Appendix A

Background Information on Debris Flows and Debris Floods

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Background Information on Debris Flows and Debris Floods

DEFINITION

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

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

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

OCCURRENCE

Debris flows and debris floods tend to occur in wet weather, but are not necessarily coincident with record rainfall or flood events. Debris flow and debris flood occurrence can be described by three consecutive processes as follows:

- *Initiation* where a mass movement is triggered at the source area in the creek headwaters. Possible trigger mechanisms include debris slides, logjam release, flood surges, and creek bed instability.

- *Transport* of the debris flow down the creek channel. The transport zone is typically scoured as the debris flow grows in size. A straight and uniformly steep gradient channel represents the most favourable transport condition.

- *Deposition* where either the channel becomes laterally unconfined or the creek gradient flattens to the point that there is insufficient energy for continued movement. Depositional landforms are known as creek fans or cones (steep fans). Damage in creek fan areas during debris flow deposition can be catastrophic. The nature of the deposited material is highly variable, but typically covers a wide range from mud to boulders, and usually also includes a significant wood debris component. Debris flow deposition may also result in flooding of adjacent areas as a result of subsequent relocation of the creek channel.

DEBRIS FLOW AND DEBRIS FLOOD PROBABILITY

While significant floods occur virtually every year on a creek system, debris flows and debris floods are usually an intermittent occurrence. Typical debris flow and debris flood return periods range from 5 to 50 years, however, occurrences at lower or higher return periods have been recorded in the Pacific Northwest. Debris flow occurrence can be put into perspective by considering geomorphological processes since the most recent glaciation about 10,000 years ago. In the first several hundred years following glaciation, the landscape was unforested and littered with glacial debris. Debris flow activity is believed to have been considerably higher than today during this period. As the landscape became forested and watersheds stabilized, debris production and debris flow activity gradually decreased. However, there is reason to believe that if the present trend of increasingly wetter conditions in coastal areas continues, debris flow occurrence will increase in frequency and possibly magnitude.

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

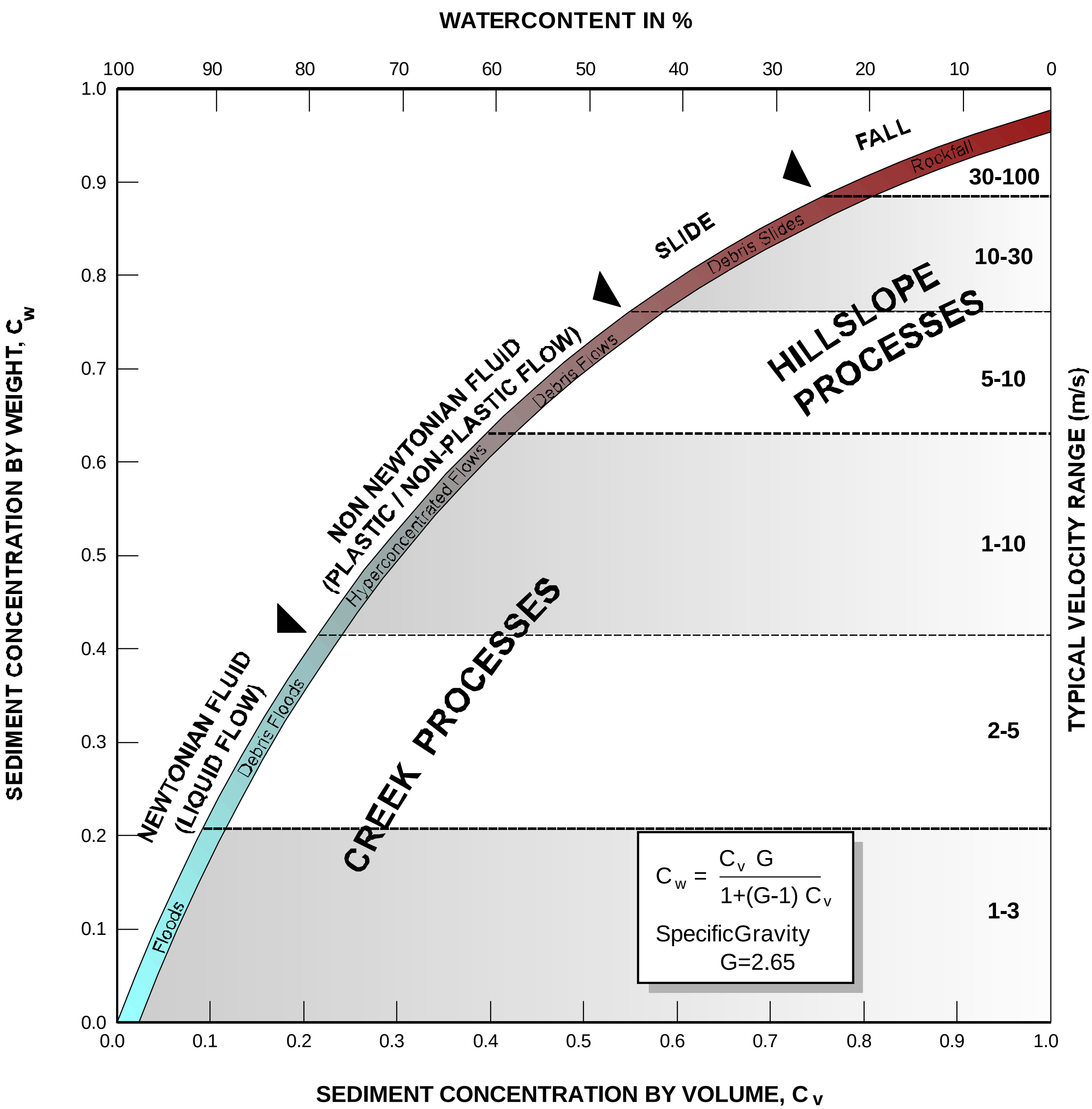
- availability of debris supply sources that contribute materials to the main creek channel and its tributaries (necessity to differentiate drainage basins between material supply-limited vs. material supply-unlimited);
- degree of instability and level of activity of the debris supply sources;
- characteristics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

As debris accumulates, a system gradually becomes "ripe" for a debris flow. The rate at which debris accumulates in a channel is a function of basin type.

Basin Types

Recent research (Jakob, 1996) has identified two distinctly different basin types. One type, referred to as weathering-limited or supply-limited, is characterized by those basins that have a limited source of sediment and thus require recharge after a debris flow event for the next one to occur. In other words, even an exceptionally intensive storm will not trigger a debris flow if not enough sediment has accumulated to produce a debris flow. The other basin type is referred to as transport-limited or supply-unlimited. In those basins, there is a quasi-infinite amount of sediment available for transport and a debris flow can be triggered as soon as a critical climatic threshold (rainfall, rain-on-snow) is exceeded.

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



Classification of Mass Movement Processes

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Figure A-1

Appendix B

Photographs

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Appendix B

Photographs

Photo 1	Upstream view of Canyon Creek after the November 1989 debris flood. The houses on the left were subsequently destroyed by the 1990 event. November 1989.
Photo 2	Damage sustained to Road 31 (Forest Service Road) upstream (top) and downstream (bottom) of the lower creek crossing during the 1989 event. November 1989.
Photo 3	Collapse of Canyon View Drive due to bank erosion during the November 1990 debris flood. November 1990.
Photo 4	Shepherd residence during the November 1990 debris flood.
Photo 5	1994 channel works at the upstream end of the berm adjacent to Canyon Creek.
Photo 6	Aerial view of Canyon Creek fan at the confluence with the North Fork Nooksack River. Note the swimming pool at the Logs Resort just left of the centre of the photo. October 2002.
Photo 7	Aerial view of Canyon Creek fan. Note the berm that extends along the right bank. October 2002.
Photo 8	Downstream view of the North Fork Nooksack River at the confluence with Canyon Creek. The Mount Baker Highway bridge is visible in the background. October 2002.
Photo 9	Downstream view of Canyon Creek near the upstream end of the berm. October 2002.
Photo 10	Exposed fan deposits on the right bank of Canyon Creek. The matrix supported nature of the deposits and weak bedding are characteristic of events with high sediment concentration. October 2002.
Photo 11	Truncated fan deposits of Canyon Creek as viewed from the North Fork Nooksack River. October 2002.
Photo 12	Trees buried by sediment immediately downstream of the fan apex on the right bank. Impact scars on the trees indicate that deposition occurred during the 1989 debris flood. October 2002.
Photo 13	Upstream view of Canyon Creek watershed from the fan apex. October 2002.
Photo 14	Typical view of Canyon Creek in lower reaches (mile 2.4, Reach 4). October 2002.
Photo 15	Downstream view of large log jam about two-thirds of a mile downstream of the Jim Creek Earthflow. October 2002.
Photo 16	Aerial view of the Jim Creek Slide. The dashed line indicates the approximate extent of the earthflow. October 2002.
Photo 17	Aerial view of the Bald Mountain Earthflow. The dashed line indicates the approximate extent of the earthflow. October 2002.
Photo 18	Downstream view of the Jim Creek Earthflow (left bank). The boulder deflector visible in the foreground was constructed in the mid 1990's in an effort to slow erosion of the toe of the earthflow. October 2002.

Photo 19 The Bald Mountain Earthflow as viewed from the Jim Creek Earthflow. The red line indicates the Jim Creek fault trace and the contact between the Chilliwack sedimentary rock on the right and Tertiary sedimentary rocks of the Chuckanut Formation to the left. October 2002.

Photo 20 Distressed trees near the toe of the Bald Mountain Earthflow. Multiple retrogressive rotational slumps are forming as the Earthflow toe is being eroded by Canyon Creek. October 2002.

Photo 21 Active movement on the Bald Mountain Earthflow as indicated by a large tension crack. Note that roots are tensioned suggesting rapid movement rates. October 2002.

Photo 22 Toe scarp of the Jim Creek Earthflow. The dashed line delineates a distinct layer of overriden organic material dated to approximately 6300 years BP, and suggests an early rapid advance of the earthflow. The contact between the Chuckanut Formation sandstones and the overlying earthflow materials is indicated by the continuous line. October 2002.

Photo 23 Aerial view of the Kidney Creek tributary watershed. October 2002.

Photo 24 Aerial view of the upper watershed. The tributary to the right of the photo is Kidney Creek. October 2002.

Photo 25 Debris avalanche in weak glacial sediments downstream of the Whistler Creek confluence. This slide may have been initiated as the result of a retrogressive cutslope failure. The large fan suggests that the debris avalanche completely liquefied after detachment. October 2002.

Photo 26 High water mark and gravel terrace in lower canyon. Photo courtesy of Doug Goldthorp, Whatcom County. August 1991.

Photo 1. Upstream view of Canyon Creek after the November 1989 debris flood. The houses on the left were subsequently destroyed by the 1990 event. November 1989.

Photo 2. Damage sustained to Road 31 (Forest Service Road) upstream (top) and downstream (bottom) of the lower creek crossing during the 1989 event. November 1989.

Photo 3. Collapse of Canyon View Drive due to bank erosion during the November 1990 debris flood. November 1990.

Photo 4. Shepherd residence during the November 1990 debris flood.

Photo 5. 1994 channel works at the upstream end of the berm adjacent to Canyon Creek.

Photo 6. Aerial view of Canyon Creek fan at the confluence with the North Fork Nooksack River. Note the swimming pool at the Logs Resort just left of the centre of the photo. October 2002.

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Photo 9. Downstream view of Canyon Creek near the upstream end of the berm. October 2002.

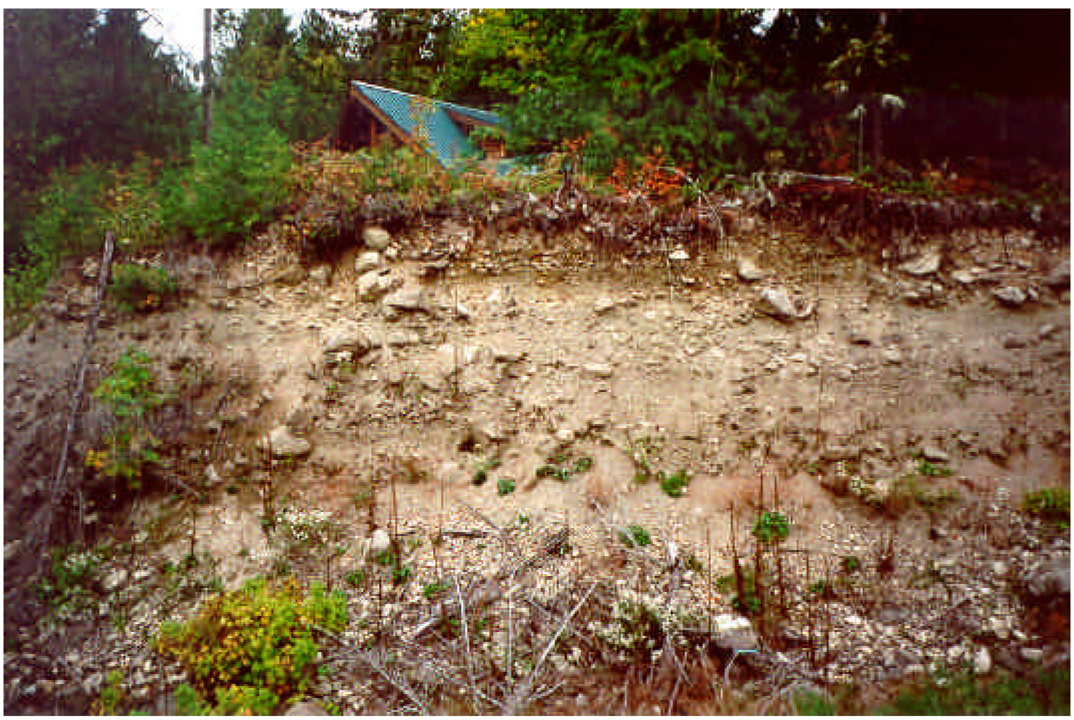

Photo 10. Exposed fan deposits on the right bank of Canyon Creek. The matrix supported nature of the deposits and weak bedding are characteristic of events with high sediment concentrations. October 2002.

Photo 11. Truncated fan deposits of Canyon Creek as viewed from the North Fork Nooksack River. October 2002.

Photo 12. Trees buried by sediment immediately downstream of the fan apex on the right bank. Impact scars on the trees indicate that deposition occurred during the 1989 debris flood. October 2002.

Photo 13. Upstream view of Canyon Creek watershed from the fan apex. October 2002.

Photo 14. Typical view of Canyon Creek in lower reaches (mile 2.4, Reach 4). October 2002.

Photo 15. Downstream view of a large log jam about two-thirds of a mile downstream of the Jim Creek Earthflow. October 2002.

Photo 16. Aerial view of the Jim Creek Earthflow. The dashed line indicates the approximate extent of the earthflow. October 2002.

Photo 17. Aerial view of the Bald Mountain Earthflow. The dashed line indicates the approximate extent of the earthflow. October 2002.

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Photo 19. The Bald Mountain Earthflow as viewed from the Jim Creek Earthflow. The red line indicates the Jim Creek fault trace and the contact between the Chilliwack sedimentary rocks (right) and the Chuckanut Formation (left). October 2002.

Photo 20. Distressed trees near the toe of the Bald Mountain Earthflow. Multiple retrogressive rotational slumps are forming as the earthflow is being eroded by Canyon Creek. October 2002.

Photo 21. Active movement on the Bald Mountain Earthflow as indicated by a large tension crack. Note that roots are tensional suggesting rapid movement rates. October 2002.

Photo 22. Toe scarp of the Jim Creek Earthflow. The dashed line delineates a distinct layer of overriden organic material, which suggests an early rapid advance of the earthflow. A number of trees stick out of this surface (white arrow), which has been dated to approximately 6,300 years BP. The contact between the Chuckanut Formation and the overlying sediment is indicated by the solid line. October 2002.

Photo 23. Aerial view of the Kidney Creek tributary watershed. October 2002.

Photo 24. Aerial view of the upper watershed. The tributary to the right of the photo is Kidney Creek. October 2002.

Photo 25. Debris avalanche in weak glacial sediments. This slide may have been initiated as the result of a retrogressive cutslope failure. The large fan suggests that the debris avalanche completely liquefied after detachment. October 2002.

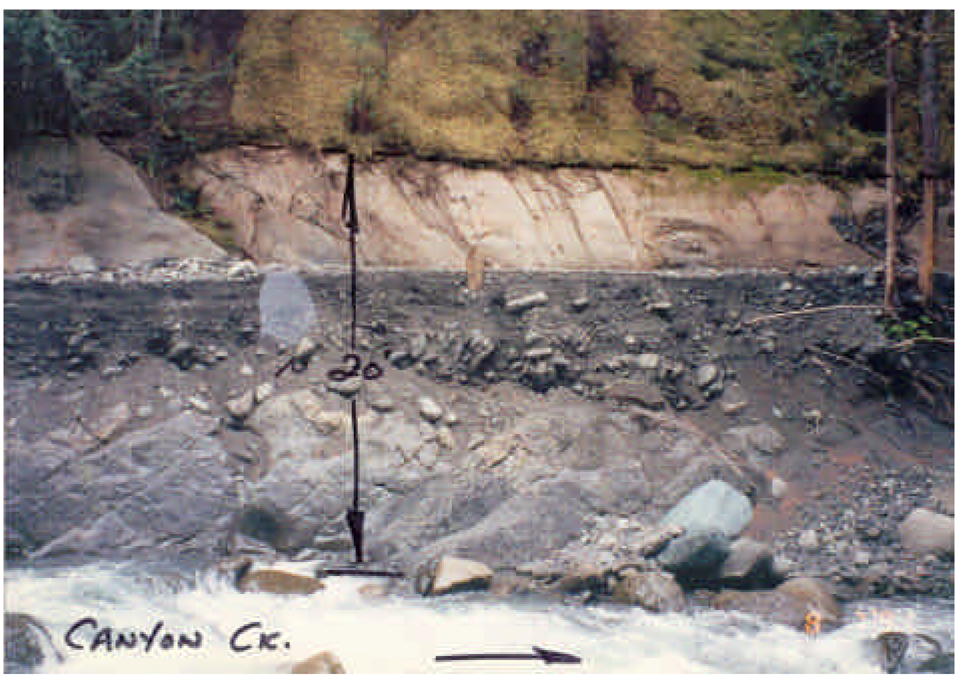

Photo 26. High water mark and gravel terrace in lower canyon. Photo courtesy of Doug Goldthorp, Whatcom County. August 1991.

Appendix C

Watershed Description

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Appendix C

Watershed Description

INTRODUCTION

This appendix provides a description of the Canyon Creek watershed including an overview of watershed characteristics, geology, geomorphology, resource use, a description of the mainstem channel, and landslides. Figure 2-1 is a detailed geomorphic map that should be used for reference with this appendix.

OVERVIEW OF WATERSHED CHARACTERISTICS

Canyon Creek is a 31 mi^2 (79 km^2) watershed that discharges into the North Fork Nooksack River between the towns of Maple Falls and Glacier (about 40 miles east of Bellingham). Most of the watershed is located within the Mt. Baker-Snoqualmie National Forest, Mt. Baker Ranger District (87.4%). Other land owners include the Washington Department of Natural Resources (2.4%) and a large private holding (Crown Pacific and Trillium, 11.2%). Elevations in the watershed range between 860 ft (260 m) at the fan apex to 6,315 ft (1,925 m) on Church Mountain (Figure 2-1).

The mainstem channel is about 17 miles long (27 km) and originates at an elevation of about 5,300 ft. From here, the creek flows to the northeast around Bearpaw Mountain before turning to the west and southwest. The channel gradient averages about 5%, although it varies considerably. The headwaters notwithstanding, some of the steepest channel gradients are located upstream of the fan apex where Canyon Creek is confined by steep slopes (Photo 13).

Past disturbances to the watershed include heavy logging, large 200 to 300-year return period stand-replacing fires, and major floods. Timber harvesting has been mostly concentrated at lower elevations adjacent to the mainstem channel and has occurred since the 1950s (nearly all the stands in the western hemlock zone are under 50 years old). Because of the past logging, there is full access to the watershed with a network of roads. The main access road, Road 31, runs to the back end of the watershed. Road 31 is paved up to the lower crossing of Canyon Creek at an elevation of approximately 2,100 ft (Figure 2-1). The only other significant crossing of Canyon Creek is Road 3160, which provides access to the Whistler Creek subdrainage.

The watershed is prone to a variety of geomorphic processes including shallow debris avalanches, rock falls, earth flows, avalanches, and debris flows. Historic forestry practices in particular have contributed to increased incidences of shallow debris avalanches and debris flows in the past two decades.

The Glacier Springs Subdivision is situated on the fan of Canyon Creek. While many of the lots on the fan remain undeveloped, more than 40 houses have been constructed.

GEOLOGY

Canyon Creek lies within a complex of faulted and imbricated crustal plates. Most of the rocks were formed several hundred million years ago and were accreted to the continental margin commencing about 100 million years ago. During accretion and translation, the rocks were metamorphosed, deformed, and faulted (Brown, 1987).

The Jurassic-Cretaceous (190-135 million years) Nooksack Group underlies much of the headwaters of Canyon Creek and part of the east and southeast flanks of Bald Mountain and northwest flank of Church Mountain. To the east, these rocks consist of argillite and siltstone formed in a submarine fan associated with an island arc (Jones, 1984). Exposures further west consist of ultramafic and serpentinized rock.

Mid to upper portions of the watershed are dominated by the Silurian-Permian (430-223 million years) Chilliwack Group. These rocks are exposed in most of the area surrounding Kidney Creek, Church Mountain, Whistler Creek and the north side of the valley to the ridge top. The group consists of basalt, andesite, dacite, volcanic breccia and tuff, and basaltic greenstone. Jones (1984) has interpreted these exposures as forming in an oceanic island arc environment. The Nooksack Group was overthrust by the Chilliwack Group during the late Cretaceous giving rise to seemingly discontinuous exposures (Brown, 1987). Downstream of Kidney Creek, bedrock consists predominantly of the Eocene Chuckanut Formation (sandstone).

GEOMORPHOLOGY

The Canyon Creek watershed was glaciated by alpine glaciers and the continental ice sheet from about 18,000 to 12,000 years ago. During this period, till was deposited throughout the watershed forming particularly thick deposits on the valley bottom. As the glaciers retreated, colluvial deposits formed on the steeper slopes and the valley bottom deposits were reworked into outwash sands and gravels.

Below Kidney Creek, Canyon Creek is generally well confined by steeper bedrock slopes and there are no significant outwash or till deposits on the valley floor (Figure 2-1). Further upstream however, the mainstem channel is characterized by discontinuous terraces that are up to 100 ft (30 m) thick. Figure 2 of Ballerini (1993) shows the typical stratigraphy of terraces in the vicinity of Whistler Creek. Here, 50 to 60 ft (15 to 18 m) of reworked till and colluvium overlies up to 3 ft (1.0 m) of thinly laminated to massive glaciolacustrine deposits, and till extends 5 to 10 ft (1.5 to 3.0 m) above the channel. In many places, the glaciolacustrine deposits contain dropstones with impact-contorted laminae. The glaciolacustrine silt and sand deposits indicate that a temporary ice-dammed lake formed in mid to upper reaches of the watershed at the onset of deglaciation.

LOGGING

The following discussion on logging is derived from the pilot watershed analysis completed by the Forest Service in 1995. The numbers quoted refer to logging within the National Forest only and do not refer to private holdings unless specifically referred to.

Some early logging occurred in Canyon Creek around 1910 and by 1940 the entire fan had been logged. However, it wasn't until the 1950s that significant levels of logging began in the watershed. Logging at this time extended up the watershed nearly to the confluence of Whistler Creek. Harvesting occurred primarily within a half mile of the main road and has been estimated at about 600 acres (3% of the watershed).

During the 1960s, there was a major increase in logging as the main road was extended to the upper end of Canyon Creek. In addition, Road 3140 was built extending into the northwestern part of the watershed, to the west of Bald Mountain and over the watershed divided into the Chilliwack watershed to the north (Figure 2-1). Another road (3130) was extended up the Kidney Creek drainage and a third system (3160) was built partway up the east side of the Whistler Creek drainage. Logging during this period was about 3,000 acres or 15% of the watershed. Again most of the harvesting occurred adjacent to the main roads, presumably via a network of skid roads.

Some extensions to the road system were constructed during the 1970s, but most of the road network was in place. Logging during the decade dropped off significantly (1000 acres) but still accounted for 5% of the watershed. Logging in the 1980's was similar to early harvesting with a total of about 600 acres. Due to concerns over increased slope instabilities associated with poor forestry practices and depressed spring Chinook runs, logging on national forest lands within the Canyon Creek watershed was halted in 1986. No logging has since taken place although private lands are still being intermittently logged. In the last decade, the watershed has primarily been used for recreational purposes including hiking, camping, fishing, and snowmobiling.

To date, approximately 5,200 acres of national forest land has been harvested in the watershed (26%), along with most of the 2,700 acres of State and private land (14%).

CREEK CHANNEL CHARACTERISTICS

This section should be read in conjunction with the geomorphic map of Figure 2-1 and the channel profile (Figure C-1). A description of the mainstem channel only extends as far upstream as Whistler Creek (approximately mile 8). Reaches further upstream were not impacted by the 1989 flood.

From just upstream of Whistler Creek to the confluence with the North Fork Nooksack River, Canyon Creek has been subdivided into 13 reaches. Table C-1 gives a brief description of each of these reaches. Reaches immediately upstream of Whistler Creek are within the upper limits of the rain on snow zone.

Table C-1
Channel Description of Canyon Creek

Reach	mile		slope (%)	width (ft)	Description
	start	finish			
1	0.0	0.7	2.5	200 to 500	Reach 1 is the fan reach of Canyon Creek. A complete description of the fan is given in Section 2.1. While the creek is about 40 ft wide at low to moderate flows, the active channel is 200 to 500 ft wide.
2	0.7	1.4	4.2	80	Upslope of the fan apex Canyon Creek is well confined in a bedrock canyon. Here the channel is bounded by steep sideslopes (> 70% gradient) that consist of a veneer of colluvium and exposed bedrock. At the mid-point of this reach, the creek flows through two tight meanders. The creek is less confined on the inside bend of both meanders with a floodplain area comparable in width to the channel.
3	1.4	1.9	7.2	65	Further upstream Canyon Creek remains confined by very steep sideslopes and the channel narrows. This reach is characterized by a steep channel gradient and the substrate consists predominantly of boulders with occasional bedrock outcrops.
4	1.9	2.8	6.9	80	Similar to Reach 3 but the channel is slightly wider (Photos 14 and 15). The scars of a number (> 7) of debris avalanches (typically < 1000 yd^3) are visible on the steep sideslopes. Most of the slides initiated on the left-side of the valley.
5	2.8	3.2	5.4	200 to 300	Reach 5 is wider depositional reach situated between two confined reaches. While the mainstem channel is several tens of feet wide, the valley floor is 200 to 300 ft wide. The 1989 debris flood inundated the valley width, stripping all existing vegetation, and creating an active channel up to 300 ft wide.
6	3.2	3.5	7.6	60 to 80	Canyon Creek is confined by the Jim Creek Slide on the left bank and the Bald Mountain Slide on the right bank. Both earthflows show evidence of ongoing slow creep. Erosion at the toe of both slides is probably a significant sediment source to downstream reaches.
7	3.5	3.9	10.4	60	Location is upstream of the Jim Creek Earthflow with portions of the Bald Mountain Earthflow on the right bank. Here, channel gradients increase to an average of over 10% and the creek is confined by steep sideslopes. At the upstream end of this reach, a falls (> 5 ft) prevents further upstream migration by all anadromous fish.
8	3.9	5.2	2.4	100 to 300	Above the falls, channel gradients are gentle (2.4%) and Canyon Creek meanders over a valley floor that is up to 300 ft wide. Sideslopes generally have gentle to moderate gradients (30 to 50%), particularly on the left bank. The upstream end of the reach is defined by the lower road crossing of Canyon Creek (Road 31) and the confluence with Kidney Creek. The channel substrate consists of gravels and cobbles.

Reach	mile		slope (%)	width (ft)	Description
	start	finish			
9	5.2	6.3	3.9	50 to 125	In general, Canyon Creek is well confined through this reach with channel widths of between 50 and 75 feet. Occasional wider sections do occur. Sideslopes are moderate to moderately steep (40 to 70%) and a number of debris avalanche and debris flow scars are visible on 2001 aerial photographs. Most of these slides initiated on the left side of the valley. The creek cuts through discontinuous terrace deposits in this reach. The terraces are probably composed of till and outwash deposits (see Geomorphology).
10	6.3	6.4	5.0	50	A short steep reach where the creek is confined by moderate (right bank) to moderately steep (left bank) sideslopes.
11	6.4	6.9	3.2	75 to 200	Similar to other wider reaches where the creek channel is several tens of feet wide by the valley floor is considerably wider. During the 1989 event, general bed scour and deposition occurred over the full valley width.
12	6.9	7.05	5.0	65	A short steep reach separating two depositional reaches.
13	7.05	7.9	2.8	125 to 300	Very similar to Reach 11. Sideslopes are generally moderate with some steeper sections. Road 3160 crosses the reach near its upper extent. Both this reach and Reach 11 are characterized by discontinuous terraces up to 100 ft in height.

LANDSLIDES

Slope instabilities, largely associated with logging, have had significant impacts on sediment delivery to the mainstem channel in the last several decades. The increased sediment supply to Canyon Creek is of significant concern because:

- The watershed is utilized by spring chinook, coho, chum, and pink salmon and steelhead trout. Increased sedimentation reduces channel stability and can increase the amount of fines on the channel substrate, both of which can have negative impacts on spawning success.

- Increased sediment supply to a channel that is prone to debris flows or debris floods, such as Canyon Creek, can increase the potential or magnitude of such creek events.

Landslide due to Forestry Activities

In response to depressed Chinook runs in the early 1980s, several agencies began studying the conditions of fish habitat for streams in the Pacific Northwest. For the Canyon Creek watershed, a landslide inventory was completed by Peak Northwest Inc. (Peak) in 1986. This study included four other watersheds within the Nooksack River Basin and was conducted for the Lummi Tribal Fisheries Department and Washington State Department of Ecology. Using aerial photohraphs dating back to 1940, the Peak study identified 111 landslides totalling 4.6 million yd^3 and they concluded that about half that amount reached the mainstem channel. Landslide types identified by the study include debris flows, debris slides, earthflows, streambank instability, and rotational slides. Of the 111 landslides, 25 were identified as earthflows by Peak. An earthflow is defined as a rapid or slower, intermittent flow-like movement of plastic, clayey earth (Hungr et al., 2001), a process which can only be attributed to two landslides in the Canyon Creek watershed. This suggests that Peak has misclassified these 25 slides, which are more likely debris flows or debris avalanches[1] that are greater than a few feet in depth.

A more recent landslide inventory was completed by Hale and Nichols (1994) for the USFS. In this study, a total of 99 landslides were identified. A majority of these slides occurred in the 1970s and early 1980s, and all but 5 were associated with forestry (within clearcuts or road prisms).

While the results of the two studies are not entirely consistent, the same general trends are observed:

- about 50% of the sediment associated with the landslides was deposited in the mainstem channel of Canyon Creek;
- a majority of the landslides (~ 90%) are associated with roads (Photo 25) and clearcuts; and
- a majority of the landslides are debris flows or debris avalanches that predominantly occurred in the 1970s, and early 1980s.

The high incidence of landslides from the late 1960s through the early 1980s is not surprising given the amount of logging in the watershed and the forestry practices used during this time. Debris avalanches or debris flows initiating on the downslope side of forestry roads are a common legacy in the Pacific Northwest due to either oversteepened fill slopes, plugged or failed drainage structures, or redirected drainage concentrating on steep slopes (Megahan and Kidd, 1972; Swanston and Swanson, 1986; Montgomery, 1994). Within clearcuts, debris avalanches typically occur 7 to 15 years after logging due to the loss of root cohesion and associated shear strength in the surrounding soils (O'Loughlin, 1974; Wu et al., 1978). Because logging was greatest in the 1960s, the expected response in clearcuts would be in the late 1960s through early 1980s (as observed). Revised forestry practices in the last decade have significantly reduced the incidence of road-related and clearcut landslides, although road drainage management continues to be a problem.

Appendix D provides a figure example of the impact of logging on the landscape of Canyon Creek.

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[1] Debris avalanche is the preferred term for debris slide and is defined as a very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel (Hungr et al., 2001).

Jim Creek Earthflow and Bald Mountain Earthflow

Two large earthflows are located in the Canyon Creek watershed. The existence of these earthflows is important to estimate outbreak flood magnitude from temporary creek blockages. For this reason, the two earthflows will be discussed here in some detail.

While a majority of landslides in the Canyon Creek watershed are associated with forestry, two large landslides situated at about mile 3.5 are natural mass movement processes. The landslides, referred to as the Jim Creek Slide (JCS) and Bald Mountain Slide (BMS), are situated on opposite sides of the valley with the JCS being drained by Jim Creek, a second order tributary watershed. A high-angle fault, the Jim Creek Fault Zone, trends northwest through the two slides (Jones, 1984; Brown, 1987).

The two landslides have previously been classified as translational/rotational slides by Peak Northwest (1986) and Hale and Nichols (1994). However, the creeping movement of high viscosity, clay rich materials as well as the surface morphology showing extensional ridges in the upper watersheds and some compressional ridges and furrows in the lower reaches indicate that the observed landslides are more correctly classified as earthflows. The two earthflows probably provide a significant proportion of naturally derived sediment to Canyon Creek. The slides are also a potential site for landslide dams as described in Appendix G. Slumps, vertical offsets, and steep scarp faces outline the boundaries of the two earthflows. Both slides extend a considerable distance upslope (Photos 16 and 17).

Earthflow origin and movement are highly associated with local sedimentary strata and bedrock geology. Bedrock in the area consists of Eocene Chuckanut Formation (fluvial sandstone), Pennsylvanian Elbow Lake Formation (chert and basalt), and Devonian – Permian sedimentary rocks of the Chilliwack Group (Jones, 1984; Brown, 1987). Exposed bedrock at the toe of the JCS exhibits slickenslides on Chuckanut sandstone blocks and serpentinized Elbow Lake Formation basalt block faces, as well as basalt altered to talc.

Ballerini (1993a) describes the JCS as consisting of a dormant portion roughly upslope of Road 31 and an active, wedge-shaped secondary slide moving downslope in a northwest direction within the major dormant slide. The toe scarp of the JCS is characterized by slide material (coarse angular fragments within a fine matrix) overlying highly fractured and sheared bedrock of the Chuckanut and Elbow Lake Formations (Photo 18). The toe scarp of the JCS is steep (70 to 80% slope gradients) and is about 1300 ft (400 m) wide and 180 ft (55 m) high. The present configuration of the toe scarp is two exposed portions separated by a narrow ridge.

As illustrated by Photos 18 and 19, the toe scarp of the BMS is not as high as the JCS. Nonetheless, bent and centre-cracked trees and tension cracks on the lower 100 m of the earthflow indicate the BMS is active (Photos 20 and 21). Continuing undercutting of the earthflow toe in combination with high pore water pressure within the earthflow creates complex rotational retrogressive failures that may creep or detach suddenly.

Grain Size Analysis

Slide material exposed at the toe of the BMS was sampled by KWL in 2002. The particle size distribution of this matrix sample is:

- coarse gravel (19 to 75 mm) – 2.4%;
- fine gravel (2 to 19 mm) – 43.3%;
- sand (0.075 to 2 mm) – 32.1%;
- silt (0.002 to 0.075 mm) – 10.2%; and
- clay (< 0.002 mm) – 12.0 %.

A high fraction of clay and silt is typical for earthflows and explain their mobility (VanDine, 1980; Bovis, 1985). Slow moving earthflows are common in the western part of the Interior Plateau of British Columbia and Washington, but rare in the wet coastal belt to which the Canyon Creek drainage belongs where the unique combination of lithological and structural geology conditions is responsible for earthflow development.

Earthflow Age

The toe scarps of both earthflows are evident in aerial photographs dating back to 1940 and it is probable that both date to deglaciation of the area about 11,000 years BP. Of interest is an exposure near the base of the JCS where the slide material overlies bedrock. Several metres above this interface a well-defined one to two meter thick layer characterized by a high density of organic material daylights on the slope (Photo 22). The configurations of the logs indicate that the unit was over-ridden by the JCS. Three of the exposed logs were sampled and yielded ^{14}C dates of 5,790 years, 6,580 years, and 6,510 years BP.

Approximately 6,000 years ago was the time when climate in the Pacific Northwest was in transition from the warmer, drier part of the Holocene to the cooler, wetter Neoglacial interval. This period showed glacial expansions in the southern Coast Mountains (the 'Garibaldi advance' of Ryder and Thomson, 1986). An early Neoglacial advance was also dated on Dome Peak in northern Washington which took place shortly after 5,000 years ago (Miller, 1969). Widespread development of small lakes and peatlands between 7,000 years and 5,000 years ago in the region suggests moister conditions during that period (White and Mathews, 1986; MacDonald, 1987). It is highly possible that the earthflows responded to an increase in moisture during this climatic transition, resulting in a rapid advance. Similar observations were made on a comprehensive study of earthflows in the western Interior of British Columbia where vigorous earthflow activity has commenced following a warm and dry Altithermal period which ended some 6,500 years ago (Bovis, 1985; Bovis and Jones, 1992).

Movement Rates

More recent movement rates of the Jim Creek earthflow have been estimated by Ballerini (1993b) using an analytical stereoplotter. Ballerini measured the offset of Road 31 and changes in the toe scarp topography from 1972, 1983, 1985, and 1991 aerial photographs. At Road 31, movement rates for the JCS were as follows:

Table C-2
Movement of the Jim Creek Earthflow at Road 31

Year	1956 – 1972	1972 - 1983	1983 - 1985	1985 – 1991	Total
Horizontal (ft)	< 0.1	4.8	2.7	14.5	22.0
Vertical (ft)	0.0	5.3	3.4	16.1	24.8
Net (ft)	0.0	6.8	5.1	21.6	33.1

[1] Data extending back to 1956 was obtained from Roger Nichols of the USFS, Mt. Baker Ranger District and crude measurements from 1956 aerial photographs (aerial photographs prior to 1972 were not of sufficient quality to use with the stereoplotter).

Further downslope, the lateral and vertical movement of Canyon Creek was measured along the left-bank at four cross-section locations:

Table C-3
Lateral and Vertical Movement of Canyon Creek Between 1972 and 1991

Year	1972 – 1983		1983 – 1985		1985 – 1991		Net (1972 – 1991)	
	lateral (ft)	vertical (ft)	lateral (ft)	vertical (ft)	lateral (ft)	vertical (ft)	lateral (ft)	vertical (ft)
A – A’	+4.4	+2.7	+3.7	-10.1	+63.4	+0.5	+71.4	-6.9
B – B’	-23.8	+2.7	-14.8	-7.6	-73.3	+0.8	-112.0	-4.2
C – C’	-31.1	+1.1	-26.5	-8.8	+95.6	-2.9	+38.0	-10.6
D – D’	-68.2	-0.6	+1.6	-6.6	-46.2	-10.8	-112.8	-18.0

A negative number indicates lateral movement of the stream channel from sections (with possible encroachment) and a positive number indicates that Canyon Creek is displaced away from the toe scarp (for lateral movement).

The measurements by Ballerini clearly indicate renewed activation of the Jim Creek Earthflow with a 350% increase in the average annual movement rate over a 19-year period. Using the offset measured at Road 31 and measured scarp-face retreat, Ballerini (1993b) estimated that the total volume of sediment contributed to Canyon Creek from the earthflow was 775,000 yd^3 between 1983 and 1991. Unfortunately, shadows on the 1972 aerial photographs obscure the scarp face and the volume contribution calculations can not be extended past 1983.

Movement rates of earthflows are associated with prolonged periods of above-normal precipitation. The effects of such increases may be delayed by several years (Bovis, 1985). Figure F-3 shows long term changes in streamflow for the North Fork Nooksack

River near Glacier. Streamflow, rather than rainfall, presents a better representation of overall changes in available soil moisture because it includes the effects of snowmelt. Figure F-3 demonstrates that streamflow maxima have increased since 1978 with a maximum increasing rate in cumulative departure from the mean between 1987 and 1990. This trend suggests an increase in available moisture, which may have accelerated earthflow movement during this period.

Movement Trigger Mechanisms

Another important variable is undercutting of the toe scarps by the streamflow of Canyon Creek. As soon as either earthflow begins to accelerate or discharges a larger failure into Canyon Creek, the opposite earthflow will be undercut at a much faster rate since Canyon Creek is now diverted against the toe of the opposite earthflow. For this reason, a sew-saw pattern of earthflow activity can be expected in the future.

It has been noted that the boulder deflectors placed at the toe of the Jim Creek Earthflow may have constricted the channel and moved high flows against the right side. Exacerbation of bank erosion at the toe slope of the Bald Mountain Earthflow was reportedly raised as a concern when the deflectors were placed (J. Thompson, pers. comm.). While the deflectors may have had this effect, it would be extremely difficult to quantify. Also, increased movement of the Bald Mountain Earthflow would probably shift the focus of toe scarp undercutting to the opposite bank, similar to the natural expected cycle. As such, this potential impact does not appear to be of sufficient concern to consider removal or modification of the existing structures.

Reasons for concern may be created when a period of abnormally wet weather persists over several months exceeding the conditions encountered in the late 1980s. In this case, an initial failure of one of the two earthflows could cause accelerated undercutting of the other earthflow which may lead to the exceedance of an internal threshold, which in turn could lead to rapid acceleration of the entire earthflow mass or large portions thereof. This process has been described in detail at the Thistle earthflow in Utah in 1983 by Kaliser and Fleming (1986). For this reason, it is recommended that both earthflows be monitored regularly to detect any changes in movement rates that may lead to extended damming of Canyon Creek.

A final trigger mechanism for the earthflows is an earthquake which is discussed below.

Seismic Influence

The geologic setting for earthquakes in the Pacific Northwest is oceanic crust of the Juan de Fuca plate descending eastward beneath low density continental crust of North America at the Cascadia subduction zone. The subduction zone is a 1,000 km long area of plate convergence and subduction that extends from British Columbia to northern California. In this geologic setting, three types of earthquakes are observed:

1. Over the last 40 years, about 90% of the small earthquakes in southwestern British Columbia and northern Washington have occurred in the continental crust of the North American plate (Rogers, 1998). There have been three major crustal earthquakes affecting the region in historical time, in 1918 (M = 7) and 1946 (M = 7.3) on Vancouver Island (Mathews, 1979), and in 1872 in northern Washington State (Malone and Bor, 1978). Interestingly, all three of these earthquakes occurred away from the Puget Sound lowland, which is the most intense region of seismicity today (Rogers, 1998). There is also good geological evidence that a large shallow earthquake occurred in central Puget Sound, near Seattle, about 1100 years ago (Atwater and Moore, 1992; Bucknam et al., 1992). This earthquake may have originated from the Seattle fault and resulted in tsunamis, landslides and areas of both uplift and subsidence.

2. Subcrustal earthquakes can occur within the subducting Juan de Fuca plate, although the maximum earthquake size is constrained to about a magnitude of 7 (Rogers, 1998). Earthquakes in this region are concentrated below the Strait of Georgia and Puget Sound and occur at depths of 45 to 65 km. Subcrustal earthquakes in 1949 (M = 7.1) and 1965 (M = 6.5) at the south end of Puget Sound caused considerable damage and initiated numerous landslides (Chleborad and Schuster, 1998). The 2001 Seattle earthquake was also a subcrustal earthquake with a magnitude of 6.8 (Clague, 2002).

3. The last type of damaging earthquake occurs along the thrust fault separating the North American and Juan de Fuca plates (plate-boundary or subduction earthquakes). Earthquakes along this boundary occur due to accumulated elastic strain along a locked zone, which tends to release catastrophically. The locked zone is located offshore, about 100 to 200 km away from Seattle, Vancouver and other coastal cities in the Pacific Northwest (Clague, 2002). Based on geophysical evidence, it is estimated that subduction earthquakes in the Pacific Northwest could have a magnitude between 8 and 9 (Heaton and Kanamori, 1984). There is also abundant geologic evidence that such damaging earthquakes have occurred repeatedly in the past, the last on January 26, 1700. Geologic evidence includes tsunami sand layers mantling buried soils and buried peat layers that indicate rapid subsidence. Geologic evidence associated with the 1700 earthquake has been found in coastal areas of Washington (Atwater, 1987; Atwater and Yamaguchi, 1991; Nelson et al., 1995), British Columbia (Clague and Bobrowskly, 1994; Benson et al., 1997) and Oregon (Darienzo et al., 1994).

   The average return period of subduction earthquakes in the Pacific Northwest has been estimated at 500 years (Atwater and Hemphill-Haley, 1997). This return period is based on a study of buried peats at estuaries in southwest Washington that record seven earthquakes in the last 3,500 years.

Of the three earthquake types, subduction and subcrustal earthquakes probably have the least potential to initiate movement of the earthflows. Subduction earthquakes occur off the outer coast and may be too far removed (> 200 km) to have a significant seismic influence at Canyon Creek. However, a large subduction earthquake has not occurred in the region within historical time. Subcrustal earthquakes are also probably too far removed, being concentrated below the Strait of Georgia and Puget Sound. Most of the significant landslides associated with the 1949 and 1964 subcrustal earthquakes occurred within King County, with none reported in northern Whatcom County (Chleborad and Schuster, 1998).

On the other hand, earthquakes within the North American plate could initiate landslides in the vicinity of Canyon Creek. For example, the 1946 Vancouver Island earthquake triggered more than 300 landslides over an area of about 20,000 km^2 (Mathews, 1979). Most of these landslides were rock falls and small debris slides. Similar slope failures can be expected at Canyon Creek should a large earthquake strike close to Glacier.

Comprehensive reviews of landslides initiated by earthquakes have been provided by Keefer (1984, 1999). Keefer (1984) has found that the areal extent of landsliding increases from 0 for a magnitude 3-4 quake to 500,000 km^2 for a magnitude 9 event. Unfortunately, there are few case studies of earthflows initiated by earthquakes. The largest earthflow generated by a recent earthquake occurred in the Republic of Georgia in 1991 (M = 7.1). This earthflow consisted of many blocks that moved independently over distances of less than 20 m (Jibson et al., 1994).

For a crustal earthquake to initiate significant movement of the Canyon Creek earthflows, at least three conditions must be met:

- the earthquake is of sufficient magnitude (probably M > 6.5) to cause significant landsliding over a wide area;
- the earthquake occurs within the vicinity of Canyon Creek, perhaps causing movement along the Jim Creek fault zone; and
- the earthflows have sufficiently high pore water pressures (i.e. antecedent precipitation) that the ground shaking induces internal deformation.

Given the available evidence, the probability of these conditions being met at Canyon Creek may lie within a 500-year return period. However, it is very difficult to quantify because of the censored data record and the lack of knowledge of moisture conditions and the necessary earthquake magnitude to initiate an earthflow.

R:\2039-001\misc\slope.xls

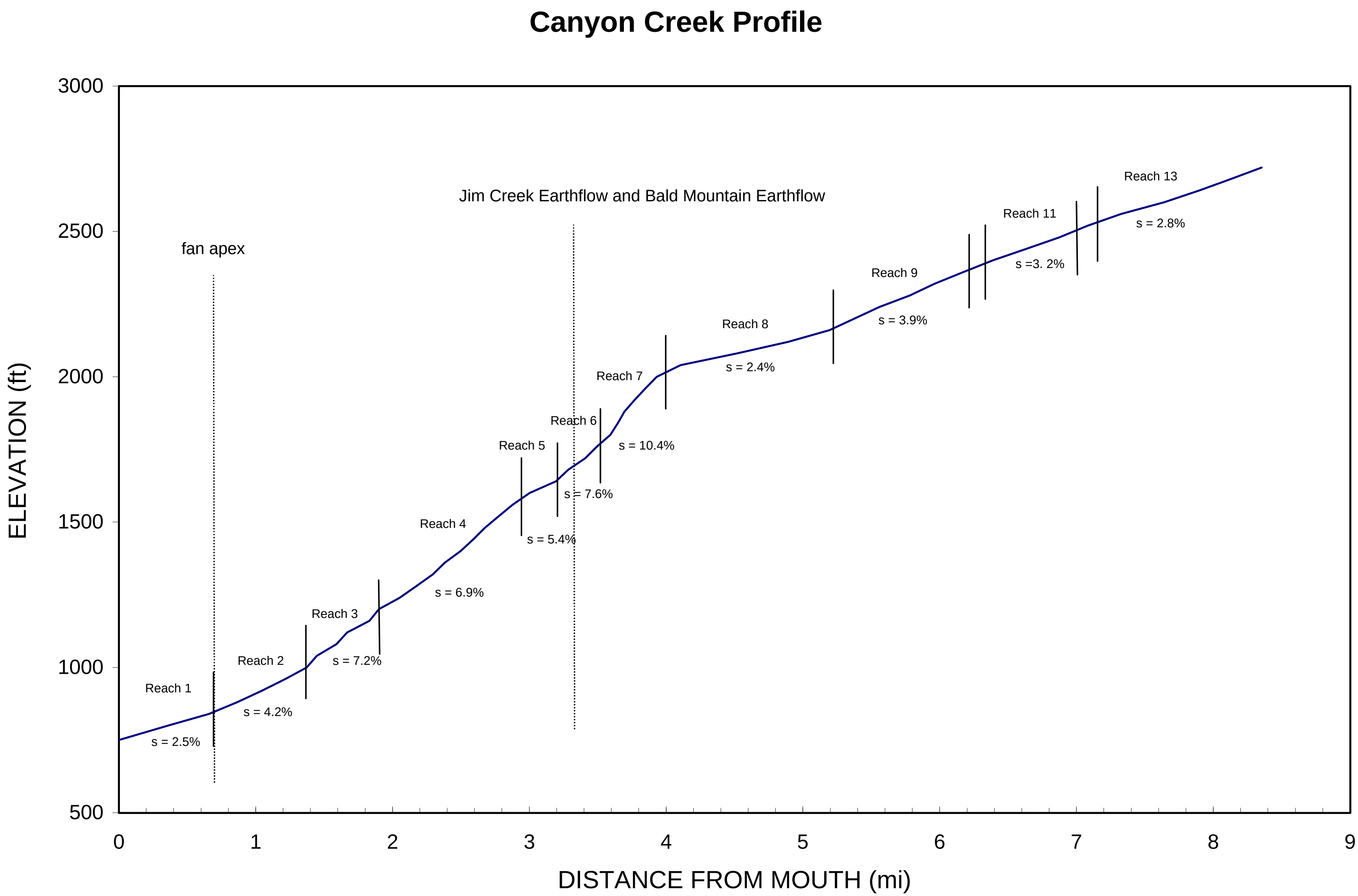

Figure C-1

Appendix D

Aerial Photograph Analysis

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Appendix D

Aerial Photograph Analysis

This section provides a list of aerial photographs that were reviewed by KWL for the study. A short summary is also provided on the visible effects of past logging and the 1989 debris flood on the landscape.

Table D-1 is a complete list of aerial photographs that were used for the analysis.

Table D-1
Canyon Creek Historic Aerial Photographs

Year	Date	Source	Scale	Project	Roll	Photo #	Notes
2001	Sept 10	DNR	1:12,000	NW-C-01	73-58 71-59 71-60 71-61 71-63	217, 218 168 – 170 61 – 63 83 – 85 113 – 115	
1991	July 22	USDA – FS	1:16,000	12 616050C	691 691 691 391 391 391 391	210 – 212 138 – 140 122 – 124 76, 77 65 – 67 124, 125 110 – 112	
1989	Sept 6	USDA – FS	1:40,000	40 616050B	389 389 1189	152 – 154 156 – 159 60 - 63	
1986	Aug 2	USDA – FS		616050A	2783 2683 2683 2583 2583	67 – 69 175 – 177 162 – 164 26 – 28 15, 16	no photos below the Jim Creek Slide
1979	Aug 12	USDA	1:24,000		1479	123, 124 116 – 118 203, 204 210, 211	photos of upper watershed only
1972	July 27, Aug 27	USDA	1:16,000	EXQ	1 6 6 6 6	122, 123 133 – 135 74 – 76 64 – 66 46, 47	
1964	July 12	USDA	1:12,000	EMM	4 4 5 5 7	196, 198 221 – 223 26 – 28 37 – 39 19 - 21	no coverage of fan area
1956	Aug 20	USDA	1:16,000	EBK	6 5 5 6	164, 165 203 – 205 84 – 85 172 - 175	

1947		USGS	1:28,000		43 44 45	161 – 163 122, 123 18 - 20	
1940	Sept 21	USGS	1:26,000		2 3 5 7	93, 94 105 – 107 186, 187 245 - 247	
DNR – Washington State Department of Natural Resources USDA FS – United States Department of Agriculture Forest Service USGS – United States Geological Survey							

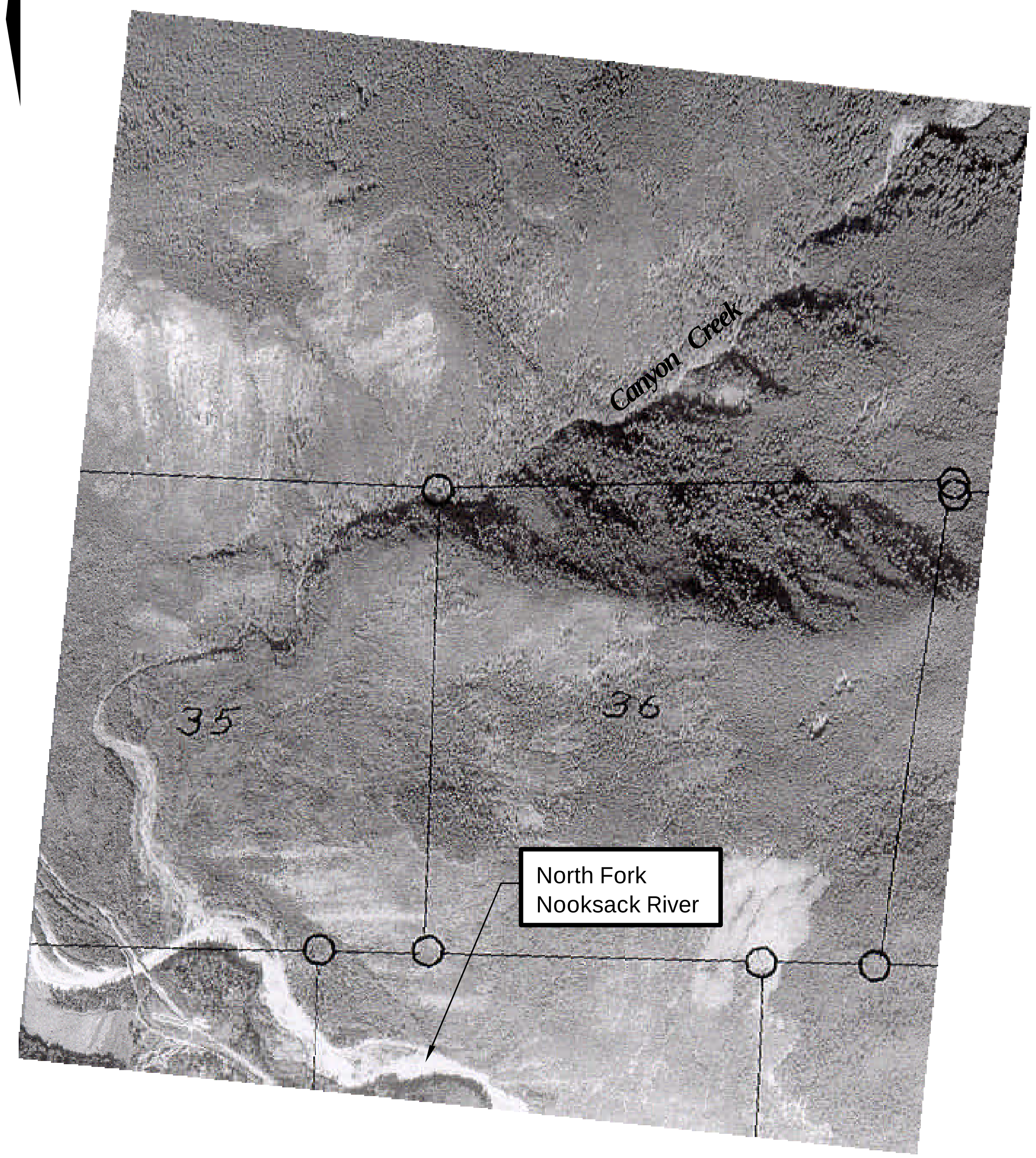
The most striking feature on the aerial photographs used for the analysis are the consequences of intensive logging activities in the 1960s through early 1980s. Numerous debris avalanches and debris flows were triggered in clearcuts and from redirected drainage and sidecast failures on poorly constructed logging roads. A high percentage of these landslides travelled to Canyon Creek elevating the natural levels of sediment input by several orders of magnitude (a more detailed account is given in Appendix C).

Another striking feature is a comparison of aerial photographs taken in 1989 (before the debris flood) and 1991. The 1989 debris flood clearly shows up on 1991 aerial photographs as the mainstem channel was significantly widened in mid to upper reaches. High water marks along the channel indicate that the debris flood evidenced on the fan was initiated downstream of Kidney Creek (Appendix E). However, upstream reaches were also obviously impacted by high water flows due to significant channel widening observed between Whistler Creek and Kidney Creek.

Figures D-1 and D-2 compare aerial photographs taken in 1940 and 1991 for lower to mid reaches of the watershed. The aerial photographs extend from the confluence with the North Fork Nooksack River as far upstream as Whistler Creek. While the scale of the aerial photographs is not sufficient to delineate small-scale features, slope instabilities associated with logging and a significantly wider mainstem channel are obvious when comparing the watershed to its pre-disturbance condition in 1940.

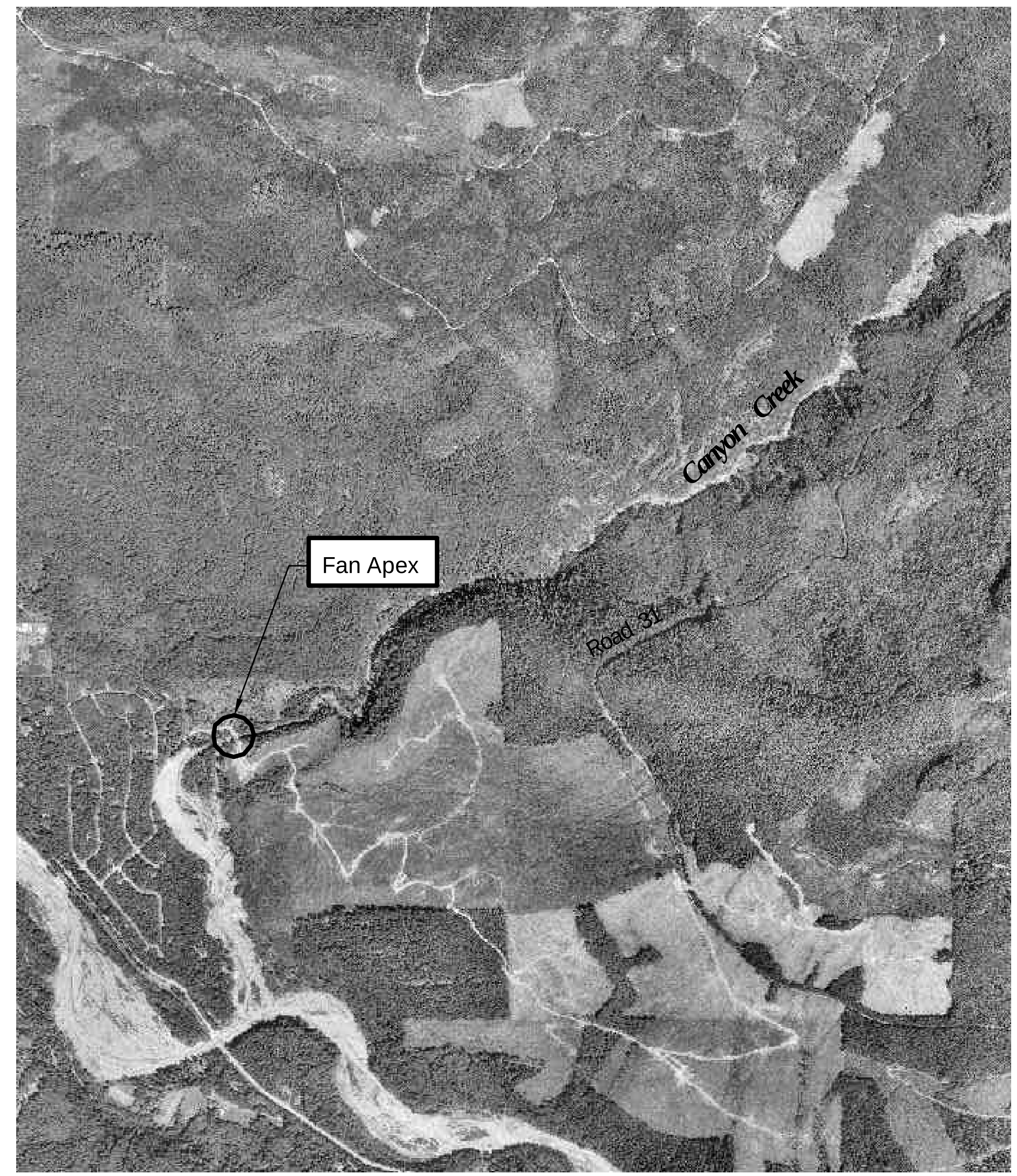
Canyon Creek Alluvial
Fan Risk Assessment
Whatcom County Flood Control
Zone District

1940



Baseplan Source: USGS aerial photograph of Sept 21, 1940

1991



Baseplan Source: USDA Forest Service aerial photograph of July 22, 1991

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0.4 0 0.4
Approx. Scale in Miles

Project No.	Date
2039.001	September 2003

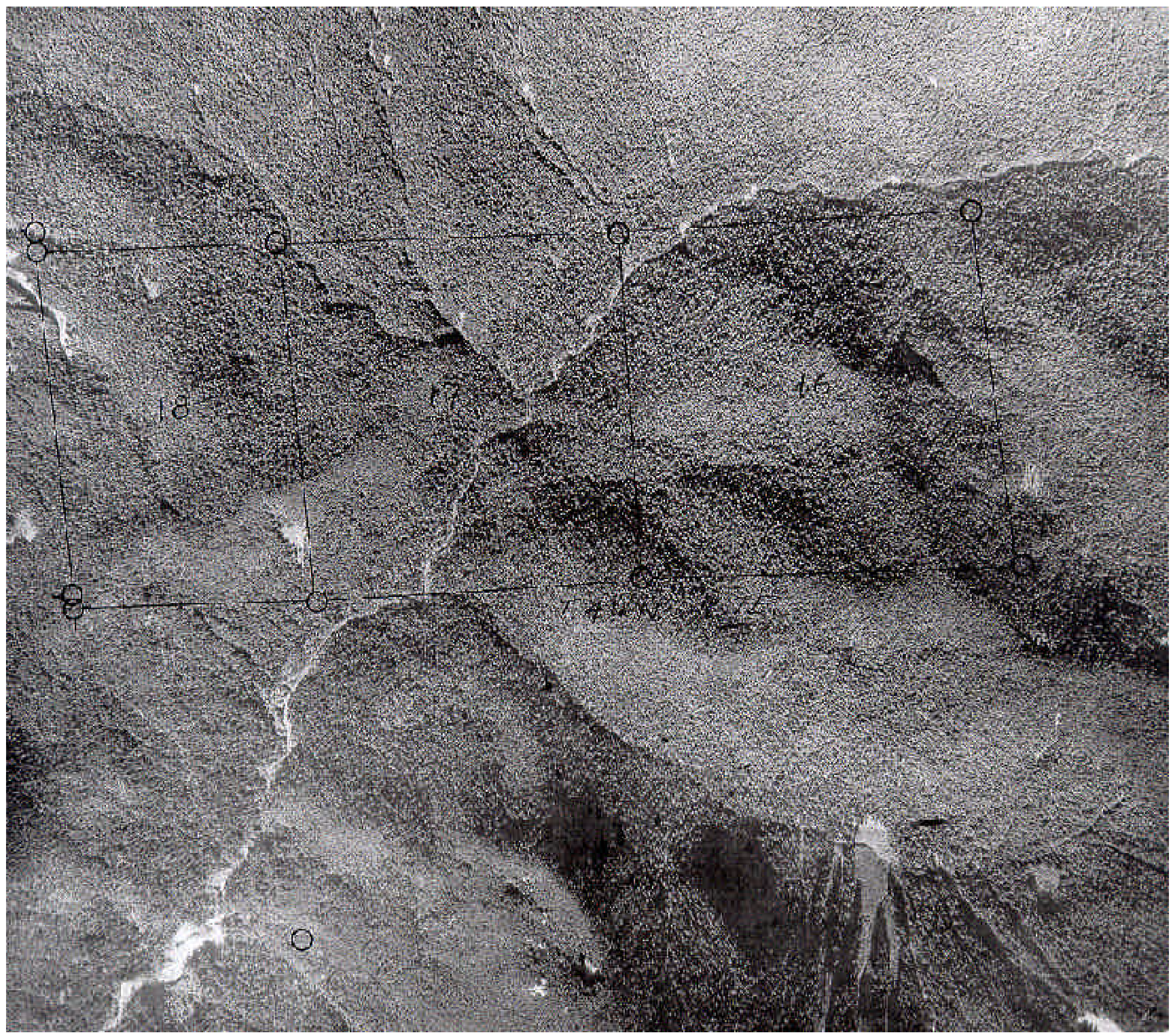
Aerial Photograph Comparison of Lower Canyon Creek - 1940 and 1991

Figure D-1

Sep.24/03

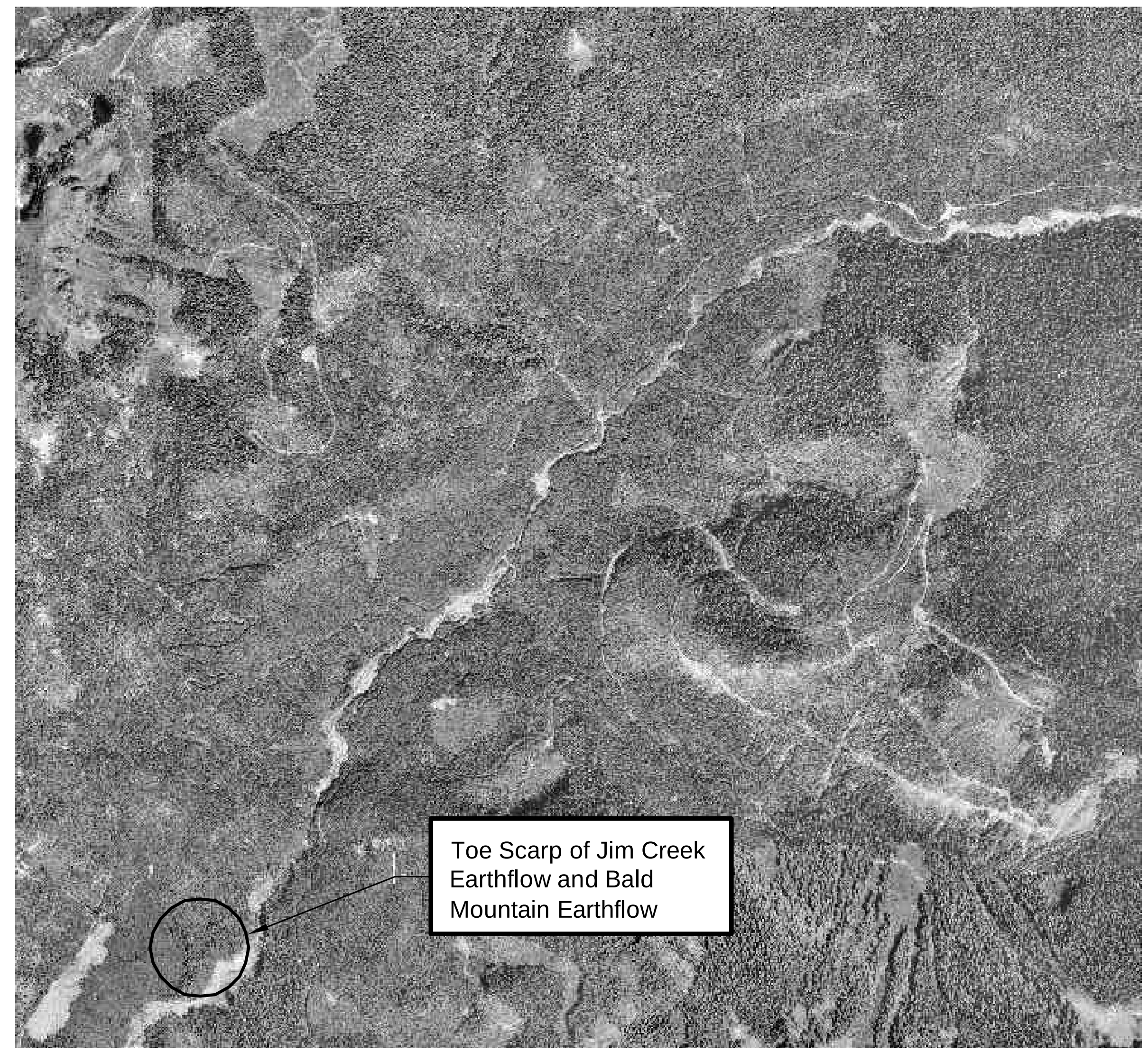
2039-001\Drawings\2039001StFigD1.DWG

1940



Baseplan Source: USGS aerial photograph of Sept 21, 1940

1991



Baseplan Source: USDA Forest Service aerial photograph of July 22, 1991

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

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0.5 0 0.5
Approx. Scale in Miles

Project No.	Date
2039.001	September 2003

Aerial Photograph Comparison of Mid Canyon Creek - 1940 and 1991

Figure D-2

Sep.24/03

2039-001\Drawings\2039001StFigD2.DWG

Appendix E

Environmental Resource Values

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Appendix E

Environmental Resource Values

The following is a summary of fish habitat in Canyon Creek. All of the information has been gathered from the Canyon Creek Pilot Watershed Analysis completed by the USDA Forest Service in 1995.

SPECIES OCCURRENCE

The mainstem channel of Canyon Creek is over 17 miles long but anadromous fish are restricted to the lower 3.9 miles due to the presence of a falls. The lower section of the creek has been utilized by spring chinook, coho, chum, and pink salmon and steelhead trout. While these species are known to occur, there have been limited surveys completed to establish accurate fish populations. Table E-1 summarizes adult fish escapement surveys completed between 1961 and 1989 by federal, state and tribal biologists.

Table E-1
Anadromous Fish Escapement Counts for Canyon Creek

Species	1961	1963	1969	1979	1981	1983	1985	1987	1989
Pink	292	3,400	14	782	50	45	28	194	1,700
Chinook	10	-	-	4	208	1	6	6	8

The above data suggest that Canyon Creek is not a highly productive basin for anadromous fish. In 1981, however, 181 spring chinook were observed in lower Canyon Creek, one of the highest concentrations of chinook spawners observed in the entire Nooksack basin. Since then, the number of spring chinook observed spawning in Canyon Creek has declined and the species has been listed under the Endangered Species Act (ESA). Bull trout have also been listed and reportedly have been observed in lower Canyon Creek.

The trend in coho, chum, and steelhead escapement at Canyon Creek is unknown. Very little data exists because few or no spawning surveys have been conducted at the time of year these species are migrating to Canyon Creek.

Resident fish species found in Canyon Creek include rainbow and cut-throat trout, char, Dolly Varden, mountain whitefish, and several species of sculpin. Brook trout populations were introduced to Canyon Creek during the 1940's and 1950's. Non-native populations of cut-throat and rainbow trout have also been released in the watershed during the past fifty years.

HABITAT CONDITIONS

Habitat conditions in Canyon Creek have been established on the basis of stream surveys in 1989, 1990, and 1992. These surveys were completed by the Forest Service and extended from the creek mouth to the confluence with Whistler Creek. Not surprisingly, the surveys indicate the fish habitat was severely impacted by the 1989 and 1990 debris floods.

Percent Pools and Pool Frequency

Since 1989, the predominant summer low flow habitat has been riffles. In 1989 riffles comprised 43% of the mainstem channel, which had grown to 87% by 1992. Glides declined from 37% to none in 1992, while pool habitat decreased from 18% in 1989 to 12% in 1992. Pool habitat of less than 30% for a stream the size and gradient of Canyon Creek is rated as poor by the Washington State Forest Practices Board (1993).

Pool frequency (expressed as pools per unit length of stream and varying by wetted channel width) in Canyon Creek is also very low. Stream channels in the Pacific Northwest rated with good to excellent pool frequencies for salmon and trout (and having similar channel widths and gradients as Canyon Creek) have channel width/pool ratios of less than 4. Overall pool frequencies for Canyon Creek were as follows: 1989 – 18, 1990 – 11, and 1992 – 21. These values reflect very poor habitat conditions for fish.

Large Woody Debris (LWD)

LWD is an important factor in forming diverse habitat for juvenile and adult salmonids. Woody debris is particularly important in the formation of pool habitat and as high quality overhead cover. Based on a review of undeveloped watersheds in Washington and Oregon, the Forest Service has established a target or standard frequency of 80 LWD pieces per channel mile for the maintenance of good salmon and trout habitat.

A major factor in the low number of pools in Canyon Creek is the lack of LWD. Average LWD pieces/mile was 53 in 1989, 23 in 1990, and 20 in 1992.

Due to extensive logging in the last 40 years that has concentrated on lower side slopes and riparian areas, LWD recruitment to Canyon Creek is also rated as low.

Mass Wasting Impacts

Appendix C provides a thorough summary of the impacts of logging on sediment delivery to the mainstem channel of Canyon Creek. High rates of sediment delivery are an obvious form of disturbance to fish habitat, including the loss of pool habitat.

Appendix F

Hydrologic Analysis

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Appendix F

Hydrologic Analysis

The 1989 event clearly demonstrated that Canyon Creek is susceptible to debris floods. Discharges of debris floods are commonly 2 to 3 times as high as water floods (Jakob and Jordan, 2001). The implication is that peak flow estimates of clearwater floods using frequency analysis are poorly suited for design purposes. However, peak flow estimates for clear water floods are still of interest for Canyon Creek as they provide a useful contrast to the 1989 debris flood. The following sections document the climate and hydrology of Canyon Creek.

CLIMATE

Canyon Creek is located in the Cascade Mountains and is characterized by a temperate marine climate. Peak flows in the area generally occur during the fall and winter when Pacific cyclones cause prolonged, orographically enhanced precipitation. These storms can last for several days and are often the cause of flooding in the Pacific Northwest. The associated flooding can be exacerbated by rapid rises in freezing level associated with warm fronts from the central Pacific, often referred to as the "Pineapple Express". This scenario, where rain falls on wet autumn snow, usually occurs in October to December before the snowpack is of sufficient thickness to absorb much rainfall before releasing it to the underlying ground.

The closest climate stations to Canyon Creek are located at Clearbrook (# 451484) and Glacier Ranger Station (# 453160). A summary of climate data from these stations is as follows:

Table F-1
Summary of Climate Station Data near Canyon Creek

Station	Lat	Long	Elevation (ft)	Record length	Mean Annual Temp (^oF)	Mean Annual Precipitation (inches)	Average Snow (inches)
Clearbrook	48°50'	122°20'	60	1931 – present	49.4	46.3	14.6
Glacier RS	48°53'	121°57'	940	1949 – 1983	47.9	66.8	52.1

While no climate station is positioned within the Canyon Creek watershed, mean annual temperature is estimated to vary from about 35^{o}F at higher elevations to about 48^{o}F near the creek mouth (USDA Forest Service, 1995). Mean annual precipitation varies from about 73 inches (1850 mm) at the fan apex to about 130 inches (3300 mm) in the upper reaches; the estimated average precipitation is 111 inches (2800 mm).

As demonstrated by Figure F-1, a majority of precipitation in the area occurs during October to March. Rain-on-snow events are most likely to occur prior to January before a significant snowpack develops. In the Western Cascade Mountains, rain-on-snow events generally occur at elevations ranging between 1,200 ft and 4,000 ft (Washington Forest Practices Board, 1997). Much of Canyon Creek lies within this elevation band and the USDA Forest Service (1995) has estimated that typically about half of the watershed could contribute to rain-on-snow runoff. However, exceptions can occur such as the rain-on-snow storm in November 1989. Observations following the storm indicated nearly complete snowmelt to an elevation of 4,500 ft in the North Fork Nooksack drainage, suggesting that 72% or more of Canyon Creek contributed to rain-on-snow runoff during that storm (USDA Forest Service, 1995).

HYDROLOGY

Canyon Creek is one of five significant tributaries to the North Fork Nooksack River upstream of Warnick (near the mouth of Canyon Creek). While the North Fork is largely fed by glaciers on Mt. Baker and Mt. Shuksan, Canyon Creek probably contributes 20 to 25% of the annual discharge of the North Fork upstream from Warnick (USDS Forest Service, 1995).

The North Fork has been gauged on a continuous basis since 1937 by the USGS. The gauge, North Fork Nooksack River below Cascade Creek near Glacier (# 12205000), is located about 8 miles upstream of Canyon Creek and has a drainage area of 105 mi^2. Both maximum daily and peak instantaneous flows are recorded at this station. Based on discharge records up to 2000, the mean annual flood is 3,900 cfs and 6,350 cfs for maximum daily and peak instantaneous flows respectively. Significant floods (> 9000 cfs) occurred on the North Fork in 1937, 1949, 1962, 1984, 1989, 1990, and 1999 (Figure F-2). All of these peak flows occurred during the late fall and early winter when the potential for rain-on-snow events is greatest. The largest flood on record for the gauge, 11,200 cfs, occurred on November 10, 1989, coinciding with the damaging debris flood on Canyon Creek.

While there is no hydrometric station on Canyon Creek, a correlation with the discharge record of the North Fork can be expected. A number of previous studies have used indirect measures to estimate peak flows of varying return periods for Canyon Creek.

Pilot Watershed Analysis for Canyon Creek (1995)

In 1995, a watershed analysis was conducted for Canyon Creek by the USDA Forest Service. In this study, the hydrology of Canyon Creek was addressed and a number of methods were investigated to estimate peak flows of varying return periods including:

1. Williams et al. (1985) developed an equation for the general study area that relates discharge (cfs) per square mile (CSM) to discharge (Q) and drainage area (A):

   $$CSM = 41.8 + 0.015Q - 0.67A$$

Using this equation and one to 100-year return period peak discharge estimates for the North Fork Nooksack River near Glacier (log normal distribution), the CSM for each peak discharge on the North Fork was calculated and applied to the 30.75 mi^2 Canyon Creek watershed.

2. The USGS has derived several regression equations for different regions in Washington that relates peak discharge to watershed area, annual precipitation, and forest cover (Cummans et al., 1975).

3. The Hydrologic Change Module procedure outlined in the Washington Forest Practices Board manual for Conducting Watershed Analysis (1998) was used to evaluate the effects of existing timber harvest on peak discharge in Canyon Creek. In this analysis, the predicted USGS peak flows are regressed against precipitation frequency estimates. WAR (water available for runoff) values that account for forest canopy disturbance are then substituted for precipitation. For each return period, peak flows estimates are calculated for average and unusual storm intensities.

The results of these three methods are summarized as follows:

Table F-2
Estimated Flood Frequency and Magnitude for Canyon Creek

Return Period (yrs)	**North Fork extrapolation** (cfs)	**USGS equation** (cfs)	**Hydrologic Change** (cfs)		**Average** (cfs)
			average storm	**unusual storm**	
2*	1,715	1,490	3,560	4,055	***2,705***
5	2,650	2,190	4,415	4,960	3,555
10	3,265	2,495	4,870	5,410	4,010
25	4,045	3,035	5,860	6,400	4,835
50	4,620	3,625	6,265	6,850	5,340
100	5,195	4,135	6,985	7,570	5,970

* The 2-year return period flood approximates the mean annual flood (MAF).

The above methods result in varying estimates. Because none of these methods is conclusive or represents a superior technique given the available information, an average of the methods is adopted as representing a reasonable estimate of peak flows. Using an average value, the 100-year return period peak instantaneous flow is estimated at 5,970 cfs.

In the USDA Forest Service report, it is also noted that 73% of all peak flows in the North Fork Nooksack River occur during the rain-on-snow months of October through January and that rain-on-snow is the dominant source of the highest peak flows. Runoff is further exacerbated by tree removal. In the Canyon Creek watershed 30% of the forest cover had been removed by 1968. Forest canopy disturbance including road construction peaked around 1972 and has since been recovering. The Hydrologic Change procedure results indicate that past logging has potentially increased peak discharges between 17 and 34% for unusual storms.

Master Thesis on Channel Morphology by Ballerini (1993a)

Ballerini (1993a) attempted a reconstruction of a regional flood frequency curve for the North Fork Nooksack River basin using the following gauging stations:

- North Fork of the Nooksack River below Cascade, near Glacier, Washington (# 12205000, 105 mi^2),
- Nooksack River at Deming (# 12210500, 584 mi^2),
- Nooksack River below Nooksack Hatchery (NFNH),
- North Fork of the Nooksack River tributary near Glacier, Washington (# 12204400, 1.15 mi^2),
- Kidney Creek near Glacier, Washington (#12205490, 2.66 mi2), and
- Slesse Creek (Water Survey of Canada gauge 08MH013, 62.5 mi^2).

Peak discharge from 1965 to 1975 was used to calculate the mean annual flood (2.33 year return period) for each of the above stations. Regression analysis of the estimates yielded the following regional equation:

$$MAF = 0.41\ A^{1.0}$$

where MAF is the mean annual flood (m^3/s) and A is drainage area (km^2).

Substitution of the drainage area of Canyon Creek in the above equation yields a mean annual flood estimate of 1,095 cfs. This estimate is considerably lower than values determined by the pilot watershed analysis (Table F-2). However, some discrepancies are expected given potential problems in the Ballerini analysis.

For example, Ballerini's comparisons include watershed areas ranging between 1.15 and 584 mi^2. Smaller watersheds (< 10 mi^2) tend to respond much more rapidly to inputs and peak flows per drainage area are generally considerably greater in comparison to larger watersheds. A more appropriate analysis would compare watersheds ranging in area between 10 and 100 mi^2. Second, a short time period (10 years) was used for the comparison. Climatic fluctuations on a decadal scale are known to impact the magnitude of peak flows. Ballerini acknowledged the second problem and recalculated the regional equation using discharge data over 25 years. However, only three stations had sufficiently long records for this analysis and these stations included the maximum and minimum watershed areas.

Ballerini also determined a flood frequency curve for Canyon Creek based on flood frequency analysis of three stations: 12210500, 12204400, 12205000. The basis of the analysis is that in regions with homogeneous flood producing characteristics, flood frequency curves for individual stream will have similarly sloping flood frequency plots. Based on this premise, the flood frequency curve for Canyon Creek was defined as:

$$Q = 28.43\ RP^{0.41}$$

where RP is the return period in years. However, the three chosen gauged watersheds do not appear to have homogenous flood producing characteristics due to widely varying watershed area.

Summary of Peak Flow Estimates

Canyon Creek has shown to be susceptible to debris floods that exceed flood discharges by several times. For this reason, any design will have to focus on debris floods rather than clearwater floods. KWL has not attempted to estimate peak flows for Canyon Creek but has reviewed previous work. Based on this review, the best estimates of peak flows for varying return periods are the average values obtained from the Pilot Watershed Analysis (Table F-2):

Table F-3
Peak Flow Estimates for Canyon Creek

Return Period (yrs)	**Discharge** (cfs)	**Discharge** (m^3/s)
2	2,705	77
5	3,555	101
10	4,010	114
25	4,835	137
50	5,340	151
100	5,970	169

CLIMATE CHANGE

Climate change is addressed in this report appendix because long-term changes in climate may affect streamflow in Canyon Creek and may cause fluctuations in movement rates of the two earthflows that join at Canyon Creek. Much of this summary is based on a detailed study on long-term changes in rainfall for the Greater Vancouver Regional District and is supplemented with analyses of discharge data of Nooksack River. The closeness of Vancouver to the Canyon Creek watershed (approx. 90 Miles) allows for some extrapolation. This summary does not replace an in-depth analysis of changes in streamflow or precipitation in the general area but may provide some insight in future hydrological changes.

Rainfall Trends in Southwestern British Columbia.

Climate variability associated with the cyclic patterns of El Niño Southern Oscillation[2] (ENSO) and Pacific Decadal Oscillation[3] (PDO) dominate the historic record of

[2] ENSO is a well-known phenomenon characterised by an east-west "see-saw" pattern in tropical SSTs that operates on time scales of months to years with a typically return interval of 3 to 7 years. The atmospheric phase of the

precipitation and temperature in British Columbia. These cyclic fluctuations are superimposed on a modest positive trend in annual precipitation over the past century in southwestern B.C. (10% of the mean value per century) which is not proven but is consistent with an enhanced hydrological cycle. It can be speculated that an enhanced hydrologic cycle would overcompensate for any dryness caused by any increases in the frequency of intense El Niños during the past quarter century.

A recent study suggests that this upward trend in annual precipitation in the central and southern interior of B.C. over the last century coincides with an increase in the frequency and intensity of North Pacific cyclones during the last 50 years. Given that most of the precipitation and the most intense precipitation falls during winter, it is important to note that there has been no geographically consistent trend in winter precipitation in the Georgia Basin when precipitation is most critical. This is in contrast to the remainder of the southern B.C., where increases in average annual precipitation from 14% to 28% per century have been identified.

Although the trend in annual precipitation is reasonably clear, evidence for significant trends in extreme precipitation is weak. Results are somewhat contradictory and depend to some degree on the length of record considered. For the period 1950-94 in southwestern B.C. there is an overall increase in high intensity rainfall frequency associated with spring, summer and fall for 1950-94, while winter months show a slightly negative trend. At the century time scale, this pattern is not evident.

Most importantly, however, all studies suggest that the frequency of occurrence of higher precipitation rates (but not extremes) is influenced by circulation changes associated with the PDO and ENSO. For the Vancouver area, there is evidence of an upward trend in the number of days when rainfall intensities exceeded 10 mm/hr for durations less than one hour. This increase began in 1977 and coincides with the step-change from a cold phase to a warm phase PDO. If the step in rainfall intensities is not a coincidence it is reasonable to expect that a reversal in this trend will occur as a change in phase of the PDO may have occurred in 1998. The next 5 years may show whether the suspected phase change of the PDO affects precipitation intensities in the GVRD.

Given predicted rising temperatures in the Pacific Northwest, the timing of snowmelt and the elevation bands affected by snowmelt and rain-on-snow will change. For the Canyon

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phenomenon is known as the Southern Oscillation, the intensity and phase of which is measured by the **Southern Oscillation Index (SOI)**. During El Niño events (negative SOI) SSTs in the tropical eastern Pacific are higher than normal and produce excess convection and precipitation in that region. La Niña events (positive SOI) are characterised by unusually warm SSTs in the western Pacific and produce strong convection and precipitation over those regions.

[3] The PDO has only recently been “discovered” and is manifested by El Niño-like changes (so-called regime shifts) in the SST distribution over the tropical and north Pacific evident at decadal time scales. The warm (positive) phase of the PDO is characterised by below normal SSTs in the central and western north Pacific and unusually warm SSTs along the west coast of North America. The cold (negative) phase produces the reverse distribution. Individual phases of this oscillation typically last for 23-35 years resulting in a 50-70 year cycle. The PDO pattern is strongly linked to atmospheric circulation over North America and the North Pacific as commonly expressed by the Pacific North American index (PNA). Low values of the PNA index are associated with a weak Aleutian Low pressure while high values are associated with a strong Aleutian Low. High values of the PNA tend to be associated with the warm phase of PDO (e.g. 1977-1988) and El Niño events.

Creek watershed, this will imply that an increasingly larger area will be subject to rainfall instead of snowfall and a thinning snowpack during the fall rain-on-snow period with an increase in elevation. The streamflow response to these changes is highly complex and discussed in the following sub-section.

Streamflow

In the Canadian Cordillera, the period from 1920 to the late 1940s was dominated by low runoff and small floods. From about 1950 to 1980 higher runoff and floods were observed during a time when precipitation totals increased 10-20% over the normal during fall and winter. The earlier period coincides with a PDO warm phase, whereas the latter period coincides with a PDO cool phase. It is important to note that streamflow response is amplified by about 50% to changes in precipitation amounts. Since about 1980 (PDO warm phase), the frequency of floods has been lower.

Fraser River has the longest streamflow record in British Columbia. A number of significant observations have been extracted from previous studies:

- seasonal changes in the timing and volume of the Fraser River flow are occurring earlier in the year on average;
- flow is higher after a La Niña winter and peak flows arrive earlier in the year following an El Niño event; and
- there is no significant trend in the date of the height of peak flow from 1912 to 1998.

The absence of significant trends in extreme precipitation in southwestern Canada is largely confirmed by studies of streamflow for the past 30 to 50 years. Southern B.C. is not experiencing more extreme hydrological events (although there are significant changes in the timing of ice break-up and spring snowmelt).

At the North Fork Nooksack River, a weak increasing trend can be discerned if peak annual instantaneous discharge or maximum annual daily flows are plotted against time. Most of this trend can be explained by an increase in streamflow peaks since the late 1970s. This increase coincides with a PDO reversal from a cold phase to a warm phase, as demonstrated in the cumulative departure from the mean[4] plot shown in Figure F-3.

Increasing temperatures will means that more precipitation will be available as rainfall rather than snowmelt. This will cause steepened hydrographs as the lag of snowmelt is decreased. Increasingly higher areas in the Canyon Creek wateshed will be subject to snowmelt in the future.

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[4] Cumulative departure from the mean plots are convenient in displaying long-term changes. To generate these plots, the mean of each data series is determined and then subtracted from each individual value. The values, which can be positive or negative, are then summed. The cumulative value for each year is then plotted against time. A descending plot signifies persistently below average values; an ascending plot signifies persistently above average values; a horizontal plot indicates values persistently near average.

In summary, it is not possible to project observed fluctuations into the future because the influence of atmospheric oscillations on precipitation is poorly understood. An in-depth time series analysis of hydrometric data would have to be conducted to identify any prominent trends (including records of stream flow, rainfall, snowwater equivalent and snow depth).

However, increasing temperature trends and more total annual precipitation may result in steeper hydrographs, and higher peak discharges which may cause an increase in sediment movement rates.

Appendix G

Debris Flood Probability and Magnitude

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CONSULTING ENGINEERS

Appendix G

Debris Flood Probability and Magnitude

INTRODUCTION

This appendix provides a comprehensive assessment of debris flood hazards at Canyon Creek, with estimates of expected return period, total volume, and peak flow. Debris flow hazards are not addressed as a concern at Canyon Creek because the gradient of the mainstem channel is too low to transport debris flows over long distances. Debris flows, however, may occur on small tributaries and cause temporary blockages of the mainstem.

For this study, the design event is specified by a return period of a hazardous event (500-year return period debris floods in the case of Canyon Creek). This method is a standard accepted by several agencies, districts and municipalities in British Columbia. For this reason, risk analysis based on the probability of death or damage to buildings and infrastructure was purposely not chosen for this study. There is no commonly acknowledged or legislated level of acceptable risk in Washington even though some precedents have been established by other studies.

The technical information provided in this appendix is important in determining the need for, and scale of, mitigative measures.

DEBRIS SUPPLY SOURCES

A determination of debris supply sources to the channel is important for a couple of reasons. First, debris supply sources should be identified in the event that individual point sources require stabilization. Second, point sources may have been caused by poor watershed management (e.g. logging practices, road construction). Identifying these sources is necessary to avoid further debris production above natural levels.

Previous studies have identified poor forestry practices as a major sediment source to the mainstem channel in the last several decades (Appendix C). Aerial photographs from 1940 illustrate that the watershed was relatively benign with respect to slope instabilities prior to logging (Figures D-1 and D-2). A study by Peak Northwest (1986) estimated that slope instabilities directly related to logging resulted in 2.3 million yd^3 of excess sediment being delivered to the mainstem channel. This situation is not unique to Canyon Creek, as increased sediment supply is a legacy of past logging practices throughout the Pacific Northwest. However, logging restrictions, improved forestry practices and watershed rehabilitation (principally road deactivation) have all attributed to watershed stabilization in the past decade. As a result, sediment input rates have declined significantly although pre-disturbance conditions are unlikely to be re-established for over a century. While individual areas within the watershed probably still require attention, there are no obvious managed areas that require immediate action.

Irrespective of slope instabilities related to logging, the watershed of Canyon Creek is subject to naturally occurring debris slides, debris flows and earthflows. Steep sideslopes are frequent on both sides of the mainstem channel throughout the watershed. These sideslopes are typically overlain by a veneer (< 3 ft) of colluvium or glacial till overlying bedrock and are subject to episodic debris avalanches. Debris avalanches typically occur during periods of wet weather, particularly in the late fall when the soils are saturated with antecedent precipitation and the Pacific Northwest is affected by a series of cyclones with high intensity precipitation. Debris flows are usually initiated by debris avalanches entering a steep channel and several tributaries prone to debris flows have been identified (Figure 2-1).

Other significant sources of sediment to Canyon Creek are the Jim Creek and Bald Mountain Earthflows. The earthflows are located on opposite sides of the valley at about mile 3.4. Both earthflows show evidence of ongoing creep and fluvial erosion at the toe of both slides is a source of sediment to the channel (see Appendix C). Coarser sediment associated with the earthflows can be distinguished from other sources by its characteristic angularity. In an effort to slow erosion rates at the toe of the Jim Creek Earthflow, the USFS constructed a series of weir deflectors out of large boulders in the mid 1990's. Given the size of both earthflows, any efforts of stabilization (outside of intensive dewatering) have a very low likelihood of success.

DEBRIS FLOOD INITIATION

Debris floods in Canyon Creek are most likely initiated by a temporary blockage of the channel due to a landslide dam. If the dam is high enough so that a lake of substantial size (several tens to hundred thousands of cubic yards) can be impounded, a catastrophic failure of the landslide dam is conceivable (Jakob and Jordan, 2001). An outburst flood in combination with the mobilization of the collapsed dam is likely to initiate a debris flood, particularly in a confined channel such as Canyon Creek.

Figure 2-1 shows that there are several areas where sideslope failures up to several thousand yd^3 could reach Canyon Creek and lead to temporary blockage. However, landslide dams involving several thousand cubic yards of sediment are unlikely to impound significant volumes of water due to steep channel gradients. While low magnitude debris floods could result, peak discharges would not approach the 1989 event. The most probable location for a significant landslide dam (> 30 ft high) to form is a sudden failure of the front of either the Jim Creek or Bald Mountain earthflows. Outbreak floods associated with the collapse of landslide dams are considered later in this appendix.

Debris floods can also be initiated by a large debris slide or debris flow impacting the main channel at an oblique angle. However, sideslopes and tributaries in Canyon Creek are generally aligned perpendicular to the channel. As a result, debris flood initiation by such a mechanism is considered unlikely.

DEBRIS FLOOD PROBABILITY

Debris flood hazard is defined by a combination of probability and magnitude. This sub-section determines the probability or frequency of debris floods at Canyon Creek. Debris flood probabilities are defined as per Table G-1.

Table G-1
Debris Flood Probabilities and their Significance

Return Period (years)	Relative Term of Probability	Probability of at Least One Occurrence in 50 Years	Significance of Probability
< 20	Very High	more than 90%	The hazard is imminent, and very likely to occur within the lifetime of a person or structure. There will generally be clear and relatively fresh signs of disturbance.
20 to 100	High	40% to 90%	The hazard is likely to happen within the lifetime of a person or structure. Disturbances are clearly identifiable from deposits and vegetation, but may not appear fresh.
100 to 500	Medium	10% to 40%	The hazard occurrence within a given lifetime is possible. Signs of disturbance such as vegetation damage may not be easily noted.
> 500	Low	less than 10%	The hazard lies outside the probability typically used for management and decision making.

Four dating methods were investigated to determine the frequency of past debris floods at Canyon Creek. These are aerial photograph analysis, dendrochronology, eye-witness reports, and radiocarbon dating.

Aerial Photograph Analysis

Aerial photograph chronosequences for Canyon Creek were inspected dating back to 1940 (Appendix D). The most striking features on the aerial photographs are the consequences of intensive logging activities in the 1960s and 1970s. Approximately 100 debris avalanches and debris flows were triggered in clearcuts and from sidecast failures on poorly constructed logging roads. About half of these landslides travelled to Canyon Creek, elevating the natural levels of sediment input by several orders of magnitude (Appendix C).

The 1989 and 1990 events are reflected on 1991 aerial photographs as the mainstem channel was significantly widened from downstream of Whistler Creek to the fan, a distance of 8 miles (Figure D-2). Aerial photographs prior to this date show no evidence of comparable disturbance (Figures D-1, D-2). Fan reaches show more variation in disturbance but again the greatest changes are associated with the 1989 and 1990 events. Based on this evidence, the 1989 or 1990 debris flood was the largest magnitude event in the past 60 years.

Additional evidence for channel changes on the fan is provided by an old township map dated 1885 (Figure G-1). While the accuracy of the map is questionable with respect to exact position and channel form of tributaries (the North Fork Nooksack River was mapped to a high precision), the map clearly shows Canyon Creek in roughly the same position as at present. One can therefore conclude with reasonable certainty that there has not been a debris flood in the past century of sufficient magnitude to initiate a dramatic channel avulsion.

Dendrochronology

The second dating method is dendrochronology. Boulders or logs transported in debris floods can impact trees and leave scars in the cambium, which subsequently begin to overgrow if the tree was not killed at impact. Cutting a wedge from this scar tissue or extracting a tree core via a 5 mm increment borer allows the reconstruction of the year of damage. In addition, if trees are partially covered with debris, growth often slows considerably. Coring a tree and counting back to a ring sequence that is very narrow enables the researcher to determine the date of the damaging creek event. For Canyon Creek, a number of suitable trees were found but previous logging has significantly reduced the number of older trees adjacent to the channel. Table G-2 summarizes the information obtained from the dendrochronologic analysis.

Table G-2
Summary of dendrochronological analysis

Sample Number	Location[1]	Dates	Last ring counted
C-F-C-1	mile 0.65	1989 (S)	1962
C-E-A-2	mile 3.7	1989 (S)	
C-W-H-3	mile 3.75	not analyzable	
C-E-C-4	mile 0.8	1937 +/- (S)	1800
C-E-H-5	mile 0.8	n/a	
C-E-C-6 (wedge)	mile 0.8	n/a	
C-W-C-7	mile 1.05	no scar	1952
C-W-C-9	mile 1.05	1980-‘90 (cw)	1923
C-W-C-10 (wedge)	mile 1.05	1983/84	1953
C-E-F-12	mile 2.45	1989	1960
C-E-C-13	mile 2.45	1989	1952
C-W-D-14	mile 2.7	1953/54	1882
C-W-C-15	mile 2.7	not analyzable	
C-E-C-16	mile 2.75	1960(S), 1984-’92 (cw)	1960
C-E-C-17	mile 2.9	1995/96	1950
C-W-C-21	Bald Mountain Slide	1750-1854 (cw)	1735
C-W-D-22 A	Bald Mountain Slide	1848-‘80 (cw), 1968-‘75 (cw)	1712
C-E-C-22B	Bald Mountain Slide	1953 +/- (S)	1953
C-E-D-24	mile 0.1	1989	1950
C-E-D-25	mile 0.1	not analyzable	

C-E-D-26	mile 0.35	1907-'19 (cw), 1937-'50 (cw), 1950-'62 (cw)	1818
C-E-D-28	mile 0.5	1937+/- (S)	1937
C-W-C-29B	mile 1.2	no scar	1942
C-W-C-29C	mile 1.2	1990/91 (cw)	1951
C-W-C-29D	mile 1.2	1990/91 (cw)	1961
C-W-H-29	mile 1.2	1957-'59 (cw), 1989 (S)	1880
C-E-D-31	mile 1.4	no scar, no cw	1903
C-E-C-32B	mile 1.4	no scar, minimum age	1904
C-C-C-34	mile 1.7	no scar, minimum age	1936
C-C-C-35	mile 1.7	no scar, minimum age	1922
C-W-D-36	mile 1.35	1962/63 (logging?)	1937
C-W-D-50	on fan	1960 +/- 3yrs	1960

CW – compression wood
S – scar

[1] location is distance upstream of Canyon Creek mouth (confluence with the North Fork Nooksack River)

Sample number has the following convention: C – Canyon Creek, location – west (W) or east (E) side of creek, tree type (C – cedar, H – hemlock, D – Douglas Fir, A – alder), and sample number (#).

The November 1989 event was dated five times via dendrochronologic methods. Many more scarred trees dating this event could have been cored. In contrast, the November 1990 event could not be dated dendrochronologically in the channels upstream of the fan apex, suggesting that this event was of significantly lower magnitude than the 1989 debris flood. Interestingly, the 1990 event caused significantly more damage on the fan (three homes destroyed). The severity of the 1990 event was caused by aggradation remaining from the 1989 event that diverted flows against the right bank near the fan apex.

The only other events that have at least 2 dates are 1937 (C-E-4 and C-E-D-28) and 1962 (C-E-C-16, C-W-D-36 and C-W-D-50). Both years are associated with above average peak flows on the North Fork Nooksack River. One can therefore conclude that unusually large floods or debris floods occurred in 1937 and 1962.

Several more trees that did not show any signs of damage by debris flood impact were included in the analysis. A number of undamaged approximately 300-year old trees whose base is located slightly higher than the 1989 event (evidenced by scars on adjacent trees) indicate that it is unlikely that debris floods larger than the 1989 event occurred over approximately the past 300 years. Trees of this age in favourable position were found on the right bank approximately 0.4 miles upstream of the fan apex (Figure 2-1).

The only previous attempt to establish the frequency of past flood and debris flood events on Canyon Creek was Ballerini (1993a). He estimated that seven high magnitude floods occurred prior to the 1989 event: 1945, 1954, 1962, 1971, 1975, 1984, and 1986. Of those events, only the 1954 and the 1962 dates match the dendrochronologic record (C-W-D-14). This observation does not discredit the dendrochronologic method, but rather points towards potential limitations in Bellerini's analysis. Ballerini derived these dates by using discharge data from regional creeks and changes in vegetation patterns on the active alluvial fan observed from historic aerial photographs. These methods are indirect and may, at best, indicate a certain likelihood of floods on Canyon Creek, but cannot be used to reconstruct reliable flood or debris flood frequencies. Nor can such methods differentiate between debris floods and floods.

Eyewitness Accounts

When a fan has been populated for a long period, eyewitness accounts or newspaper records can be an invaluable source of information for creek events. The first residence on the Canyon Creek fan was constructed in the late 1950's by the original owners of the Logs Resort – Mr. and Mrs. Ohlson. The Logs Resort used to have an in-ground swimming pool located on the margin of the active channel. Hazel Ohlson recalls that flood waters breached the pool in 1971 (January 30), 1975, 1989, and 1990 (Ballerini, 1993a). The 1990 flood buried the pool in sediment. The 1989 and 1990 events were undoubtedly debris floods associated with dam outburst events. However, flood events in 1971 or 1975 could not be corroborated by other sources. While there is not necessarily a correlation between peak flows on the North Fork Nooksack River and debris flood events on Canyon Creek, the peak annual flows on the North Fork in 1971 and 1975 were not unusual. If debris floods did occur during either of these years, it is doubtful that peak discharges exceeded either the 1989 or 1990 event.

A debris flood associated with a dam-outbreak flood is reported to have occurred on January 2, 1984. Roger Nichols of the USFS documented an outburst flood that possibly initiated at the Jim Creek Slide and travelled to the fan (USDA Forest Service, 1995). On the fan, there was up to 2 feet of deposition and the creek migrated over to the right side of the channel. At the site of the two earthflows, Nichols observed that the creek had migrated from against the Bald Mountain Slide to run along the Jim Creek Slide (Nichols, pers comm). In a conversation, Nichols also noted that Mr. Ohlson had recalled a significant flood event that occurred around November 19, 1962. This event reportedly caused some localized flooding around the buildings of the Logs Resort and is coincident with a large flood on the North Fork (Figure F-2).

Radiocarbon Dating

A fourth possible method to determine the age of older (> 250 years) debris flood events is radiocarbon dating of organic material. This method requires the location of organic material at depth that was unquestionably deposited by a debris flood. Two areas on the fan and areas along the channel were investigated for the location of datable material. Particularly promising was a fresh cut in fan deposits near the fan apex and truncated fan deposits along the North Fork Nooksack River south of Mount Baker Highway (Photos 10 and 11). Despite an intensive search over an embankment length of half a mile and an exposure 20 to 30 feet in height, no organic material was found and therefore radiocarbon dating was not used to reconstruct debris flood frequencies. For the same reason, trenching that may have uncovered organic material on the fan surface was not attempted.

A lack of organic material in exposed fan deposits suggests that a majority of the fan was constructed immediately after deglaciation. For many fans in British Columbia and Washington, a majority of deposition occurred immediately following deglaciation when large volumes of unconsolidated sediment were unvegetated and susceptible to mass wasting (Ryder, 1970).

Summary

The available evidence indicates that the 1989 event was probably the largest event that has occurred during the past 300 years on Canyon Creek. Large floods or small to moderate sized debris floods likely occurred in 1937, 1962, 1984, and 1990. Geomorphic evidence of these events is limited, however, and cannot be used to determine reliable discharge estimates. The design event will be further specified by the dam outbreak modelling considered later in this appendix.

In conclusion, it appears that high-magnitude debris floods occur at return periods of centuries (10% to 40% probability in 50 years) at Canyon Creek. Such events are particularly dangerous because the hazard may easily be erased from human memory and physical evidence overgrown or eroded, and therefore not properly recognized in the field. In contrast, eye-witness accounts and limited botanical evidence indicate that small to moderate sized debris floods occur on a decadal scale.

DEBRIS FLOOD MAGNITUDE

Determination of debris flood magnitude involves consideration of both the total volume of a debris flood and the peak discharge. Total volume is important for those mitigative structures that contain the debris, whereas peak discharge estimates are required for mitigative structures that channelize the debris and for the design of bridges.

Unless the mechanism of debris flood initiation is well understood or evidence exists of a prior event, there are no reliable methods available to estimate either the peak discharge or total volume of debris floods. In British Columbia, the 200-year return period flood is often doubled to obtain an approximate discharge estimate for debris floods. Jakob and Jordan (2001) have shown that this value may be too low for debris floods of similar return periods and that a factor of three may be more appropriate. However, such methods are approximate at best and considerable variation exists from site to site.

Canyon Creek is unique in that the 1989 debris flood was well documented by the USFS. There is also reasonable evidence that indicates high magnitude debris floods in Canyon Creek are initiated by outbreak floods from landslide dams. Due to the confined nature of the creek, a flood surge from an outburst flood would remain in the channel to the fan apex. The following documents the estimated peak discharge of the 1989 event and compares it to various outbreak flood scenarios that have been modelled with FLDWAV, a flood routing model.

1989 Debris Flood

Mr. Donald Richardson was contracted by the United States Forest Service (USFS) to estimate the peak discharge of the 1989 event (Richardson, 1990). Discharge estimates were determined at two locations: within the bedrock canyon several hundred feet upstream of the fan apex (Photo 26) and immediately downstream of Kidney Creek at about mile 5.2 (Figure 2-1). The peak discharge estimates were based on high water levels observed along the channel on June 11, 1990. Richardson employed the slope-area method to estimate peak flows at both locations (Benson and Dalrymple, 1967).

For the bedrock canyon reach above the fan apex, cross-sections were defined 200 ft apart. The upstream section had an area of 1050 ft^2 (97.5 m^2) while the downstream section had a cross-sectional area of 780 ft^2 (72.5 m^2). With a flood height difference of about 6 ft, the peak flow was estimated to 16,100 cfs (455 m^3/s). Flow velocities at the two sections were calculated to 15.3 ft/s (4.7 m/s) and 20.6 ft/s (6.3 m/s) respectively.

In contrast to discharge estimates near the fan apex, high water levels downstream of Kidney Creek indicated a peak discharge of 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 the 1989 event was the result of an outbreak flood from a large landslide dam or a large log jam.

The peak flow of the 1989 event is almost three times larger than the estimated 100-year return period water flood (Q_{100}) of approximately 6,000 cfs (170 m^3/s). Such an increase in discharge is not atypical, as peak flows of debris floods are commonly 2 to 3 times higher than the 200-year return period water flood (Jakob and Jordan, 2001).

KWL Observations

During a traverse of the channel in October 2002, KWL noted that scour marks were still visible in several locations. A notable scour line is located about 800 ft upstream of the fan apex (Photo 26). Here the scour line is situated 16 ft (5 m) above the channel bed, which is consistent with USFS observations. Due to potential changes in channel geometry and a lack of consistent scour lines, detailed cross-sectional measurements were not taken by KWL to back calculate peak discharge.

The peak discharge calculations by Richardson (1990) employed Manning's equation to calculate average velocity. While this method has proved reliable for clearwater floods, it is not clear whether it is appropriate to use for debris floods due to sediment concentrations up to 35% by volume. In the absence of eyewitness observations, debris flood velocities can also be estimated using the superelevation at bends or the runup on obstructions, as defined by mud lines left by peak flows. The superelevation equation is given by Chow (1959) as:

$$v = (g\ r_c\ \Delta h \cos\theta / B)^{0.5}$$

where v is average velocity, g is the gravitational constant, r_c is the radius of curvature, B is the surface width, θ is the channel slope, and Δh is the superelevation between two sides of the flow. A well defined superelevation line from the 1989 event is still visible at a sharp channel bend, located about 1500 ft upstream of the fan apex (Figure 2-1).

The runup or velocity head equation can be applied to flows that run up against an obstruction oriented roughly perpendicular to the flow direction. The equation developed by Chow (1959) results from the assumption that all the kinetic energy of a moving object is converted to potential energy:

$$v = (2\ g\ \Delta h)^{0.5}$$

Wigmosta (1983) used a combination of empirical measurements and theoretical analyses of laminar viscous flow around a cylinder to derive a slightly different formula.

$$v = (1.21\ g\ \Delta h)^{0.5}$$

Wigmosta's formula was specifically developed for the runup of flowing debris on trees in the path of a flow. During the channel traverse by KWL, mud lines up to 8 ft in height were observed at several locations in lower reaches. Using the above equations, the following debris flood velocities have been calculated:

Table G-3
Debris Flood Velocity Calculations

Formula	Variables	Velocity
$v = (2 \cdot g \cdot \Delta h)^{1/2}$ Runup – Chow	$g = 32.2$ ft/s^2 $\Delta h = 8$ ft	23 ft/s
$v = (1.21 \cdot g \cdot \Delta h)^{1/2}$ Runup – Wigmosta		17.7 ft/s
$v = (g\ r_c \cos\theta\ \Delta h / B)^{1/2}$ Superelevation	$r_c = 165$ ft $\Delta h = 13.8$ ft $B = 130$ ft $\theta = 6\%$	23.6 ft/s

None of these equations diverge significantly from the estimated velocities of Richardson (1990) and as such, the estimated peak discharge of the 1989 debris flood is thought to be reasonably accurate.

Ballerini (1993b)

Ballerini (1993b) also attempted to reconstruct the peak discharge of the 1989 event by measuring high water marks at eight locations between the fan apex and Whistler Creek. Six of the cross-sections were located downstream of Kidney Creek. From the upstream end, the measured cross-sectional areas were 375, 445, 490, 660, 475, and 1540 ft^2. These areas were then multiplied by velocity, which was calculated using equations derived by Costa (1983) and Jarrett (1987). Ballerini (1993a) argued that the commonly used slope-area method (Benson and Dalrymple, 1967) was not appropriate for Canyon Creek as the method was developed on gently sloping rivers. The velocities calculated by Ballerini varied between 10 and 12 ft/s, resulting in a peak discharge estimate of 5,680 cfs (161 m^3/s) at the fan apex.

Ballerini's reconstruction of the peak flow was a difficult task as he observed high water marks several years after the event, unlike Richardson (1990) who visited the site soon after. Less confidence is placed in Ballerini's estimates for two reasons. First, the estimated velocities are much too low for a dam outbreak flood within a confined channel. Second, Ballerini discarded the two highest discharge estimates on the grounds that the cross-sectional area was overestimated due to channel erosion that occurred after channel filling. Debris floods tend to deposit their sediment load on the falling limb of the hydrograph. Thus, measured high water marks occur prior to sediment deposition. Furthermore, due to steep channel gradients it is unlikely that significant sediment deposition occurred at any of the confined sites measured by Ballerini.

Summary

In summary, the best estimate of the 1989 debris flood is a peak discharge of about 16,100 cfs at the fan apex with an average flow velocity of 15 to 23 ft/s.

Dam Outbreak Modelling

The estimated peak discharge of the 1989 event is about three times greater than Q_{100}. Because this value is far in excess of potential runoff generated floods, the implication is that the 1989 event was generated by a geomorphic event. The most likely explanation is a temporary blockage of the mainstem channel by a landslide dam and a subsequent outbreak flood caused by overflows breaching the dam. There are a number of locations where debris avalanches could dam the river, particularly in lower confined reaches (Figure 2-1). However, potential debris avalanches at these locations would only impound several tens of thousands of cubic yards of water – an insufficient volume to generate an outbreak flood that approaches the 1989 event.

Large landslide dams (> 30 ft) are most likely to form where the Jim Creek and Bald Mountain earthflows intersect the mainstem channel of Canyon Creek. Here, landslide dams up to 100 ft in height are thought to be possible. While earthflows are generally characterized by extremely slow creep rates, rapid movements can occur. One of the best documented cases is the Thistle Landslide Dam in Utah (Kaliser and Fleming, 1986). The Thistle earthflow began to move on April 13, 1983 and within a period of six days more than 360 ft (110 m) of displacement had occurred. The earthflow blocked Spanish Fork Canyon, creating a lake 165 ft (50 m) deep and 3 miles (4.8 km) long. Reactivation of the earthflow coincided with record-breaking precipitation in September (> 500% above normal) and above normal precipitation from October through April (150 to 170%). While the landslide dam persisted for five months, an emergency overflow spillway and a tunnel were constructed to drain the impounded lake in a successful effort to prevent a catastrophic collapse (Hansen and Morgan, 1986).

The example provided by the Thistle case study demonstrates the potential for earthflows to create significant landslide dams. To determine whether outbreak floods at the Jim Creek Slide could result in events similar in discharge to the 1989 debris flood, various landslide dam scenarios have been modelled using the National Weather Service (NWS) FLDWAV hydraulic model.

FLDWAV

FLDWAV is a general flood routing model that is capable of simulating unsteady flow conditions. While FLDWAV can be used for a number of different flow conditions, it is particularly well suited to model dam outbreak flood waves. The model uses the dynamic wave method based on the complete one-dimensional Saint-Venant unsteady flow equations. Of the many routing techniques available, only the dynamic wave method accounts for the acceleration effects associated with outbreak floods and the influence of downstream unsteady backwater effects produced by channel constrictions, dams, bridges, and tributary inflows.

A distinguishing characteristic of dam outbreak floods is the very short duration of peak flows, particularly from the beginning of rise until the occurrence of peak flow. The time to peak discharge is a function of how long it takes a breach in the dam to form and is usually in the range of minutes to hours. In comparison, runoff generated floods tend to form over a period of hours to several weeks. The rapid rise in the hydrograph of an outbreak flood causes it to have acceleration components of far greater significance than those associated with a runoff generated flood (Fread, 1998).

Based on initial channel conditions, the FLDWAV model computes the outflow hydrograph from the dam and routes the resulting flood wave through the downstream channel. The downstream routing is of particular interest as outbreak floods are attenuated as they are routed through a channel or floodplain due to the effects of floodplain storage, frictional resistance to flow, flood wave acceleration components, and downstream channel constrictions. If the river contains significant storage such as a wide floodplain, a dam outbreak flood can be extensively attenuated and its time of travel is increased significantly. Even when the channel approaches a rectangular cross-section, the flood wave can experience appreciable attenuation. In comparison, runoff generated floods experience considerably less attenuation (Fread, 1998).

Model Inputs for a Landslide Dam at Jim Creek Slide

Required as input into the FLDWAV model are channel geometry, base flow, dam height, time of failure or breach time (time from beginning of breach formation until it reaches its maximum size), the final width at the bottom of the breach, and roughness co-efficients.

1. The channel geometry is based on USGS topographic mapping and field observations. The mainstem channel was traversed by KWL in October 2002 from the mouth of Canyon Creek to about a half mile upstream of the earthflows, a

distance of about 4 miles. Channel width downstream of the earthflows varies between 65 ft and 230 ft while the channel slope varies between 4% and 7.5% (Table C-1, Appendix C). For the model, a total of seventeen cross-sections are defined from about a third of a mile upstream of the earthflows to the fan apex, a distance of 3 miles. The resulting cross-sections have simplified rectangular geometries, reflecting the generally steep sideslopes and confined nature of the channel. Considerable more effort would be required to replicate actual field conditions. However, the level of effort required is not considered necessary for Canyon Creek as the channel downstream of the potential landslide dam has a relatively simple geometry and the model is not sensitive to minor variations in cross-section.

2. The outbreak flood was assumed to occur during an intense rainstorm with the resulting runoff approaching the 25-year return period flood – a base flow of 4,800 cfs. There is no evidence to suggest that debris floods only occur during longer return period floods. However, activation of the earthflows is likely to occur during or following a period of high antecedent precipitation. Hence, a 25-year return period was chosen as an appropriate average.

3. Three different dam heights were simulated: 30 ft, 65 ft, and 100 ft based on different failure scenarios. A 100 ft dam height was derived by assuming rotational failure or block sliding of a 120 to 150 ft thick and up to 150 ft long section of the Jim Creek earthflow. The height was determined from the uppermost tension cracks upslope of the exposed face. The Jim Creek earthflow is in an extensional phase with active loss of toe support by undercutting of Canyon Creek. This combination of factors suggests that a failure of this magnitude, although not observed in historic time, is possible for a 500-year return period. Higher landslide dams could be created by a sudden surge of either earthflow as observed at the Thistle earthflow in Utah in 1983 (Kaliser and Fleming, 1986). Although a similar behaviour is theoretically possible at the two earthflows at Canyon Creek, conditions leading to such an event are considered to exceed the 500-year return period used for design in this study.

4. Breach time or time of failure (τ) was varied between ten and thirty minutes. For overtopping failures, the beginning of breach formation is after the downstream face of the dam has eroded away, and the resulting crevasse has progressed back across the width of the dam crest to reach the upstream face. Appropriate selection of breach time is critical, as model results are typically very sensitive to this parameter with lower breach times resulting in higher peak discharges. The range of values chosen is based on research by Froelich (1987, 1995) who investigated 43 dam breaches ranging in height from 15 to 285 feet (with all but 6 between 15 and 100 ft). Based on his work, the following predictive equation can be obtained:

   $$\tau = 0.59\ V_r^{0.47} / h_d^{0.9}$$

   where V_r is the reservoir volume (acre-ft) and h_d is the height of the dam. The standard error of estimate for τ is $\pm$ 0.9 hr, which is an average error of $\pm$ 70%.

5. The final breach width was assumed to vary between 33 and 50 ft (10 and 15 m), which is close to the active channel width of 65 to 80 ft at the earthflows. The sideslopes of the breach were assumed to have a 1:1 ratio. The chosen width values were based on the work of Froelich from which the following equation is derived:

   $b = 9.5\ k_o\ (V_f\ h_d)^{0.25}$

   where b is average breach width (ft),and k_o = 0.7 for piping and 1.0 for overtopping. The standard error of estimate for b is ± 94 ft or an average error of ± 54%. Because the potential breach width at the earthflows is constrained by a relatively narrow channel, variations in breach width do not have a significant impact on peak discharge.

6. Manning's n roughness values ranging between 0.06 and 0.075 were used with the higher values reflecting increased channel slope. Because outbreak floods are rarely observed, there is considerable uncertainty associated with the selection of appropriate roughness values. This uncertainty arises from flows in areas that are infrequently inundated (or have never been) and the effects of transported debris. However, it has been shown that Manning's n is not an very sensitive parameter when simulating dam outbreak floods (Fread, 1998).

Model Results for a Landslide Dam at Jim Creek Slide

Using the above input parameters, the outbreak modelling results for a landslide dam at the two earthflows are summarized as follows:

Table G-4
Jim Creek Slide Dam Outbreak Flood Modelling Results

Landslide Height (ft)	**Failure Time** (min)	**Breach Width** (ft)	**Peak Discharge at Dam** (cfs)	**Peak Discharge at Fan Apex** (cfs)	**Average Velocity** (ft/s)	**Travel Time** (min)
100 ft high dam impounded volume of 330 acre-ft	10	33	30,000	24,700		
	10	50	31,100	24,700	25	9
	12	33	26,500	22,300		
	12	50	27,200	22,600	24	9.5
	15	33	21,900	19,400		
	15	50	22,600	19,400	23	10
	20	33	17,500	16,100		
	20	50	18,400	16,600	21	11
	30	33	13,800	13,100		
	30	50	14,100	13,300	19	12
30 ft high dam volume of 23 acre-ft	10	50	5,900	4,800	13	17

65 ft high dam volume of 120 acre-ft	10	50	12,700	10,600		
	15	50	10,100	9,200	16	15
	20	50	8,800	8,100		
Note: Peak discharge values are rounded to the nearest one hundred.						

The data in Table G-4 illustrate several important points:

- The estimated peak discharges for the various landslide dam scenarios are highly sensitive to the breach time. For a 100 ft high dam, the peak discharge for a breach time of 10 minutes is more than twice that for a 30 minutes breach time (Figure G-2). In contrast, terminal breach width is a relatively insensitive parameter.
- Peak discharge from the landslide dams attenuates 10 to 20% before reaching the fan apex (Figure G-3). A lack of significant attenuation is expected given the steep channel gradients and the well-confined channel.
- An outbreak flood resulting from a 30 ft high landslide dam largely attenuates before reaching the fan apex.

The results indicate that a landslide dam of significant height (> 60 ft) is required to generate outbreak floods that approach the observed 1989 peak discharge. Smaller dams will not impound sufficient water for a large peak discharge at the fan even in the event of a near instantaneous breach (significant attenuation can occur in the wider reach immediately downstream of the earthflows particularly without a large volume of impounded water).

The results further indicate that the observed peak discharge of the 1989 debris flood is consistent with a potential 100 ft high landslide dam that formed a full breach in approximately 20 minutes. However, Roger Nichols of the USFS visited the two earthflows immediately after the 1989 event and found no evidence of a landslide dam. Nichols postulated that the outbreak flood was the result of a 15 to 20 ft high large woody debris dam that formed at the site of the two earthflows (Nichols, pers. comm.). However, this hypothesis cannot be corroborated by the modelling results of a hypothetical 30 ft high dam, which shows a significantly lower discharge as reconstructed for the 1989 event.

Dam Outbreak Flood at Reach4/5 Transition

To further investigate the potential source of the 1989 debris flood, dam outbreak floods were modelled at the downstream end of Reach 5 – approximately 0.5 miles downstream of the two earthflows. Here, the channel abruptly transitions from a 300 ft wide valley floor to a confined 80 ft wide channel. Large woody debris dams could easily form at this location during flood events at the flow constriction.

There are other sites downstream where large debris avalanches (in the order of thousands of cubic yards) could dam Canyon Creek to a height of several tens of feet.

However, aerial photographs from 1989 and 1991 clearly indicate that the 1989 debris flood was not the result of a large debris avalanche in lower reaches.

Two dam heights were modelled at the Reach 4/5 transition: 20 ft and 33 ft. The latter number is considered a maximum dam height formed by an accumulation of large woody debris. Failure times were estimated to be near instantaneous (2 min and 4 min) given the organic composition of the dams. Modelling results are as follows:

Table G-4
Reach 4/5 Dam Outbreak Flood Modelling Results

Landslide Height (ft)	**Failure Time** (min)	**Breach Width** (ft)	**Peak Discharge at Dam** (cfs)	**Peak Discharge at Fan Apex** (cfs)	**Average Velocity** (ft/s)	**Travel Time** (min)
33 ft high dam impounded volume of 65 acre-ft	2	50	22,400	12,800	23	8
	2	80	25,100	13,900	24	8
	4	50	16,300	11,100	21	9
	4	80	16,900	11,700	22	8.5
20 ft high dam volume of 25 acre-ft	2	50	11,300	7,200	18	11

Note: Peak discharge values are rounded to the nearest one hundred.

Table G-4 shows that outbreak floods from the large woody debris dams attenuate between 30 and 45% by the time they reach the fan apex, which is considerably more than outbreak floods at the site of the two earthflows. This difference can be attributed to near instantaneous breach times and the much higher volume of impounded water for the earthflow location, which result in considerably different flow hydraulics.

The above results for peak flows at the fan apex are still less than the observed peak discharge of the 1989 debris flood (Figure G-4). However, a complicating factor in downstream routing of floods from natural-dam failures is the bulking and debulking of flood waters with debris and sediment as the flood moves down valley (Costa and Schuster, 1988). The potential for flood flow bulking appears to be an especially important process in glacial terrain where easily eroded sediment can be incorporated into the flow (Clague et al., 1985). Because debris floods can have sediment concentrations that approach 35% by volume (Figure A-1), the peak discharge results of Table G-4 could be bulked up by a similar factor, resulting in similar discharge estimates as observed for the 1989 event.

Summary

While it remains unclear what geomorphic process is responsible for the 1989 debris flood (landslides or log jams), the dam outbreak modelling has demonstrated that the required conditions can be replicated. The modelling results indicate a peak discharge of up to **25,000 cfs** at the fan apex for an outbreak flood at the site of the Jim Creek and Bald Mountain earthflows confluence resulting from a 100 ft high landslide dam. Based on all available evidence, this peak discharge has been chosen as the **design event** (500-year return period). This value does not consider the potential for flood flows to bulk up with debris and sediment. However, there are a number of uncertainties associated with the analysis (e.g. breach time, amount of entrainable sediment downstream) such that an estimate of 25,000 cfs is considered to be reasonably conservative.

For lower magnitude debris floods, eye-witness accounts suggest a frequency on a decadal scale (very high probability). Debris floods that occur on a decadal scale most likely occur as a result of large woody debris or debris avalanche dams (10 to 20 feet high) that temporarily form in the narrow confines of Reaches 2 and 3. For very high probability debris floods (20-year return period), it is suggested that peak discharges approach the Q_{100} estimate of approximately 6,000 cfs. Frequency – magnitude relationships of debris floods on Canyon Creek are summarized in Figure G-5.

Higher peak discharge values could be achieved if either earthflow would suddenly surge, as observed at the Thistle earthflow in 1983, when flow rates approached 3 ft/hr. However, previous research indicates that such earthflow surges are relatively rare events (Bovis and Jones, 1992). Large earthquakes are a possible trigger for an earthflow surge, but the available evidence suggests the possibility of such an event may lie outside the 500-year return period considered as the design event for this study (see Appendix C).

Debris Volume

Debris volumes were established by using the flood outbreak hydrographs and multiplying the peak discharges by appropriate sediment volume concentrations (maximum of 35%). Estimates for debris flood volumes are summarized in Table G-5.

Table G-5
Debris Flood Volumes at Canyon Creek

Return Period (years)	**Probability**	**Sediment Volume** (yd^3)
< 20	More than 95%	10,000
20 to 100	95% to 90%	45,000
100 to 500	40% to 90%	150,000

DEBRIS FLOOD SCENARIOS AT CANYON CREEK

Debris flood scenarios have been postulated for three probability categories based on observations and professional judgement (Table G-6).

Table G-6
Scenarios for Different Event Probabilities at Canyon Creek

Probability	Probability of at Least One Occurrence in 50 Years	Process	Estimated Debris Volume (yd^3)	Estimated Peak Discharge (cfs)	Scenario
Very High	more than 90%	Debris Flood	10,000	6,000	A temporary dam (debris flow or log jam) forms in the canyon causing a short lived blockage (minutes).
High	40% to 90%	Debris Flood	45,000	12,000	A debris slide or debris flow reaches the main channel in the canyon section of the creek causing a temporary blockage (up to half an hour).
Medium	10% to 40%	Debris Flood	150,000	25,000	A rotational slide or block slide at Jim Creek earthflow creates a 100 ft high landslide dam. The landslide dam fails by rapid incision causing an outbreak flood.
Volume and peak discharge estimates represent the upper end of return periods.					

Figure G-5 summarizes the estimated flood and debris flood magnitude and frequency relationship at Canyon Creek. The figure is plotted on logarithmic scales for convenience and does not necessarily suggest purely logarithmic relations. The two lines shown on Figure G-5 represent distinctly different creek processes. The line for flood frequency was created by summarizing hydrologic information (Appendix F). The line for debris floods is an integration of modelling results, the 1989 debris flood, and eye-witness accounts of flooding extent. It is therefore associated with some error that cannot be properly quantified. According to Figure G-5, the 1989 debris flood had an approximate volume of 70,000 yd^3.

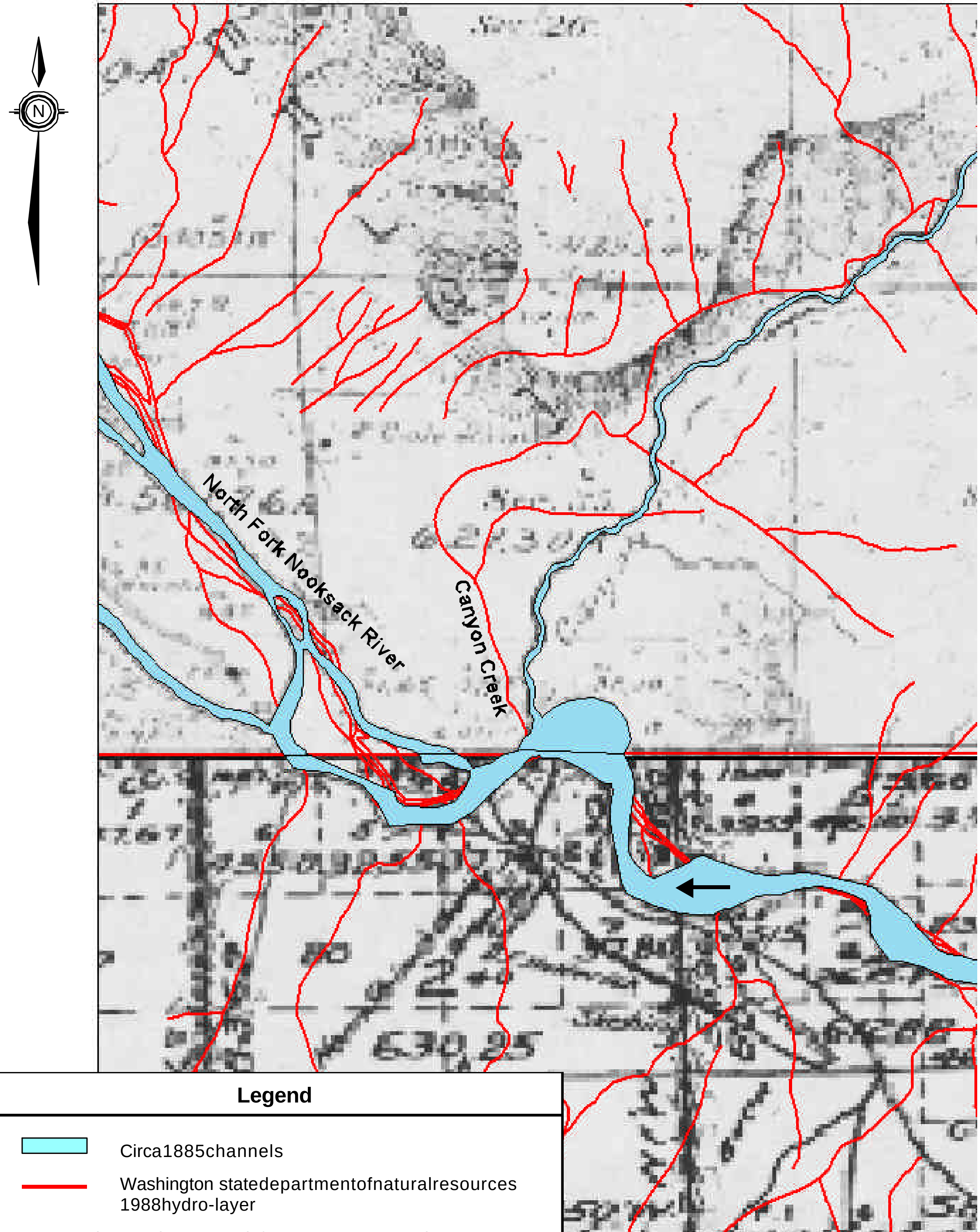
The debris flood frequency curve indicates that the 1989 event has a return period of about 200 years. In contrast, the botanical evidence indicates that the 1989 debris flood was probably the largest event that has occurred during the past 300 years on Canyon Creek. While the two numbers are different, their differences are consistent with the return period concept. A 200-year return period indicates that a debris flood will **on average** be equalled or exceeded once in any 200-year period. A 200-year debris flood does **not** indicate a debris flood every 200 years.

The lines shown on Figure G-5 can not be indefinitely extended linearly into higher return periods because of sediment supply limitations and maximum landslide height for creek blockage.

SUMMARY

This appendix provides a detailed assessment of the debris flood hazard, including estimates of the frequency and magnitude of events. There is strong evidence that the 1989 debris flood was the largest event in the last 300 years and had a return period of approximately 200 years. The peak discharge of the 1989 event has been estimated at 16,100 cfs (455 m^3/s) which corresponds to a total sediment volume of approximately 70,000 yd^3. Field evidence indicates that the 1989 debris flood was the result of outbreak floods from temporary landslide dams.

Various dam outbreak flood scenarios were modelled using FLDWAV, a general flood routing model that is capable of simulating unsteady flow conditions. These modelling results indicate that the design debris flood, which corresponds to a **500-year return period** event (medium probability class), is estimated to have **a peak discharge of 25,000 cfs** (700 m^3/s). The associated **debris volume** transported beyond the fan apex is estimated to **150,000 yd^3**. Lower magnitude debris floods are expected to occur on a decadal scale with suspected events in 1937 and 1962 and known events in 1984 and 1990. While larger debris floods are conceivable, their origin (sudden earthflow surge) is considered to occur at intervals exceeding the return period of 500 years considered in this study.



Legend

Circa1885channels

Washington statedepartmentofnaturalresources 1988hydro-layer

Note: Backgroundcoverage isfromGLOsurveys,circa1885.

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KERR WOOD LEIDAL associates limited CONSULTING ENGINEERS

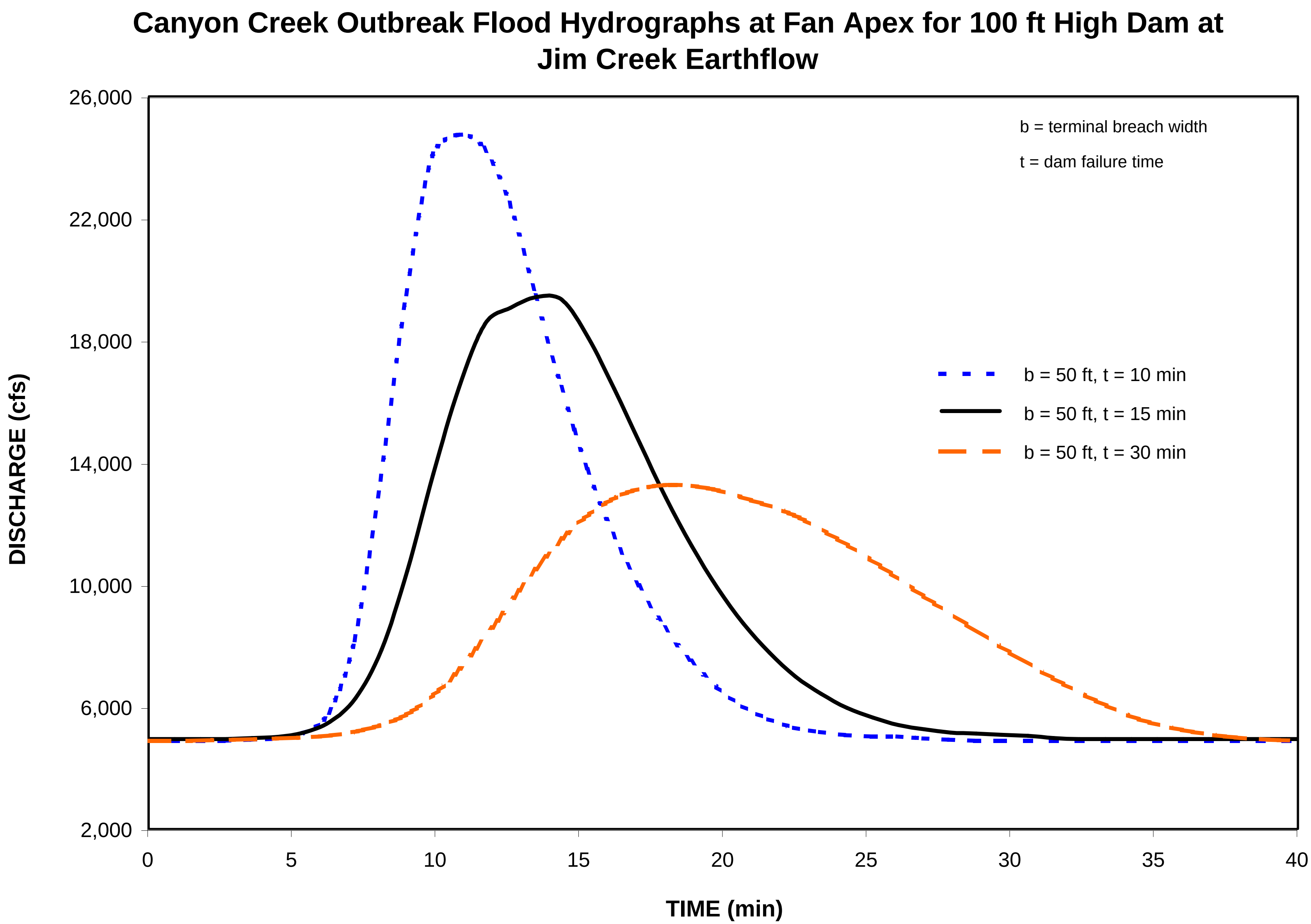
Canyon Creek Alluvial Fan Risk Assessment
Whatcom County Flood Control Zone District

ProjectNo.	Date
2039.001	September2003

NottoScale

1885 Government Land Office Map of Canyon Creek Confluence with the North Fork Nooksack River

Figure G-1



Canyon Creek Outbreak Flood Hydrographs at Fan Apex for 100 ft High Dam at Jim Creek Earthflow
DISCHARGE (cfs)
26,000
22,000
18,000
14,000
10,000
6,000
2,000
0
5
10
15
20
25
30
35
40
TIME (min)
b = terminal breach width
t = dam failure time
b = 50 ft, t = 10 min
b = 50 ft, t = 15 min
b = 50 ft, t = 30 min

Figure G-2

R:\2039-001\fldwav\results.xls

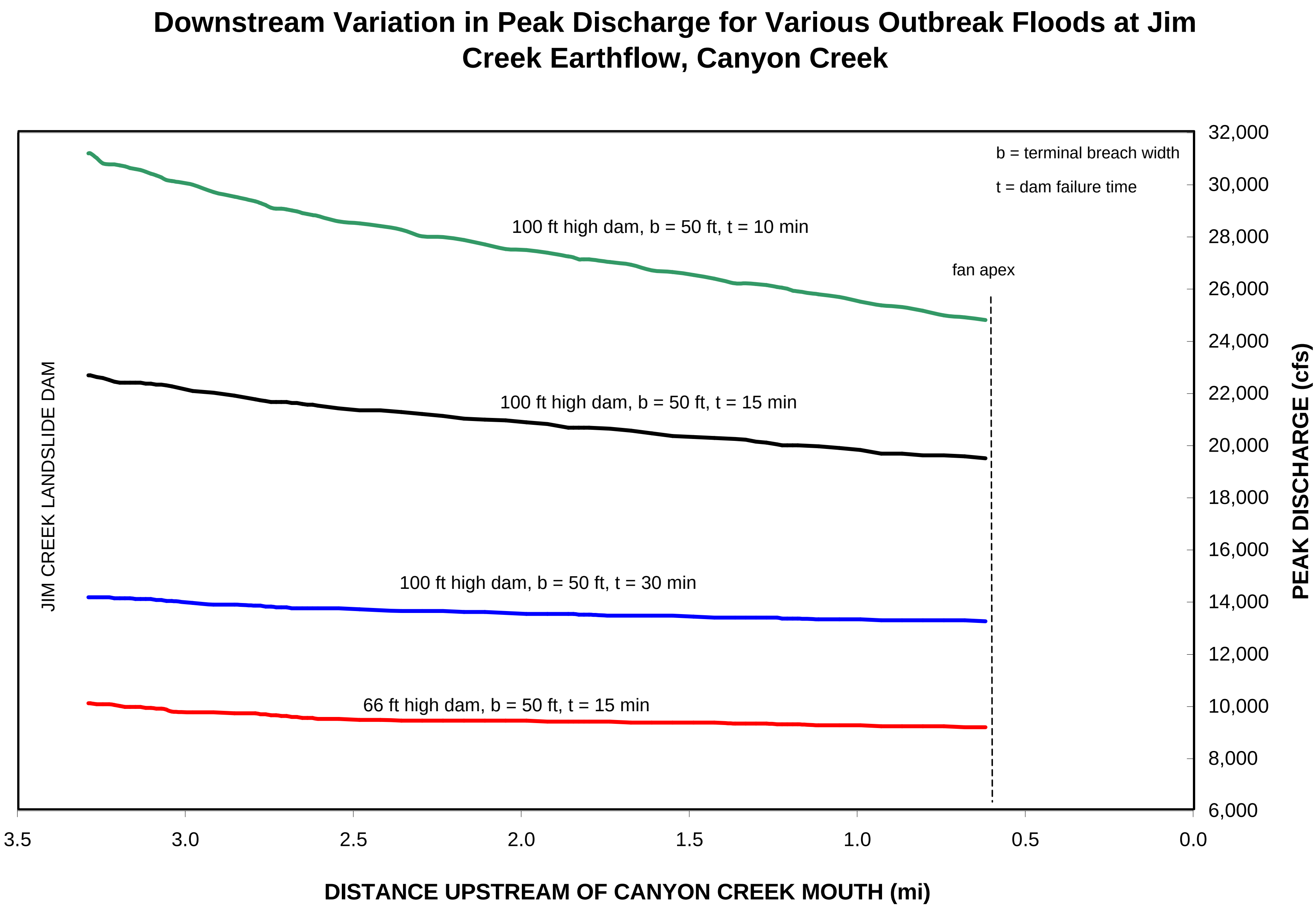


Figure G-3

Canyon Creek Outbreak Flood Hydrographs at Fan Apex for a Large Woody Debris Dam at Reach 4/5

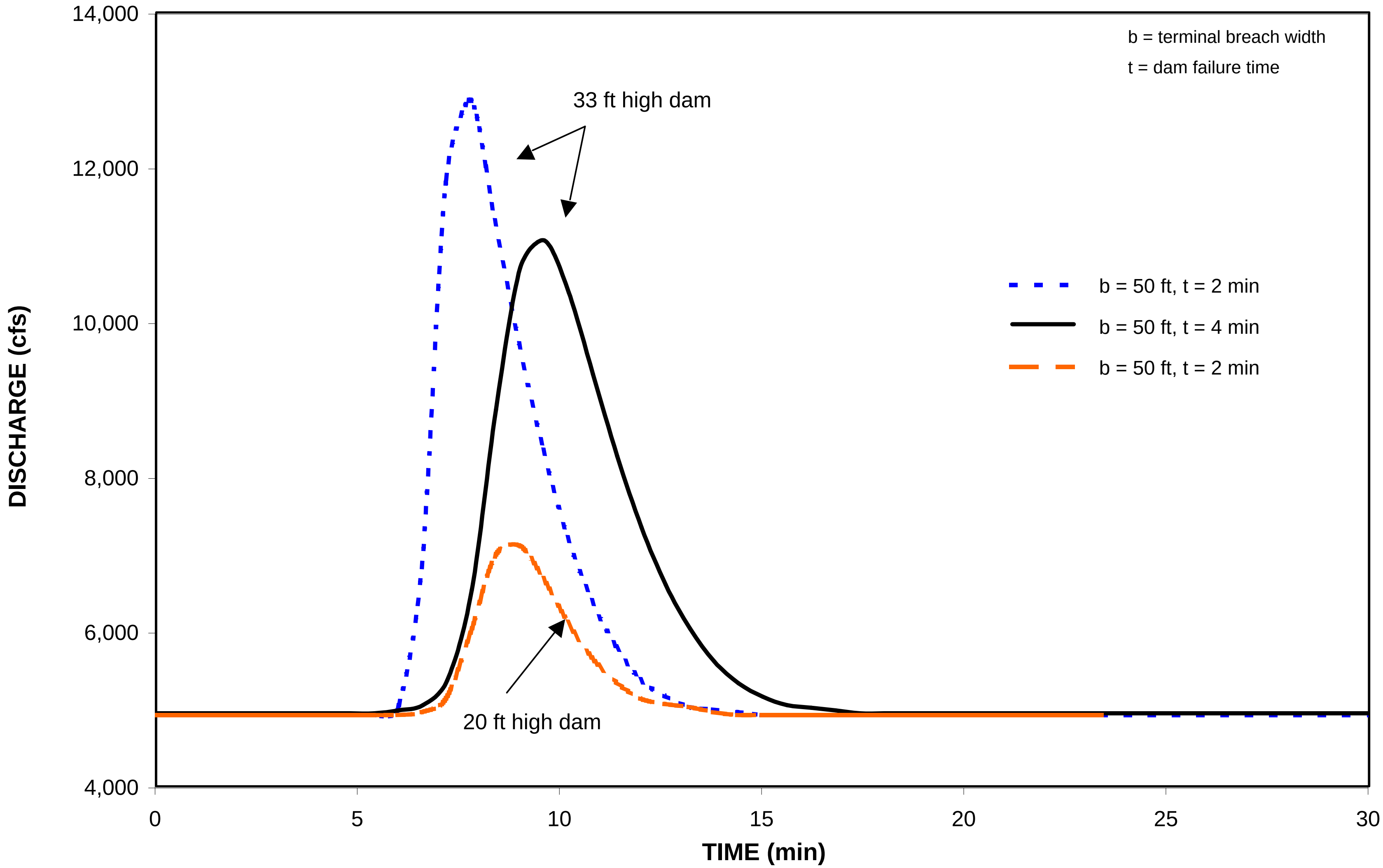
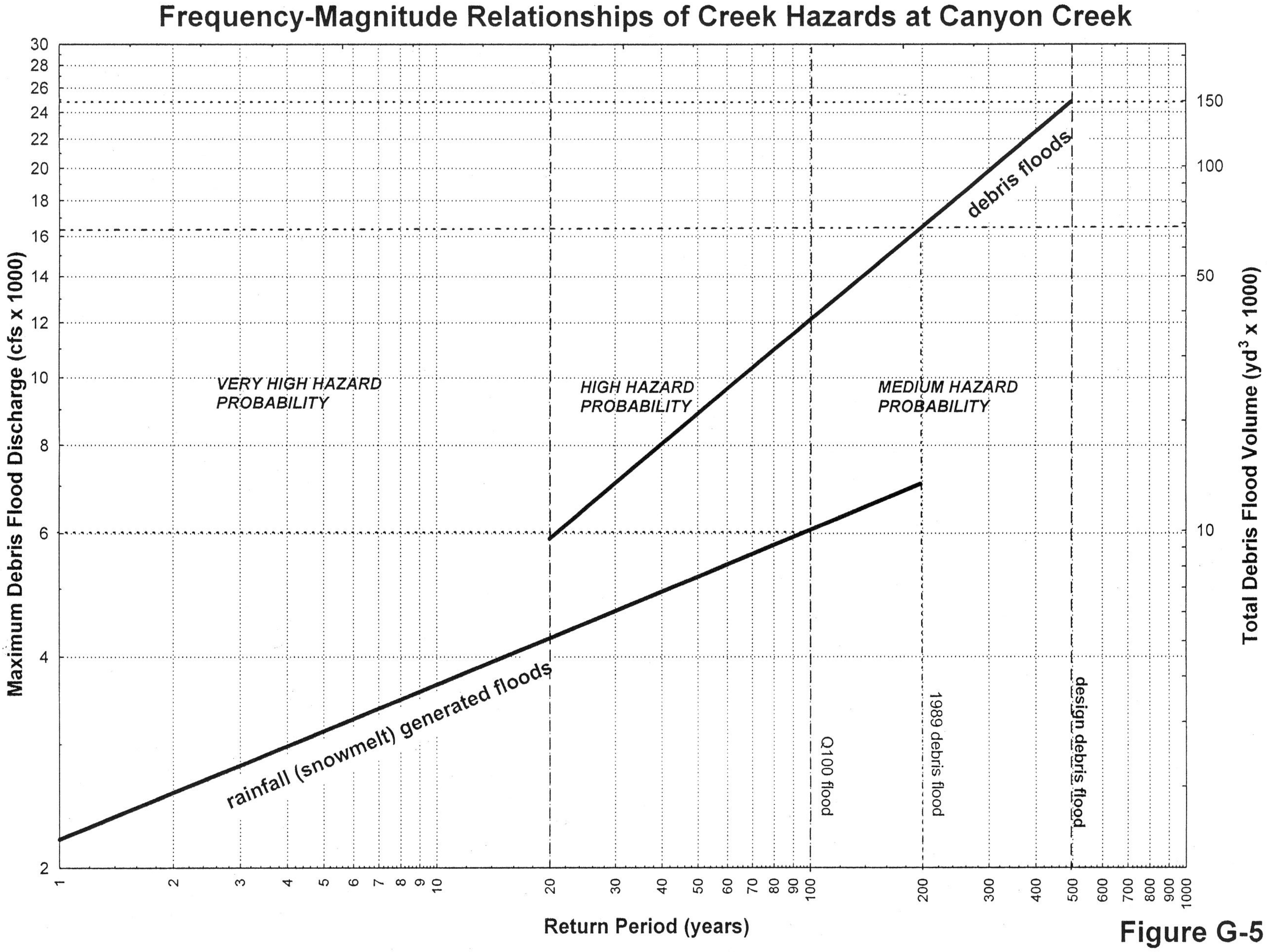


Figure G-4



Frequency-Magnitude Relationships of Creek Hazards at Canyon Creek
Maximum Debris Flood Discharge (cfs x 1000)
Total Debris Flood Volume (yd³ x 1000)
Return Period (years)
VERY HIGH HAZARD PROBABILITY
HIGH HAZARD PROBABILITY
MEDIUM HAZARD PROBABILITY
debris floods
rainfall (snowmelt) generated floods
Q100 flood
1989 debris flood
design debris flood
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
10
50
100
150
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
1000

Figure G-5