Whatcom County Flood Control Zone District

Canyon Creek Alluvial Fan Risk Assessment

Final Report
September 2003

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KWL File No. 2039.001

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associates limited
CONSULTING ENGINEERS

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EXECUTIVE SUMMARY

Whatcom Country Flood Control Zone District retained Kerr Wood Leidal Associates to investigate debris flood hazards at Canyon Creek and identify a range of mitigative measures for consideration. A debris flood is defined as a very rapid surging flow of water in a steep channel, heavily charged with debris. A debris flood represents a more hazardous geomorphic process than a pure water flood. The 1989 and 1990 events at Canyon Creek are categorized as debris floods.

The investigation concludes that a large debris flood at Canyon Creek may result from an outbreak flood following breach of a temporary landslide dam. The most likely location for such a blockage is at the toe of either the Jim Creek earthflow or the Bald Mountain earthflow. The landslide dam would likely breach rapidly, causing an outbreak flood that would incorporate landslide debris and downstream channel debris. FLDWAV software was used to model the outbreak flood for different landslide dam heights.

In consultation with Whatcom County, a 500-year return period was selected as a design criteria for debris floods at Canyon Creek. This is consistent with recent practice in British Columbia for creek hazards beyond pure water floods.

The study concludes that a 500-year return period debris flood would have a peak discharge of approximately 25,000 cfs (700 m^3/s) and a total sediment volume of approximately 150,000 yd^3 (115,000 m^3) at the Canyon Creek fan apex. The 1989 debris flood peak discharge is estimated at approximately 16,100 cfs (455 m^3/s), with a debris volume of approximately 70,000 yd^3 (54,000 m^3). This corresponds to a return period of approximately 200 years (which is consistent with dendrochronologic evidence). The 1990 debris flood was significantly smaller but more damaging (its effects being exacerbated by a change in fan morphology after the 1989 debris flood).

Debris flood runout on the Canyon Creek fan was modelled with FLO-2D software in order to estimate the flow depth and velocity on the fan for the design event. The model scenarios included existing conditions, berm removal, and a breach of the existing berm. The deposition of the design event was illustrated in map form (Figure 3-1). This map was used as a basis for defining three hazard zones on the fan (Figure 3-2).

A wide range of mitigative measures was reviewed. It is concluded that the proposed buy-out would be an effective risk reduction measure because it incorporates most of the highest hazard land on the fan. It would be appropriate to develop site-specific land use regulations for the rest of the developed area on the basis of Figure 3-2. Consideration should be given to removing the lower two-thirds of the berm and using the riprap to reinforce the right bank adjacent to Canyon View Drive (subject to land ownership and jurisdictional constraints). A number of other mitigative measures are also identified for consideration in Section 4.6. These may be implemented by Whatcom County, with referral to other agencies where appropriate.

Section 1

Introduction

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1. INTRODUCTION

1.1 BACKGROUND

STUDY AREA

Canyon Creek is a 31 mi^2 (79 km^2) watershed that discharges to the North Fork of the Nooksack River near the town of Glacier (Figure 1-1). Forestry is the primary land use within the watershed and extensive logging occurred from the 1960s to the 1980s. Poor logging practices and road construction resulted in numerous slope instabilities and significantly increased sediment supply to Canyon Creek. Much of the Canyon Creek fan is developed (Glacier Springs subdivision, the Logs Resort).

Figure 1-2 shows the Canyon Creek watershed. A detailed map of the Canyon Creek fan is included as Figure 1-3.

1989 AND 1990 DEBRIS FLOODS

In November 1989, a large debris flood occurred on Canyon Creek. This event had a peak flow of approximately 16,100 cfs (455 m^3/s) and destroyed one house on the fan. A smaller event in November 1990 destroyed three additional houses. A section (several hundred feet) of County road was also rendered unpassable. The extent of damage of the 1990 event was primarily due to aggradation on the upper fan from the 1989 debris flood.

After the 1989 event, the US Soil Conservation Service constructed an armoured berm to protect the Glacier Springs Subdivision and the Mount Baker Highway. The berm was destroyed during the 1990 event. Whatcom County received disaster funding from the Federal Emergency Management Agency (FEMA) to construct a more extensive armoured berm. This berm was constructed in 1994 along the right (west) bank and extended from the fan apex to the creek mouth.

CREEK MANAGEMENT ISSUES

In the past decade, a number of studies have been conducted on Canyon Creek. These studies focussed on evaluating geomorphic processes and flooding, and identifying possible mitigative measures. Despite this work, Whatcom County felt that additional work was necessary to clarify the existing hazards and risks.

As part of a long-term strategy, Whatcom County has received state and federal funding to acquire a number of undeveloped and developed lots on the active portion of the Canyon Creek fan. However, Whatcom County is concerned that future floods or debris floods could damage other development on the fan. The three main issues facing Whatcom County decision-makers are:

1. Does the proposed buy-out adequately reduce the debris flood risk on the Canyon Creek fan?
2. What should be done with the existing berm?
3. Should development be restricted or prohibited in any areas of the fan and what would be considered appropriate mitigation measures should development continue?

Whatcom County retained Kerr Wood Leidal Associates (KWL) to complete a detailed study of Canyon Creek to provide information that will enable the above three issues to be addressed.

1.2 CREEK HAZARDS

Steep mountain creeks may be subject to geomorphic processes beyond pure water floods. Sediment and debris from watershed instability may provide the impetus for debris flows or debris floods. Some background information on debris floods and debris flows is provided in Appendix A.

The 1989 and 1990 events at Canyon Creek have been previously described as debris-laden floods, debris floods, landslide dam break floods, dam burst floods, boulder floods, debris flows, and debris torrents, creating some confusion as to the true process. Based on descriptions and photographs of these events, they are best described as *debris floods* initiated by landslide dam outburst floods.

DEFINITIONS

According to Hungr et al. (2001), a *debris flood* is a very rapid, surging flow of water, heavily charged with debris, in a steep channel. The sediment may 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. While debris floods carry an unusually high amount of sediment and/or organic debris, the concentration is not high enough to transform the event character from a flood to a landslide (e.g. debris flow). Debris floods are typically triggered by temporary channel blockages and discharges can be 2 to 5 times as high as water floods (Jakob and Jordan, 2001).

From this definition, the terms debris-laden flood, dam burst flood, landslide dam break flood, and boulder flood are all appropriate descriptions of the Canyon Creek events. However, the term debris flood is preferred for consistency of terminology.

The 1989 and 1990 Canyon Creek events are not classified as *debris flows*. A debris flow is a rapid flow of saturated non-plastic debris in a steep channel (Hungr et al., 2001). A debris flow is typically initiated by a point source failure that channelizes at impact with the main creek channel. A debris flow may reach up to 50 times the peak discharge of a 200-year return period clear water flood (Jakob and Jordan, 2001). Coarse-grained debris flows of the Pacific Northwest have sometimes been referred to locally as debris torrents, but the use of this term is discouraged.

DEBRIS FLOWS VERSUS DEBRIS FLOODS

This sub-section describes the principal differentiating characteristics between debris flows and debris floods.

Debris floods can be distinguished from debris flows by water content. Debris floods may be visualized as an extension of the flood process with largely turbulent flow, whereas debris flows are more laminar due to a higher percentage of solids. Debris floods typically have a volumetric sediment concentration of 15% to 35%, whereas debris flows may have a sediment concentration of 45% to 75%. However, the water content of debris flows is highly variable due to the heterogeneity of debris flow surges and the transition from the bouldery front to the more fluid afterflow. Debris floods and debris flows can transition longitudinally downstream due to the bulking or debulking of channel sediment.

There are two reasons that debris floods are considered the principal hazard on the Canyon Creek fan:

1. In the Pacific Northwest, debris flows typically occur in basins smaller than 2 mi^2 (5 km^2) where the mean channel gradient is greater than 18% (Hungr et al., 2001). At lower gradients, a debris flow typically loses momentum, begins to deposit, and then transforms into a debris flood. The average channel gradient of Canyon Creek is about 7% for a distance of 3.3 miles (5.3 km) above the fan apex. Above that point, the gradient averages 3%. Only a debris flow having a high clay content, such as a debris flow from a volcanic source area, could sustain flow on such a low gradient. A debris flow could initiate along several of the steep tributaries in the watershed, however, any tributary debris flow would likely deposit near the confluence with Canyon Creek.

2. The average gradient of the Canyon Creek fan (2.5%) is indicative of primarily fluvial processes rather than landslide activity. The stratigraphy of the fan supports this conclusion. Larger sub-rounded boulders are interbedded with fluvial sands and gravels, typical of debris flood deposition. Debris flow deposits are typically matrix supported, with subangular to angular boulders. Inverse grading (with the coarsest clasts on top) is observed in most coarse grained debris flow deposits. Furthermore, well confined debris lobes and levees, typical for debris flows are absent on the Canyon Creek fan.

Debris floods are a poorly understood process because they are rarely observed and often occur as transient phenomena during debris flows. Debris floods can be caused by a variety of processes. A common process is breaching of a temporary stream blockage caused by a tributary debris flow or landslide. The discharge from an outbreak flood depends strongly on the composition and geometry of the landslide dam and the geometry of the downstream channel. The latter determines the degree to which a debris flood will attenuate before reaching the fan apex. Therefore, the above-noted typical range for debris flood discharge of 2 to 5 times the 200-year return period flood should only be used as a guideline (Hungr et al., 2001; Jakob and Jordan, 2001).

1.3 WORK PROGRAM

OBJECTIVES

The work program for this study was developed on the basis of the following primary objectives:

- investigate the history of debris floods
- quantify the debris flood hazard;
- review risk mitigation alternatives;
- identify appropriate mitigative actions; and
- define key issues associated with possible implementation of mitigation measures.

With this information, Whatcom County can then consider implementation of mitigative measures at Canyon Creek.

DESCRIPTION OF WORK PROGRAM

The work program for this study is summarized in Table 1-1.

Table 1-1
Work Program

Work Task	Description
1. Project Initiation	**1.1 Project Initiation Meeting** ▪ Review proposed work program and budget estimate. ▪ Confirm information sources and agency contacts. ▪ Obtain background information, including previous reports, digital maps, and other pertinent information. ▪ Discuss potential for further development on the fan and adjacent areas. ▪ Identify key stakeholders and discuss stakeholder involvement in project. ▪ Review project schedule and deliverables.
	1.2 Background Information ▪ Review background information. ▪ Summarize background information for inclusion in report.

	Work Task	Description
2	**Air Photo Review and Mapping**	**2.1 Air Photo Review** ▪ Review complete aerial photograph chronosequence. ▪ Document historic watershed activity. ▪ Identify priority areas for field investigation.
		2.2 Watershed Maps ▪ Transfer watershed information into GIS environment. ▪ Produce preliminary watershed and fan maps.
3.	**Field Investigation**	**3.1 Watershed Investigation** ▪ Perform helicopter survey (including still photography). ▪ Investigate logging-related and natural slope instabilities. ▪ Visit major sediment source areas.
		3.2 Channel Investigation ▪ Traverse selected channel reaches. ▪ Obtain channel cross-sections at key locations. ▪ Evaluate potential landslide dam locations; estimate dam height and impoundment volume. ▪ Obtain dendrochronological (tree) samples for debris flood frequency analysis.
		3.3 Fan Investigation ▪ Inspect existing dikes and bank protection works. ▪ Investigate potential for avulsions. ▪ Identify possible locations for mitigation structures.
4.	**Technical Analyses**	**4.1 Hydrologic Analysis** ▪ Review previous hydrologic studies and peak flow estimates. ▪ Perform a brief hydrologic review to select design peak flows. ▪ Review available climate data to investigate long-term changes in rainfall frequency and magnitude.
		4.2 Hazard Analysis ▪ Identify problems associated with past and future watershed activities. ▪ Estimate debris flood frequency from dendrochronology and previous studies. ▪ Estimate event magnitude (peak discharge and total volume). ▪ Establish frequency – magnitude correlations. ▪ Model potential outbreak floods with FLDWAV. ▪ Model debris flood runout on fan for a 500-year return period event with FLO- 2D. ▪ Prepare multi-colour integrated hazard map for fan (to reflect existing conditions).
		4.3 Consequence Analysis ▪ Document consequences of previous events. ▪ Consider potential consequence represented by buildings, roads and other infrastructure. ▪ Use hazard map to evaluate potential consequences of future events.

	Work Task	Description
5.	Preliminary Draft Report	**5.1 Prepare Draft Report** ▪ Prepare preliminary draft report to document Tasks 1 to 4. ▪ Initial report review by project team. ▪ Submit draft report for review.
6.	Risk Mitigation Alternatives	**6.1 Risk Mitigation Objectives** ▪ Select design events for risk mitigation. ▪ Consult with client to establish objectives for risk mitigation. ▪ Determine the need for active and/or passive risk mitigation measures.
		6.2 Mitigative Structures ▪ Determine whether the proposed buy-out is an appropriate risk mitigation strategy. ▪ Determine the need for upgrading and/or modifying the existing berm. ▪ Determine the need for bank protection works on the outside of the berm. ▪ Identify potential environmental constraints and sensitivities.
		6.3 Warning Systems ▪ Consider the applicability of various types of warning systems.
		6.4 Watershed Management Actions ▪ Identify general watershed restoration measures to reduce watershed instability. ▪ Provide recommendations for future forestry operations. ▪ Consider the need for landslide stabilization and/or monitoring.
		6.5 Land Use Planning Measures ▪ Provide input to ongoing land use regulation activities. ▪ Provide recommendations for floodproofing development on the fan. ▪ Provide input to anticipated highway upgrading.
7.	Risk Mitigation Plan	**7.1 Risk Mitigation Review** ▪ Workshop to confirm risk mitigation objectives, review risk mitigation alternatives, and discuss applicability of each alternative. ▪ Refine risk mitigation alternatives based on workshop proceedings.
		7.2 Preferred Alternative ▪ Select a preferred alternative.
8.	Report Preparation	**8.1 Draft Report** ▪ Prepare final draft report including mitigative measures. ▪ Initial report review by project team. ▪ Submit report to client for review.
		8.2 Final Report ▪ Finalize report following feedback. ▪ Submit final report.

REPORT FORMAT

This report includes technical appendices that document specific parts of the investigation program (photographs, watershed description, aerial photograph analysis, environmental resource values, hydrology, and debris flood probability and magnitude assessment). Inclusion of most of the detailed technical content in the appendices allows the main report body to focus on the assessment and mitigation of debris flood risks.

1.4 PROJECT TEAM

This report was written by Matthias Jakob, Ph.D., PG, Hamish Weatherly, M.Sc., PG, and Mike Currie, M.Eng., P.Eng. (BC), of KWL.

The debris flood frequency and magnitude analysis was performed by Matthias Jakob. Hamish Weatherly of KWL completed the hydrologic investigation. Hamish Weatherly and Matthias Jakob performed the outbreak flood modelling and debris flood modelling on the fan.

Input on behalf of Whatcom County was provided by Paula Cooper, PE, Paul Pittman, PG, Doug Goldthorp, PG, and Roger Nichols, Eng. Geol., of the U.S. Forest Service.

The project also involved input from the Whatcom County River and Flood Committee and the Canyon Creek area residents (through a public information meeting on May 10, 2003).

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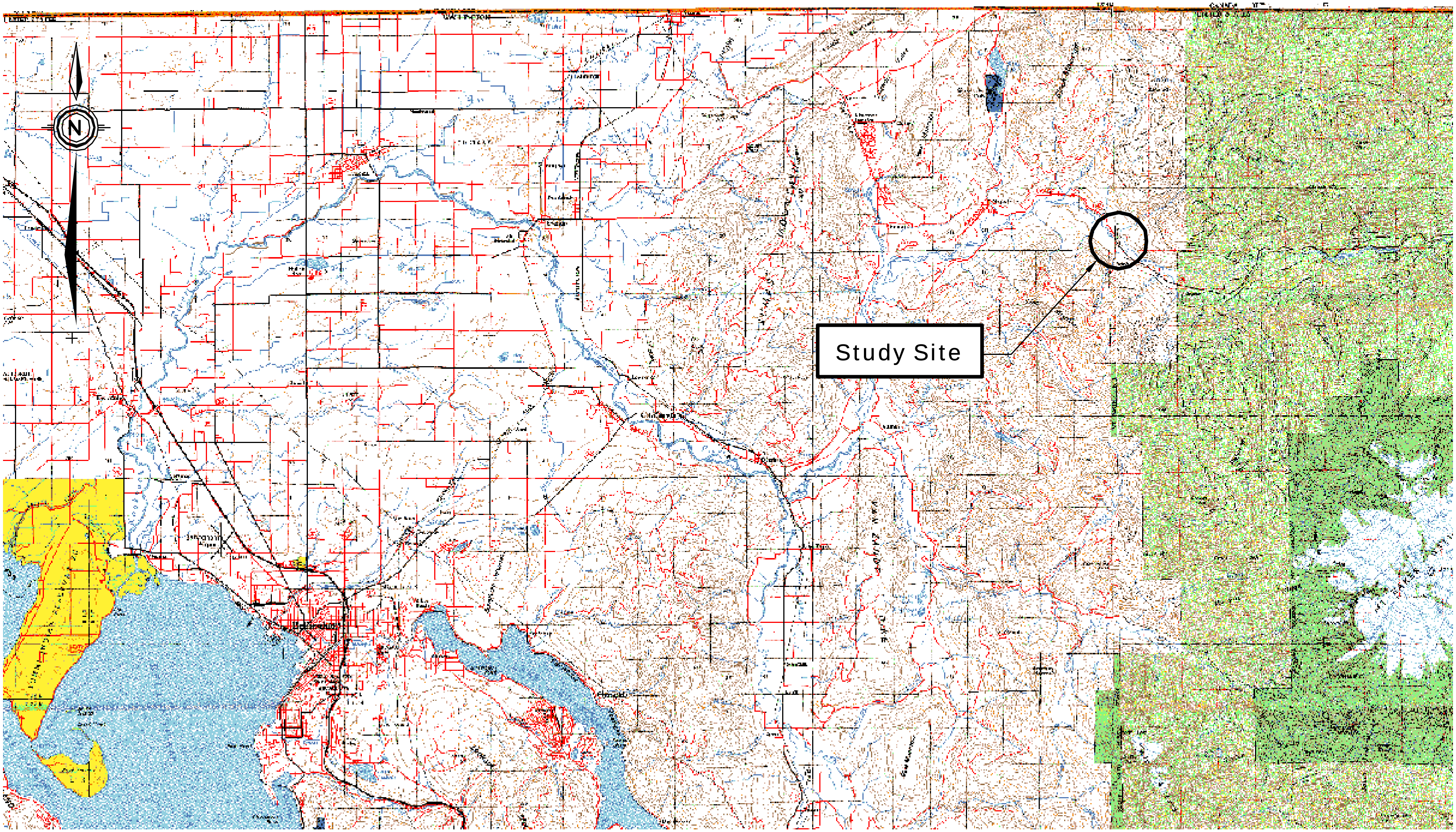

Baseplan Source: MT.Baker, Wash. - B.C. Nw4 Concrete (NM10-12) 1:250,000 Scale Map N4830 - W12100/30x60 (1979)

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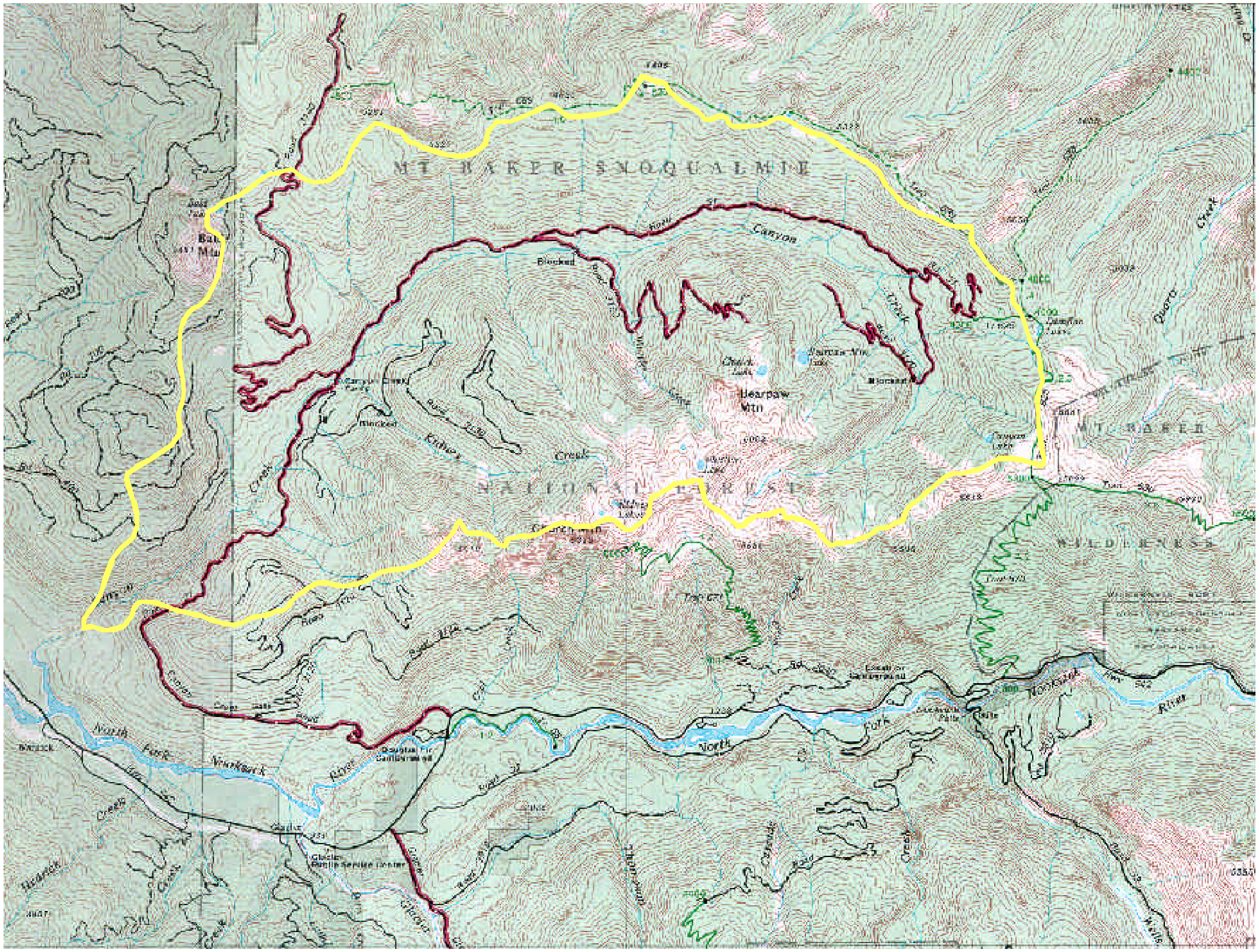
6000 0 6000

Scale in Metres

Location Map

Figure 1-1



BaseplanSource:1:69,500GreenTrails,Inc.MtBaker,Wa-No13(1996)

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Canyon Creek Alluvial Fan Risk Assessment
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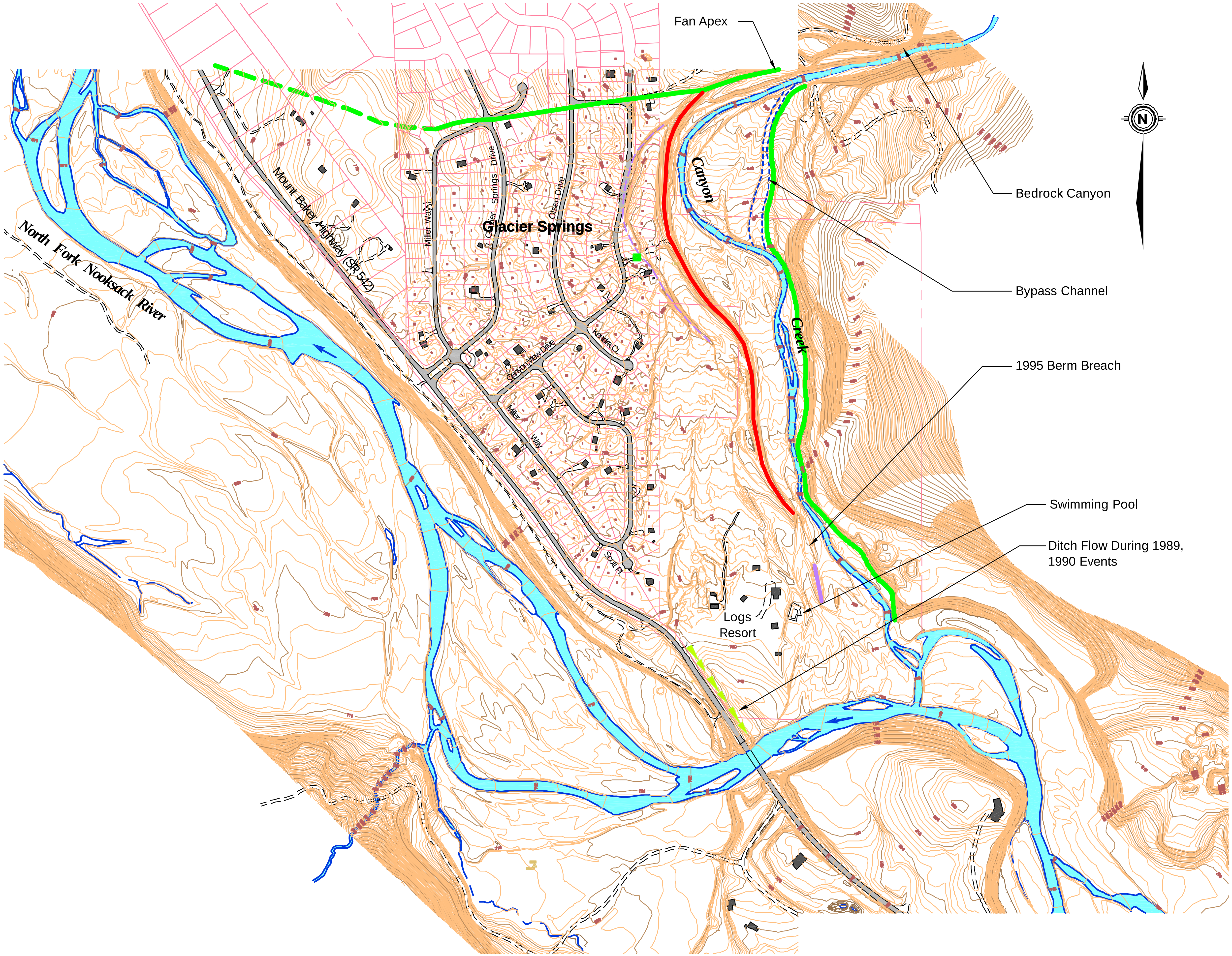
1 0 1
Scale inMiles

Watershed Map

Figure 1-2



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Legend

- Armoured Berm
- Berm
- Property Line
- Former Shepherd Residence
- Limit of 1989,1990 Bank Erosion
- Fan Boundary

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400 0 400
Scale in Feet

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Canyon Creek
Fan Map

Figure 1-3

Sep.24/03

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Section 2

Recent Debris Floods and Mitigative Actions

2. RECENT DEBRIS FLOODS AND MITIGATIVE ACTIONS

This section describes the recent debris flood events, and documents previous mitigative actions and studies at Canyon Creek. A description of the Canyon Creek fan is also provided.

This section should be read in conjunction with Appendix B (photographs), Appendix C (watershed description), Appendix D (aerial photograph analysis), Appendix E (environmental resource values), Figure 2-1 (a geomorphic map of the watershed), and Figure 2-2 (a 2001 air photo of the Canyon Creek fan).

2.1 CANYON CREEK FAN

The Canyon Creek fan began to form about 11,000 years ago, shortly after deglaciation of the North Fork Nooksack River valley. Fluvial deposition and episodic debris floods have created a fan with an area of approximately 220 acres (100 ha). Development on the fan commenced in the mid 1950s by the Ohlsen family, the original owners of the Logs Resort. The Glacier Springs subdivision was subsequently developed on the fan (Figure 1-3). Glacier Springs includes about 282 lots, a quarter of which are located north of the fan boundary. There are presently more than 40 houses on the fan.

The fan apex is located at elevation of about 865 ft (260 m) where Canyon Creek emerges from the confines of a bedrock canyon. After the creek discharges from the canyon, it turns sharply to the left and continues to the southeast. Canyon Creek discharges to the North Fork Nooksack River approximately 900 ft (270 m) upstream of the Mount Baker Highway Bridge. The Glacier Springs subdivision is located on the right (west) bank approximately 30 ft (9 m) above the creek bed while the forested left (east) bank is situated 8 to 10 ft (2.4 to 3 m) above the creek bed. Below the sharp bend, the left bank is formed by the toe of the mountain and bedrock is exposed in places. The creek is separated from the right bank by a 20 ft to 30 ft (6 m to 9 m) high berm that was constructed in 1994.

The fan reach of Canyon Creek is about 0.7 miles (1.1 km) long to the confluence with the North Fork Nooksack River (Photos 6, 7, and 8). The average channel gradient on the fan is 2.5%. The low flow channel is 15 ft (4.5 m) to 25 feet (7.5 m) wide, and the active channel ranges between 200 ft (60 m) and 450 ft (140 m) in width. During the 1989 debris flood, the active channel was completely inundated by water and debris and all vegetation was stripped. In the following decade, patchy vegetation has re-colonized within the active channel.

In the past 50 years, the Glacier Springs subdivision has not been flooded. However, portions of the Logs Resort, which occupies a low lying area on the fan relative to the Glacier Springs subdivision, have been flooded.

Other development on the fan includes the Mount Baker Highway, which roughly delineates the downstream edge of the fan. Much of the downstream end of the fan has been truncated by the North Fork Nooksack River, exposing massive debris flood sediments (Photo 11).

2.2 1989 DEBRIS FLOOD

DESCRIPTION OF EVENT AND DAMAGE ON FAN

The impetus for the present study was an extremely large flood event on November 9 and 10, 1989 that destroyed one house and threatened four others. Based on the flood description and the watershed characteristics, this event was a debris flood. A local resident, Mr. Shepherd, reported that 20 to 25 ft (7 to 8 m) of sediment was deposited in front of his house during the event (GeoEngineers, 1992). The Shepherd residence was situated about 1,000 ft (310 m) downstream of the fan apex along the right bank (by convention looking downstream). The 1989 event deposited an extremely large amount of sediment on the upper fan, as illustrated by Photo 1. The houses visible in the photo were destroyed by the 1990 event (Section 2.3). Overbank deposition associated with the 1989 event is still visible (Photo 12).

Mr. Shepherd also reported seeing an 8 ft (2.4 m) high temporary debris dam in front of his house during the flooding (GeoEngineers, 1992). This dam broke and the material was transported downstream within a few minutes after he noticed it. The home that was destroyed was located upstream of Mr. Shepherd's residence on the right bank. No serious damage was sustained within the Logs Resort but localized flooding did occur. Some of the overflow through the Logs Resort followed an existing depression toward the Mount Baker Highway where it then flowed southeast to the North Fork Nooksack River following a ditch line located on the east side of the highway.

Immediately following the flood, a contractor was hired to construct a 1,200 ft (360 m) long bypass channel that commenced at the fan apex (GeoEngineers, 1992). The bypass channel was positioned along the east margin of the fan in order to provide an overflow path away from existing development.

PEAK FLOW ESTIMATE

Representatives of the US Forest Service (USFS) estimated that the 1989 event had a peak flow of about 16,100 cfs (455 m^3/s) at the mouth of the canyon. This estimate was based on the height of scour marks within the bedrock canyon (Photo 26). This estimate of the 1989 event peak flow is about three times large than the estimated 100-year return period water flood of 6,000 cfs (170 m^3/s). In contrast, the peak flow about 4.5 miles (7.2 km) upstream of the fan apex was estimated to be only 3,060 cfs (87 m^3/s). The dramatic increase in discharge between the two reaches, especially in the absence of intervening tributaries of significant size, indicates that the 1989 debris flood was the result of an outbreak flood from a landslide dam or a large log jam.

DAMAGE IN UPPER WATERSHED

While the debris flood that damaged the fan obviously initiated in the lower reaches, considerable damage also occurred in the mid to upper reaches of the watershed. The lower bridge of Road 31 was severely damaged (mile 5.2) and road sections immediately upstream and downstream of this point were washed away (Photo 2). The middle bridge crossing at Whistler Creek was also severely damaged, cutting off access to Road 3160 (Figure 2-1). Associated with the road damage was significant widening of the mainstem channel in unconfined reaches (Figures D-1 and D-2, Appendix D).

The damage in the upper watershed appears to have been the result of outburst floods that initiated several hundred feet upstream of the confluence with Whistler Creek. According to Roger Nichols of the USFS, a snow avalanche (4,800 ft elevation) may have triggered a debris flow that blocked the mainstem channel at this location. A review of the 1991 air photos indicates that the debris flow initiated within a well-defined gully (Figure 2-3). However, there is no consensus that a snow avalanche triggered the debris flow. John Thompson (pers. comm.) noted that the snowpack at the Mount Baker ski area was only 2 to 2.5 ft (0.6 to 0.75 m) during the 1989 event and was therefore not likely sufficient for a snow avalanche to initiate.

Whatever the origin, the resulting dam appears to have impounded sufficient water that a series of outburst floods occurred (Nichols observed four terraces upstream of the natural dam after the event). These outburst floods resulted in significant channel widening downstream and extensive scour of terrace deposits along the creek margin (Figure 2-3). Given the availability of abundant sediment within and adjacent to the channel, the outburst floods probably entrained sufficient sediment to be described initially as debris floods. However, the lack of confinement and relatively gentle channel gradient (approximately 3%) downstream of Whistler Creek probably transformed the event character to a flood by the time the peak flow reached the confluence with Kidney Creek (where there is no indication of an event of unusual magnitude).

WATERSHED CONDITIONS

Logging impacts may have been a factor in the extent of damage caused by the 1989 debris flood. Studies by Peak Northwest (1986) and Hale and Nichols (1994) documented about 100 landslides within the Canyon Creek watershed, most of which were associated with logging roads and clearcuts. About 50% of the sediment associated with the landslides (2.3 million yd^3 or 1.8 million m^3) is believed to have deposited in the mainstem channel of Canyon Creek. This documented increase in mass wasting frequency and magnitude may have amplified the potential for temporary dam formation and subsequent debris flood initiation. Appendix C provides more details on the landslide studies.

1990 REPAIRS

In January 1990, the US Soil Conservation Service (SCS, now the Natural Resource Conservation Service) made emergency repairs on the upper fan, placing riprap along the right (west) bank for a lineal distance of about 800 ft (240 m). The riprap had a maximum size of 5 ft (1.5 m) and was extended vertically down about 20 ft (6.1 m), which was thought to approximate the elevation of the creek bed prior to the 1989 event (GeoEngineers, 1992). The riprap was subsequently buried to a depth of 12 ft (3.7 m) to protect against scour. It was expected that moderate to low flows would scour a channel against or near the riprap. However, the original creek channel was not restored as part of the SCS riprap project and the flow was left in the bypass channel (GeoEngineers, 1992).

2.3 1990 DEBRIS FLOOD

DESCRIPTION OF EVENT

On the same date the following year, Canyon Creek experienced another debris flood. Sediment accumulated at the entrance to the bypass channel and the primary flow direction was toward the adjacent residences. Because the creek channel was not restored in conjunction with the SCS riprap project, there was little channel capacity for flood flow. Sediment deposited by the 1989 debris flood had filled most of the creek channel from the mouth of the bedrock canyon to the Shepherd residence and beyond.

According to Mr. Shepherd, the 1990 event deposited an additional 5 ft (1.5 m) of sediment adjacent to his property. The creek flow subsequently overtopped the SCS riprap and rapidly incised laterally into the fan. The eroded area was about 200 ft (60 m) wide by 650 ft (200 m) long and severely damaged about 300 ft (90 m) of Canyon View Drive (Photo 3). An additional three houses were destroyed by the erosion and the eastern half of the Shepherd residence was undercut and later removed (Photo 4). Much of the SCS riprap was transported downstream. Mr. Ohlsen, the former owner of the Logs Resort, reported finding riprap in the North Fork Nooksack River about 2,500 ft (760 m) downstream. Again, the Logs Resort sustained only minor flooding with no significant damage.

The 1990 event appears to have been another debris flood, but of significantly lower magnitude than the 1989 event. Mr. Shepherd is reported as stating that on the night of the 1990 event, the creek became quiet for a period of about three hours which was followed by a large explosion and a loud rush of water, causing him to abandon his house for the night (Ballerini, 1993a). This description is consistent with a debris flood initiated from an outbreak flood of a temporary dam.

DENDROCHRONOLOGY

Creek events can impact trees and leave scars, which subsequently overgrow. Cutting a wedge from this scar tissue allows the reconstruction of the year of damage. Coring a tree and counting back to a ring sequence that is very narrow enables the researcher to determine the date of the event. As described in Appendix G, a number of impact scars on trees upstream of the fan apex have been dated. The earliest recorded tree scar is 1989. A lack of scars for the 1990 event (compared to numerous for 1989) suggests a debris flood of significantly lower magnitude.

2.4 ENGINEERING STUDIES – EARLY 1990S

PURNELL AND ASSOCIATES, 1991

Following the 1989 and 1990 debris floods, Purnell and Associates (1991) were retained by the Glacier Springs Homeowners Association to address the potential erosion hazards to the subdivision. Based on a brief reconnaissance of the fan, Purnell identified three hazard zones where future erosion could occur (see Section 2.8). It was recommended that a comprehensive study of Canyon Creek be performed to assess the most useful and economical means of reducing the risk of future damage to the development. Purnell noted that such a study was beyond the scope of their reconnaissance.

GLACIER SPRINGS FEASIBILITY STUDY, 1992

Following the Purnell report, Whatcom County retained GeoEngineers (1992) to determine the most cost-effective method of rebuilding and protecting Canyon View Drive and to assess the vulnerability of the Glacier Springs subdivision to damage from future events on Canyon Creek. GeoEngineers considered three primary options to protect against future flooding. The first two options involved channelizing any future events down to the North Fork Nooksack River.

Option 1 With this option, a heavily armoured berm would be constructed near the mouth of the canyon to divert flow into the diversion channel. Berms on both sides of Canyon Creek would then confine the flow to the North Fork.

Option 2 Option 2 is similar in that berms would be constructed on both sides of the creek to channelize the flow. It differs in that the upper berms would follow the channel as repaired by the SCS. The right bank would be armoured about 30 ft (9 m) vertically while the left berm would be lower (20 ft, 6 m). A lower left bank would favour overflow to the inside of the bend, away from development.

Option 3 The third option was to construct a berm along the same alignment as the 1990 SCS revetment. The berm would extend slightly farther upstream and downstream than the SCS section and would be armoured with riprap to the top of the bank. It was recommended that the ground surface behind the left bank be horizontal or slope downward for a perpendicular distance of at least 100 ft (30 m) for the length of the berm. The sloped surface would allow for an overflow area in the event of peak flows.

Because of high cost and the potential liability to Whatcom County from unforeseen consequences (due to significant changes to the geomorphic and hydraulic character of Canyon Creek), GeoEngineers did not recommend either of the channelization options.

A do nothing scenario was not recommended as it was thought highly likely that future peak flow events could overtop the right bank in the vicinity of the former Shepherd residence and flow to the southwest.

1994 REPAIRS

Whatcom County approached FEMA (Federal Emergency Management Agency) to determine whether funding could be obtained for the creek works on Canyon Creek after the 1990 debris flood. FEMA reviewed the project and recommended that detailed discussion and a cost benefit analysis of repair options be completed prior to approval of the selected option. This request resulted in a second report by GeoEngineers dated April 5, 1994. In that report, two additional repair options were considered (Options 4 and 5).

Option 4 was very similar to Option 3 and involved:

- constructing a 20 to 30 ft (6 to 9 m) high armoured berm on the right bank of the upper fan;
- placing the base of the riprap about 10 ft (3 m) below the creek bed to protect against potential scour;
- moving the creek further east into its position prior to the 1989 debris flood;
- constructing 10 to 15 ft high unarmoured berms on both banks in lower reaches to provide protection to the Logs Resort and the Mount Baker Highway (Option 3 provided no such provision);
- blasting a channel through a rock point located upstream of the Logs Resort (the exposed bedrock tended to deflect flows toward the Logs Resort during high flows);
- fish habitat restoration in the upper channel;
- riparian planting; and
- constructing groynes on the upper channel to reduce flows against the armoured right berm.

Also considered was Option 5, which involved the buy-out of all Glacier Spring properties potentially affected by future creek events. GeoEngineers and Whatcom County considered Option 4 to be the most beneficial and cost-effective option for repair of existing flood damage and protection against future damage.

2.5 1994 CONSTRUCTION PROGRAM

PROGRAM DESCRIPTION

Between June 13 and November 17, 1994 most of the elements of Option 4 were constructed by Whatcom County using funds from FEMA (GeoEngineers, 1995). The final design involved construction of a 20 to 30 ft (6 to 9 m) high armoured berm on the right bank over a lineal distance of 2,400 ft (730 m). The berm was tied into high ground near the fan apex (Photo 5). Riprap was only placed on the river side of the berm and a low inset floodplain was constructed against the toe of the armoured berm (Photo 9).

The installed riprap rock had an average size of 4.9 ft (1.5 m) and was designed for a 100-year return period peak flow of 5,000 cfs (142 m^3/s) (GeoEngineers, 2000). GeoEngineers (2000) expressed the opinion that flood flow in Canyon Creek in excess of 5,000 cfs is extremely unlikely. This statement contradicts the USFS derived peak flow estimate of 16,100 cfs (455 m^3/s) for the 1989 event (Richardson, 1990).

Below the riprapped section, the berm was extended downstream a further 450 ft (137 m) to provide additional protection to the Logs Resort. However, this section of the berm was not armoured (Figure 1-3). The proposed berm on the left bank in the lower reaches was eliminated as a contract item because it was felt that the existing natural bank provided adequate flow deflection. Elimination of the left berm also provided additional area for sediment deposition during peak flow events.

Additional measures included the construction of five groynes in the upper channel, blasting through the bedrock deflector, reconstruction of Canyon Drive, and the installation of instream fish habitat enhancements. Input for the fish habitat enhancements was received from the Lummi Indian Nation, Nooksack Indian Tribe, the USFS, and the Washington State Department of Fisheries. However, this input was not acted upon as it was requested that the channel be allowed to adjust before enhancement took place (Nichols, pers. comm.).

SHORELINE PERMIT

Before proceeding with construction, Whatcom County filed an application for a shoreline substantial development permit. The permit was filed with the Whatcom County Hearing Examiner and was required prior to commencing the recommended works. In the decision by the Examiner (file # SHS94-0001), Conclusion of Law #1 stated that “The dike or levee proposal … is a reasonable interim step…” for moving toward a long-term solution. One of the conditions approving the shoreline permit prohibited routine maintenance without new permits.

At the hearing, the Washington State Department of Ecology agreed to support the proposed berm as a temporary measure. In their view, the primary purpose of the berm was to protect against potential avulsion through Glacier Springs to the Mount Baker Highway. At the same time, the Department of Ecology strongly encouraged Whatcom

County to develop and pursue a buy-out or relocation of the alluvial fan hazard area properties and to cease approving new building permits.

Furthermore, the Department of Ecology stated that “the only long-term solution is to relocate all occupants of the alluvial fan and to re-route the Mount Baker Highway to the fan apex of Canyon Creek” (letter dated January 24, 2001 from Mr. Barry Wegner of the Department of Ecology to Mr. Doug Goldthorp of Whatcom County Planning & Development Services).

2.6 1995 FLOOD

The 1994 works were tested by a relatively high peak flow in November 1995. A description of this event indicates that it was a predominantly water flood rather than a debris flood. Nonetheless, reported flood damage included the following (GeoEngineers, 1997):

- extensive erosion of the low flow floodplain adjacent to the armoured berm in the upper reach;
- breaching of the unarmoured berm near the Logs Resort (piping was observed prior to failure);
- damage to three of the groynes and the complete break-up of the other two;
- localized piping in the upper reach; and
- burial or removal of all fish enhancement structures.

Some scour was also reported in the upper channel, and 3 to 6 ft (1 to 2 m) of aggradation occurred in the lower reach. Aggradation associated with the 1995 event extended into the North Fork Nooksack River and created a partial blockage (the sediment delivery exceeded the transport capacity of the North Fork flows). The partial blockage was sufficient to cause left bank erosion and there was concern for potential undermining of the Mount Baker Highway east bridge abutment. The North Fork Nooksack River has since mobilized and truncated distal portions of the fan. The partial blockage can possibly be attributed to the berm construction on Canyon Creek, which confines the channel and reduces the potential area of both overflows and sediment deposition.

2.7 LONG-TERM MANAGEMENT STRATEGIES

1999 INTER-FLUVE REPORT

Whatcom County was eligible to receive additional FEMA funding to repair the riprap along the berm toe and reconstruct the groynes. However, the County was unable to utilize the funding before it expired in 1998, primarily due to a complete turnover in the River and Flood Section Staff and permitting issues associated with the Endangered Species Act (ESA). This was prior to the ESA listing of spring chinook and bull trout in 1999. Because both of these species reside in Canyon Creek, the permitting of berm repairs since the listing is expected to be even more difficult. Even with the existing minor damage, the structure is considered active in the Army Corps of Engineers PL 94-99 Program.

At this point, Whatcom County decided to re-evaluate the long-term management strategy for hazard mitigation on the Canyon Creek fan. In early 1999, Whatcom County retained Inter-Fluve to develop and evaluate long-term hazard mitigation strategies. Inter-Fluve (1999) identified a number of broad alternatives that address alluvial fan management within the deposition zone (i.e. the fan). Management approaches within the source zone (i.e. slopes within the watershed that supply sediment to the channel) were not discussed in detail as reasonable approaches to control sources have already been or are currently being addressed. Management approaches within the transport zone (i.e. the channel above the fan apex) were not addressed due to access issues and feasibility.

Four general alternatives were presented in the Inter-Fluve report:

1. No action with maintenance of existing structures.
2. Property purchase.
3. Strengthen the existing armoured berm, extend it further downstream, and raise it in lower reaches.
4. Construction of a debris basin at the fan apex to store sediment during peak flow events.

The 1999 report does not recommend a specific approach, but rather states that the following items should be considered in any decision:

- all properties on the fan are potentially at long-term risk, including the Mount Baker Highway;
- channel processes on alluvial fans are unpredictable and defy quantification, therefore, any structural approaches will require perpetual maintenance;
- confinement of the channel will promote further development on the fan and thereby increase the risk and potential for significant loss of property; and
- channel confinement alone does not address long-term aggradation, only a debris basin approach, which requires sediment removal and maintenance, will address long-term sedimentation on the fan.

This report resulted in discussion about mitigative measures, but no immediate action was initiated.

2000 REPORT

As a second phase to the 1999 report, Whatcom County requested that Inter-Fluve (2000) provide concept level designs and cost estimates for five project alternatives:

1. Repair and maintain the existing armoured berm upstream of the Logs Resort (Alternative 1b also considered the purchase of the resort).
2. Repair and maintain the existing berm with extension and realignment downstream to improve protection of the Logs Resort.
3. Relocate the armoured berm to the west and downstream extension of the relocated berm.
4. Acquire all riverside property on a short-term basis and acquire all potentially at-risk property on a long-term basis.
5. No action.

For each of the above alternatives, Inter-Fluve assessed the expected level of performance for various flood events. This assessment involved hydraulic analyses to determine whether the armoured berm could be damaged by future large flood events. Using a design flow of 15,000 cfs (425 m^3/s), the average velocity in the upper channel was estimated at 24.9 ft/s (7.6 m/s). Under these flow conditions, it was concluded that riprap with a median size of 10 ft (3 m) and a maximum size of 16 ft (5 m) would be required on the outside of the bend in the upper reach. Preliminary hydraulic analyses also indicated that the height of the existing berm would have provided about 10 ft (3 m) of freeboard for the 1989 event at the channel bend. However, it was noted that the calculations did not consider the potential for significant sediment deposition or super-elevation of flow at the channel bend.

Based on the above results, Inter-Fluve concluded that the riprap along the upper berm could not have withstood the peak flows experienced during the 1989 event. The riprap installed in 1994 had a maximum size of approximately 5.6 ft (1.7 m) and an average diameter of 4.9 ft (1.5 m). However, Inter-Fluve note that the required size of rock for a discharge of 15,000 cfs (425 m^3/s) is essentially unfeasible with respect to material availability and construction.

Inter-Fluve also completed hydraulic analyses for Alternative 3 where the natural embankment lying approximately 200 ft (60 m) behind the existing berm was assumed to be armoured (and the berm was removed). Based on this topography, the estimated flow velocity was 16.4 ft/s (5 m/s) with a recommended mean diameter of 4.6 ft (1.4 m) for riprap on the outside of the channel bend.

In summary, Inter-Fluve concluded that:

- berm repair and extension will be susceptible to significant damage during moderate to extreme flood events, and risks to properties will remain moderate for flood events;
- alternatives 4 (property purchase) and 5 (no action) fail to address risks to the Mount Baker Highway in the event of a major channel avulsion;
- the highest level of long-term protection to both the highway and properties is Alternative 3 - the relocation and extension of the berm; and

- berm relocation is the most costly alternative evaluated ($1 million) and its performance will perpetually rely on monitoring and maintenance.

The results of Inter-Fluve's study was presented to the Whatcom County Flood Control Zone District Advisory Committee (FCZDAC). After consideration of the long-term risks and costs associated with protecting development on the fan, the FCZDAC recommended the County pursue funding for a buy-out project and limit new development on the fan.

In recent years, Whatcom County staff have worked with the County Council and the community to develop a buy-out project to mitigate hazards on the highest risk portion of the fan (see Section 2.9).

2.8 HAZARD MAPPING

The reports by Purnell and Associates, GeoEngineers and Inter-Fluve included hazard mapping of the fan. The hazard zones identified were in the event that no further action was taken to protect against future debris floods and floods.

PURNELL AND ASSOCIATES

Purnell and Associates identified three hazard zones on the fan where future erosion could occur (Figure 2-4). Each of the hazard zones was assigned a level of risk and are defined as follows:

Hazard Zone 1 This zone was identified as the most likely area where future damage to the subdivision could occur due to ongoing erosion. The hazard area encompasses twice the cumulative erosion area of the 1989 and 1990 events. Zone 1 was defined as an area of immediate or high erosion risk.

Hazard Zone 2 Zone 2 is located along the southeast portion of the subdivision and includes an intermittent stream that runs along high ground. The headwall of the intermittent stream was observed to erode to the north when flowing. In the event the headwall of the intermittent stream reached the main channel of Canyon Creek, a major shift of Canyon Creek to the west was thought to be possible. Zone 2 was identified as a low risk area, although significant alteration to the creek could increase the risk.

Hazard Zone 3 The potential hazard of Zone 3 was delineated on the basis of a low point in the side of the bank where some overspillage reportedly flowed during the 1990 event. Purnell and Associates felt that significant overflows from Canyon Creek could occur if a debris dam formed in the vicinity of the bank. Zone 3 was defined as an intermediate risk zone.

GEOENGINEERS

GeoEngineers (1992) divided the fan into five zones with three risk levels (Figure 2-4). The identified risk zones predate the berm design and construction (also true for Purnell). The zones are defined as follows:

Low Risk	It is unlikely that the zone will be damaged during a flood similar in magnitude to the 1989 event (design flood).
Moderate Risk	The zone might be damaged during a flood similar in magnitude to the 1990 event and will probably be damaged during a design flood.
High Risk	There is a better than average chance that damage will occur during a flood of 1990 magnitude and some damage will almost certainly occur from the design flood.

INTER-FLUVE

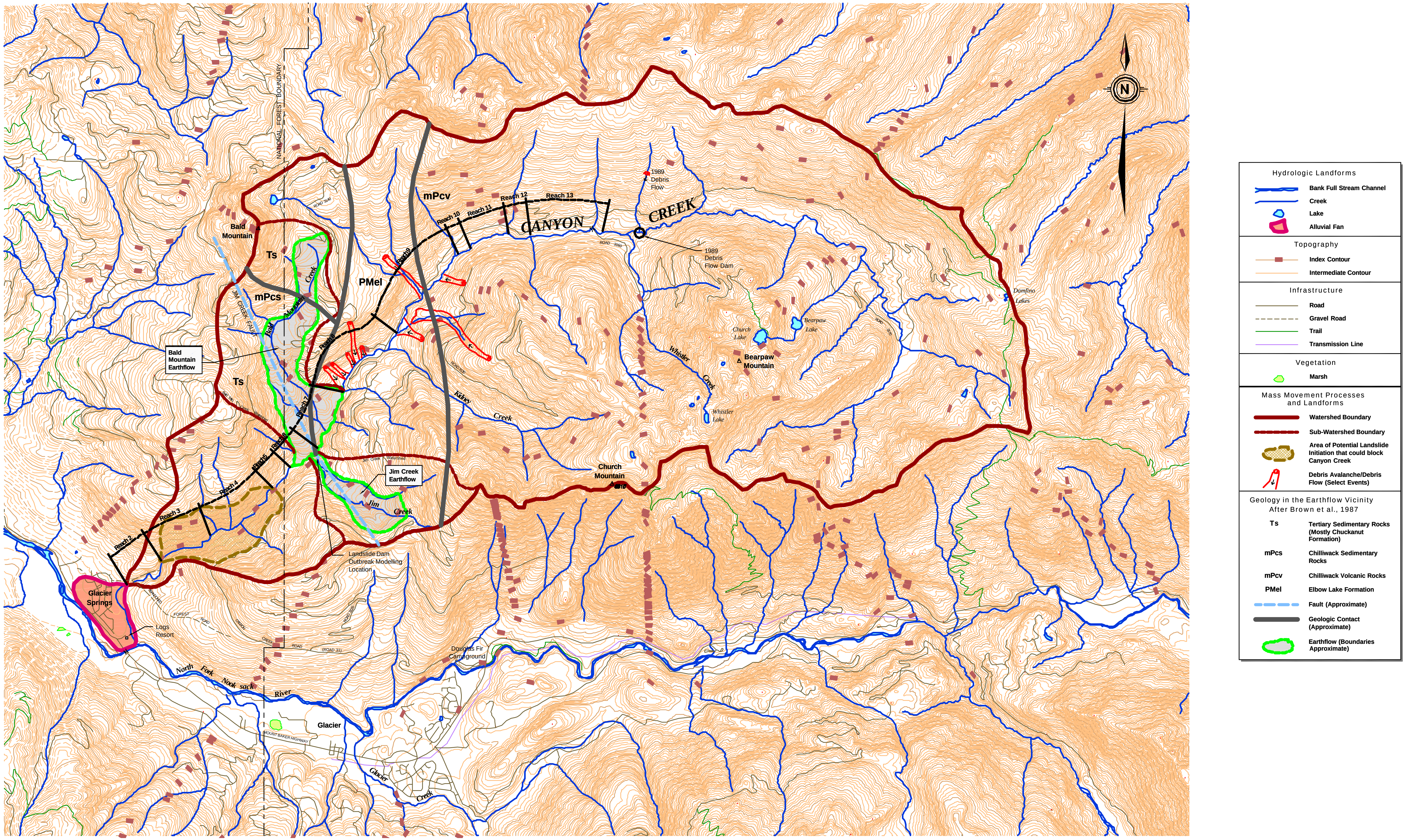
Inter-Fluve (2000) defined two buy-out zones on the fan. Zone 1 includes properties at short-term risk while properties within Zone 2 are at long-term risk. Properties identified at short-term risk include those properties that are currently located on the active fan margin, as well as those that lie within approximately 200 ft (60 m) of the active fan margin in the upper reach where westward channel migration has been most active. These properties include:

- a large section of the Logs Resort;
- Lots 3-18 of Block 1, Division 2, Glacier Springs Subdivision; and
- Lots 2-12 of Block 7, Division 2, Glacier Springs Subdivision.

2.9 PROPERTY BUY-OUT

Based on the conclusions presented by Inter-Fluve and the hazard mapping, Whatcom County felt that continued maintenance of the existing berm would not provide an adequate level of long-term protection to Glacier Springs, given the number of residences that ultimately could be constructed on the fan. The County subsequently submitted a Hazard Mitigation Grant Application to FEMA to acquire properties adjacent to the active portion of the fan. The proposed buy-out would include the acquisition (and removal) of four properties with single family residences and the Logs Resort with seven structures (Figure 2-5). The buy-out cost is estimated at $1 million. As of April 2003, Whatcom County had received notice that their buy-out grant application had been approved.

The buy-out project is being planned in partnership with the Whatcom Land Trust (WLT). The WLT has been awarded grant funding from the Salmon Recovery Funding Board to purchase undeveloped lots in the high-risk area and the Logs Resort lands.



Canyon Creek Alluvial Fan Risk Assessment
Overview Map of Canyon Creek Watershed

0.5 0 0.5
Scale in Miles

Figure 2-1

KERR WOOD LEIDAL associates limited
CONSULTING ENGINEERS

Sep.24/03

2039-001\Drawings\2039001StFig2-1.DWG

Baseplan Source: Washington State Department of Natural Resources. September 10, 2001. Project NW-C-0, Roll 73-58, Photo 217

KERR WOOD LEIDAL associates limited CONSULTING ENGINEERS

Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Project No.	Date
2039.001	September 2003

1000 0 1000
Approx. Scale in Feet

2001 Aerial Photograph of Canyon Creek Fan

Figure 2-2

Sep.24/03

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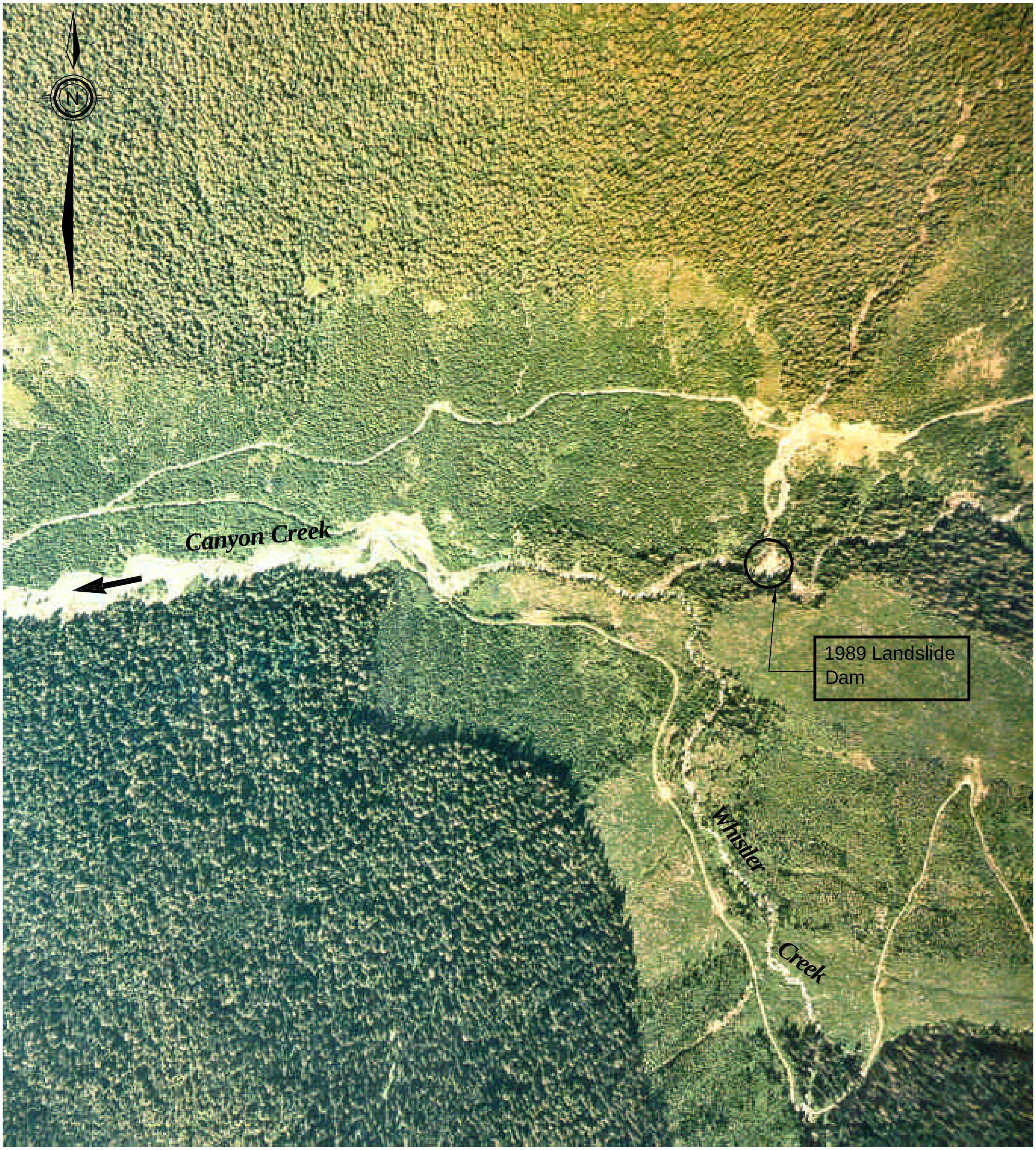


Baseplan Source: United States Forest Service. July 22, 1991. Project 12 616060C, Roll 691, Photo 66.

KERR WOOD LEIDAL associates limited CONSULTING ENGINEERS

Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Project No.	Date
2039.001	September 2003

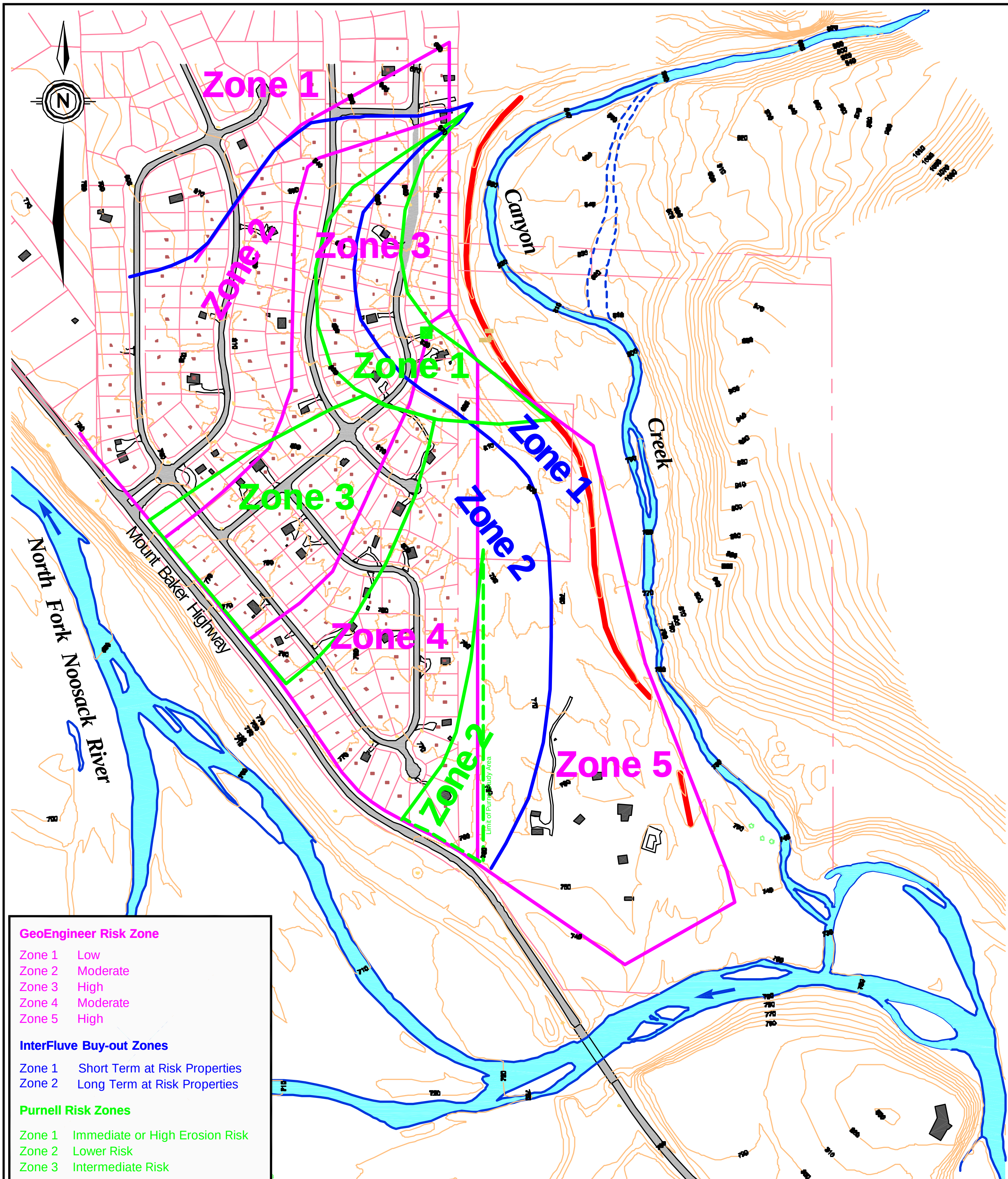
1000 0 1000
Approx. Scale in Feet

1991 Aerial Photograph of Canyon Creek - Whistler Creek Confluence

Figure 2-3

Sep.24/03

2039-001\Drawings\2039001StFig2-3



KERRWOOD LEIDAL associates limited CONSULTING ENGINEERS

Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Project No. 2039.001

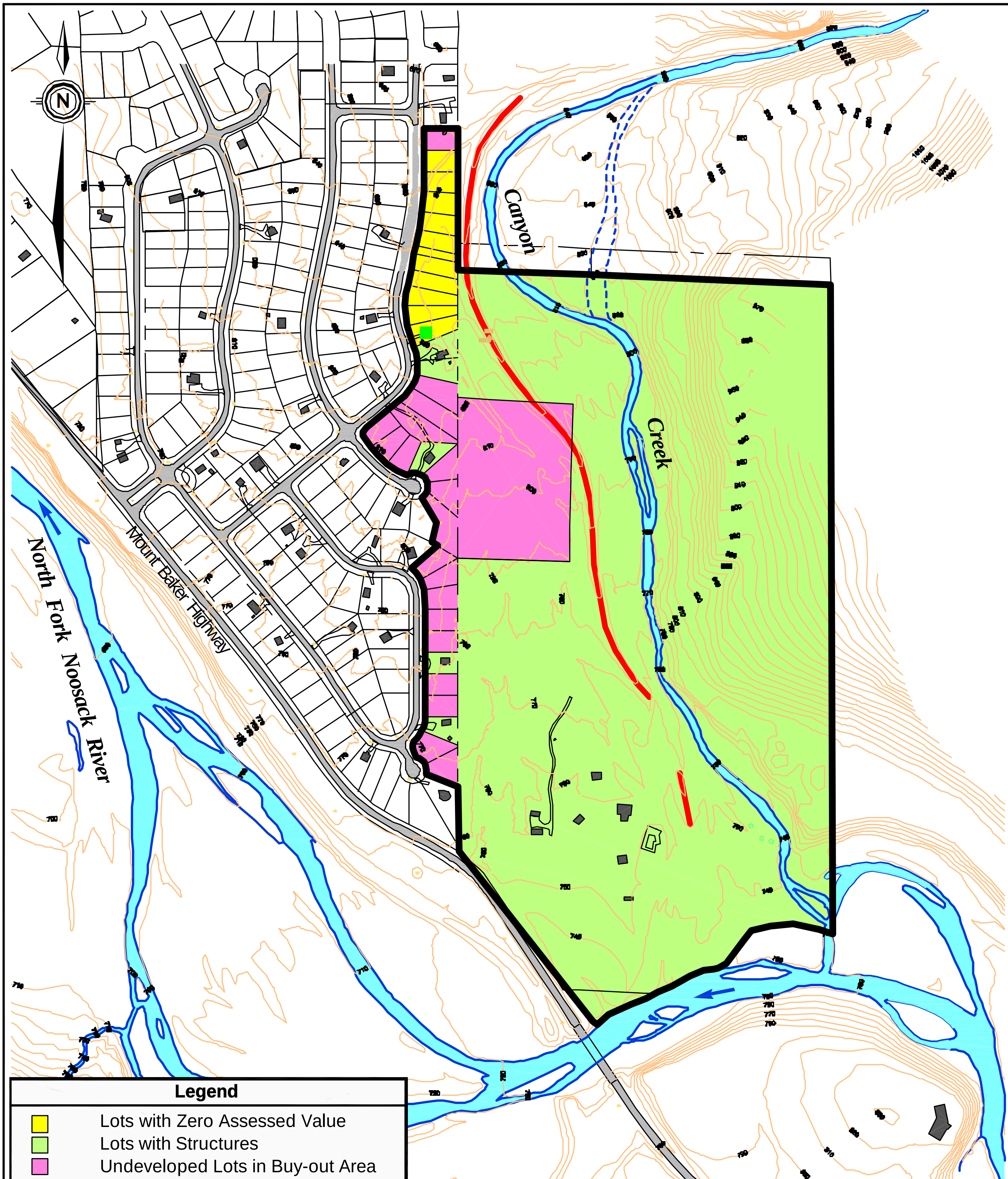
Date September 2003

500 0 500
Scale in Feet

Previous Canyon Creek Fan Hazard Zones

Figure 2-4

'2039-001\Drawings\2039001StFig2-4.Dwg Oct.02/03



KERRWOOD LEIDAL associates limited CONSULTING ENGINEERS

Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Project No.	Date
2039.001	September 2003

500 0 500
Scale in Feet

Whatcom County Proposed Buy-out Area on Canyon Creek

Figure 2-5

Sep.24/03
2039-001\Drawings\2039001StFig2-5.Dwg

Section 3

Debris Flood Risk Analysis

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

3. DEBRIS FLOOD RISK ANALYSIS

3.1 INTRODUCTION

This section provides a risk analysis related to debris flood and flood hazards on Canyon Creek. This includes:

- analysis of debris flood and flood *hazards*;
- assessment of the potential *consequences*; and
- establishment of *risk* and the need to implement mitigative measures.

The primary purpose of this section is to identify the risk management issues that are important to Whatcom County in considering possible implementation of mitigative measures. For the purpose of this report, 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 mitigative measures, depends on both the degree of hazard and the potential consequence.

3.2 DEBRIS FLOOD AND FLOOD HAZARDS

This sub-section is a summary of Appendices F and G. It quantifies the hazards posed by debris floods and floods at Canyon Creek. The hazard assessment represents an evaluation of the watershed capability to produce these types of events, independently of the potential consequences of such events. Floods are dealt with first because flood magnitude has some bearing on the assessment of debris flood hazards.

DESIGN FLOOD EVENT

Design of mitigation works for flood hazards requires that the design flood event be quantified. In Washington State, the 100-year return period flood is the accepted standard for flood protection. Appendix F provides a hydrologic analysis for Canyon Creek. Previous studies have used a variety of methods to estimate peak instantaneous flows. KWL reviewed these estimates and suggests the following design peak flow estimate:

Return Period (years)	Canyon Creek Peak Flow	
	(cfs)	(m^3/s)
100	6,000	170

In addition to the peak flow magnitude, it is necessary to consider the potential for flood flows to be accompanied by bedload and wood debris.

DEBRIS FLOOD PROBABILITY AND MAGNITUDE

Appendix G provides a comprehensive analysis of the probability (frequency) and magnitude (volume and discharge) of debris floods on Canyon Creek.

In general, a probability can be attached to the occurrence of debris floods of a particular magnitude. This is a physical assessment of the hazard, independent of the consequences of such an event. In many situations, different debris flood magnitudes may occur on a particular creek with varying probabilities. For example, small or medium size debris floods usually occur more frequently than larger ones. This is particularly true for creeks with multiple tributary branches and large amounts of debris. The probability of events such as debris flows, debris floods, avalanches, and landslides is often best assessed with extreme value distributions similar to those used in flood frequency analysis.

Frequency-magnitude relations are largely controlled by the watershed type (in terms of the amount of sediment available for transport). Watersheds with a quasi-infinite amount of stored debris respond more readily to triggering hydroclimatic events and show a very large range of possible debris flood magnitudes. Watersheds with a limited amount of stored debris have to recharge after each significant event, and hence the amount of available debris at any given time may be limited. Other factors influencing the frequency-magnitude relationship for debris floods are the severity of hydroclimatic events, watershed morphometry, geotechnical characteristics of the source materials, and vegetation cover. Seismic events can also potentially influence the frequency and magnitude of debris floods by initiating landslides, particularly under saturated conditions (Chleborad and Schuster, 1998; Keefer, 1999). The above factors have been considered in the development of a frequency-magnitude relationship for Canyon Creek.

For purposes of this report, Appendix G defines the following probability classifications for debris floods:

Probability	Return Period	Probability of at Least One Occurrence in 50 Years[1]
Very High	less than 20 years	more than 90%
High	20 to 100 years	40% to 90%
Medium	100 to 500 years	10% to 40%
Low	greater than 500 years	less than 10%

[1] Probabilities are rounded to the nearest 5%.

The return period is defined as the average recurrence interval for a particular event magnitude. For example, a 100-year return event will, on average, be equaled or exceeded once in any 100-year period. Greater return periods indicate less frequent (and larger magnitude) events. The probability of occurrence noted in the above table provides a more easily interpretable measure of hazard probability.

DESIGN STANDARD FOR DEBRIS FLOODS

For development of debris flood mitigation measures, a *design debris flood event* may be selected. In Washington State, however, there is no established design standard. Alluvial fan hazard areas are addressed by the Federal Emergency Management Agency (FEMA) in their guidelines for high risk flood hazard areas (FEMA, 1987). At present, the regulatory 100-year return period flood levels for setting insurance rates are based on flood frequency analyses of pure water floods. While this may be an appropriate design standard for rivers that are primarily subject to floods, it is not considered an appropriate design standard for mountain creeks that are subject to debris floods or debris flows. Floods show poor correlation to the frequency and magnitude of debris floods (Jakob and Jordan, 2001). Statistical flood analyses do not take into account the geomorphology and land use conditions in the watershed that may lead to debris floods. Nor do they consider the potential for flow obstructions on the fan or aggradation associated with a debris flood. These are significant factors that can affect inundation patterns (Raines et al., 1997).

With respect to other related hazards, the US Army Corps of Engineers uses a 500-year return period for artificial dam failures. In addition, the US Geological Survey has recently attempted to plan for 500-year return period events in areas potentially affected by lahars around Mount Rainier.

Under state legislation enacted in 1990, alluvial fans fall under the critical areas classification of the Washington State Growth Management Act (GMA) as geological hazardous areas [WAC 365-190-080 (4) (d) (viii)]. The classification and designation of critical areas is intended to assure the long-term conservation of natural resource lands and to preclude incompatible land uses and developments. The Act establishes guidelines to assist in the classification of critical areas, which is intended to lead counties and cities to develop appropriate regulatory and non-regulatory actions in response. The GMA requires local governments to identify and regulate hazards on alluvial fans. The Act provides considerable latitude as to how hazardous areas are best regulated, and does not designate a design return period.

In 1995, a new section was added to the GMA to ensure that counties and cities consider reliable scientific information when adopting policies and development regulations to designate and protect critical areas. The new GMA section, RCW 36.70A. 172, requires all counties and cities in Washington to include the best available science in developing policies and development regulations to protect the functions and values of critical areas. In addition, counties and cities shall give special consideration to conservation or protection measures necessary to preserve or enhance anadromous fisheries.

WHATCOM COUNTY CRITICAL AREAS ORDINANCE

In 1992, Whatcom County completed an inventory of alluvial fans with a view to adopting a Critical Areas Ordinance (CAO) pursuant to the GMA (Fox et al., 1992). This inventory identified 150 alluvial fans in Whatcom County, of which 46 were documented as having known historic events and development. The Canyon Creek fan was identified as being subject to frequent debris floods but a hazard rating was not developed. On May 26, 1992, after extensive public input, Whatcom Council adopted an interim CAO.

The current Whatcom County CAO with amended Critical Areas Regulations was adopted on November 3, 1997. Canyon Creek falls under the definition of an alluvial fan hazard area (Section 16.16.340):

> "… those areas on alluvial fans where flooding, boulder floods, and/or debris torrents have the potential to damage or harm the health or welfare of the community. They include the area generally corresponding to the path of recent and potential future stream flooding, boulder flooding, and/or debris torrents as determined by local topography, hydrology, and depositional history on the fan. Alluvial fan hazard areas are geologically hazardous areas and therefore critical areas."

Regulatory requirements for alluvial fan hazard areas include (Section 16.16.350):

A. No critical facilities shall be constructed or located in geologically hazard areas without fully mitigating the hazard.

H. All projects on an alluvial fan hazard area must be engineered and constructed to withstand alluvial fan hazards and/or flooding equivalent to the largest known event evident on the fan as determined by professional assessment.

I. Clearing within alluvial fan hazard areas is prohibited without adequately addressing the significance of tree retention in an assessment report.

DESIGN DEBRIS FLOOD FOR CANYON CREEK

While there is heightened awareness of the hazards associated with fans in Whatcom County, a design return period for debris floods and debris flows has not been designated. In British Columbia, there is increasing consensus that the *design debris flood* should be based on a 500-year return period (10% in 50 years probability of occurrence), that correlates to the upper level of the **medium probability event**. For the purpose of this report, Whatcom County has selected the 500-year return period debris flood as the design event for Canyon Creek.

Debris floods on Canyon Creek are the result of outburst floods following the sudden break up of a landslide dam or log jam blocking the channel. Canyon Creek is particularly prone to such damming events because the mainstem channel is narrow and confined by steep slopes for several miles upstream of the fan apex.

The 1989 and 1990 events confirm that the Canyon Creek fan is subject to debris floods. Botanical evidence and eye-witness accounts also suggest that debris floods also occurred in 1937 (±), 1962, and 1984. The 1989 debris flood, with a peak discharge of 16,100 cfs (455 m^3/s), was probably the largest during the past 300 years.

Within a 500-year return period, debris floods exceeding the 1989 event are considered probable. Approximately 3 miles upstream of the fan apex, two large landslides (the Jim Creek earthflow and the Bald Mountain earthflow) are situated on opposite sides of the main valley (Figure 2-1). Both earthflows are active and contribute significant volumes of sediment to the creek (Appendix C). The Jim Creek earthflow is in an extensional phase with active loss of toe support by the undercutting action of Canyon Creek. Based on tension cracks observed above the exposed face, a dam height of up to 100 ft (30 m) is thought to be possible by rotational or block failures. Although not observed in historic time, a failure of this magnitude is thought to be possible within a 500-year return period. To determine the peak discharge associated with a 100 ft (30 m) high dam, various dam outbreak scenarios were modelled using the hydraulic model FLDWAV (Appendix G).

Estimated debris flood magnitudes for various probability classifications on Canyon Creek are summarized as follows (Appendix G):

Probability	Probability of Occurrence in 50 Years	Debris Flood		
		Volume (yd^3)	Peak Discharge (cfs)	Peak Discharge (m^3/s)
Very High	more than 90%	10,000	6,000	170
High	40% to 90%	45,000	12,000	340
Medium	**10% to 40%**	**150,000**	**25,000**	**700**

Note: The above magnitude estimates are based on current understanding of debris floods. The results are consistent with section RCW 36.70A 172 of the Growth Management Act of Washington State that requires all counties to include the best available science in developing regulations for critical areas.

Based on the medium probability criterion, the design debris flood for Canyon Creek is estimated as a peak discharge of **25,000 cfs** (700 m^3/s), combined with a debris volume of **150,000 yd^3** (115,000 m^3). A frequency analysis of the above results indicates that the 1989 debris flood is rated at a return period of approximately 200 years.

3.3 DEBRIS FLOOD MODELLING

FLO-2D MODEL

The hydraulic model FLO-2D was used to model maximum flow depth and velocity in order to assess the hazard posed by the design debris flood event at Canyon Creek. FLO-2D is a two-dimensional flood routing model that is commonly applied to predict overbank flooding. However, it is also useful for analyzing unconventional flooding problems, such as unconfined flows over complex topography, debris floods, and debris flows. FLO-2D is on FEMA's list of approved hydraulic models for unconfined flow flood insurance studies.

MODEL SCENARIOS AT CANYON CREEK

Three scenarios were selected for modelling with FLO-2D:

1. The debris flood follows the existing channel of Canyon Creek and remains confined by the existing berm.
2. The berm is breached at its upstream end with most of the debris flood being confined in the channel between the berm and Glacier Springs.
3. The berm is removed.

MODEL RESULTS

The model results for the design event are illustrated by Figure 3-1. This map represents a composite of the three model scenarios. The figure also shows the anticipated extent of severe erosion that is inferred from the model results, but is not a direct model output.

The debris flood impact zones are based on the following definitions:

Zone	Definition			
	v (ft/s)	**d** (ft)	**D** (ft)	**Description**
Red	> 15	> 8	> 2	Direct impact zone
Orange	5 – 15	3 – 8	0.75 – 2	Indirect impact zone
Yellow	< 5	< 3	< 0.75	Sedimentation zone
Areas of nuisance flooding or sedimentation are not specifically delineated. v = maximum flow velocity, d = maximum flow depth, D = maximum boulder size (diameter)				

The area considered subject to severe erosion is shown on Figure 3-1 as follows:

Zone	Definition	Description
Hatched	> 4 ft horizontal or vertical scour	Severe erosion potential

The impact zones shown on Figure 3-1 are not exact, but are best estimates based on the model results and experience. It should be recognized that a large debris flood on Canyon Creek could result in debris deposition that results in flow surges that are somewhat unpredictable. As a result, the debris flood deposition could vary from that illustrated by Figure 3-1. Areas of yellow could become orange and vice-versa, particularly with the rapidly varying flow characteristics of a debris flood.

It is very important to understand that the zones delineated on Figure 3-1 reflect existing conditions. If a debris flood or large flood were to occur that caused significant channel changes or aggradation, the zones would have to be redefined on the basis of the future channel conditions. As an illustration of this point, despite its lower magnitude, the November 1990 debris flood at Canyon Creek caused more damage than the 1989 event because the 1989 event had significantly changed the channel alignment and aggraded the channel near the fan apex. Consequently, the zones identified on Figure 3-1 are valid only until the next major event on Canyon Creek at which time it would have to be updated.

DISCUSSION OF MODEL RESULTS

The model results for the Scenario 1 show that the existing berm is high enough to contain the design debris flood, but the lower left bank will be inundated. None of the existing buildings, including those of the Logs Resort, would be flooded.

The maximum flow velocity would range from 20 ft/s to 32 ft/s (6 m/s to 10 m/s) against the upper end of the berm. While the berm at this location is armoured, the riprap has an average size of about 5 ft (1.5 m), and was designed to withstand a peak flow of only 5,000 cfs (GeoEngineers, 2000). Thus, the existing riprap is not likely to withstand the design event, and the berm would likely be breached. This conclusion is consistent with the previous hydraulic analyses of Inter-Fluve (Section 2.7).

A particularly hazardous scenario is if the berm becomes breached at its upper end and the debris flood becomes confined in the channel between the berm and Glacier Springs. In such a scenario, areas in and around the Logs Resort would be inundated to an average depth of 2 ft to 4 ft (0.6 m to 1.2 m), with some localized depressions flooding to a depth of about 8 ft (2.4 m). The right bank would also be subject to significant erosion, potentially undermining Canyon View Drive and several properties.

If the berm is removed, in the absence of any significant flow obstructions there would be flooding in and around the Logs Resort but not likely to the extent that buildings would be damaged. However, flow obstructions in the form of debris deposition could result in unpredictable flow surges to the extent that structural damage could occur at the Logs Resort. This potentially applies to Canyon View Drive and other locations as well.

The model results indicate that the deepest flow near the fan apex would be confined to the existing channel. Without the berm, however, a new channel is likely to form against the right bank and undermine Canyon View Drive.

It should also be recognized that there is a flood overflow/deposition hazard on the lower fan that is not specifically illustrated by the modelling results of Figure 3-1.

HAZARD MAP

The modelling results for the design debris flood event (Figure 3-1) can be used to define hazard zones on the fan. Figure 3-2 presents a hazard map for the Canyon Creek fan. Three hazard zones are defined:

Zone 1 The highest hazard zone, potentially subject to direct debris impact or severe erosion during a debris flood. In the event of a debris flood or other exceptional flooding, there is an increased risk for loss of life or property. This area is not recommended for land development without regional off-site flood control works or engineered works designed to mitigate for flow depths up to 8 ft, velocities up to 15 ft/s (except in the hatched area where flow depths up to 12 ft and velocities up to 25 ft/s could be experienced), and lateral channel migration and scour conditions similar to those experienced in the 1989 and 1990 events.

Zone 2 Potentially subject to erosion due to long-term channel migration. Also subject to flood overflow/deposition to a depth of up to 4 ft (1.2 m) and a velocity of up to 6 ft/s (1.8 m/s). Land development should be subject to an engineering report with on-site mitigative measures.

Zone 3 Potentially subject to flood overflow/deposition to a depth of up to 2 ft (0.6 m) and a velocity of up to 3 ft/s (0.9 m/s). Land development should be subject to elevating buildings above the surrounding ground elevation.

This hazard map provides a tool for Whatcom County to regulate land development on the Canyon Creek fan.

3.4 POTENTIAL CONSEQUENCE

This sub-section provides an assessment of the potential debris flood consequences on Canyon Creek. Understanding these impacts is important as they determine the risk that forms the basis for consideration of mitigative measures.

CONSEQUENCE RATING SYSTEM

The overall potential consequences of debris floods are rated as follows:

Consequence	Description
Very High	Direct debris impact with extensive structural damage.
High	Direct or indirect debris impact with some potential for structural damage along with significant sediment deposition and flooding.
Medium	Indirect debris impact. No structural damage but damage to houses and property from sediment deposition and flooding.
Low	Sediment deposition and flooding with minor property damage only.
Very Low	Virtually no damage.

While this rating system focuses on structural and property damage, the potential for injury and loss of life should also be considered. In general, this will decrease in accordance with the consequence rating.

DEBRIS FLOOD CONSEQUENCES AT CANYON CREEK

There are a number of significant potential debris flood consequences at Canyon Creek. These are listed as follows:

- Severe erosion leading to undercutting of Canyon View Drive and potential collapse of buildings located along the west margin of the lower fan behind the existing berm. Loss of life is possible.

- Impact and deposition at Logs Resort which could lead to structural damage at the Logs Resort. Loss of life is possible.

- Overtopping of Mount Baker Highway southwest of the Logs Resort. Erosion of the high bank of the North Fork Nooksack River is possible with subsequent undermining of the road surface and possible collapse of the road surface. Injury or loss of life is possible if vehicles drive into the chasm.

- Erosion of the north embankment of Mount Baker Highway and potential partial loss of the road surface. Injury or loss of life is possible if vehicles veer off the road. This would most likely occur if the event were to occur at night.

- Flooding and/or debris deposition on all parts of the Canyon Creek fan, to the degree indicated by Figure 3-2.

- Partial blockage of the North Fork Nooksack River due to excessive aggradation. A partial blockage could result in undermining of the east abutment of the Mount Baker Highway Bridge. Such an occurrence was a potential concern in 1995 during a flood event (Section 2.6).

It should be noted that the above potential consequences are not unique to the Canyon Creek fan. For all developed alluvial fans that are subject to debris floods, there is the potential for loss of life and extensive property damage.

3.5 POTENTIAL DEBRIS FLOOD RISKS

DEFINITION AND CLASSIFICATION OF RISK

Natural hazard risk can be defined as the combination of hazard (event probability and magnitude) and consequence (vulnerability to damage). Assessment of both hazard and consequence, and therefore risk, can be performed qualitatively on the basis of analysis and judgement. For this study, the hazard probability is defined on the basis of return periods in Appendix G and Section 3.2. Consequence is rated according to the rating table in Section 3.4.

Qualitatively, risk can be assessed for a fan area by using the following matrix:

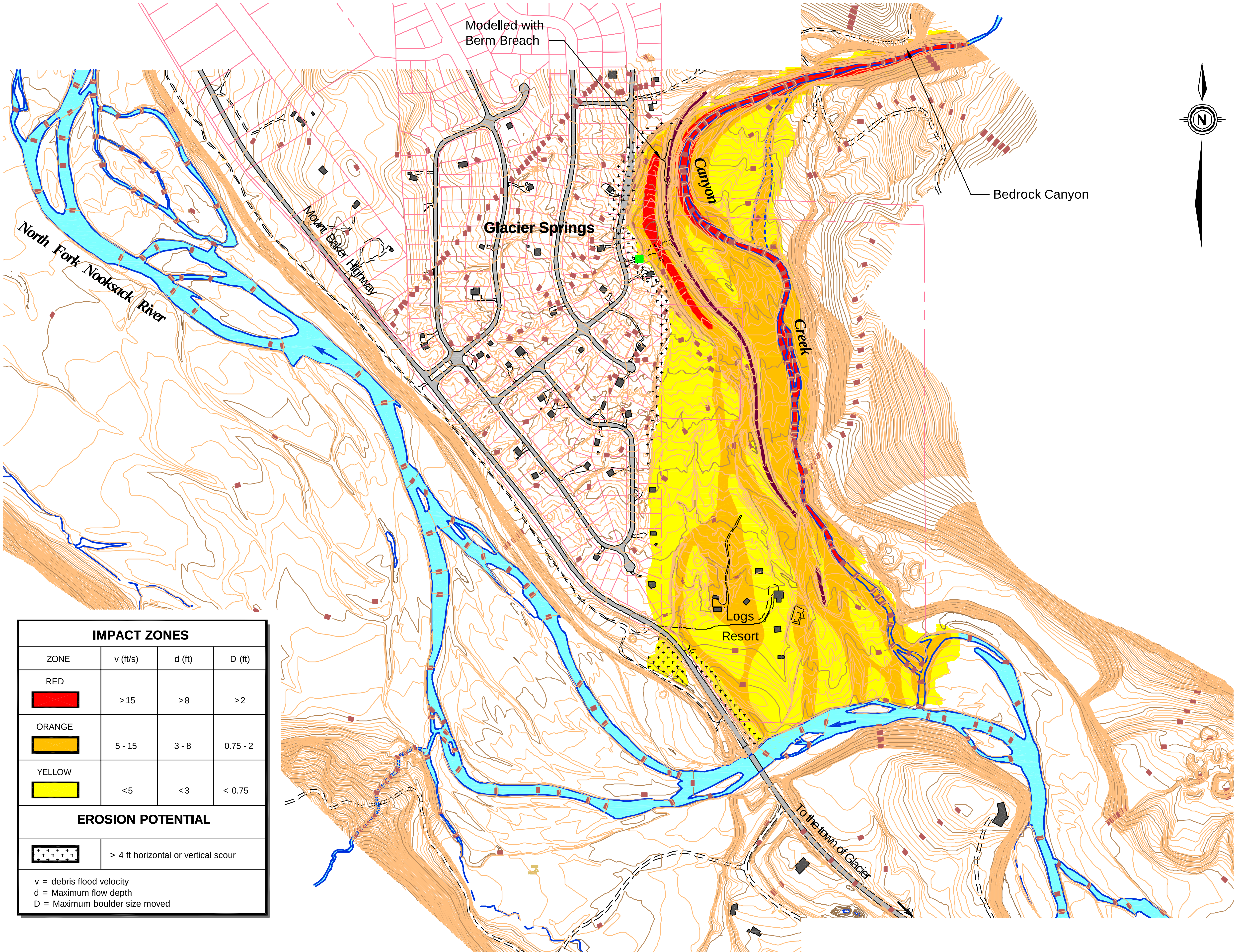
Hazard Probability	**Consequence**				
	Very High	**High**	**Medium**	**Low**	**Very Low**
Very High	Very High	Very High	High	Medium High	Medium Low
High	Very High	High	Medium High	Medium	Low
Medium	High	Medium High	Medium	Medium Low	Low
Low	Medium	Medium	Medium Low	Low	Very Low

EXISTING LEVEL OF RISK AT CANYON CREEK

Based on the above table and the results of the debris flood modelling, the existing level of risk at Canyon Creek for various debris flood hazard scenarios is as follows:

Hazard Probability	Existing Conditions	
	Consequence	**Risk**
Very High	Low	Medium High
High	Medium	Medium High
Medium	**Very High**	**High**

The above table illustrates that under existing conditions, the design event (a medium probability debris flood) at Canyon Creek poses a high risk (bold row). The implication is that events having return periods of 100 to 500 years (40% to 10% chance in 50 years) will cause damage to multiple houses by debris impact or erosion.



IMPACT ZONES

ZONE	v (ft/s)	d (ft)	D (ft)
RED	>15	>8	>2
ORANGE	5 - 15	3 - 8	0.75 - 2
YELLOW	<5	<3	< 0.75

EROSION POTENTIAL

> 4 ft horizontal or vertical scour

v = debris flood velocity
d = Maximum flow depth
D = Maximum boulder size moved

Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Legend

Berm
Property Line
Former Shepherd Residence

Notes:

1. The impact zones are delineated as a composite of several modelled scenarios. They include a potential breach of the existing berm as shown.
2. The dimensions and locations of mapping features are approximate and are based on a 1994 survey.
3. Property lines are based on cadastral information supplied by Whatcom County Flood Control Zone District.
4. The modelling results provide information on the 500-year return period debris flood under existing conditions. The map does not account for subsequent events which may significantly change the zones. Survey of affected areas and remodeling would then be necessary.
5. The debris flood hazard to North Fork Nooksack River will depend on the discharge of the river at the time of the debris flood on Canyon Creek.
6. Patterns of sediment transport and deposition during a debris flood could result in yellow impact zones becoming orange and vice-versa.

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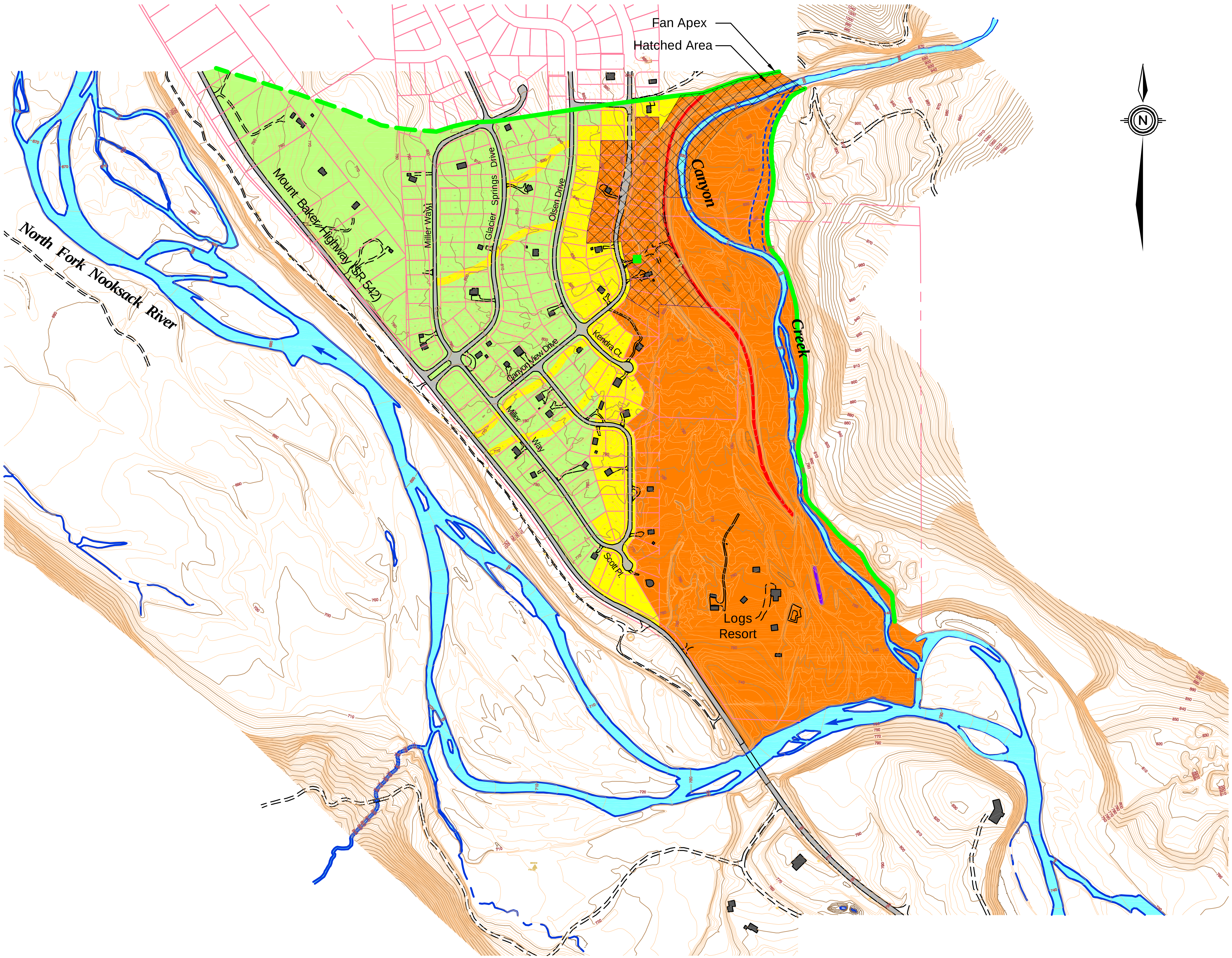
500 0 500
Scale in Feet

Project No.	Date
2039.001	September 2003

Canyon Creek Debris Flood Modelling Results for Design Event

Figure 3-1

Sep.24/03
2039-001\Drawings\2039001StFig3-1.DWG



Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

Legend

- **Armoured Berm**
- **Berm**
- **Property Line**
- **Former Shepherd Residence**
- **Fan Boundary**
- **Approximate Fan Boundary**

HAZARD ZONES

ZONE 1
Area potentially subject to direct debris impact or severe erosion during a debris flood. In the event of a debris flood or other exceptional flooding, there is an increased risk for loss of life or property. Not recommended for land development without regional off-site flood control works or engineered works designed to mitigate for flow depths up to 8 ft, velocities up to 15 ft/s (except in the hatched area where flow depths up to 12 ft and velocities up to 25 ft/s could be experienced), and lateral channel migration and scour conditions similar to those experienced in the 1989 and 1990 events.

ZONE 2
Area potentially subject to erosion due to long-term channel migration. Also subject to flood overflow/deposition, depth up to 4 ft, velocity up to 6 ft/s. Land development should be subject to an engineering report with on-site mitigative measures.

ZONE 3
Area potentially subject to flood overflow/deposition, depth up to 2 ft, velocity up to 3 ft/s. Land development should be subject to elevating buildings above the surrounding ground elevation.

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400 0 400
Scale in Feet

Project No.	Date
2039.001	September 2003

Canyon Creek Debris Flood Hazard Zones

Figure 3-2

Oct.07/03
2039-001\Drawings\2039001StFig3-2.DWG

Section 4

Risk Mitigation Alternatives

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4. RISK MITIGATION ALTERNATIVES

4.1 INTRODUCTION

Section 3 documents creek-related hazards, defines the potential consequences of creek events, and describes the risks that arise from the combination of creek hazards and potential consequences. Based on those findings, this section reviews alternative strategies that may be considered for risk mitigation at Canyon Creek. For the purposes of considering possible applications, the focus is on events in the order of the design debris flood – a peak discharge of 25,000 cfs (700 m^3/s) and a corresponding sediment volume of 150,000 yd^3 (115,000 m^3).

ALTERNATIVE STRATEGIES

There are two general strategies for mitigating debris flood 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 flood hazard affects a developed area. Passive measures can complement active measures to provide a more comprehensive approach to risk mitigation.

A zero solution (do nothing) with implementation of neither active nor passive measures, implies full risk acceptance by decision-makers and residents. From a technical perspective, and the perspective of Whatcom County, a zero solution is not considered an appropriate option at Canyon Creek.

CONSIDERATION OF MITIGATIVE MEASURES FOR CANYON CREEK

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

- land use planning and development;
- warning systems;
- watershed management actions; and
- debris flood mitigation structures.

A preferred approach to risk mitigation is suggested at the end of the section. This is based on the stated desire of Whatcom County to favour passive measures and avoid instream channel works.

4.2 LAND USE PLANNING AND DEVELOPMENT

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

ZONING

In some cases, a fan may be delineated into zones of varying hazards, either with or without mitigation measures. This may result in portions of a 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.

At Canyon Creek, Figure 3-1 shows areas that are subject to damage under existing conditions. Figure 3-2 defines three debris flood hazard zones for the Canyon Creek fan. The definition of hazard zones in Figure 3-2 takes a longer term view than the single event modelled under current conditions in Figure 3-1. Figure 3-2 provides a tool for Whatcom County to regulate land development on the Canyon Creek fan.

LAND ACQUISITION

In many cases, acquisition of hazard land to preclude development is an effective alternative to constructing mitigation structures. Land acquisition can also be effective in keeping critical areas under public ownership (i.e. lands that may be needed in the future for construction of works or creek maintenance).

At Canyon Creek, land acquisition in the form of the proposed buy-out has already been selected as a key component of risk mitigation by Whatcom County. The proposed buy-out will be very effective in that it incorporates most of the highest risk lands on the fan.

At Canyon Creek, acquisition of additional property along the creek corridor may be beneficial in view of potential changes in channel condition. Development activity in this area should be closely scrutinized, and land acquired where there are opportunities to do so.

DEVELOPMENT OF EXISTING LOTS

Figure 3-2 provides a basis for Whatcom County to implement site-specific land use regulations for the Canyon Creek fan. It is suggested that this involve:

Zone 1	No further land development in the absence of regional off-site mitigative works. The extent of Zone 1 correlates well with the proposed buy-out area, so land development interest in this area is anticipated to be minimal.
Zone 2	Development requires an engineering report with site-specific mitigative measures (anticipated to include a specified building elevation above the surrounding grade, plus erosion protection measures).
Zone 3	Development may proceed with building elevations above the surrounding grade. Such elevations may be prescribed by Whatcom County such that there is no need for owners to obtain engineering reports. Specific attention needs to be given to any localized swales or depressions that may be present.

Such an approach would need to be carefully integrated into the existing regulatory framework of Whatcom County.

FOREST MANAGEMENT ON FAN

Trees can provide an important role in dissipating some of the energy of a debris flood or debris flow on a fan. At Canyon Creek, under existing conditions, it would be best to retain the existing tree cover in the upper fan area. This area is apparently owned by a private logging company.

4.3 WARNING SYSTEMS

Systems can be installed to provide warning of an impending debris flood (advance warning system), a debris flood occurring (event warning system), or after a debris flood has occurred (post-event warning system).

In addition to probable false warnings, concerns with warning systems include:

- finding a recognized authority to accept management responsibility;
- protecting the authority from excessive liability exposure; and
- ensuring uninterrupted system operation.

The three types of warning systems and their applicability to Canyon Creek are discussed below.

ADVANCE WARNING SYSTEMS

Advance warning systems can involve real-time monitoring of precipitation and creek flow data to determine when hydrological conditions approach a threshold for regional landslide occurrence and debris flood activity. Activities in high-risk areas may then be restricted and public notification considered. The period of notice may range from a few hours to a day or two. Warnings will typically apply to all creeks in a regional area as opposed to any specific creek. False warnings may occur relatively often. An advance warning system in the form of a hydroclimatic threshold for landslide initiation has recently been developed for use on the North Shore mountains of Vancouver (Jakob and Weatherly, 2003).

At Canyon Creek, an advance warning system would be most applicable for warning watershed users of high risk periods. An advance warning system could also warn downstream residents and road users of high risk periods, but given the high likelihood of false warnings, it would not provide an effective means for temporarily relocating residents.

EVENT WARNING SYSTEMS

Event warning systems may provide warning of an event in progress. Such systems would typically involve cables (tripwires) or sensors (geophones, ultrasonic devices) in a creek channel which emit a signal when displaced by a debris flood or triggered by vibration during a debris flood.

An event warning system could be designed for Canyon Creek, but it would be difficult to achieve more than a few of minutes warning before debris flood impact on the fan. False warnings could also occur periodically, eroding public confidence in the system.

POST-EVENT WARNING SYSTEMS

Post-event warning systems may be useful in providing notice of a service disruption of critical infrastructure, such as bridges. Such a system would have been effective in preventing multiple deaths in 1981 on the Squamish Highway in British Columbia, resulting from several vehicles driving unknowingly into a gorge following a bridge washout.

At Canyon Creek, the Mount Baker Highway crossing of the North Fork Nooksack River has been identified as being at risk due to debris flood overflows or a partial channel blockage. A bridge collapse could trigger a gate to close automatically, thereby preventing cars from inadvertently driving into the channel following an event. Given the risk at Canyon Creek, it may be appropriate to install such a system.

4.4 WATERSHED MANAGEMENT ACTIONS

A number of watershed management actions can be considered at Canyon Creek.

WATERSHED STABILIZATION

Watershed stabilization activities can be considered to reduce the level of debris flood hazard. Such measures attempt to tackle the problem at the source area where debris is generated.

At Canyon Creek, the high level of logging in the 1960s through the 1980s initiated a number of landslides that reached Canyon Creek. This increased the debris load in the creek system, and may have increased the magnitude of the 1989 debris flood. Since the extensive logging, there has been a ban on further logging on USFS land (logging continues on private land) and a number of the logging roads have been deactivated.

Given that some instabilities remain from previous logging in the Canyon Creek watershed, it may be appropriate to perform a stability assessment and implement any appropriate mitigative actions.

Any future logging or road building activity in the Canyon Creek watershed should be based on appropriate geomorphology and engineering expertise to ensure that there is no resultant increase in the probability or magnitude of debris floods.

EARTHFLOW MONITORING

A likely trigger for future debris floods on Canyon Creek is a large block slide off of either the Jim Creek earthflow or the Bald Mountain earthflow. Such a slide could block Canyon Creek and result in a large outbreak flood. Given this possibility, it would be appropriate to monitor the movement rates of the earthflows using simple ground based methods or repeat radar interferometry. Because both earthflows are extremely large, any stabilization efforts (outside of intensive dewatering) have a very low likelihood of success.

Any significant trends in movement of the earthflows may warrant future review of the risk analysis for the Canyon Creek fan.

4.5 DEBRIS FLOOD MITIGATION STRUCTURES

There are several types of mitigation structures that can be constructed to mitigate debris flood risks. This sub-section provides a brief description of such structures and their potential application at Canyon Creek.

DEBRIS BASIN OR DEBRIS BARRIER

Debris barriers and debris basins are the most prevalent mitigative structures for risk mitigation on debris flood and debris flow creeks. They are described and discussed as follows:

Debris Basin A debris basin is a constructed storage area in which the sediment and woody debris of a debris flood 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. The only possible location for a debris basin at Canyon Creek would be near the fan apex. Construction of a debris basin at this location would cost roughly $1,000,000.

Debris Barrier 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. At Canyon Creek, a debris barrier could be constructed in the canyon immediately upstream of the fan apex but construction would be expensive (roughly $1.2 million).

For either a debris basin or a debris barrier, significant maintenance work would be required after any significant event. For maintenance purposes, it would be necessary to provide equipment access to the structure.

If a debris basin or a debris barrier were to be considered at Canyon Creek, the following practical aspects would need to be addressed:

- the area of construction must be acquired or covered by a right-of-way;
- an appropriate financial mechanism needs to be developed for construction, routine maintenance, and post-event maintenance;
- a lead proponent needs to be identified who will administer the construction program;
- an ongoing maintenance authority needs to be identified;
- an appropriate design needs to be completed, involving a stakeholder consultation program;
- environmental issues need to be addressed and environmental approvals need to be obtained; and
- an operation and maintenance manual needs to be developed to identify monitoring, inspection and maintenance activities.

Neither a debris basin or debris barrier is considered desirable at Canyon Creek given the need for instream channel works, and the associated up-front and ongoing maintenance costs.

DEFLECTION BERM

A deflection berm is another type of structural measure that has previously been implemented at Canyon Creek. The purpose of a deflection berm is to deflect a debris flood to an area that it will not cause damage. As there is the potential to transfer risk from one area to another, it is important to ensure that a deflection berm project does not have any undesirable consequences.

Hydraulic analyses indicate that the Canyon Creek deflection berm would not likely withstand the design debris flood event, and would likely be breached during a large event (some damage occurred during a moderate flood in 1995). Another problem with the berm is that it confines Canyon Creek to a very narrow corridor, reducing the area available for sediment deposition and flow attenuation. By constricting Canyon Creek, the berm somewhat funnels sediment to the North Fork Nooksack River, potentially exacerbating the potential for a partial blockage of the North Fork. In addition, no plans or formal commitment to maintain the berm exist, and therefore it can not be relied upon as a long-term mitigative measure.

Some considerations regarding the existing Canyon Creek deflection berm are as follows:

- The lower two-thirds of the berm would best be removed. Removal of this portion of the berm would remove the most significant constriction in the floodway and dramatically increase the area for natural creek processes to occur. If the proposed buy-out proceeds, there will no longer be a need to protect the Logs Resort lands that are protected by the lower berm.

- It would be advisable to armour the right bank adjacent to Canyon View Drive. If the lower portion of the berm is removed, the riprap from the removed berm could be used to armour the right bank. The cost of berm removal and armouring of the right bank would be approximately $300,000.

- The upper third of the berm would best not be removed. Removal could be considered if the right bank adjacent to Canyon View Drive is armoured.

- Consideration should be given to the construction of a new deflection berm along the north side of the Mount Baker Highway. Debris flood avulsions could overtop the highway southwest of the Logs Resort. Erosion of the high bank of the North Fork Nooksack River is then possible with subsequent undermining of the road surface and possible collapse of the road surface. Construction of a 10 ft (3 m) high deflection berm for a lineal distance of about 1000 ft (300 m) would mitigate against such an occurrence. The cost of such a deflection berm would be about $500,000.

4.6 PREFERRED RISK MITIGATION ALTERNATIVES

The purpose of this report is not to select one of the mitigation alternatives for implementation. However, it is appropriate to indicate which alternatives have merit at this time. Following a review of the available risk mitigation alternatives at Canyon Creek (and in consideration of engineering issues, environmental issues, aesthetics and cost), viable mitigation measures include the following:

Buy-out:	Proceed with the proposed buy-out to the fullest extent possible.
Land Acquisition:	Consider acquiring additional lands along the creek corridor and on the fan as opportunities arise in the future.
Land Use:	Adopt the hazard zones of Figure 3-2 for land use planning. Avoid further development in Zone 1 and regulate Zones 2 and 3 accordingly.
Fan Management:	Preclude logging in the forested area on the upper fan (which is apparently owned by a private timber company).
Event Warning System:	Consider installing a system to warn against a collapse of the Mount Baker Highway Bridge over the North Fork Nooksack River.
Advance Warning System:	Consider installing a regional advance warning system to provide public warning of high risk periods for debris avalanches, debris flows, and debris floods.
Watershed Stabilization:	Review previous instabilities from logging and road building to determine whether additional restoration measures are warranted at this time.
Watershed Management:	Ensure that any future forestry activity in the Canyon Creek watershed is subject to appropriate geomorphic and engineering advice in order to avoid increasing the probability and/or magnitude of debris floods.
Monitoring:	Consider monitoring movement rates of the Jim Creek earthflow and the Bald Mountain earthflow via simple ground based methods or repeat radar interferometry.
Inspection:	Perform periodic inspections of the Canyon Creek channel and watershed, particularly after any extreme event.
Existing Berm:	Consider removing the lower two-thirds of the berm in order to increase the area available for natural creek processes.
Armour Right Bank:	Consider armouring the right bank adjacent to Canyon View Drive, possibly using riprap from removal of the lower two-thirds of the existing berm.

Mount Baker Highway: Consider constructing a berm along the highway to protect it against debris flood damage.

Mitigation Structures: Consider further implementation of mitigation structures as a possible long-term risk reduction measure that may be warranted in the future.

Some of these measures would be appropriate for direct implementation by Whatcom County, while others would be more appropriately referred to other agencies.

Section 5

Summary and Recommendations

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5. SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

The key points in this report are summarized as follows:

CANYON CREEK

1. Canyon Creek is defined as the watershed upstream of its confluence with the North Fork Nooksack River. The total watershed area is 31 mi^2 (79 km^2).

2. Key features in the watershed are a partially paved watershed access road, extensive logged areas, and two large earthflows that flank Canyon Creek several miles upstream of the fan apex.

3. Major events occurred on Canyon Creek in 1989 and 1990. These events are categorized as debris floods.

HAZARD ASSESSMENT

4. Appendix F provides a hydrologic review which results in the 100-year return period peak instantaneous flood flow being estimated at 6,000 cfs (170 m^3/s).

5. A watershed investigation has been performed to identify geomorphic factors that may influence debris flood occurrence. A detailed watershed map has been produced to document geomorphic conditions (Figure 2-1).

6. The primary debris flood mechanism on Canyon Creek is a landslide dam outbreak flood originating from the Jim Creek earthflow or the Bald Mountain earthflow. FLDWAV software was to model outbreak flood scenarios.

7. Appendix G provides an analysis of debris floods, resulting in the following 500-year return period (10% chance in 50 years) magnitude estimates:

	Event Type	Peak Discharge	Volume
Canyon Creek	Debris Flood	25,000 cfs 700 m^3/s	150,000 yd^3 115,000 m^3

This magnitude is defined as the 'design event' for the purpose of this report.

8. It was determined that the 1989 debris flood had a peak discharge of approximately 16,100 cfs (455 m^3/s) and a return period of approximately 200 years.

9. Debris flood runout at Canyon Creek was modelled using FLO-2D software to determine the potential flow depth and velocity for the design event (Figure 3-1).

10. A derivative hazard map was created (Figure 3-2) to illustrate three hazard zones.

RISK ASSESSMENT

11. For the purpose of this report, risk is defined as the combination of the hazard severity (probability and magnitude) and potential consequence (i.e. vulnerability to damage should an event occur).

12. The consequence of a debris flood for the design event at Canyon Creek under existing conditions is rated as very high (i.e. direct debris impact with extensive structural damage).

13. A major debris flood at Canyon Creek is likely to cause structural damage to buildings at the Logs Resort. There is potential for loss of life. Furthermore, several houses and parts of roads could be undercut by erosion. Portions of the debris could overwhelm the Mount Baker Highway, erode its steep bank to the North Fork Nooksack River, and potentially cause failure of the road surface.

14. The existing level of risk at Canyon Creek for the design event under existing conditions is high. This implies a high priority for mitigative measures.

RISK MITIGATION

15. The proposed buy-out would be a very effective risk mitigation measure in that it incorporates most of the highest risk land on the fan.

16. The hazard zones on Figure 3-2 may be used as a basis for site-specific regulation of lands on the Canyon Creek fan.

17. Consideration could be given to removing the lower two-thirds of the berm and using the riprap to reinforce the right bank adjacent to Canyon View Drive (subject to land ownership and jurisdictional constraints).

18. Other risk mitigation measures are also identified for consideration:

    - acquire additional lands along the creek corridor and on the fan as opportunities arise in the future;
    - preclude logging in the upper fan area;
    - install an event warning system on the Mount Baker Highway Bridge;
    - install a regional advance warning system to provide a public advisory;
    - review previous forestry instabilities in the watershed to determine whether additional restoration measures are warranted;

- ensure that any future forestry activity in the watershed is subject to appropriate geomorphic and engineering advice to ensure that the probability and magnitude of debris floods is not increased;
- monitor movement rates of the Jim Creek earthflow and the Bald Mountain earthflow;
- perform periodic inspections of the Canyon Creek channel and watershed;
- possibly construct a berm along the Mount Baker Highway to protect it from debris flood damage; and
- possibly implement mitigative structures as a long-term measure that may be warranted in the future.

Some of these measures would be appropriate for direct implementation by Whatcom County, while others would be more appropriately referred to other agencies.

5.2 RECOMMENDATIONS

It is recommended that Whatcom County disseminate the results of this study as follows:

1. Advise property owners and residents on the Canyon Creek fan regarding the contents of this report.

2. Submit copies of this report to relevant agencies, possibly including:

   - US Forest Service;
   - Washington State Department of Natural Resources;
   - Washington State Department of Fish and Wildlife;
   - Washington State Department of Ecology;
   - Lummi Nation;
   - Nooksack Tribe; and
   - the Washington State Department of Transportation.

In terms of mitigative measures, it is recommended that Whatcom County:

3. Proceed with the proposed buy-out to the fullest extent possible.

4. Implement site-specific land use regulations on the basis of Figure 3-2.

5. Consider removing the lower two-thirds of the berm and using the riprap to reinforce the right bank adjacent to Canyon View Drive (subject to land ownership and jurisdictional constraints).

6. Consider implementation of the other risk reduction measures identified in Section 4.6 (page 4-8), with referral to other agencies where appropriate.

5.3 REPORT SUBMISSION

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