a section of slope that will react with positive pore water pressures under the new water loading, and will eventually fail. A good example of this is shown in Photo 7.
- Cutslope failures. Particularly in soft soils and steep bedrock which dips at angles subparallel to the slope, failure can occur when the slope is undercut during road construction. In the case of soft soils, the steepened slope angle can lead to rotational slumps, or raveling which may turn into a chronic erosion problem. In the case of steeply dipping or foliated bedrock, the joints may be daylighting in the cutslope and slide along the dip, foliation or schistosity. No cutslope failures were detected in the Deroche Creek watershed.
- Failures along cutblock boundaries due to windfall. It has been observed that uprooted trees along cutblock boundaries can be associated to landsliding. Although the exact associations of this process are not known, it is speculated that either the vibration of a falling tree may lead to failure, or the opening of the soil by the uprooting and the subsequent water ingress.
- Increase in runoff after logging. Clearcut logging has been shown to increase the total amount of water available for runoff due to a lack of canopy intercept and

subsequent sublimation, as well as increases in melt rate. Melt ratios (ratio between melt rate in clearcuts vs. forested areas) are typically increased by 1.3 and 2 after clearcut logging. The consequence is that proportionally more water is available during the melt season for runoff. It also means that the hydrograph is "peakier" if substantial areas of the watershed are logged at the same time.

- Ground disturbance by machinery. This may loosen the soil and lead to a drop in the friction angle N' . However it is believed that this effect is minor compared to others.

In some cases, more than one disturbance is present at a given site, since slope failure is typically caused by a combination of factors. An overview of available air photographs of the Deroche Creek watershed showed that 13 landslides over the past 40 years are associated with forestry activities, compared to 3 which were considered natural. Table 2 summarizes the data.

Table 2. Landslide activity from natural and logging-related sources at Deroche Creek

Year of air photography	Natural	Logging-related		
		Open slope	Channel Sideslope	Road Fill Slope
1963	1 debris slide	0	1 debris flows	1 debris slide
1971	1 debris slide	0	1 debris slide	2 debris flows
1979	0	0	0	3 debris flows
1983	0	0	1 debris slide	2 debris flow
1988	1 debris slide	0	0	0
1993	0	0	0	2 debris flows
Total	3 landslides		13 landslides	

No attempt was made to calculate the volumes of debris slides and debris flows of natural versus logging-related landslides, but using landslide area as a surrogate, logging related landslides are probably by two orders of magnitude more efficient in delivering sediment to Deroche Creek compared to natural landslides.

It is evident then that Deroche Creek's sediment load has increased substantially over the past three decades. Much of this sediment has not yet been transported to the fan area and is still within the creek system. Future floods will remobilize this material which will eventually arrive at the fan apex.

4.2 Logging history

Like many watersheds close to early settled areas in the lower Fraser Mainland, Deroche Creek has witnessed several cycles of logging over the past 5 decades. Throughout the 1950s, 60s and 70s access to the watershed has been by the main logging road from the town of Deroche (Figure 1). In the 1950s and early 60s, logging was limited to the eastern part of the watershed on moderately steep slopes. In the later 60s this logging road was extended and crossed Deroche Creek main stem at an elevation of 760 m to then snake up to an elevation of 960 m. In the late 60s and early 70s, extensive areas were logged on the west side of the basin. A new cycle of logging followed in the late 1980s in the extreme upper and western part of the watershed and the northern section. New access roads were provided from Norrish Creek. One of these reaching the saddle on the west side at around 1000 m and one reaching the northern saddle at 1000 m. In total approximately 40% of the watershed has been logged over the past 50 years (see Figure 1).

4.2.1 Potential debris flow source areas

The propensity for landslides to occur in watersheds with intensive logging activities is largely a factor of the type of disturbance. Landslide initiation locations in logged and roaded terrain are only secondarily a function of terrain, and are mostly influenced by the type and intensity of disturbance. Poor road construction has been identified as the most important factor in determining the location of failures. Figure 5 shows a map of areas at which failure is most likely to occur in the future as well as runout scenarios for those failures that are likely to transform into debris flows, an example of which is shown in Photo 12.

4.2.2 Debris flow yield rate and probable volume

One of the biggest unknowns in debris flow behaviour is the rate at which material is being entrained during the downslope path of a debris flow. Within the transport zone, yield rate, which is expressed in cubic meters of material eroded per meter channel length, depends on the amount of material presently available in the channel. In purely colluvial channels, there may be a quasi infinite amount of sediment available. Most tributaries of Deroche Creek, however, are underlain by bedrock and therefore the amount of entrainable sediment is finite. As more and more sediment is being entrained during a debris flow, the wetted perimeter (i.e. the area covered by the front surge of a debris flow) increases and subsequently more material can be eroded from the channel sidewalls. Without a detailed sediment survey of each side channel (one tributary per field day), it is not possible to quantify this yield rate. For this study, yield rates were averaged based on past experience and precursory channel observations.

4.2.3 Debris flow runout

An attempt was made to calculate the runout of debris flows entering Deroche Creek at tributaries T-4, T-5, T-6 (Figure 4). The variables used for each tributary are listed in Table 3.

Table 3. Input parameters for debris flow runout calculation for T-4, T-5, T-6 and mainstem

Input parameters	T-4	T-5	T-6	Mainstem
Θ is the runout slope angle (average)	9°	9.5°	9.5°	10°
Θ_0 is the entry slope	15°	20°	20°	15°
U_0 is the flow velocity	10 m/s	8 m/s	8 m/s	5 m/s
H_0 is the flow depth	4 m	4 m	4 m	3 m
Runout in Deroche Creek	600m-fan	500-?	500-?	1000-?

constants:

g is the acceleration of gravity

9.81 m/s²

S_f is the friction slope (assumed)

$\tan 10^\circ$

- Table 3 shows that there is a variety of scenarios possible. The unknowns that will determine whether a debris flow will travel to the fan or not, are:
- the arriving peak discharge which will determine the flow depth,
 - the volume, which will determine the magnitude of the impact,
 - further entrainment or deposition of material downstream,
 - the contents of fines of the debris flow matrix, and
 - the flow velocity at given sites along the channel.

At this point in time and with the present lack of data that allows calibration from former flows, debris flow science cannot provide accurate enough figures to determine the runout distance of debris flows as they impact Deroche Creek. However, air photo evidence suggests that once a debris slide or tributary debris flow impacts the channel of Deroche Creek, it will travel for several hundred meters before enough material has been deposited alongside the channel, at which time the debris flow is transformed into a debris flood.

It is believed that debris flows from tributaries T-4, T-5, T-6 and the mainstem of Deroche Creek, will travel at least several hundred meters and possibly over one kilometer, but are unlikely to reach the fan as a debris flow. Nonetheless, analysis in Section 3.5 suggests that even if the debris flow transformed into a debris flood, peak discharge could be as much as four times the calculated 200- year flood flow.

4.2.4 Debris flow dam outbreak scenarios

There are several geomorphic processes acting in mountainous watersheds that can affect stream discharge. At Deroche Creek the two most prevalent mechanisms are debris flows travelling some distance down the main stem, and debris flows and debris slides discharging and blocking the main channel until the landslide dam is overtopped and collapses. The main tributaries are shown on the creek profile on Figure 4. This section focuses on the latter scenario. Likely locations for landslide dams along Deroche Creek are marked on Figure 5. There are other locations, particularly in the canyon extending to about 300 m elevation. However, locations of rock or debris slides in this area are difficult to pin point without a detailed investigation of these slopes, which would likely be cost prohibitive. Exact modeling of dam outbreak scenarios is not possible with the data at hand. The biggest unknowns are:

- The volume of the slide into the channel which determines the dimensions of the landslide dam;
- The height, width and length of the landslide dam which determines the water volume stored behind it;
- The exact topography of the channel upstream of the landslide dam which determines the water volume and depth;
- The material composition of the landslide dam that determines the breach rate.

In the following, calculations are made to determine an approximate discharge rate for the landslide-generated dam outbreak scenario. The main simplifying assumptions are:

- The dam has a trapezoidal cross section;
- The landslide dam is largely impermeable and the reservoir fills up completely before dam breach;
- The dam breaches abruptly and completely; and
- The flow will accelerate but obtain steady flow conditions before arriving at the fan.

The assumptions were chosen to simplify volumetric calculations and to simulate the worst case scenario and therefore present a conservative approach.

Dam break scenarios can also be simulated by means of computer models. These models are much more sophisticated than the analysis presented herein, however, they require detailed input data that is not available in this study. Most of these models are based on one-dimensional equations of unsteady flow and finite-difference solutions. They can take into account supercritical and subcritical flows, which is not accounted for in these calculations. The input parameters for

these models are very specific and are not matched by the uncertainty involved in the estimation of the debris flow volume or dam geometry. For these reasons, the more sophisticated dam break models were not used in this study.

Various authors have compiled data on actual dam outbreaks from which they developed empirical formulae that correlate peak discharge with dam height, and, water stored behind the landslide dam e.g. Blown and Church (1985), Costa and Schuster (1988), Clague and Evans (1994), and Walder and O'Connor (1997). Although valid as first approximations, these formulae have recently been criticized by Walder and O'Connor (1997) who emphasize the importance of breach rate in determining flood peak discharge. They suggest that the hydrograph at the breach depends primarily on a dimensionless parameter, $\eta = kV_0/g^{1/2}d^{7/2}$, where k is the mean erosion rate of the breach, d is the lake level drop during the flood, which in the worst case, equals the dam height, V_0 is the lake volume, and g is the gravitational constant. Walder and O'Connor's formulae are probably the most accurate but leave the difficulty of assuming an appropriate breach rate.

Peak discharge estimates are listed in Table 4, for a five metre high dam and a stored water volume of 25,000 m³, according to the various authors.

Table 4. Peak discharge estimates for dam outbreak scenario at T-4 confluence

Authors	Formula	Qp (m ³ /s)
Blown and Church (1985)	$Q_p = 2.7(H_d V)^{0.42}$	894
Costa and Schuster (1988)	$Q_p = 0.0158(PE)^{0.42}$	248
Clague and Evans (1994)	$Q_p = 0.063(PE)^{0.41}$	787
Walder and O'Connor (1997)*	$Q_p = 0.99(H_d V)^{0.40}$	249
Walder and O'Connor (1997)†	$Q_p = 1.51(g^{1/2}d^{3/6})^{0.06}(kV_0/d)^{0.34}$	791

* empirical formula used by Walder and O'Connor

† mathematically derived formula by Walder and O'Connor, assuming a breach rate of 10 m/min

PE is the potential energy of the outbreak flood expressed as the product of H_d , V , and 9800 Newtons/m³

k is the breach rate

H_d and d are the dam height and lake level drop, respectively

V and V_0 is the volume of water impounded

Using Mr. Sokkanen's account that the 1989 dam did not fail for at least 6 to 10 hours. Back calculation indicated that at an average inflow rate of 10 m³/s a total volume of about 200,000 m³ may have been stored behind the landslide dam. For the last formula, a breach rate (k) of 1m/min was assumed.

In order to model dam failure, it is important to understand the mechanism of failure. Three cases of dam failures are conceivable (Takahashi, 1991):

- Erosive destruction due to overtopping;
- Abrupt sliding collapse; and
- Progressive failure.

In case 1, the dam body has a low permeability and large shear strength and the water supply from upstream is large. In case 2, the dam has a higher permeability and is weaker than in case 1. In case 3, the permeability of the dam body is very high and seepage appears at a lower point on the downstream face of the dam before the water table rises to the top of the dam. Having observed remnants of debris flow dams in channels, it appears that considerable strength is derived from the coarseness of the bulk of the material, while the finer sediment fraction and organic debris effectively reduce permeability. Consequently, modelling was confined to failure case 1.

It is essential to determine the method for peak discharge estimation that is most suitable for application in this study. All empirically derived equations lack important information about breach rate that has been identified as the main determining variable for peak outflow estimates (Walder and O'Connor, 1997). Breach rate, however, is a function of material composition and breach geometry, as well as reservoir dimensions. The assumed breach rate of 1 m/min must therefore be viewed with some skepticism.

The Clague and Evans (1994) formula represents an upper boundary for a variety of outbreak scenarios including moraine dam collapse, glacial dam collapse, and landslide dam collapse. It is therefore very conservative. The Costa and Schuster (1988) equation is derived from least-squares regression analysis, which implies a mean rather than a maximum value for peak discharge, and must therefore be regarded as too low for design purposes. Walder and O'Connor's (1997) discharge formula is close to Costa and Schuster's and has also been obtained by regression analysis. The formula by Blown and Church is similar to the solution by Clague and Evans in that it is derived from a maximum envelope curve, based primarily on large dams, and therefore may not apply to the problem presented here. The problem with all data sets is that they include very few cases involving small failures. Consequently, there is some uncertainty pertaining to the validity of the above formulae for small failures.

Considering the limitations of the above formulae and using geomorphological judgement, a peak flow of 300 m³/s is considered a conservative estimate for the reach immediately below the site of the potential dam breach. It can be expected that this peak flow will attenuate by 10-20% due to overbank flow as it approaches the fan apex. This implies that the flood discharge arriving at the fan

apex would be approximately 240 - 270 m³/s, which is reasonably close to the estimate of 200-240 m³/s indicated in Section 3.3.

4.3 Sediment links and sediment transport

Many watersheds in British Columbia have high forestry and fisheries values, and some act as community watersheds such as Deroche Creek. Integrated resource management has been suggested as a concept by several authors but has not made it to an operational stage. An exception is work conducted by Hogan and Willford (1989) who attempted to link erosion to fish habitat. Their classification system can be transferred to suit the needs of this study. Figure 6 shows the links of sediment transfer in Deroche Creek.

The ability of a stream channel to entrain and transport sediment is a function of several factors (e.g. stream velocity, local channel gradient, nature of the bed and bank materials, channel shape and morphology, etc.). However, it is rarely feasible to collect specific data regarding these factors and it is usually impossible to rely on direct measurements when making management decisions at the operational level.

Without quantifying the time dependent transfer of sediment through the tributary and main system it is not possible to predict when a significant sediment wedge will work its way down to the fan area and cause serious aggradation. An example of a sediment wedge which will be moved only in the largest floods, is shown in Photo 12. This aggradation was caused by a debris flow that initiated from a road fill failure as shown on Photos 8 and 13. In light of the observations made in this report, it is probable that such aggradation can be expected and should be included in the planning of future channel works and maintenance budget.

5.0 DEBRIS FLOW AND DEBRIS FLOOD MITIGATION MEASURES

Debris flows are the result of natural geomorphological processes that may be enhanced by human activities. Therefore, debris flow mitigation can aim to reduce the impact of naturally occurring mass movement processes and also minimize the influence of human activity. These measures focus mainly on the upper watershed and are usually cost intensive since these areas are much more difficult to access with heavy machinery. At the same time, measures can be taken at the apex of the alluvial fan before the mass movement reaches the populated part of the fan or threatens to destroy other structures. Measures to deal with debris flows are discussed below together with their applicability to the Deroche Creek situation. These and other options are summarized in Table 13.1, Section 13 in the main body of report by HayCo.

5.1 Active Measures

Active measures include various engineering works along the channel or in the basin.

5.1.1 Channel improvements

Channel improvements will reduce the flood hazard, but are insufficient to provide protection from debris flows. They include stream bed and bank armoring, check dams to prevent channel scour as well as bedload removal, channel shifts, side slope stabilization, and berm construction.

5.1.2 In-stream debris barriers

In-stream debris barriers upstream of the fan apex are appropriate where access is easy to empty the basin after a debris flow or debris flood has occurred, and where low channel gradients allow the storage of sufficient volume of debris. The steel grillage could either be tied directly into the surrounding bedrock or be attached to steel reinforced concrete wingwalls. Examples for those types of structures are shown in Figure 7.

At Deroche Creek, the best location for such a barrier would be just upstream of the community water intake. Alternative sites further upstream are much more difficult to access by vehicle, and expensive roads for construction and maintenance would have to be built. Furthermore, point impact forces and dynamic thrust would be extremely high in the channel, which implies that any in-stream barrier would have to be massive implying high construction costs.

An in-stream debris barrier above the fan apex would contain the coarsest fraction (>300 mm) of the design debris flow or debris flood volume and would pass finer material (<300 mm) to maintain channel characteristics and fish habitat downstream. A high concentration of organic material in the flow could cause a complete closure of the structure, which would imply that all incoming debris would have to be retained by the structure. A steel grillage structure with 800 mm hollow steel girders with a thickness of approximately 30 mm, 5-7 m high anchored into bedrock would be required. This would require an access road into the basin through bedrock. Alternatively, the steel grillage could be made removable to allow direct frontal access. Costs for an instream debris barrier are likely to range between \$ 0.5 and \$ 1 million.

5.1.3 Energy Dissipation Structures (EDS)

A subclass of in-stream debris barriers are energy dissipation structures (EDS) which are designed to discourage channelization, and facilitate deposition in the upper part of the fan. There is some space in the upper fan of Deroche Creek for the installation of EDS, but it would have to be guaranteed that the spreading of debris is limited to an undeveloped area and that the water is refunneled back into the main stem of Deroche Creek. EDS have been successfully employed to decrease the momentum of snow avalanches. The EDS for Deroche Creek could be a phalanx of three to six steel reinforced pyramid shaped concrete structures.

These concrete pyramids would deflect the debris mass in different directions, increase flow width, decrease flow depth and hence encourage water drainage. This would lead to more rapid deposition than if the flow remained channelized. Early deposition would not only decrease the probability of downstream scour and impact forces, but would also decrease the volume of the flow before it arrived at the unconfined section of the fan.

5.1.4 Erosion control in the upper Deroche Creek watershed

Erosion control in the upper basin is feasible for basins in which distinct areas of instability such as talus slopes, ravelling glaciofluvial materials, unstable road sections or sections of brittle bedrock have been identified. In the case of Deroche Creek, potential zones for debris flow initiation identified in Figure 5 are mostly limited to logging roads. Access is possible via Norrish Creek by two different road systems. It is strongly recommended to deactivate road sections that are prone to failure.

5.1.5 Debris Basins

Debris basins are large containment areas that are maintained empty while awaiting the arrival of a debris flow or debris flood. When a debris flow occurs, it is designed to arrest and retain the debris deposited, hence reducing any damage downstream of the basin. Depending on the design, some of the material can be conveyed through the outlet structures into the original creek bed. This has the effect of maintaining the original channel characteristics. Debris basins are structurally fairly easy to implement if sufficient space is available. The proper design of debris basins calls for reliable prediction of debris flow magnitude. If it is constructed too far downstream on the fan, the flow must be channelized and the channel armoured to reach the basin. If it is built close to the fan apex, higher impact forces and scour prevention will require a more costly construction. Debris basins need to be emptied after each event which requires easy access into the basin after debris flood events. In the case of Deroche Creek, it is fortunate that a large area suitable for a debris basin exists downstream of the community water intake. A basin of this kind would probably cost approximately \$ 2 million.

5.2 Passive Measures

Passive measures do not involve any construction and are based on accepting the present risk, delineating areas where no development should take place. This option may be implemented in combination with berm. To do nothing (zero solution) is not a responsible option in the case of Deroche Creek because the fan is populated and there is a high probability that a debris flood of significant magnitude will recur on the fan within the next 10-50 years.

5.2.1 Zoning

Ideally, debris flow hazards should be identified before development proceeds, and the area can be delineated in which no development should take place. Obviously, there are political and social difficulties associated with this approach. Zoning at Deroche Creek under existing conditions without constructing defence measures implies high costs associated with property acquisition and the expected public resistance.

5.2.2 Covenants

Several covenants are possible to implement in the Deroche Creek watershed. First, no additional building be allowed in a corridor on both sides of the creek specified by the flood hazard maps. Second, bylaws could be created that would require that existing houses be sheltered from debris impact by either raising the foundations, and reinforcing the piers or foundations on which the buildings are supposed to stand, or erecting triangular steel-reinforced concrete deflection structures upstream of the houses with the base of the triangle facing the house and the point facing upstream.

5.2.3 Additional logging in the watershed.

Clearcutting and poor road construction in addition to poor drainage management has led to a number of significant landslides in the Deroche Creek watershed. It is very important that any further logging plans be scrutinized by geoscientists or geotechnical engineers familiar with modern standards of road construction and cutblock layout according to the Forest Practices Code of British Columbia. **Logging in community watersheds or watersheds with important downslope resources must be conducted with extreme care to avoid detrimental consequences stemming from landsliding within cutblocks or from logging roads.**

6.0 CONCLUSIONS AND RECOMMENDATIONS

Deroche Creek watershed has witnessed a number of significant landslides some of which have led to downstream flooding through outburst of small landslide dammed lakes in the middle and upper channel. The vast majority of large landslides is due to forestry activities, particularly substandard road construction and poor or no drainage management. Poor logging practices and road construction in the Deroche Creek watersheds should not continue since they:

- threaten structures and human life along the channel and on the fan
- jeopardize of fish habitat downstream
- lower timber values for the future forest usage

According to the findings of this report, recommendations in this report are aimed at two separate issues:

First, a debris barrier should be erected in the vicinity of the community water intake. Second, the upper watershed should be stabilized by a number of measures.

Debris barrier:

The design of the debris barrier should allow water and material less than 300 mm to pass to maintain the stream channel morphology below. The structure should be approximately 5 m high and consist of a square grid of steel girders. An access road into the catchment basin upstream of the barrier needs to be constructed to allow clearing of debris after significant events have taken place.

Upper watershed stabilization measures:

- Prepare detailed road deactivation prescription of all existing roads, which should be implemented as soon as possible.
- Prior to permanent road deactivation, proper drainage paths should be constructed across the upper logging roads maintaining all natural flow paths. Water diversion that may lead to an enlargement of the natural drainage area must be avoided at all cost.
- Any further logging or road construction plans should be reviewed by a qualified geotechnical engineer or geoscientist.
- Monitor the site after heavy rainstorms to assess the stability throughout the winter months. The most likely time for debris flow initiation in the general area is from the end of October through December, but they can occur at other times such as convective storms (thunder storms) during June, July and August.

7.0 CLOSURE

Conclusions and recommendations presented herein are based on site observations made on September 18 and 19, 1999. This report has been prepared for use by Hay & Company Consultants which includes distribution as required for purposes for which this assessment was commissioned. This assessment has been carried out in accordance with generally accepted geoscience practice. Geoscience judgment has been applied in developing the recommendations in this report. No other warranty is made, either expressed or implied.

Neither hydrology nor geomorphology is classified as a precise science, and therefore some uncertainty in the estimates for discharge and volumes presented in this report will remain. Alluvial fans are by definition a hazardous area, and will remain so, even after mitigation measures are implemented.

EBA trusts this report satisfies your present requirements. Should you have any questions or comments, please contact our office at your convenience.

Respectfully submitted,

EBA ENGINEERING CONSULTANTS LTD.

Prepared by:



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

Reviewed by:



Nigel Skermer, M.Sc., P.Eng.
Geotechnical Consulting Engineer

VA@VANPROJECTS\1999\99-86217\report.doc

REFERENCES

- Blown, I. and Church, M. (1985). Catastrophic lake drainage within the Homathko River basin, British Columbia; Canadian Geotechnical Journal, V.22, 551-563.
- Clague, J.J., Mathews, R.W., Guilbault, J.-P., Hutchinson, I., Ricketts, B.D. 1997. Pre Younger Dryas resurgence of the southwestern margin of the Cordilleran ice sheet, British Columbia, Canada. *Boreas*, 26: 261-278.
- Clague, J.J. and Evans, S.G. (1994). The formation and failure of natural dams in the Canadian Cordillera. Geological Survey of Canada. Bulletin 464.
- Clague, J.J. Late Quaternary geology and geochronology of British Columbia. Part 1: radiocarbon dates. Geological Survey of Canada, Paper 80-35.
- Costa, J.E. and Schuster, R.L. (1988). The formation and failure of natural dams; Geological Society of America Bulletin, v.100, 1054-1068.
- Gruenewald, Norbert, 1999. Personal communications, October 1999.
- Hogan, D.L. and Wilford, D.J. 1989. A sediment transfer hazard classification system: linking erosion to fish habitat. Proceedings of watershed '89. A conference on the stewardship of soil, air and water resources.
- Jakob and Jordan, 1999. Design flood estimates in mountain streams: The need for a geomorphic approach. In: Canadian Water Resources Association: Confronting Uncertainty: Managing Change in Water Resources and the Environment. Richmond, B.C. Oct. 27-29.
- Jakob, M., Martin, S., Skermer, N., Campbell, C., Anderson, D. and Fuller, T. 1998. A record breaking debris flow at Hummingbird Creek, Mara Lake, B.C.
- Sokkanen, Kauko, 1999. Personal communications, October 1999.
- Takahashi, T. and Yoshida, H. 1979. Study on the deposition of debris flows, Part I – deposition due to abrupt change of bed slope. *Annals, Disaster Prevention Research Institute*, Kyoto University, 22 B-2.
- Walder, J.S. and O'Connor, J.E. (1997). Methods for predicting peak discharge of floods caused by failure of natural and constructed earthen dams. Water Resources Research In press.

Photo 1. Densely jointed bedrock of the Harrison Lake Formation



Photo 2. Interface between basal and weathered ablation till in the upper watershed



Photo 3. Cross-section of older fan deposits along Morton Road

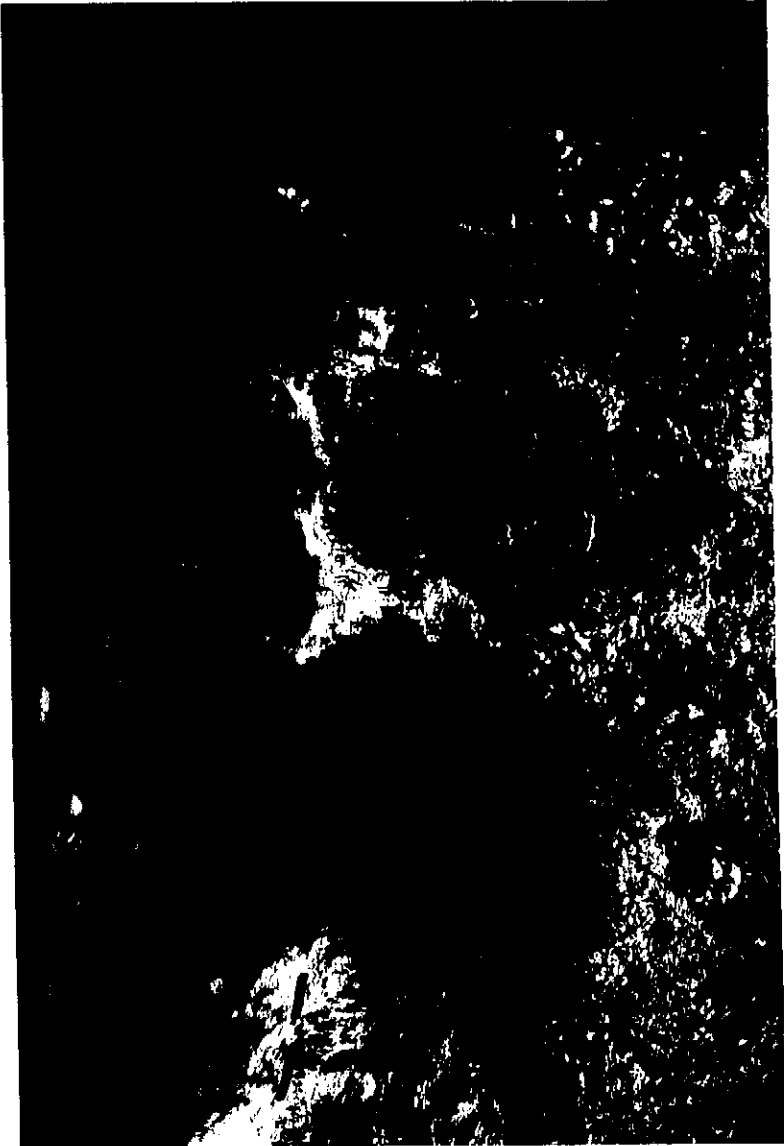


Photo 4. Channel section adjacent to Mr. Gruenwald's property where v was calculated



Photo 5. 1970s failure in fluvio-glacial sediments triggered by redirected road drainage

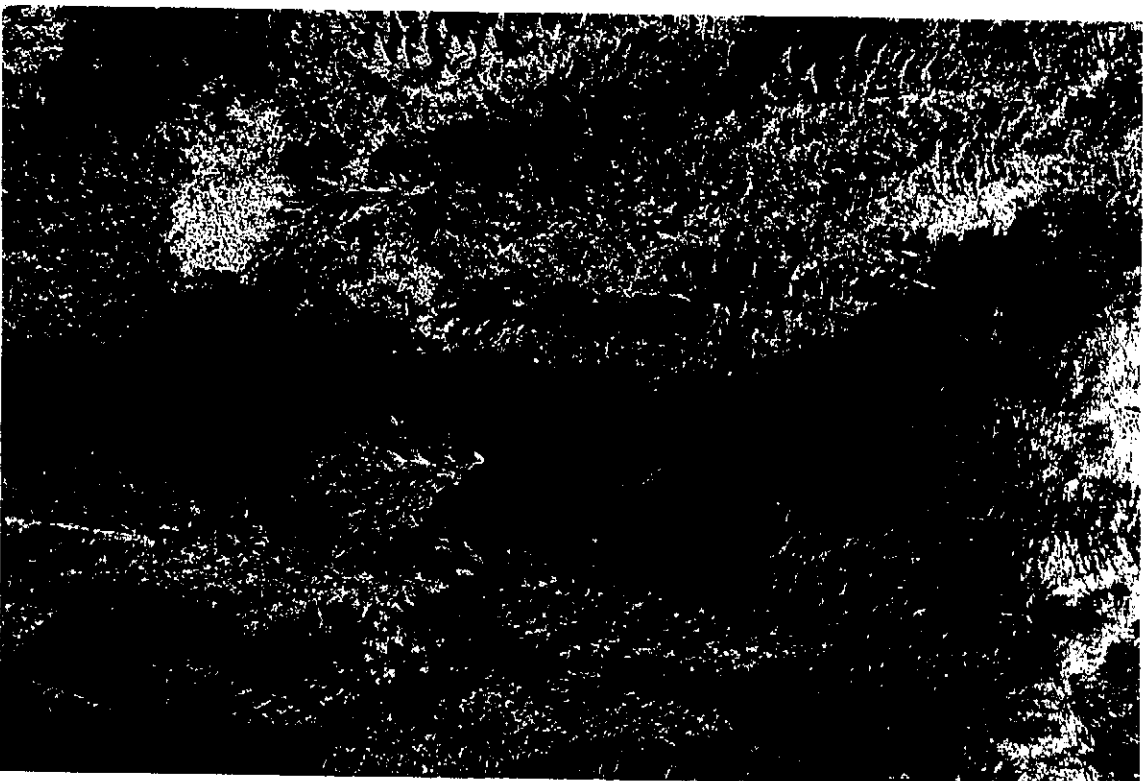


Photo 6.

Fill slope failures from logging road in upper watershed

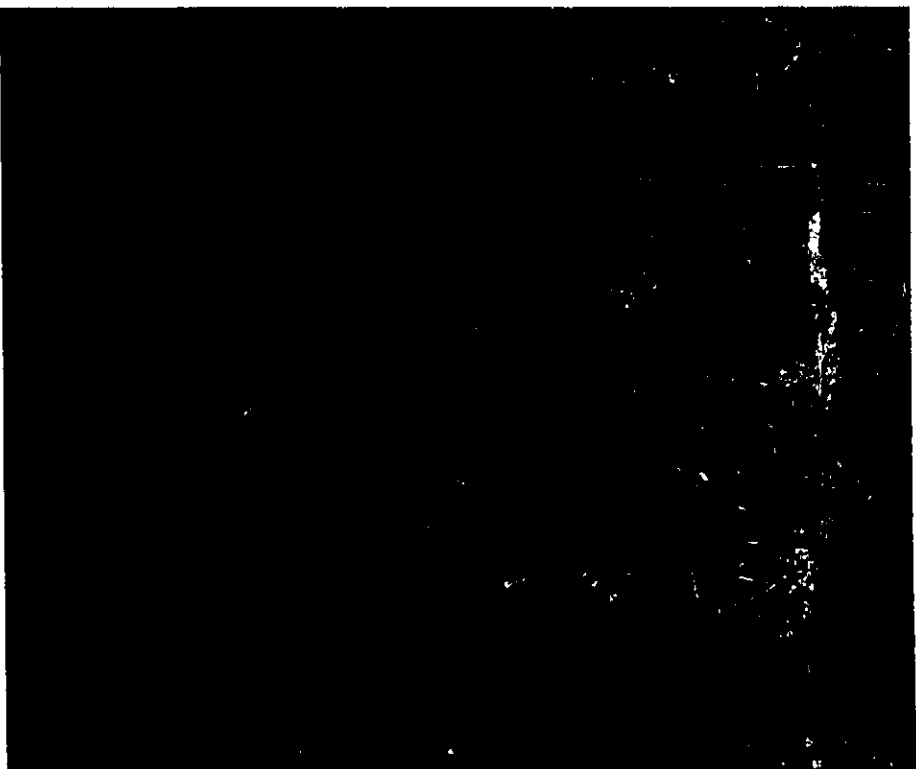


Photo 7.

Low-gradient fill slope failure due to redirected drainage in upper watershed

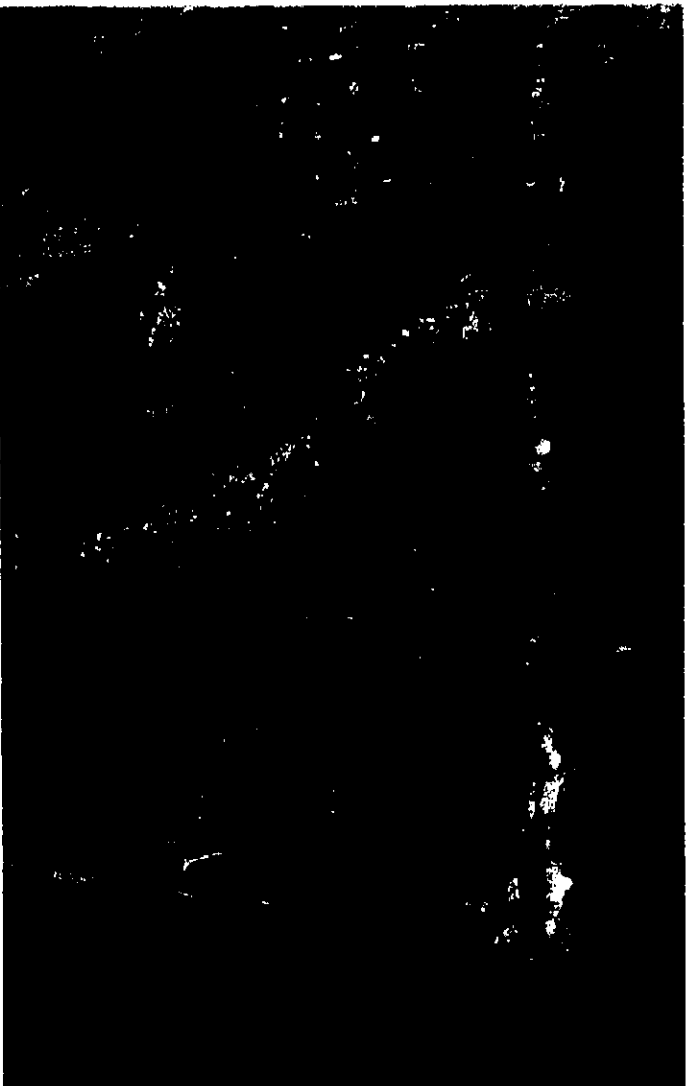


Photo 8. Fill-slope failure that transformed into debris flow, upper watershed



Photo 9. Extensive tension crack along upper road in upper western watershed



Photo 10.

Tension cracking and small fill slope slump along upper road



Photo 11.

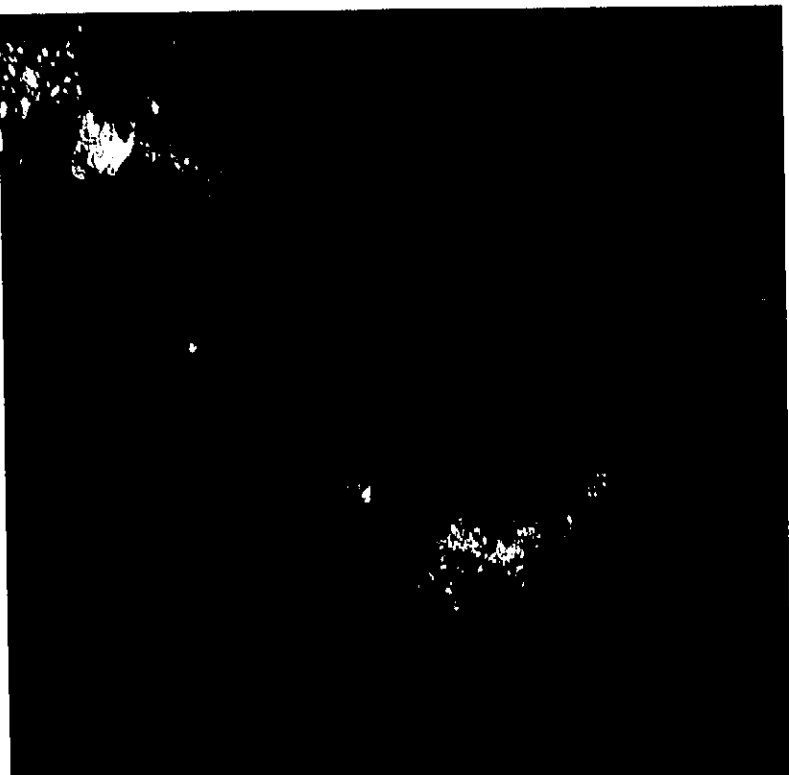
1987/88 clearcutting along ridgecrest of western sub-watershed

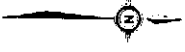
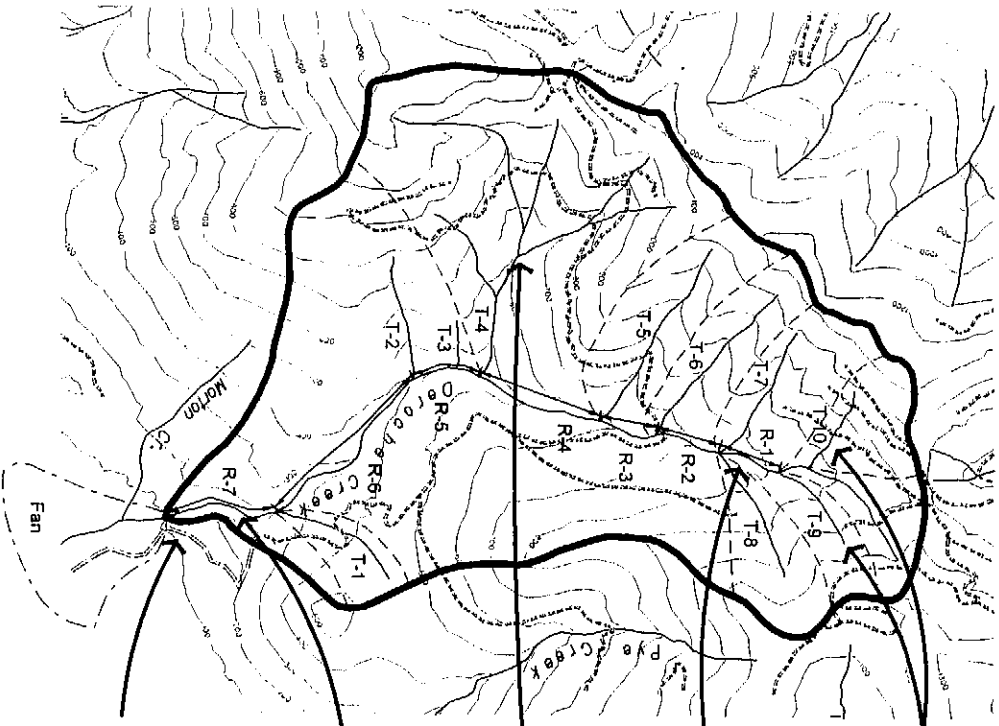


Photo 12. Sediment wedge caused by debris flow in Deroche Creek mainstem



Photo 13. Debris flow track and very large boulder upslope of Photo 12





* Sediment is currently being produced in tributary basin T-9 and T-10. Sediment enters the stream channels with up to several 1000 m³. Sediment may be deposited in the tributary channel or be conveyed directly to the main channel.

* Given that the sediment enters the mainstem channel (R-1) in this example, the sediment may be transferred downstream for several hundred meters or stall at the point of impact with the main channel. When deposited, sediment is stored intermittently until the next major flood or debris flows move it further towards the creek fan. Additional sediment maybe entrained in R-1.

* There is a high likelihood that sediment will likely be produced from landsliding in the T-4 watershed. The overall impact will not only be a function of the T-4 sediment delivery, but will have a cumulative effect of sediment movements at T-9 and T-1.

* This cascading effect is followed from one tributary basin into the mainstem reach, then to the point of the next contributing tributary basin and so on down the stream until it reaches the creek fan.

* On the fan, sediment wedges from former landslides in T-9, T-10 and T-4 arrive at the fan apex and can cause sudden and significant aggradation during future flood events. Mitigation structures need to consider the amount of aggradation that can reasonably be expected over time. This requires monitoring of current sediment storage reaches and the downstream progress during significant floods.

- Drainage basin divide
- Logging Roads
- Tributary basins
- Creek fan area

Applied from figure 2 in Hogan and Wilford (1989)

EBA Engineering Consultants Ltd.		eco	
CLIENT	HAY & COMPANY	PROJECT	DEROCHE CREEK DEBRIS FLOW & DEBRIS FLOOD STUDY
DATE	1999/12/06	TITLE	SEDIMENT LINKS
DWN.	ML	FILE NO.	0807-99-86217
CHKD.	MJ	FIGURE	6

C

C

C

Figure 3. Relationship between debris flow peak discharge and total volume for a worldwide data set. Data from British Columbia are superimposed expressed as diamonds and crosses.

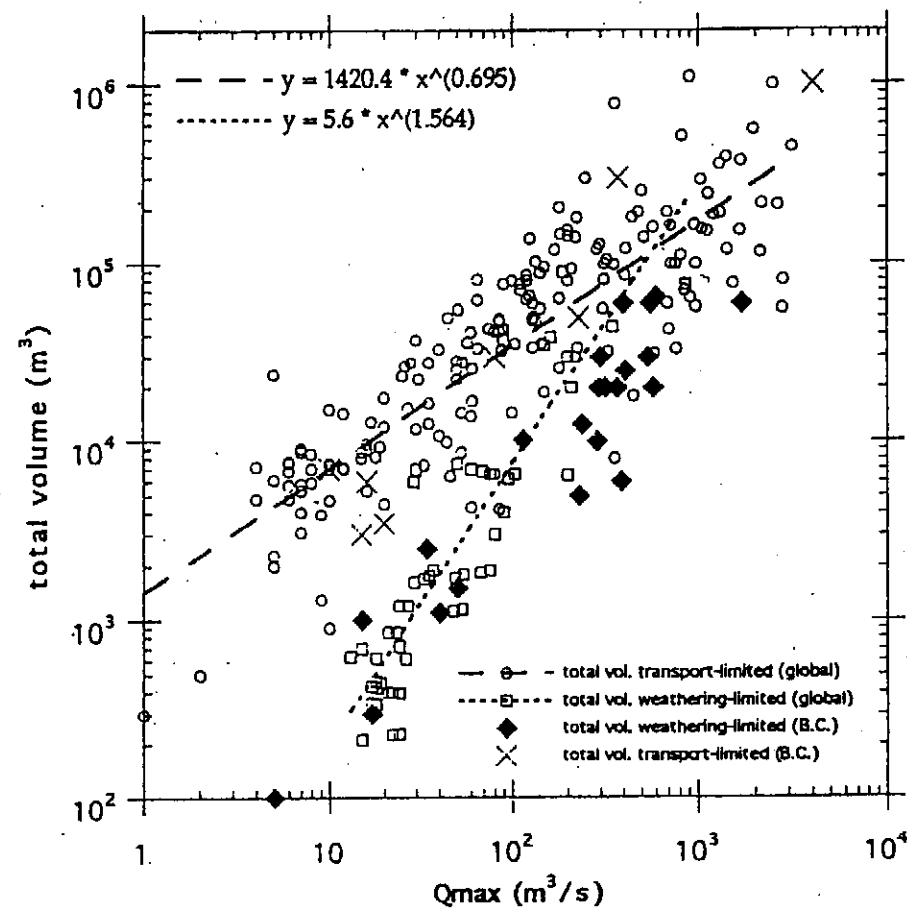
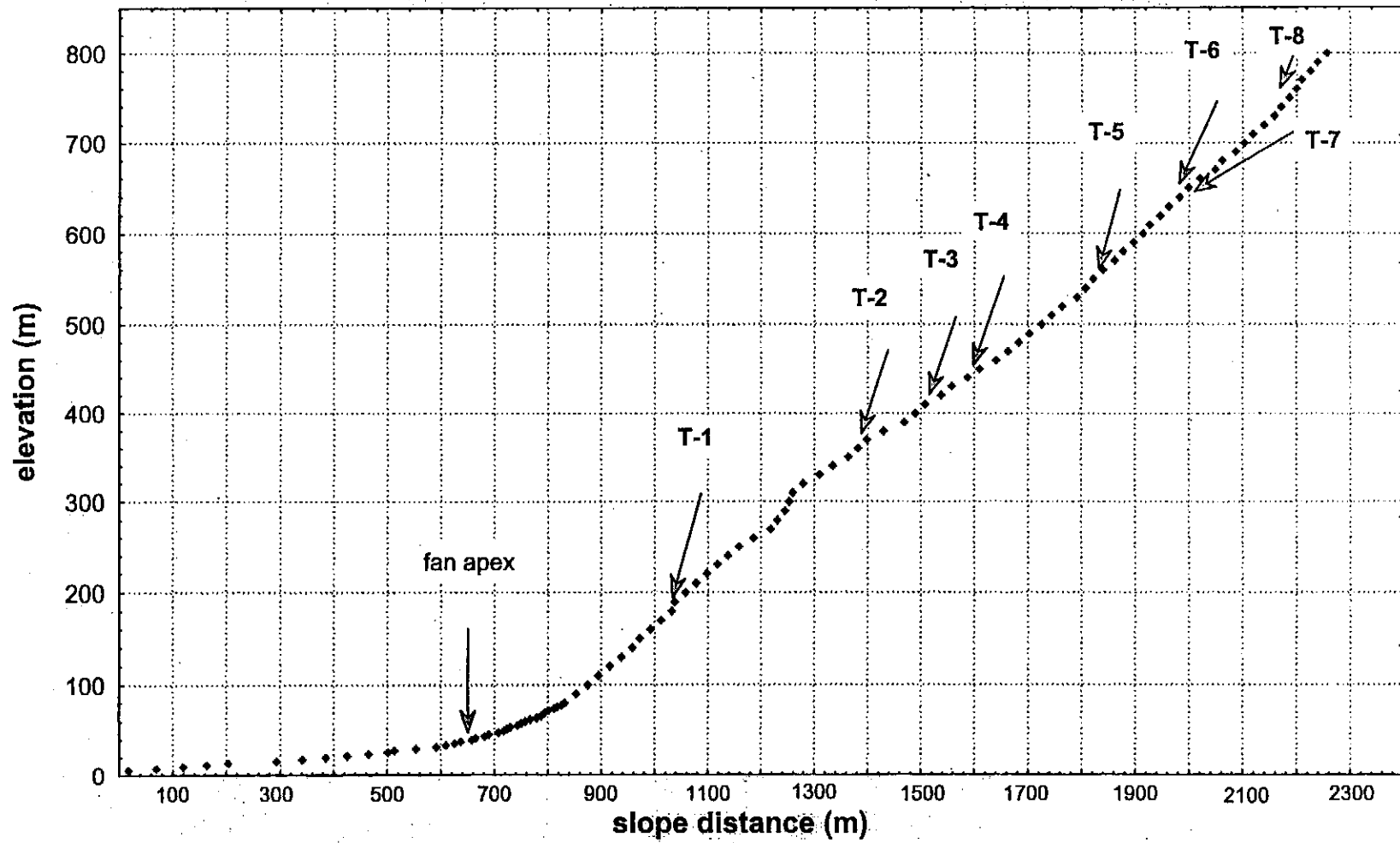
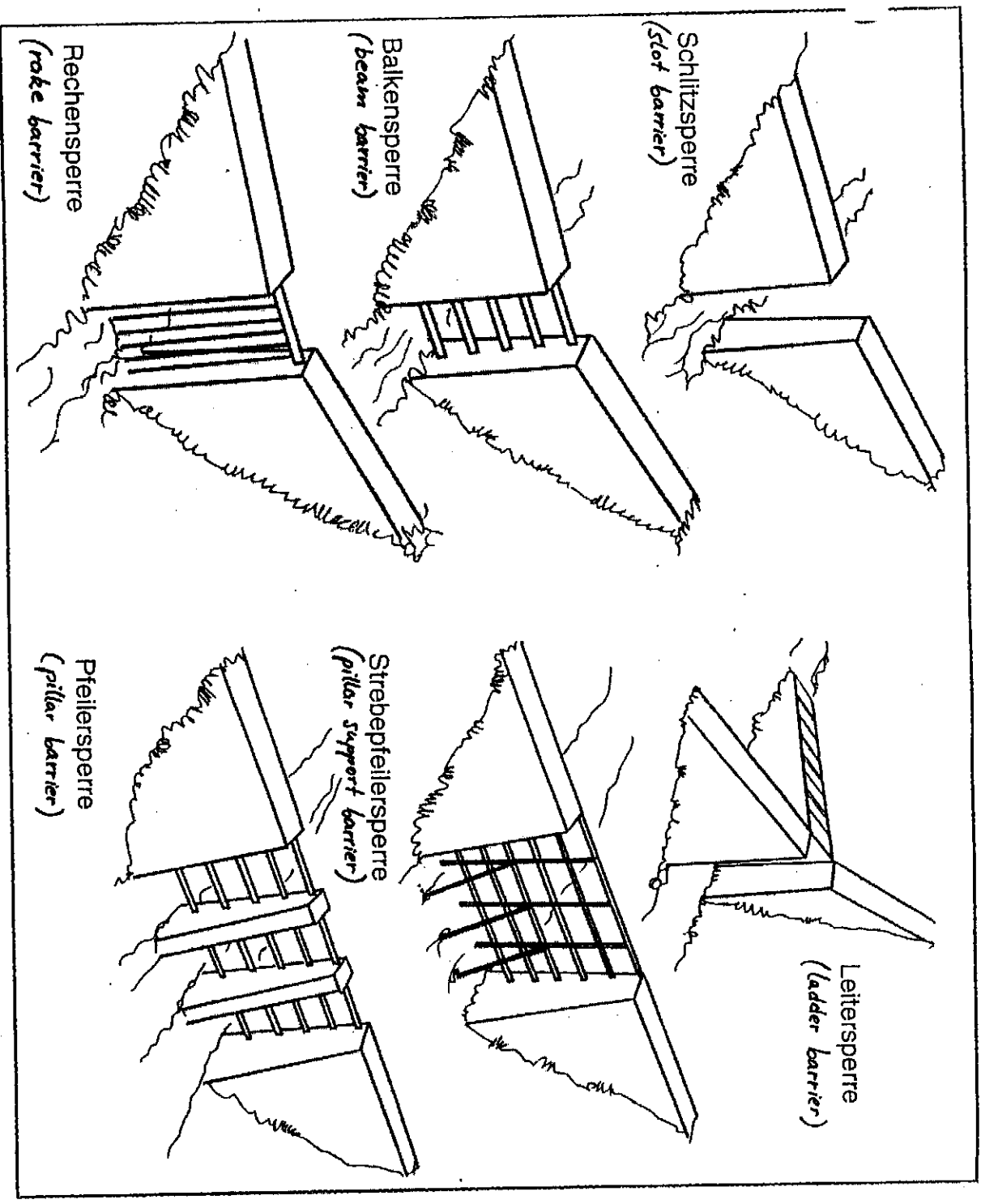
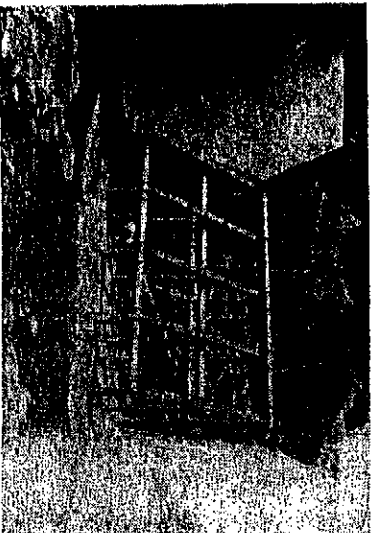
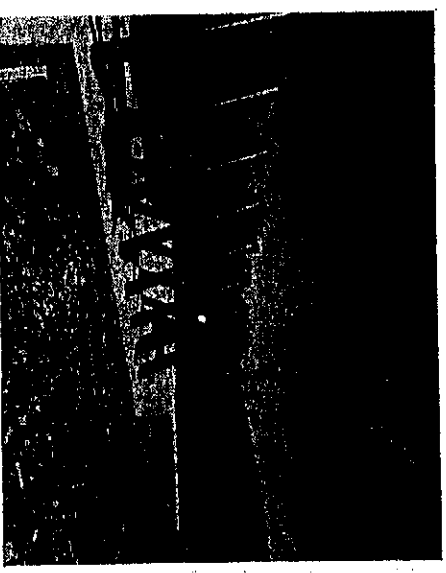


Figure 4. Deroche Creek profile and tributary junctions





Wood-debris entrapment facility



A-type silt dam

Figure 7:

Examples of In-Stream Barriers

APPENDIX 2

Deroche Creek Environmental Review - 0806-99-86217

Field Notes

The environmental field assessment was conducted on November 5, 1999. A heavy rainfall event had occurred the previous day. The sky was 60% overcast at the start of the survey, with an air temperature of 10.5 °C and the wind blowing from the southwest at approximately 10 km/h (estimated). The Deroche Creek water temperature was recorded at 6.5 °C, and the water was clear (very low turbidity). The stream flow stage was considered to be moderate.

During the field assessment, EBA completed a Ministry of Environment, Lands and Parks (MELP) Stream Survey Site Card, and walked the stream from the mouth to the Morton Road crossing, a distance of approximately 1,400m. Along the way, notes were recorded on riparian vegetation and signs of wildlife and wildlife habitat. Within this reach of the stream, two distinct sub-sections were observed, based on gradient and channel type: from the mouth to the CPR bridge, and from the CPR bridge to the Morton Road crossing.

At its confluence with Nicomen Slough, Deroche Creek flows through a fan-shaped delta consisting mostly of fines, with some gravels. Grasses were the dominant vegetation cover, and provide habitat for waterfowl (A flock of unidentified ducks was flushed out of the grassy areas during the survey). The channel morphologic type in this section was Riffle-Pool, with the stream substrate consisting predominantly of gravels and fines. Moving upstream, a large shallow pond was found just downstream from the first road bridge. Five adult chin salmon in pre-spawning condition were observed to be holding in this pool. Upstream of the first road bridge, the channel was constrained by what appeared to be dykes on both banks. An increase in the channel aggradation was also noted upstream from the road bridge. Measurements taken between the first road bridge and the CPR bridge indicate that the average channel width was 9m and the average wetted width was 5m. The average stream gradient in this section was measured at approximately 1.5%. The residual pool depth was measured at an average of 0.25m. No bankfull depth measurements were made in this reach. A number of channel disturbance indicators were noted in this section, including extensive riffle areas, homogeneous bed materials and large sediment wedges. No functional (i.e. anchored Large Woody Debris (LWD)) was encountered in the stream channel). The riparian vegetation consisted of black cottonwood trees (*Populus trichocarpa*), estimated at 50-80 years old, alder (*Alnus* sp.), willow (*Salix* sp.), sedges (*Carex* sp.), Douglas maple (*Acer glabrum*), bigleaf maple (*Acer* sp.), thimbleberry (*Rubus parviflorus*) and Himalayan blackberry (*Rubus* sp.). One potential wildlife tree was identified (just downstream of the CPR bridge). Other wildlife signs included coyote scat on the left bank at the CPR bridge.

Upstream of the CPR bridge, the channel gradient increased to an average of 4%, and the channel morphology changed to Cascade-Pool. The banks in this section appeared more natural (i.e. not man-made dykes) and consisted of cobbles and boulders. The predominant bed materials in this section were cobbles and gravels. The average bankfull depth was measured at an average of 0.6m and the average bankfull and wetted widths were measured at 9m and 6m, respectively. The average residual pool depth was measured to be 0.17m. A number of channel disturbance indicators were noted in this section, including eroding banks, elevated bars and disturbed stone lines. No functional (i.e. anchored) LWD was encountered in the stream channel. The riparian vegetation in this section included more conifers, including western redcedar (*Thuja plicata*). A number of sidechannels were also noted in this section. Two specimens of American Dipper (*Cinclus mexicanus*) were observed by the streamside in this section.

