Sediment Source Mapping, Detailed Channel Assessment, and Reconnaissance Sediment Budget for Williams Creek for the Period 1949 to 2001

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1 INTRODUCTION

1.1 Background

This report was commissioned by the Lakelse Lake Sockeye Recovery Plan Committee in Terrace, B.C. The study was co-funded by Fisheries and Oceans Canada (DFO), Prince Rupert, B.C.; the Lakelse Watershed Society, Terrace, B.C.; B.C. Timber Sales (BCTS), Ministry of Forests, Terrace, B.C. and Forest Sciences Section, B.C. Ministry of Forests, Smithers, B.C.

The Lakelse watershed sustains very high fisheries values and is one of the premier watersheds of the Skeena system. It is a major producer of coho, sockeye, and pink salmon (Skeena Fisheries Commission 2003). The very high sockeye values within the Lakelse watershed stem from the superb spawning and rearing habitat (DFO 2005) in the lower reaches of the main tributaries to Lakelse Lake, namely Williams, Sockeye Hatchery, and Scully Creeks.

Sockeye escapements to Lakelse Lake have been low in recent years and appear depressed relative to historic levels. Based on visual escapement surveys for Lakelse Lake between 1992–2003, the Lakelse Lake sockeye stock has experienced a 92% decline over the last three cycles (DFO 2005). Numerous assessments of Lakelse Lake water quality and lake habitat have been conducted over the past 30 years, including studies of sediment loading, landslide dynamics, watershed hydrology, and restorative enhancement options (DFO 2005). Based on the results of these studies, it is thought that spawning and incubation habitat are most limiting for sockeye production in the Lakelse watershed.

Williams Creek and its lower tributaries, Sockeye Creek and Blackwater Creek, typically receive 80% of Lakelse sockeye spawners (DFO 2005), which use the spawning habitat on the alluvial fan in the lower three reaches of Williams Creek. A previous study (DFO 2005) has found the alluvial fan has a somewhat unstable channel that receives large amounts of sediment from the unconfined third reach and from bank erosion in the fourth reach. Recent watershed assessments rated the overall habitat components in Williams Creek drainage, such as channel, fish habitat, riparian, hillslope, and road conditions as poor (Reese-Hanson 2001; DFO 2005).

The Lakelse Lake Sockeye Recovery Plan committee aims to gain a better understanding of how channel changes on the alluvial fan and sediment input from the hillslopes may have affected spawning habitat in Williams Creek. The committee is also interested in restoration projects to improve sockeye spawning success in the historically important lower reach of Williams Creek.

This study has two components: (1) sediment source mapping and reconnaissance sediment budgeting upslope of the alluvial reaches used as spawning habitat in the

Williams Creek valley, and (2) detailed channel assessment of the alluvial lower stream reaches. The sediment source mapping is intended to add to our understanding of current and recent hillslope processes contributing to sediment input to the stream network, sediment movement through the stream system, and delivery to the lower stream reaches. The detailed channel assessment of the alluvial lower reaches of Williams Creek is intended to provide information about past channel changes that may have impacted spawning habitat. An understanding of past processes and current conditions is required to form the basis for planning restoration projects to enhance spawning habitat in the alluvial reaches.

1.2 Objectives

Objectives of the sediment source mapping were to identify the origin, type, and timing of sediment mobilized on the hillslopes of the Williams Creek valley and to depict the sources on a 1:20,000 scale map. Objectives of the reconnaissance sediment budget were to provide an estimate of sediment volumes mobilized on the hillsides, routed through the channel system, and delivered to the alluvial reaches.

The objectives of the channel assessment were to relate changes in channel morphology to changes in sediment supply delivered to the lower 6 km of Williams Creek, and to investigate the subsequent transport of sediment through the fan to Lakelse Lake.

2 STUDY AREA

The study area is located in the Lakelse watershed, approximately 20 km south of Terrace, B.C., in the Kalum Forest District in northwestern British Columbia. Williams Creek is the major tributary to Lakelse Lake.

The study area comprises the Williams Creek valley and the alluvial stream reaches (Figure 2-1) on the fluvial fan at the mouth of Williams Creek valley. The mountainous valley of Williams Creek covers an area of 17,002 ha. Including the area covered by the large alluvial fan and the drainage basins of the two tributaries, Sockeye Creek and Blackwater Creek, the total watershed area of Williams Creek is 21,007 ha.

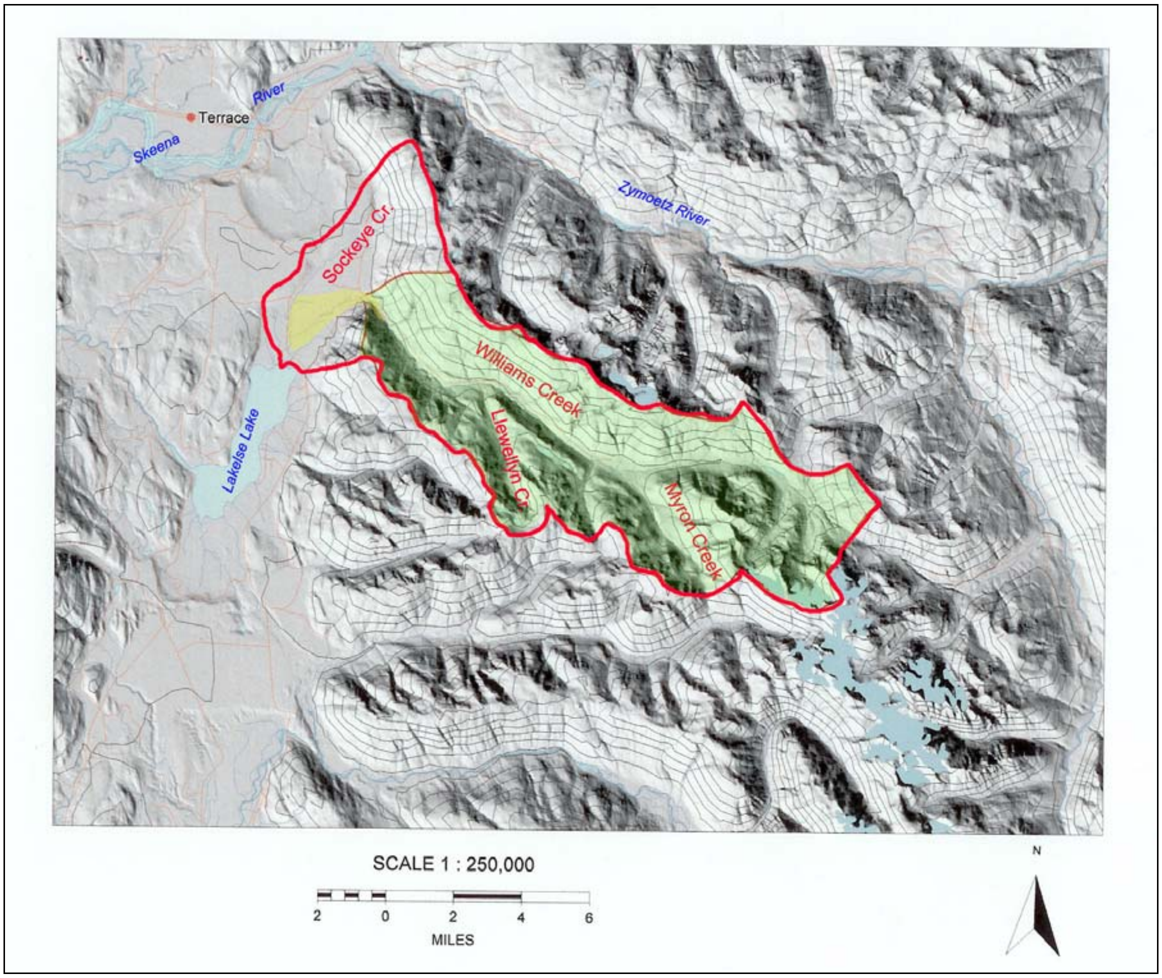

Figure 2-1. Study area overview map. Green shading: area covered by sediment source mapping. Yellow shading: area covered by detailed channel assessment.

2.1 Physiography and Geology

The Williams Creek drainage is located in the Kitimat Ranges, along the eastern margin of the rugged Coast Mountains (Holland 1964).

Williams Creek originates in a high-elevation periglacial valley surrounded by steep alpine ridge crests 1800 to 2040 m above sea level (asl). There is a small residual glacier on steep valley headwalls. The upper end of the main valley, at 700 m asl, is marked by the confluence of several headwater tributary streams. From there, the narrow main valley extends more or less straight northwesterly for 25 km, steeply incised between forested valley walls, alpine ridges, and cirques, alternating with moderately steep to subdued alpine terrain at 1600 to 1800 m elevation. In the lower 12 km of the Williams Creek valley, the main channel is confined in a bedrock-controlled canyon, incised 20–30 m into the narrow valley floor. In the lower two kilometres of the valley, the channel becomes partially unconfined on a narrow floodplain and forms a gravel bed channel. Where the valley opens into the wide valley flat of Kitsumkalum Trough, at 140 m asl, Williams Creek has built a 4-km long alluvial fan. A third of the fan area is currently active. At the distal end of this fan, Sockeye Creek, a low gradient tributary fed mostly by run-off from the forested steep open slopes bordering Kitsumkalum Trough, enters Williams Creek from the north. Blackwater Creek enters from the west. A 2-km long, very low gradient reach connects the alluvial fan with Lakelse Lake, at 80 m elevation.

Bedrock (Figure 2-2) in the western (lower) part of the Williams Creek valley consists of granodiorite of late Cretaceous and Tertiary age (Ministry of Energy, Mines and Petroleum Resources 2005). These light-coloured, medium to coarse-grained rocks intruded into older volcanic rocks, the Telkwa Formation of the Jurassic Hazelton Group, which underlies the eastern (upper) part of the valley. Rocks of the Telkwa Formation are typically red, maroon, and grey-green, fine-grained to aphanitic volcanic breccias, tuffs, and flows, of basaltic to rhyolithic composition (Tipper 1976). A narrow band of older rocks, limestone, marble, and calcareous sedimentary rocks is exposed on the alpine ridge along the north side of the valley, between the granodiorite and the volcanic rocks of the Telkwa formation. These sedimentary rocks are of Devonian to Permian age and are overthrust onto the volcanic rocks of the Telkwa formation (Ministry of Energy, Mines and Petroleum Resources, 2005).

Bedrock formation was followed by tectonic uplift of the Coast Mountains during the Tertiary period. Erosional dissection of the uplifted surface accelerated, and with recurrent glacial erosion and deposition during the Pleistocene epoch, the major valleys were modified. Glacial erosion in the mountains increased local relief and ruggedness (Maynard 1999).

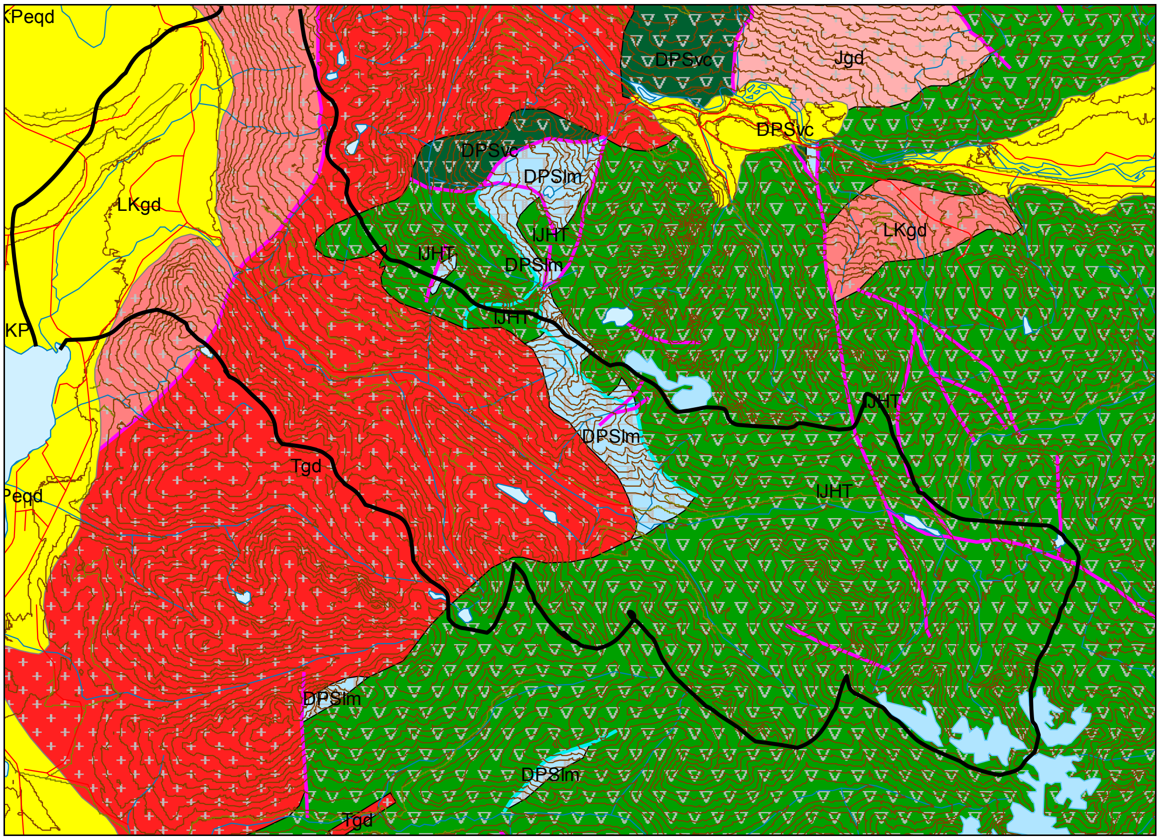

Figure 2-2. Bedrock Geology in Williams Creek. DPSlm: Stikine Assemblage of Devonian to Permian age; limestone, marble, calcareous sedimentary rocks. lJHT: lower Jurassic Hazelton Group -Telkwa Formation; calc-alkaline volcanic rocks. LKgd: late Cretaceous unnamed granodioritic intrusive rocks. Tgd: Tertiary unnamed granodioritic intrusive rocks. Yellow: Quaternary sediments. Williams Creek watershed outline shown in black.

Deposition of surficial material in the Williams Creek valley mostly covered lower valley walls. Thick deposits of bouldery–gravelly glaciofluvial material were deposited on valley wall toe slopes. Similarly textured colluvial material was deposited on lower and mid-elevation valley walls, most likely from periglacial debris flows and debris slides (pers. comm., D. Maynard, 1998). Lower slopes of tributary valleys, such as Llewellyn Creek (Sub-basin 16), contain finer-textured loamy to clay-loam glacial till deposits. This is also found at Myron Creek (Sub-basin 29) and Sub-basin 40. Upper elevations are characterized by a high proportion of bare bedrock and thin colluvium (Maynard 1999).

2.2 Flood History

Williams Creek is an ungauged watershed, although streamflow was monitored in 1954 (WSC station 08EG008). We reviewed streamflow records and historical accounts of flood events for the Terrace–Kitimat region to approximate the timing and size of flood events in Williams Creek. A complete listing is given in Appendix 2, Table 10-3. The most notable floods in the past century that likely had significant impacts on Williams Creek occurred in 1917, 1935, 1966, 1974, 1978, 1990, and 1991.

The number of flows exceeding bankfull discharge ($Q_{1.5}$) was estimated from nearby gauged watersheds to determine the number of sediment transport events likely to have occurred in Williams Creek (see Andrews and Nankervis 1995). Discharge records from Little Wedeene Creek, Hirsch Creek, Kitimat River, and Exchamsiks Creek were selected for analysis since the flood regimes of these watersheds are dominated by winter rainstorms or rain-on-snow events, with occasional large spring floods. The flood statistics of these watersheds were assumed to be similar to those of Williams Creek, given their relatively close proximity to one another in the North Coastal Mountains hydrological zone. $Q_{1.5}$ was estimated for each watershed with a log-Pearson Type III distribution with results given in Table 2-1.

Table 2-1. Frequency of $Q_{1.5}$ in watersheds near Williams Creek

Watershed	Period of record	$Q_{1.5}$ (m^3/s)	No. flows > $Q_{1.5}$
Hirsch Creek	1966–2003	146	41
Kitimat River	1964–2003	843	40
Little Wedeene Creek	1966–2003	109	50
Exchamsiks Creek	19622003	291	44

Cumulative departure plots of the annual maximum daily discharge of the four nearby gauging stations used above and maximum annual 12-hour precipitation for Terrace are in Figure 2-3. Assuming that changes in the record reflect broad, regional changes in climate and not local changes in land use or streamflow generation, it is assumed here that Williams Creek followed a similar pattern to the other stations over the entire period of record (1913 to 2003). Inflection points between broad and sustained changes in the record are assumed to indicate points where river behaviour may have changed as well. The analysis shows nine distinct hydrologic periods for the Williams Creek region since 1913. Of relevance to this study, the magnitude of discharge events was generally below average from 1935 to 1955, and remaining above average until 1966. The record fluctuated from 1967 to 1993 with four relatively short phases (below average discharges from 1967 to 1973; above average from 1974 to 1978; below average from 1979 to 1986; above average from 1987 to 1993). Currently, Williams Creek region has been in a period of below average discharge since 1994.

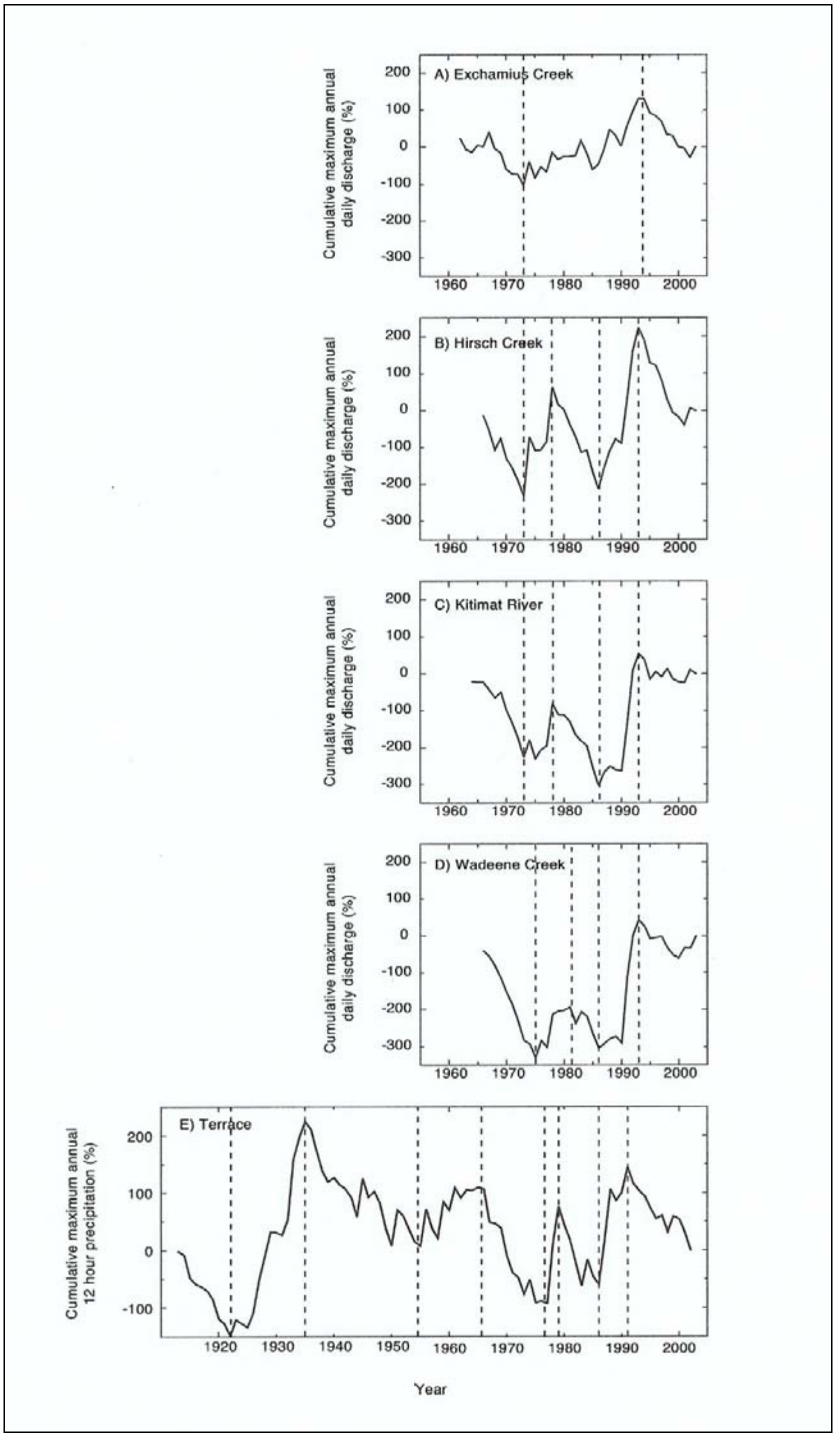

Figure 2-3. Cumulative departure plots of maximum annual daily discharge for Exchamsiks Creek, Hirsch Creek, Kitimat River, Wedeene Creek, and cumulative departure plot for maximum annual 12 hour precipitation for Terrace. The dashed lines delimit periods of broad regional (and generally uniform) climate conditions. Periods with a positive trend indicate flood flows and/or intense precipitation events were generally above average in magnitude, while periods with a negative trend indicate flood flows and/or intense precipitation events were generally below average in magnitude.

2.3 Resource Use and Development History

Resource use and development history is summarized here based on a review of forest cover maps and air photos used in this study. Development in the Williams Creek watershed began on the fan prior to 1949 with construction of what is now known as Old Lakelse Lake Drive with both a bridge and a ford crossing through the channel in upper reach 3, at the fan apex. There was a cutblock along the right bank of the reach, likely harvested in the late 1930s or early 1940s, judging by the condition of the forest cover in 1949. Between 1949 and 1960, some logging occurred adjacent to reach 4 and included a portion of the valley bottom. Highway 37 was under construction during this period, with a ford crossing in upper reach 1 (the bridge was completed in 1963). A fish fence was built across lower Williams Creek in 1950, and a small fish hatchery was in operation from 1962 to possibly 1967 (Skeena Fisheries Commission 2003).

Most forest development (Figure 2-4) on the fan occurred between 1960 and 1975, with streambank logging along reaches 1 through 3. This included roads and trails through the riparian forest and wetlands, occasionally crossing into the active channel. Recent forest harvesting (1975–2001) has been limited to a small area along reach 3, often in association with residential development. Overall, development on the fan has been relatively extensive, with the largest changes to forest cover occurring between 1960 and 1975. Although not all streambanks were initially logged in any given period, the channel often occupied the previously logged riparian area, as the channel shifted laterally across the fan surface, following the path of an old road or trail on at least one occasion.

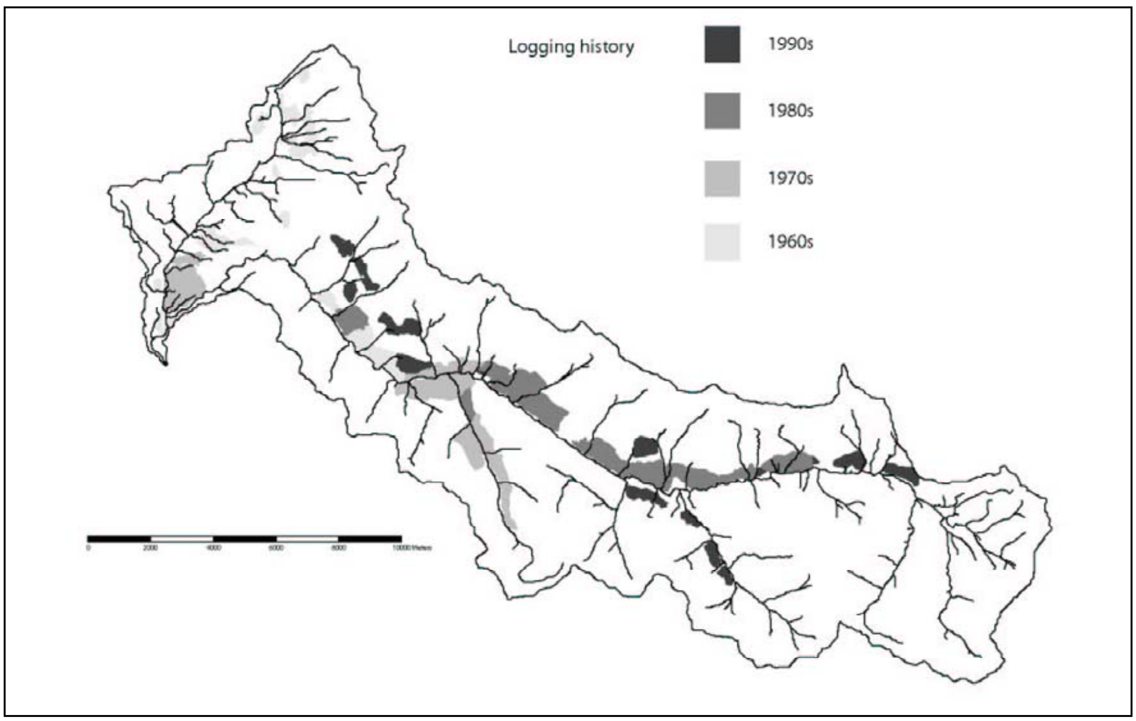

Figure 2-4. Logging history in Williams Creek watershed, 1960-2000

Within the Williams Creek valley, in the mountainous area upstream of the old Lakelse Lake Highway crossing, development started just prior to 1960. Approximately 2.3 km of logging road was built, mostly on the alluvial valley floor. By 1968, a small clearcut had been logged just south of sub-basin 3, at the upper end of reach 4.

By 1981, forest road construction and clearcut logging had accessed the north side of lower Williams Creek valley and Llewellyn Creek. Extensive clearcutting had taken place along the lower slopes of Llewellyn Creek valley.

By 1988, 37 km of logging road were built in the Williams Creek valley and its mountainous tributaries.

By 2001, some of the branch and in-block roads built in the 1970s and 1980s had been deactivated and started to become overgrown. An additional 72 km of logging road had been built since 1988, bringing the total length of road (active, inactive, and de-activated) to 111 km.

3 METHODS

3.1 Sediment Source Mapping

For the purpose of conducting a sediment source survey based on air photo interpretation, a sediment source was defined as a site of exposed mineral soil visible on 1:30,000 air photos. This would typically include landslides, debris flows, larger stream bank and gully wall failures, and ravelling bedrock cliff faces. Sediment is entrained at the source by water, snow or gravity, and transported downslope to a valley bottom stream.

3.1.1 Information sources and materials

The following sources of information were used for the sediment source mapping:

- Black and white aerial photographs, taken in 2001, 1988, 1968, and 1949; supplemented by air photos taken in 1939 and 1981 (Appendix 1, Table 10-1)
- TRIM topographic base maps for BCGS map sheets 103I. 038, 039, 040, 048, 049, 050
- Bedrock geology maps (Ministry of Energy, Mines and Petroleum Resources 2005)
- Quaternary geology map (Clague 1984)
- Terrain, terrain stability, and surface erosion potential mapping at 1:20,000 (Maynard 1999).

3.1.2 Field investigation

During the summer of 1998, as part of terrain and terrain stability mapping by Denny Maynard and Irene Weiland, 2–3 days of field work was conducted along roads and lower slopes in the Williams Creek valley and Llewellyn Creek and Myron Creek drainages (Maynard 1999).

On September 16, 2005, Jim Schwab and Irene Weiland took a 2-hour reconnaissance helicopter flight, covering the mid- and upper Williams Creek valley and headwater tributary basins. Field observations were made of significant sediment sources and documented with oblique aerial photos.

On July 20, 2006, Irene Weiland took a half-day field trip into the lower part of Williams Creek valley and to Williams Creek stream crossing sites.

Additional information about the main stem channel in lower Williams Creek valley was gained from conversations with the kayaking community (Shane Spencer, Terrace, BC).

3.1.3 Air photo interpretation

The sediment source mapping covered the Williams Creek valley and the mountainous drainage area upstream of Williams Creek fan. The valley was divided into 33 sub-basins (numbers between 1 and 40), capturing tributary streams and gully systems that drain into the main stem of Williams Creek.

Sediment sources in each sub-basin were stereoscopically identified on 1:30 000 black and white aerial photographs taken in 2001, and were delineated using point and line symbols.

To capture the historic development in sediment source activity, older air photos were reviewed. Complete air photo coverage for the valley was available for 1949 (1:30 000), 1968 (1:30 000), 1981 (1:60 000), 1988 (1:20 000), and 2001 (1:30 000). Some air photos taken in 1936 and 1939 were also reviewed.

3.1.4 Digital map preparation

The digital mapping of sediment sources was completed by Chartwell Consultants Ltd. of North Vancouver, B.C. The delineated sediment source features were transferred from the air photos to the 1:20 000 TRIM map base using mono-restitution. The sediment source symbols were digitally captured in IGDS format and translated into Arc/Info. Map production was completed in Arc/Info. Each sediment source was assigned a 2-digit feature code, reflecting its morphologic characteristics, activity and connectivity. The feature code was recorded in the database file linked to the digital mapping, and was used to build the sediment source map legend (Figure 3-1).

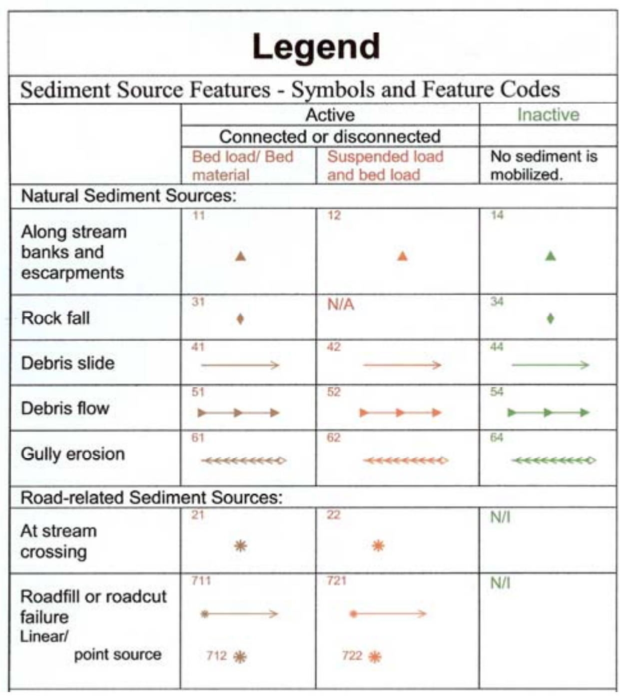

Figure 3-1. Sediment source map legend

3.1.5 Sediment source catalogue

We described each sediment source with respect to location, geomorphic characteristics, and activity status. These attributes were compiled in the sediment source catalogue, prepared as a Microsoft Excel spreadsheet, which is available as a separate file (digital format only). The following attributes were described for each sediment source: (1) location, (2) geology and terrain information, (3) geomorphic site description for the initiation zone, and (4) sediment source status information.

Similar mapping and cataloguing of sediment sources was completed for the Zymoetz River watershed (Weiland et al. 2000), for several watersheds in the Kispiox drainage (Date and McCully Creek watersheds (Weiland 1998), Nangeese River watershed, (Weiland 2002), Kispiox River watershed (Weiland 2002)) and Deep Creek watershed in the Kalum Forest District (Weiland 2005).

3.1.5.1 Location

UTM co-ordinates, map sheet number, and watershed sub-basin number provide information about sediment source location. UTM co-ordinates on linear features refer to the starting point of the map symbol.

3.1.5.2 Terrain information

Landscape position, vegetation cover, bedrock geology, surficial geology (including parent material and implied soil texture (Howes and Kenk 1997; Maynard 1999), geomorphic process activity, slope steepness, and drainage (where available) were described for the initiation zone of each sediment source. The information was collected from aerial photographs, existing terrain mapping, or air calls from the helicopter overview flight. The information was catalogued using the Terrain Classification System for British Columbia (Howes and Kenk 1997).

3.1.5.3 Geomorphic site description

The geomorphic site description included characterization of the type of mass wasting; the feature location such as gully wall, open slope. or stream bank; and the sediment source texture and sediment transport mode. Depending on its soil texture (coarse or fine), a sediment source may be contributing to bedload[1] or to suspended load[2] in downstream reaches. Soil texture was determined from existing terrain information. Colour coding on the 1:20 000 sediment source map reflects the dominant texture of a sediment source as coarse- (colluvium, fractured bedrock) or fine-textured (glacial till, lacustrine deposits).

[1] Bedload is transported along the bed of the channel during high stream flow events. Bedload typically includes medium- to coarse-textured sand, pebbles, and cobbles. Blocks are transported in colluvial processes such as debris flows and debris floods.
[2] Suspended sediment is transported in suspension. It typically includes clay, silt, and fine sand. During receding flow levels and decreasing flow velocity, suspended sediment particles are deposited in pools, wetlands, slow-moving stream reaches, and on lake bottoms. As flow levels recede, sand size particles drop out of suspension first, while clay particles may stay in suspension for one to several days.

3.1.5.4 Sediment source status information

A) *Sediment source activity:* Sediment source activity since 1949 was determined from 1:30 000 and 1:21 000 scale air photos, supported with evidence from helicopter observations in 2005. The sediment source map shows sediment sources that were active in 1949, 1968, 1988, or 2001 in red or brown, and inactive sediment sources in green. In the database, sediment sources were classified as either active or inactive for 1949, 1968, 1988, and 2001. Definitions of active and inactive status are given in Table 3-1.

Table 3-1. Description of sediment source activity status

Status	Description
Active (A)	The air photo shows evidence of a recent landslide event or ongoing gully erosion. Initiation zone and transport zone of debris slides and debris flow tracks are freshly scoured, and bare of vegetation. A deposition zone may be visible with evidence of recent disturbance.
Inactive (I)	The air photo shows evidence of past disturbance and erosion along the initiation zone and transport zone of debris slides and debris flow tracks. Sites are mostly revegetated, or are beginning to revegetate. This includes tracks obscured by forest canopy, some of which may sporadically still be producing small amounts of sediment.

B) *Connectivity:* The connectivity of a sediment source to a valley-bottom stream was determined from air photos, supported by helicopter-based air calls and oblique air photos. A sediment source was described as either connected or disconnected in 1949, 1968, 1988, and 2001. A sediment source was considered connected when a non-vegetated slide track or channel was visible on the air photo or from the helicopter between the sediment source and the valley-bottom stream.

3.1.6 Reconnaissance sediment budget

Based on the estimated size of the sediment source and the timing of its activity, the sediment volume generated over 52 years (1949–2001) was estimated for sediment sources classified as active and connected.

A sediment budget can be expressed for a given area with the following term:

$O = I - \Delta S$,

where O is sediment output, I is sediment input, and ΔS is the change in sediment storage.

3.1.6.1 Sediment input

The amount of sediment generated at each source was estimated from air photo measurements following a methodology described by Campbell and Church (2003). The volume of sediment generated at each source was calculated as the product of slope length, erosional depth (measured perpendicular to the slope) and track width along the initiation-transport zone of the sediment source. The following assumptions were made when estimating length, width, and depth from the air photos:

Length of the feature was marked during air photo interpretation. Slope length was measured in ARC/Info. Length for initiation zone (IZ) and transport zone (TZ) were then determined assuming a 1:3 proportion for IZ:TZ length (Campbell and Church 2003).

Width was estimated during stereoscopic air photo interpretation and measured to the nearest 10 m.

Scouring depth was assigned based on several assumptions:
(1) Slope failure typically occurs along the weathering front in surficial materials or at the contact with the underlying competent bedrock. Depth of slope failure can be assumed to be equal to the average depth of the weathering front (1 m in glacial till and glaciofluvial material) or, on shallow colluvial sites, the average depth to bedrock (0.5 m or less).

(2) Lower valley walls tend to have deeper surficial material than upper valley walls and alpine sites, due to glacial and post-glacial deposition.

(3) The majority of sediment volume is produced during the initial failure of the sediment source or, in the case of sediment sources with recurrent activity, following a period of recharge. Low-activity sites, on the other hand, are non-vegetated and appear active on the air photos, but show little change over the surveyed period of time, and may have produced little sediment during the observation period.

(4) A scouring depth of 1 m was found to be representative by Campbell and Church, (2003), and is consistent with the average weathering depth in the Terrace area. In shallow colluvial soils on upper valley walls and alpine areas, scouring depth along the initiation zone was assumed to be 1 m. This is consistent with field observations made by the author in the Terrace area. In deep glacial deposists, scour depth in the initiation zone was assumed to be 2 m. In the transport zone, depth was assumed to be half the depth of the initiation zone. These default depth assumptions were adjusted where helicopter observations and oblique photos revealed deeper deposits.

3.1.6.2 Sediment storage and sediment output

A portion of the mobilized sediment is typically deposited in a deposition zone on the open slope or at the mouth of a gully, and does not reach the valley-bottom stream. Deposition zones were identified on air photos (but not consistently delineated) and included the following landscape elements: fans, cones, and slopes less than 10–12° (20–22%). Following the methods described by Campbell and Church (2003), the amount of sediment transported to the stream network was expressed as a fraction (η = 0.1, 0.33, 0.66, or 1.0) of the sediment input generated in the initiation-transport zone. The throughput factor η reflects the ratio of the initiation-transport zone length to the distance between the deposition zone and the stream. Where the initiation-transport zone was long and the distance short, the ratio was large and the throughput factor was 0.66 or 1.0. These default assumptions were adjusted where more detailed evidence was available from helicopter observations and oblique photos.

3.1.6.3 Sediment output variations since 1949

In order to track sediment output variations over the decades since 1949, the estimated sediment output volume was assigned proportionally to one of four observation periods. Observation periods were defined by the intervals between the years of air photograph coverage: pre-1949, 1949 to 1968, 1968 to 1988, and 1988 to 2001 (to 2005 where data was available). The assignment was based on the following assumptions, simplifications, and considerations:

The majority of sediment at each source was mobilized and delivered to the stream network during the initial mass wasting event. Subsequently, sediment sources were active at a much slower rate for two to four or more decades. Some debris flow tracks are subject to recurrent activity with a relatively low sediment yield, where there is little time for sediment recharge between mass wasting events.

Sources with an initial event between 1949 and 2001 were catalogued as “new activity.” For these, 70–80% of the estimated output volume was assigned to the observation period in which the initial event occurred. The remaining 20–30% was proportionately assigned to subsequent observation periods, considering the number of years during each air photo interval. Sources that appeared continuously active since 1949 with little apparent change were considered long-term sources with low activity. It was assumed that the initial event had taken place prior to 1949. In these cases, 70% of the estimated sediment output volume was assigned to the pre-1949 period, and 30% to subsequent observation periods.

3.1.6.4 Accuracy of sediment volume estimates

Sediment volume estimates were made based on air photo interpretation of sediment source length, width, and assumed default scour depths in the initiation and transport zones of each feature. Accuracy of volume estimates has the following limitations:

<u>Air photo scale</u>: Most air photos had a nominal scale of 1:30 000 (1949, 1968, 2001 series). At this scale, small point features on steep streamside escarpments or gully sidewalls may be partially obscured by the forest canopy or by the effects of air photo parallax. Thus, their size or their level of activity may be underestimated, or they could be overlooked altogether.

<u>Air photo intervals:</u> The air photo series were taken 18–20 years apart. Smaller point source failures and roadside failures which were repaired and stabilized shortly after they occurred may no longer be apparent on the subsequent air photo series.

<u>Geometric measurements:</u> Measurement of linear feature length depends on the photo typing and the accurate transfer to the digital map file. Photo typing typically has an accuracy of 0.3–0.5 mm, due to the width of the marking pen used. At 1:30 000 scale, the accuracy of feature length is ± 9–15 m, or 5–10% for a 200 m-long feature. Width measurements using a ruler had a typical inaccuracy of 0.3–0.5 mm, or 9–15 m on the ground. This translates into a 30–50% inaccuracy for a 30 m-wide linear feature. Point features on the air photos were typically 0.5–1.5 mm wide and 1–2 mm long, the equivalent of 15–45 m × 30–60 m on the ground. Given an accuracy of 0.3–0.5 mm, or ± 9–15 m on the ground, measurements for a 15 m × 30 m point source may have an inaccuracy of ± 50%.

<u>Scour depth</u> estimates were applied as default depths equivalent to average regional weathering depths of 0.5, 1, or 2 m, depending on macro-slope position, assumed material type, and location in the initiation or transport zone. Actual scour depth may be 2–3 times greater, depending on sediment recharge in gullies and debris flow tracks since the last event. On the other hand, steep gully channels subject to frequent run-off events or snow avalanches may have a shallower scour depth. At point sources and small debris slides on stream bank escarpments, actual scour depth varies greatly based on site conditions. The estimate of scour depth may have an inaccuracy of ± 50–200%.

In summary, the two largest factors contributing to the inaccuracy of volume estimates are deviations from the assumed scour depth and air photo scale. Volume estimates given for the reconnaissance sediment source budget were considered accurate within the order of magnitude.

3.2 Photogrammetric Channel Survey

3.2.1 Image block triangulation

The lower 6 km of Williams Creek were surveyed from air photos acquired in 1949, 1960, 1975, 1988, and 2001 using Leica Photogrammetry Suite (LPS) software. An inventory and description of all images used in the analysis is given in Appendix 1 (Table 10-2). Interior orientation parameters (focal length, principal point, and radial lens distortion) for each camera used to acquire imagery in 1975, 1988, and 2001 were obtained from calibration reports provided by the Base Mapping and Geomatic Services (BMGS) of the Integrated Land Management Bureau (Ministry of Agriculture and Lands). However, calibration reports for images acquired in 1949 and 1960 were missing from government records. Focal length and the principal point were estimated for these images by performing a self-calibrating bundle block adjustment in LPS.

The BMGS also provided TRIM aero-triangulation exterior orientation parameters and 56 ground control points (GCPs) for images acquired in 2001. In general, GCPs derived from these data have an absolute positional accuracy of ± 10 m when placed on well-defined planimetric features, while spot features are accurate to ± 5 m of their true elevation (Geographic Data BC 1992). These data were used to triangulate the 2001 images using standard photogrammetric equations for interior, relative, and absolute orientation (see Leica Geosystems 2005). The root-mean-square (RMS) error of the triangulation was 0.398 pixels. Images from the remaining survey years were then assembled into the block with GCPs bridged from the 2001 images to stable, discrete points on the older imagery (e.g., rock outcrops, buildings, bridge pilings, etc.). On average, five GCPs were located on each image. The 2001 images were then fixed in space, and the entire image block triangulated relative to the 2001 images. The final RMS error for the entire image block was 0.981 pixels.

3.2.2 Planimetric channel mapping

Once the images were triangulated, planimetric channel features were mapped with a digital stereoplotter (ERDAS Stereo Analyst). Three-dimensional polygons representing water surface, channel bars, vegetated channel bars, islands, overbank scour, wetlands, valley bottom, large woody debris accumulations, and riprap were digitized and saved to a shapefile. Narrow channels (generally < 5 to 10 m) obscured by the riparian tree canopy (at least in part) were mapped as indefinite linear features and coded as flood channels. Channel banks were often obscured by riparian vegetation and not mapped by direct observation. In this case, the position of the bank was assumed to be located along the border between the active channel (bars and water surface) and the relatively stable, vegetated fan surface. In addition to river features, transportation, infrastructure, development, and forest harvesting on the fan and adjacent to the mainstem channel were also mapped.

3.2.3 DEM generation and post-processing

A DEM (digital elevation model) was generated for each year of imagery from the triangulated image block using a fifth-order polynomial TIN interpolation in the LPS software. Ground resolutions ranged from 1.6 to 7.7 m (10 times the image resolution—see Appendix 1, Table 10-2). Each DEM was subset by channel polygons mapped with the stereoplotter to create a series of channel feature DEMs and then post-processed to remove any blunders generated by the extraction process (i.e., bars were post-processed separately from islands, etc.). This included application of a failure warning model (Gooch and Chandler 2001), exclusion of unmatched points interpolated in the extraction process (Leica Geosystems 2005), elimination of spikes and pits by comparison to a low resolution DEM filter-map (Westaway et al. 2003), and elimination of any locally extreme edge pixels adjacent to pixels removed in the previous steps (edge points were considered "extreme" if they exceeded one standard deviation beyond the mean of a three-by-three pixel matrix). Channel feature DEMs were then combined back into a single DEM for each year surveyed. Pixels excluded in the post-processing were re-interpolated (as above) to create a continuous DEM surface. Three-dimensional shapefiles outlining the boundary of each channel feature were used as breaklines in the interpolation process.

3.2.4 Water surface adjustment

Submerged portions of each DEM were excluded from the post-processing routine since the channel bed was usually obscured by reflections on the water surface, and/or the water was too deep to correct for refraction (see Westaway et al. 2000). Instead, the average water depth (d_w) at the time of image exposure was estimated by first creating a DEM of the water surface at mean annual flood (Q_{maf}) interpolated from elevations acquired along the channel margin with the stereoplotter (i.e., the three-dimensional shapefiles). In this analysis, Q_{maf} was assumed to inundate that portion of the active channel mapped as water surface or channel bar (vegetated bars and wetlands were excluded). A second DEM of the water surface at the time of image exposure was interpolated from elevations acquired along the water's edge, again measured with the stereoplotter. This DEM was combined with the channel bar DEM and then subtracted from the DEM of the flood stage at Q_{maf}. The difference between the two DEMs gives the visible channel depth (d_v) exposed to the camera at the time of image capture.

An estimate of Q_{maf} was then calculated for each reach by the scale relation developed by Eaton et al. (2002) for flood flows in British Columbia:

$$Q_{maf} = kA_d^{0.7493} \tag{1}$$

where A_d is the drainage basin area and k is a scale ratio for mean annual discharge, set to 2.6 for Williams Creek watershed (Eaton et al. 2002, Figure 8). The average channel depth (d) at Q_{maf} was then calculated for each reach by the Manning equation:

$$v = \frac{R^{\frac{2}{3}} s^{\frac{1}{2}}}{n} \quad (2)$$

where v is the velocity, R is the hydraulic radius, s is the reach slope, and n is the Manning roughness coefficient. The continuity equation was also used to determine d at Q_{maf}:

$$Q = Av = wdv \quad (3)$$

where A is the channel cross sectional area and w is the channel width. Assuming d can reasonably approximate R in a wide, shallow river, Equations 1 and 2 can be combined by substituting v of Equation 1 into Equation 2 and then rearranging to solve for d, giving

$$d = \frac{n^{\frac{3}{5}} Q^{\frac{3}{5}}}{s^{\frac{3}{10}} w^{\frac{3}{5}}} \quad (4)$$

Given an estimate of n and measurements of w (planimetric area of each reach divided by reach length along the thalweg) and s (difference between upstream and downstream elevations on the DEM divided by reach length along the thalweg), the average depth of water at the time of image capture (d_{w}) can then be calculated by:

$$d_{\text{w}} = d - d_{\text{v}} \quad (5)$$

The results are given in Table 3-2. Submerged elevations of each DEM were estimated by subtracting d_{w} from each water surface DEM created above.

3.2.5 Data quality

A subset of GCPs derived from the 2001 TRIM aero-triangulation data was withheld from the triangulation process for use as independent check points to assess the relative errors in the photogrammetric data (relative errors describe the uncertainty of locating one point relative to another in the image block, regardless of the absolute position of each point in space). Relative errors were calculated for the image block triangulation (a measure of overall image block uncertainty), the DSM (a measure of planimetric or channel mapping uncertainty), and the DEM (a measure of elevational or bed surface uncertainty). Uncertainty in the data was calculated in terms of mean error (ME) and standard deviation error (SDE) (Taylor 1997). ME is a measure of overall surface accuracy and can indicate a systematic bias or error in the observed data. ME for the 2001 triangulated image block in the X, Y, and Z axes were 0.032, -0.14, and -0.11 m, respectively. Given that these errors were not significantly different from 0.0 ($t_{0.05,2,9}$), it was concluded that there were no systematic errors in the 2001 image block triangulation.

SDE is a measure of the precision or random error and was assessed by the standard deviation of residuals about the mean. Planimetric SDE associated with locating a single point (∂q_p) in the triangulated images is given by:

$$\delta q_p = \sqrt{\delta x^2 + \delta y^2} \qquad (6)$$

where *x* and *y* are the standard deviation errors of any point in X, Y space, respectively. Relative planimetric and elevational SDEs for the 2001 image block were ± 0.26 and 0.29 m, respectively. Additional checkpoints were then bridged from the 2001 image block to the older images (Table 3-2). Planimetric and elevational checkpoint errors ranged from ± 1.5 to 3.8 m and from ± 1.2 to 2.4 m, respectively. These errors generally became larger with the older imagery, likely reflecting the difficulty in locating common, high quality points to bridge between years of imagery as terrain and infrastructure features change through time, the quality of cameras used to acquire the imagery, image scale, and lack of calibration reports (the later pertaining to images acquired in 1949 and 1960).

Table 3-2. Physical and hydraulic reach characteristics for the study period

Year	A_d (km^2)	Q_{maf} (m^3/s)	*s*	*n*	*w* (m)	*d* (m)	d_w (m)
Reach 1							
2001	207	142	0.0015	0.037	27.4	2.62	1.91
1988	207	142	0.0011	0.037	28.1	2.82	1.60
1975	207	142	0.0019	0.037	36.9	2.04	0.92
1960	207	142	0.0017	0.037	33.7	2.24	0.76
1949	207	142	0.0016	0.037	29.1	2.48	1.33
Reach 2							
2001	172	134	0.0070	0.087	38.8	2.05	1.70
1988	172	134	0.0087	0.087	49.2	1.66	0.83
1975	172	134	0.0080	0.087	49.5	1.70	1.12
1960	172	134	0.0082	0.087	50.1	1.68	0.72
1949	172	134	0.0092	0.087	29.1	2.25	1.21
Reach 3							
2001	169	122	0.0092	0.067	54.2	1.31	1.01
1988	169	122	0.0100	0.067	69.9	1.10	0.52
1975	169	122	0.0107	0.067	84.6	0.96	0.84
1960	169	122	0.0093	0.067	59.3	1.24	0.72
1949	169	122	0.0097	0.067	65.2	1.15	0.47
Reach 4							
2001	165	120	0.0122	0.089	38.9	1.72	1.32
1988	165	120	0.0126	0.089	39.3	1.70	1.30
1975	165	120	0.0141	0.089	53.1	1.37	1.14
1960	165	120	0.0131	0.089	37.6	1.72	0.25

The position of each checkpoint was then measured with the stereoplotter to quantify the uncertainty in the DSM used to create the channel maps. A significant planimetric ME was detected in all years except 1949 (see Table 3-3 for details). These were treated as systematic errors and subsequently removed from the data by transforming map coordinates in the X and Y dimensions by the amounts listed in Table 3-4. Relative planimetric and elevational SDEs ranged from ± 0.26 to 4.9 m and from ± 0.42 to 2.4 m, respectively (Table 3-3).

Table 3-3. Planimetric and elevational SDE in the photogrammetric data

	Image block triangulation errors (± m)		DSM errors (± m)		DEM errors (± m)
Year	XY	Z	XY	Z	Z
2001	0.29	0.29	0.26	0.42	0.59
1988	1.7	1.3	1.5	1.3	1.8
1975	1.6	1.3	2.2	0.93	1.1
1960	3.8	1.7	3.4	1.3	2.0
1949	4.1	2.9	4.9	2.4	3.7

There was no way to directly quantify the elevational error in the post-processed DEMs, since there were no independent checkpoints on the river available for analysis. However, once the uncertainty in the DSM was quantified, an additional 30 points were randomly located on channel bars for each year of imagery with elevations measured with the stereoplotter. These measurements were compared to the elevations derived from the DEM. In this step, each checkpoint was associated with two sources of uncertainty: a ME and SDE associated with the DSM, and a ME and SDE associated with the checkpoint derived from the DEM (an accumulated error associated with the precision of checkpoint co-ordinates). This accumulated uncertainty was removed from the error statement by:

$$\delta y_{\mathrm{DEM}} = \sqrt{\delta q_t - \delta x_{\mathrm{DSM}}} \qquad (7)$$

where q_t is the total or accumulated checkpoint SDE (checkpoints placed on the DEM with the stereoplotter), x_{DSM} is the checkpoint SDE derived from the stereoplotter, and y_{DEM} is the checkpoint error present in the DEM alone. Relative SDE ranged from ± 0.59 to 3.7 m for the channel bars (Table 3-4). This procedure was then repeated for the 30 points measured with the stereoplotter on stable vegetated surfaces near the river from the 2001 image block (points were placed on bare ground between trees and shrubs). The vegetated portions of the DEM had a SDE of ± 1.4 m (Table 3-4).

Table 3-4. Planimetric and elevational ME in the photogrammetric data. All errors were observed as the difference between the survey data and the photogrammetric DEM. Thus, negative errors show DEM observations above the true surface and vice versa.

	Image block triangulation errors (± m)			DSM errors (± m)			DEM errors (± m)
Year	X	Y	Z	X	Y	Z	Z
2001	0.032	0.14	0.11	0.21[a]	0.20[a]	0.10	-0.097
1988	0.049	0.27	1.2[a]	0.28	0.23	1.0[a]	-1.6
1975	2.0[a]	0.031	-1.2[a]	1.7[a]	0.21	-1.6[a]	0.034
1960	-1.5	1.5	0.36	-2.2[b]	1.90[b]	-0.26	-1.2
1949	-0.43	1.7	-0.52	-0.044	1.5	-2.4	-2.0

[a] ME is significantly different from 0.0 ($t_{0.05,2,9}$)
[b] ME is significantly different from 0.0 ($t_{0.05,2,10}$)

4 SEDIMENT SOURCES

4.1 Sediment Source Description by Sub-basin

Sediment sources were found in one of the following source areas:

- Lower Williams Creek valley including minor tributaries, between Old Lakelse Lake Drive and Sub-basin 19 (Figure 4-1, green shading);
- Mid valley section and small, steep tributary basins (Figure 4-1, yellow shading);
- Larger tributary valleys entering mid-valley from the south side (Figure 4-1, pink shading);
- Headwater tributary basins (Figure 4-1, dark grey shading).

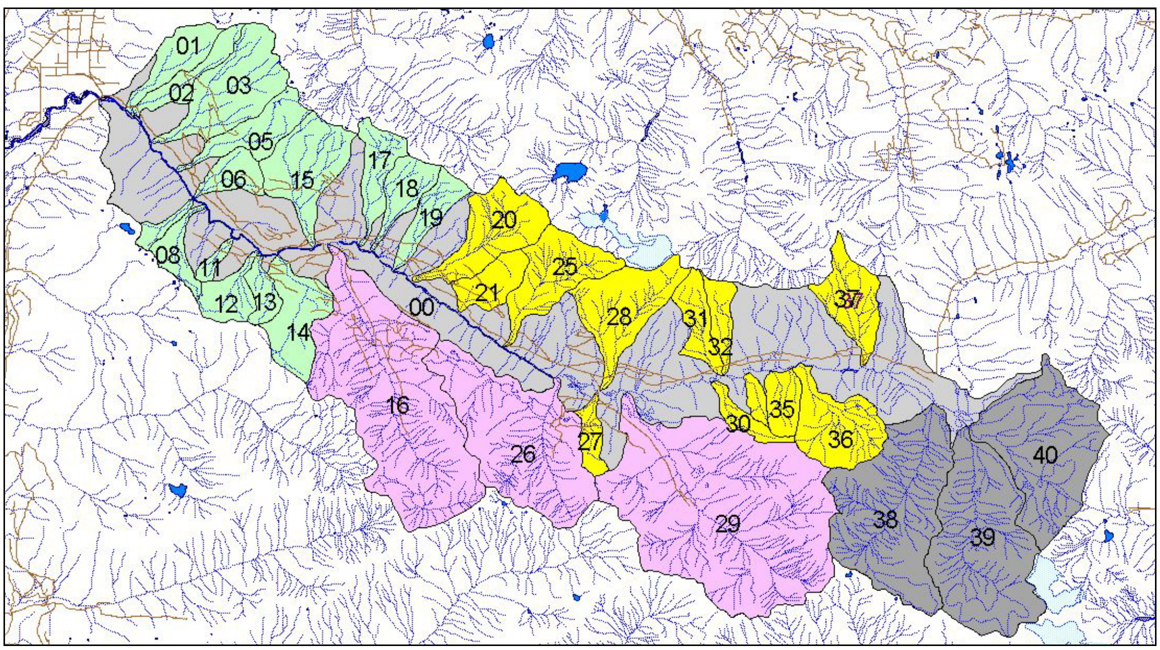

Figure 4-1. Location of subbasins in Williams Creek Valley.

4.1.1 Lower Williams Creek valley

Sub-basin 00/1: This sub-basin captured sediment sources along the lower main stem of Williams Creek, outside of the sub-basins described above. Several small point source failures existed along the tall bedrock (#00-20 to #00-23) and gravel embankments (#00-25,26) of Williams Creek. Failures were typically located along the outside of stream bends. At source #00-20, initial failure occurred prior to 1949. The other stream bank

Figure 4-2. Natural sediment source on the stream side embankment along Williams Creek (#00-25).

failures (Figure 4-2) apparently occurred post-1968 and prior to 1988. Several open slope debris slides (#00-16, 17, 19, 32) occurred post-1988 in clearcut areas. These slides did not reach a stream and did not contribute sediment to Williams Creek. A large natural debris slide (#00-28) initiated on the forested open slope above a clearcut area between 1968 and 1988 and ran to the valley floor. Landslide debris was partially deposited on the valley floor and partially delivered to Williams Creek.

The main-stem channel of Williams Creek between sub-basin 26 confluence and the upper end of reach 4 (mouth of SB03) is confined between 15–30 m tall embankment slopes and fractured, granitic bedrock cliffs. The channel was predominantly a bedrock channel, and gravel accumulation was rare (S. Spencer, pers. comm., 2006). This is in sharp contrast with the alluvial reach 4, 1 km above the Old Lakelse Lake Drive bridge. The sediment composition in the alluvial reach 4 was 40–70% granodiorite and 30–60% volcanic and volcaniclastics by volume. Light-coloured granodiorite clasts dominated the large cobble and boulder fraction, while darker, red and maroon volcanic clasts dominated the pebble fraction.

<u>Sub-basin 1</u> (SB01, 179 ha): The lower gully walls were subject to a pre-1949 wildfire. Mineral soil was exposed on much of the western gully wall, and the colluvial fan at the mouth of the gully was partially burnt. Vegetation on the lower fan was dominated by deciduous trees. There was likely sediment deposition on the fan apex and some disturbance on the lower fan associated with the post-wildfire debris movement. By 1968, the gully sidewall was greened-up, and there was no evidence of further sediment deposition on the fan apex. By 1988, a new, small gully sidewall failure (#1-3) had become active, and some new deposition was visible at the fan apex, most likely related to reworking of channel sediment during high flows. By 2001, gully sidewalls had continued to green-up.

<u>Sub-basin 2</u> (SB02, 140 ha): This narrow basin is drained by a moderately incised draw, which is well defined only on the lower valley wall. The sub-basin was subject to wildfire

prior to 1949, and numerous open-slope shallow debris slides were visible. They were de-coupled from the stream network and did not deliver sediment to the valley floor. By 1968 they were greened-up. Between 1968 and 1988, a debris flow occurred in the sub-basin, initiating at mid-elevation on the valley wall. The debris flow travelled for 1300 m to the valley floor, where deposition was obvious on the colluvial fan apex and the floodplain. This event may have occurred in the same time interval as considerable channel widening of Williams Creek at the mouth of SB02. By 2001, the deposition and transport zones of the debris flow track were greened-up. Sediment output from this sub-basin was considerable during the debris flow event, but was negligible for the rest of the time.

Sub-basin 3 (SB03, 445 ha): The gully draining SB03 was prominent on the lower valley wall, and marks the eastern margin of the pre-1949 burn. The gully west side was burned, the east side was forested. In 1968, recent sediment deposition was obvious at the mouth of the stream. In 1988, in-channel blocky debris accumulation mixed with logs was visible at site #03-1 and #03-2, associated with localized gully sidewall instability. Sediment deposition at the mouth of the fan had ceased and the channel banks were re-vegetated. In 2001, the in-channel debris accumulation was still visible and unchanged, and no new activity was apparent at the mouth of the gully stream.

Sub-basin 4: This sub-basin was merged into sub-basin 00/1.

Sub-basin 5 (SB05, 220.2 ha): The gully draining SB05 was prominent on the mid to lower valley wall. Gully sidewalls were steep, but no gully sidewall failures were identified on the air photos. The gully floor channel appeared undisturbed and unchanged over the years. The sub-basin appeared to have little sediment output since 1949.

Sub-basin 6 (SB06, 127.3 ha): The sub-basin encompassed only lower valley wall slopes between SB05 and SB15. Stream flow was most likely ephemeral. No sediment sources were identified in the sub-basin.

Sub-basin 7 (SB07, 49.7 ha): In 1949 and 1968, the narrow sub-basin was drained by a forested gully. Activity was limited to the gully floor channel at mid-elevation, and sediment output was low. By 1988, a debris flow/debris flood initiated in the channel starting at mid elevation. Sediment delivery was directly to Williams Creek, with little toe slope deposition. The debris flow widened its track on the lower valley wall, where it was eroding into glacial till. This lower section continued to erode in 2001.

Sub-basin 8 (SB08, 113 ha): The gully draining SB08 was incised into bedrock on the upper and mid valley wall, where steep bedrock sidewalls episodically produced rubbly and blocky sediment. In the lower valley wall section, there were numerous small-scale gully sidewall failures in glacial till. These failures have been active since pre-1968, episodically producing fine- and coarse-textured sediment which was transported to Williams Creek.

Sub-basin 09 and 10: These sub-basins were merged into sub-basin 00/1.

Sub-basin 11 (SB11, 38.3 ha): The narrow sub-basin was drained by a gully with apparent past sediment transport along the upper reaches. No new activity appeared on air photos since 1949.

Sub-basin 12 (SB12, 144.6 ha): The multi-branch gully system draining this sub-basin started at the crest of the valley wall. In the upper reaches, the gully was cut into bedrock. No significant changes to the gully sidewalls or the gully floors were obvious over the 52 years since 1949, but it is likely that bare bedrock faces and partially obscured debris slide tracks have produced some coarse-textured sediment. In the lower reaches, the gully channel appeared undisturbed and gully sidewalls were stable throughout the 1949 to 2001 observation period.

Sub-basin 13 (SB13, 89.8 ha): The branched gully system draining this steeply sloping sub-basin started at the valley wall crest. Gully sidewalls appeared stable in 1949 and 1968 and the gully floor channel appeared undisturbed. Evidence of small-scale gully sidewall instability appeared on the larger-scale air photos in 1988, some of which persisted in 2001. Based on the undisturbed appearance of lower valley wall reaches since 1949, little sediment appears to have been contributed from SB13.

Sub-basin 14 (SB14, 298.5 ha): The main gully draining SB14 appeared to be following a bedrock lineament. The gully sidewalls showed evidence of historic debris slides and bedrock falls, but there was little evidence of new activity since 1949.

Sub-basin 15 (SB15, 377.4 ha): The forested sub-basin was drained by a dendritic stream network on the steep upper valley wall slope. On the lower valley wall, a more prominent single gully developed. Gully sidewalls were typically stable, with localized bare bedrock cliffs. In the lower reaches, several small debris slides have appeared since 1968, with little apparent activity since 1988. The gully floor channel appeared undisturbed throughout the 52-year observation period. In 1988, the sizeable colluvial cone/fan at the mouth of this gully showed evidence of channel disturbance immediately above the Williams Creek forestry road, likely due to sediment deposition rather than scour. The channel appeared undisturbed below the road crossing. Little of the sediment produced by gully sidewall failures appeared to have reached Williams Creek.

Sub-basin 16: This sub-basin (Llewellyn Creek) is described in section 4.1.2.2.

Sub-basin 17 (SB17, 177.5 ha): This forested sub-basin was drained by a single-branch gully which initiated in subdued alpine terrain. On the steep forested upper valley wall slopes, the gully was incised into bedrock. Episodically, these bedrock walls have produced rubbly and blocky sediment. Activity was slow and seems to have changed little between 1949 and 2001. The lower gully and the fan appeared undisturbed. Sediment contribution from sub-basin 17 appeared low.

Sub-basin 18 (SB18, 156.7 ha): This mostly forested sub-basin drained the steep-sided flanks of a small alpine peak. On the upper valley walls, the drainage network was barely incised, and appeared to be subject to snow avalanche activity. A gully started at the top of the lower valley wall. Gully sidewalls were stable and the gully floor stream appeared undisturbed since 1949. Two small gully sidewall failures appeared near the mouth of the gully, where the stream was incised into older colluvial deposits. Sub-basin 18 contributed little sediment to Williams Creek since 1949.

Sub-basin 19 (SB19, 149.6 ha): Drainage of the forested sub-basin started in subdued alpine terrain. The subalpine, steep, forested upper valley wall slopes have been impacted by debris flows in the tributaries to the SB19 gully. More recently (pre-1968), a debris flow was active in the upper reaches of the main gully, while the channel appeared undisturbed in the mid reaches. By 2001, the lower reach showed several small gully sidewall failures in a post-1988 cutblock. These failure scars may be old, pre-dating logging and obscured by the canopy on 1988 air photos, or they may have occurred since 1988. Sediment volume generated from sediment sources in sub-basin 19 was low.

4.1.2 Mid-section of Williams Creek valley

Sub-basin 00/2: This sub-basin captured the middle reaches of main stem Williams Creek and adjacent open slope valley walls. Few sediment sources existed in this sub-basin. Stream bank erosion along the main channel created sediment source #00-36 during a pre-1988 event.

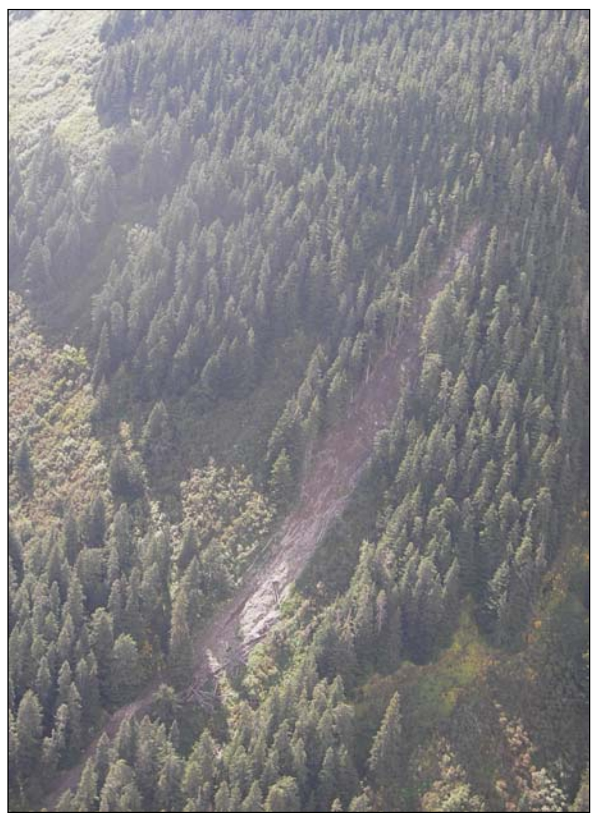

Figure 4-3. Debris slide in upper Williams Creek valley (#00-47)

Between 1988 and 2001, a debris slide (#00-35) initiated on logged steep lower valley wall bedrock outcrop and ran to the valley floor. Approximately 75% of the debris slide volume was deposited on the narrow valley floor, and 25% may have entered Williams Creek. Between 2001 and 2005, a debris slide (#00-47) initiated on a steep, forested slope at mid elevation in thin colluvium over bedrock (Figure 4-3). The debris slide ran to the valley floor, and entered an inactive back channel on the Williams Creek flood plain. Since 1949, sediment contribution from this sub-basin to Williams Creek has been relatively low, considering the size of the sub-basin.

Main-stem Williams Creek has a locally unconfined channel upstream of the Sub-basin 26 confluence, with predominantly cobble-pebble channel bed material.

4.1.2.1 Sub-basins 20–37, except sub-basins 26 and 29 (Myron Creek)

Sub-basin 20 (SB20, 363.5 ha): This stream drained a subalpine basin with steep sidewalls, which are intersected by several northwest-southeast trending lineaments. These lineaments coincide approximately with the mapped geologic contact of the tertiary granites which dominate the lower valley, and the Permian sedimentary rocks which form the alpine ridge crest along the north side of the valley. Until 1968, sediment was mainly produced on the steep and rocky alpine side slopes (#20-1, #20-11), but was not transported out of the subalpine bowl. During a pre-1988 event, a debris slide (#20-2) occurred high on the northern basin wall und quickly turned into a debris flow track (#20-5) following one of the lineaments. The debris flow scoured the channel for 2.5 km (#20-15, #20-18). Debris was partially deposited on the valley floor fan, and partially transported to Williams Creek. This event mobilized an estimated 20 000 to 45 000 m^3 of sediment, of which 10 000 to 22 000 m^3 probably entered Williams Creek. Little new sediment source activity occurred between 1988 and 2001. Sediment output to Williams Creek appears to have been moderate to low since the initial pre-1988 event.

Sub-basin 21 (SB21, 164 ha): The sub-basin covered the forested, open-slope on the lower valley wall of Williams Creek, between SB20 and SB25. A small gully sidewall failure produced some sediment following logging and road construction in a post-1988 event. This sediment was transported and deposited along the SB21 stream. Output to Williams Creek has been low.

Sub-basins 22, 23 and 24: These sub-basins were merged into sub-basin 00/2.

Sub-basin 25 (SB25, 348 ha): The sub-basin comprised a steep-sided, subalpine to alpine basin adjacent to SB20. Several scoured gullies were deeply incised into bedrock on the north side of the basin (Figure 4-4). Sediment transport out of the dendritic gully system (#25-11 to #25-15) into the basin floor and beyond into stream 25 appeared to have increased significantly during a pre-1988 event. In 1968, the stream channel draining from the basin floor appeared undisturbed under closed forest

Figure 4-4. Scoured bedrock gullies in subbasin 25

canopy. By 1988, the channel along the transport zone had widened as a result of scour and/or deposition and the forest canopy along the channel was open. In 2001, the channel was still wider than in 1968. Material was slowly transported out of this reach, and bedload deposition occurred on the valley floor fan. Below Williams Creek FSR, the fan showed little evidence of disturbance by either sediment deposition or scour.

A fine-textured sediment source in glacial till or weathered volcanic bedrock was located along the incised stream banks (#25-20) of the basin floor. This source has been active, producing fine-textured sediment at a slow, steady rate since pre-1949. Fine-textured sediment was transported as wash load to Williams Creek.

Sub-basin 26: This sub-basin is covered in section 4.1.2.2.

Sub-basin 27 (SB27, 89.8 ha): The narrow, small sub-basin on the southern valley wall started in a snow avalanche initiation zone in the alpine. On the upper valley wall, there were two small rockfall sites on the gully sidewall. Sediment entering the upper sub-basin was trapped by a low gradient reach on a lower valley wall bench. Sediment output to Williams Creek was low to nil.

Sub-basin 28 (SB28, 407.1 ha): Two steep gully systems joined at the road crossing of stream 28. Both gullies have generated considerable amounts of coarse sediment from gully wall failures since pre-1949. Sediment entrainment by, and throughput through the gully floor stream varied from slow to occasionally rapid. Both gully floor streams have been disturbed (scour and aggradation) since pre-1949, and sediment was deposited on the valley floor fan. Evidence of channel disturbance on the fan extended from the fan apex to the confluence with Williams Creek, indicating that a considerable amount of sediment entered Williams Creek. Pre-1968, a new gully sidewall failure (#28-7) added a moderate to large amount of sediment to the western branch of the gully system (Figure 4-5). Little change appeared to have occurred by 1988. By 2001, several of the subalpine gully sidewall sources had started to revegetate, while

Figure 4-5. Actively failing gully sidewalls in subbasin 28/1.

sediment delivery from the gully system to the valley floor fan continued. Between 2001 and 2005, a new gully sidewall failure (#28-9) occurred in fractured bedrock, adding additional sediment to the gully floor channel. This sediment was transported through the gully system, partially depositing on the fan and partially reaching Williams Creek.

Sub-basin 29: This sub-basin (Myron Creek) is covered in section 4.1.2.2.

Sub-basin 30 (SB30, 86.3 ha): In this steep, narrow sub-basin, sediment was generated on the gully sidewalls at the start of a deep and narrow bedrock gully in the subalpine. Activity was ongoing and sediment production was low to moderate. All generated sediment was transported to the valley floor fan/cone, either by seasonal high flows or snow avalanches. The sediment was partially deposited on the valley floor fan, but most of the sediment likely reached Williams Creek.

Sub-basin 31 (SB31, 158.3 ha): The sub-basin drained hummocky, subdued alpine terrain upslope of steep forested valley wall slopes. Starting in the subalpine, a two-branch gully system was deeply incised into the steep, forested slope. Sediment was generated from bedrock exposure at site #31-3. A considerable amount of blocky and rubbly sediment was generated from gully walls at site #31-1 and transported along the debris flow track (Figure 4-6). The lower debris flow track (#31-2) is currently loaded with sediment, as transport out of the reach is slower than accumulation from upstream sources. Transport through the lower steep reaches of Stream 31 occurred at a steady, slow rate. Deposition on the valley floor fan has been in equilibrium with scour since 1949. Over the past 52 years, and possibly longer, sediment output from SB31 to Williams Creek has been lower than input from active upslope sediment sources. The sediment stored in the debris flow track could be mobilized by an extreme run-off event at any time, causing a large debris flow which would run to the valley floor and partially enter Williams Creek.

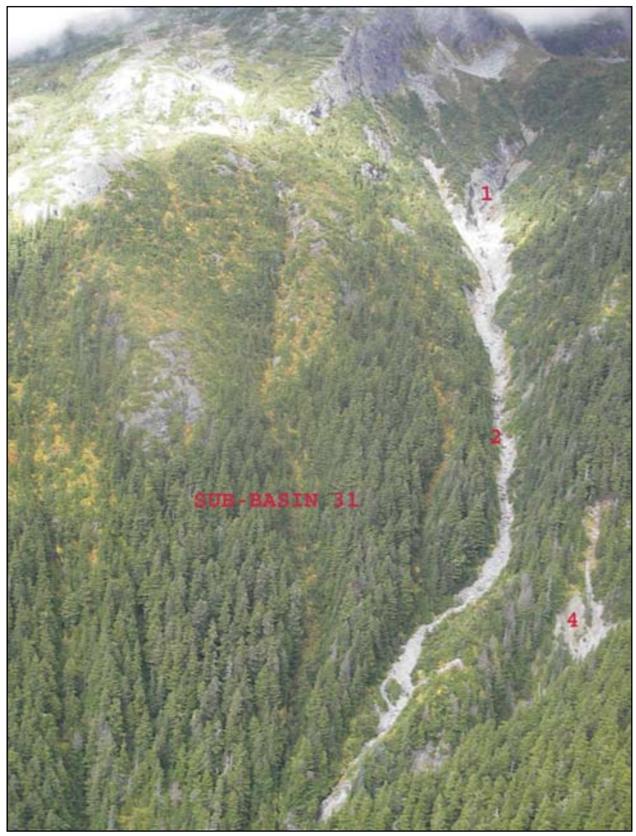

Figure 4-6. Debis flow track #31-2 in subbasin 31

Sub-basin 32 (SB32, 111.1 ha): The gully system received coarse-textured sediment from gully sidewall failures in fractured bedrock in steep, subalpine reaches (Figure 4-7). Transport through the steep bedrock gully to the valley floor fan was direct and has occurred at a steady rate since 1949. However, transport was less than input from subalpine gully sidewall sources. This has left the gully floor channel at 32-7 loaded with coarse sediment.

Sub-basin 33 (SB33, 47.6 ha): Weathering bedrock along the upper gully reaches produced a slow supply of blocky-rubbly sediment. Throughput through the steep, narrow bedrock gully to the valley floor cone was direct. The cone apex was eroding and little or no sediment is stored on the cone. Throughput to Williams Creek was immediate (Figure 4-8).

Figure 4-7. Subbasin 32, gully floor is loaded with sediment.

Figure 4-8. Erosion into cone apex at the mouth of gully 33, and sediment transport to Williams Creek.

Sub-basin 35 (SB35, 126.6 ha): Small debris flows and rock fall activity were the main processes that moved weathered and fractured rock from steep, upper valley wall bedrock cliffs to the lower valley wall cones. The channel disappeared just below the cone apex and coarse sediment was entirely deposited on the upper cone. Large snow avalanches ran regularly to Williams Creek, but transported little sediment.

Sub-basin 36 (SB36, 359.8 ha): The sub-basin contained two glacial cirques with neoglacial activity. Cirque walls were steep, partially glaciated bedrock cliffs, subject to rock and ice fall. Cirque floors contained rapidly receding, remnant cirque glaciers with a series of bare terminal moraine ridges. Meltwater run-off from the remnant cirque glaciers across the loose, unvegetated moraine ridges appeared to be largely subsurface, and sediment entrainment and transport were low. A third remnant glacier in this sub-basin was located hanging on the upper valley wall above a steep bedrock cliff. Glacial meltwater run-off generated sediment through erosion along a bedrock gully. This sediment was deposited at the toe of the bedrock wall on a cone apex. In the lower reaches, stream 36 transported little sediment, but delivered all of it to Williams Creek.

Sub-basin 37 (SB37, 263.5 ha): The main gully in SB37 started in the alpine on moderately steep slopes. No sediment sources were identified in the alpine. As the gully stream reached the steep subalpine and forested valley side slopes, it became incised into bedrock (Figure 4-9). Several gully sidewall failures (#37-3 to #37-6 and #37-9) existed in bedrock along the forested, mid-elevation gully reaches. They have been active since pre-1949, slowly producing sediment. Sediment entering the gully stream has been transported along the narrow, incised channel and was partially deposited on the valley floor fan. Some of the sediment reached Williams Creek. The sediment regime in Sub-basin 37 has changed little over the 52 years since 1949.

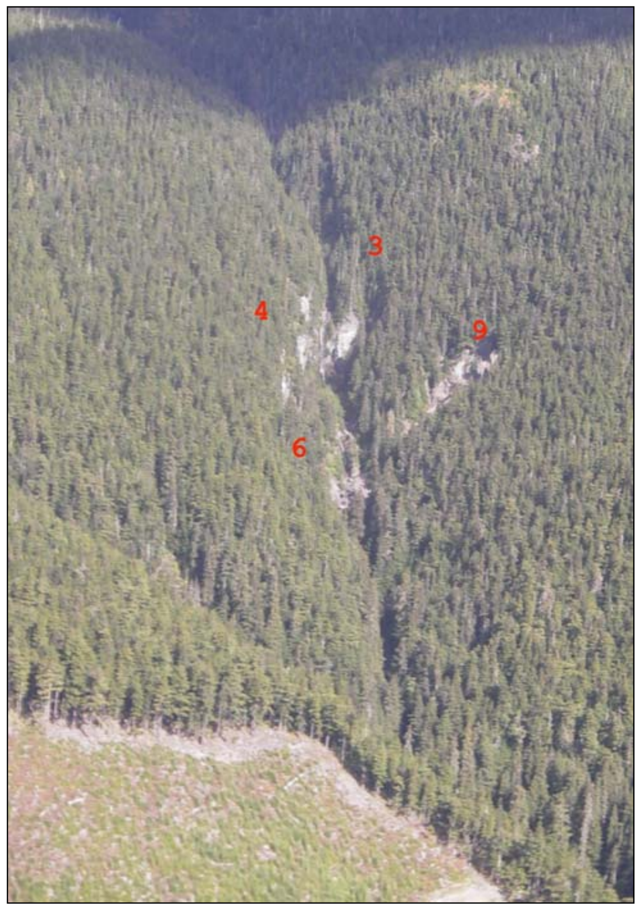

Figure 4-9. Subbasin 37, mid-elevation valley wall.

4.1.2.2 Tributary valleys entering mid-section Williams Creek from the south

Sub-basin 16 (Llewellyn Creek, 1553.5 ha): The main sediment sources in sub-basin 16 were several debris flow gullies on the steep, subalpine valley walls at the valley head. Significant sediment volume was mobilized pre-1968, causing channel widening and aggradation in the upper reach of Llewellyn Creek. By 2001, this sediment wedge had partially moved downstream and was partially re-vegetated. A secondary sediment wedge formed pre-1968 downstream of the confluence of tributary 16/2. The aggraded sediment may have been mobilized from the tributary 16/2 channel from upstream reaches of Stream 16-main channel, or from gully erosion in the #16-24 avalanche track.

In the lower valley, a debris slide (#16-9) occurred between 1949 and 1968 on the tall streamside escarpment in glacial till. The landslide debris created a temporary logjam in Llewellyn Creek which trapped large volumes of sediment until 2001. After 1968, logging started in lower Llewellyn Creek. Clearcut logging on steep, gullied streamside embankment slopes re-activated numerous debris slide tracks before (#16-11, #16-121, #16-122) and after 1988 (#16-123). These failures were investigated on the ground and were described (polygon B, site 1-3) by Acer Resource Consulting Ltd. (2003). Landslide debris was partially deposited on the narrow floodplain, and partially delivered to Llewellyn Creek. By 2001, these clearcut failures had largely re-vegetated.

Tributaries to Llewellyn Creek (16/1, 16/2) were mostly incised in bedrock. Airphotos showed little change over time and little sediment was generated from these drainages.

Sub-basin 26 (SB26, 989.2 ha): SB26 was a short tributary valley, which started at a low divide in the subalpine on the south side of Williams Creek valley. Several snow avalanche tracks in the upper tributary valley brought coarse sediment (rubble, small block) generated as rock falls (#26-11 to #26-23) from bedrock cliffs in the snow avalanche initiation zones to the valley bottom stream. Rate of sediment input to the valley bottom stream was low.

The forested valley on the east slope consisted of gullied glacial till on the lower slopes and colluvium on the upper slopes. The gullies were inactive; only site #26-25 episodically produced fine textured sediment from surface erosion at a slow rate.

The valley floor stream in SB26 was incised between steep embankment slopes, which consisted of bedrock complexed with glacial till. There were several debris slides (#26-26 to #26-35) along the embankment slopes generating coarse- and fine-textured sediment at a slow rate, which entered the stream directly. These sediment sources have been active since 1949 with little change. During a pre-2001 event, an additional slide (#26-38) occurred on the embankment slope.

Also included in the sub-basin is a long valley wall bench parallel to Williams Creek (SB26/1). Sediment generated on small gully sidewall failures upslope of the bench was trapped by two lakes on the bench. Sediment contribution from SB26/1 has been very low.

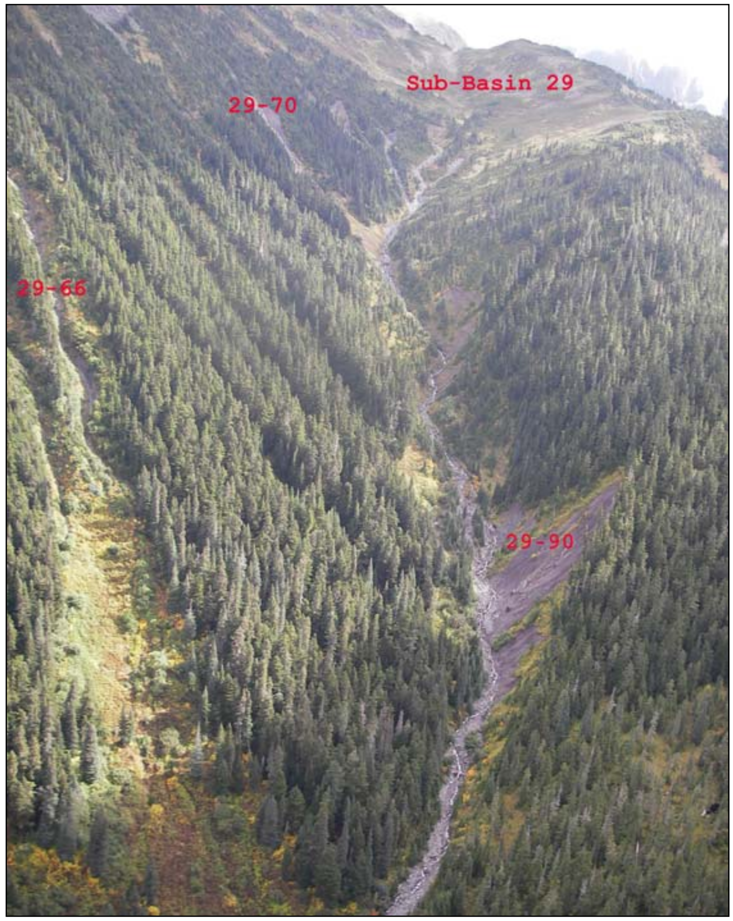

Figure 4-10. Headwaters of subbasin 29 (Myron Creek).

Sub-basin 29 (SB29, Myron Creek, 2086.4 ha): The sub-basin was a long tributary valley draining the alpine and subalpine divide on the south side of Williams Creek. Eastern headwater slopes consisted of gullied glacial till and colluvium. Gully erosion was active (#29-60 to #29-76), particularly in glacial till. A 50 m high and 30–40 m wide debris slide (#29-90) occurred along the stream bank escarpment in the headwater reach of stream 29 (Figure 4-10). This significant sediment source has been active since 1949, depositing fine- and coarse-textured sediment in the stream, causing local aggradation.

The mid valley of Myron Creek was dominated by steep alpine cirques towering over forested lower valley walls. Steep bedrock cirque walls were subject to rockfall, debris slides, and episodic debris flows, which deposited material onto talus slopes. Large snow avalanches and seasonal large run-off events transported sediment out of the eastern alpine cirques (29/2, 29/5) into stream 29 at a slow but ongoing rate, while little sediment is transported out of the western alpine cirques (29/1, 29/6, 29/7).

In the lower reaches, stream 29 and its tributary (29/2) was 20 to 30 m deep, incised into the broader valley floor. Streamside escarpment slopes consisted of glacial till and have been subject to occasional debris slides. Initial sediment source activity occurred mostly prior to 1949.

4.1.3 Upper Williams Creek valley, headwater tributaries, and basins

<u>Sub-basin 38</u> (SB38, 993.7 ha): Sub-basin 38 was a glaciated tributary valley, which entered Williams Creek from the south. The U-shaped valley was flanked by steep valley walls and several alpine cirques. The valley head consisted of a 150 m-tall bedrock cliff - talus cone complex, which formed a steep step between the tributary valley floor and the glaciated hanging valley above. Considerable ice retreat in the hanging valley since the end of the little ice age (1860 DC) exposed approximately 500 m of neoglacial basal moraine in the lowest part of the hanging valley. Prior to 1949, a meltwater outburst flow eroded a 350 m-long, 20–30m wide, 5–10 m deep pre-glacial channel (#38-8 and #38-10) into the neoglacial basal moraine (Figure 4-11). Some of this substantial sediment volume was partially deposited at the very edge of the hanging valley, but most of the volume was transported down the hanging valley step to the SB38 valley floor. Additional sediment was derived from the rugged valley sidewalls in form of rock fall and debris flows (Figure 4-12).

Figure 4-11. Headwaters of subbasin 38.

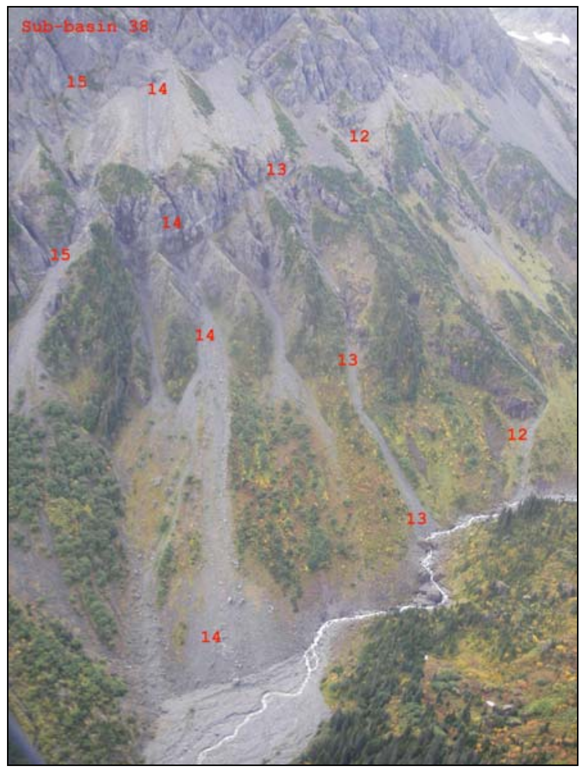

Figure 4-12. Valley walls near the valley head of subbasin 38.

The upper valley floor reach of stream 38 had a wide, braided channel where aggraded sediment is presently being reworked. The aggraded sediment became entrained during high flows, and moved down-channel as sediment wedges to the mouth of stream 38. One such sediment wedge arrived at the large fan at the mouth of stream 38 during a peak run-off event between 1949 and 1968, causing channel change and overbank deposition on the fan. This was clearly indicated on air photos by a swath of standing dead timber on the fan. There was no evidence that a similarly active geomorphic event has occurred in the sub-basin since 1968. Sediment delivery to the upper reach, entrainment from the upper reaches, and transport to the mouth appeared ongoing at a high equilibrium rate.

Sediment from SB38 entered Williams Creek along an unconfined stream reach with gentle gradient (1.8% for 2 km). This reach showed evidence of fresh aggradation in 1968, a result of the pre-1968 sediment transport event. After 1968, gravel bars started to revegetate. The channel showed no sign of new aggradation, indicating that sediment output from SB38 has been in equilibrium with the Williams Creek channel configuration since the pre-1968 event.

Sub-basin 39 (SB39, 980 ha): Sub-basin 39 is the U-shaped headwater reach of Williams Creek, entering the main valley from the south. Similarly to sub-basin 38, the valley was flanked by steep valley walls and rugged alpine cirques. The valley head was formed by a 100 m-high, steep bedrock cliff–talus cone complex, leading to a glaciated hanging valley above. Similarly to sub-basin 38, peri-glacial erosion has cut a wide meltwater channel into recently exposed neoglacial basal moraine. However, the eroded sediment was deposited on the hanging valley floor, and sediment delivery out of the hanging valley was extremely low.

Sediment delivery to stream 39 was mainly from several debris flow tracks (#39-14, #39-41), which were located on the valley sidewalls (Figure 4-13) and fed sediment into the

Figure 4-13. Subbasin 39, valley wall debris flow track

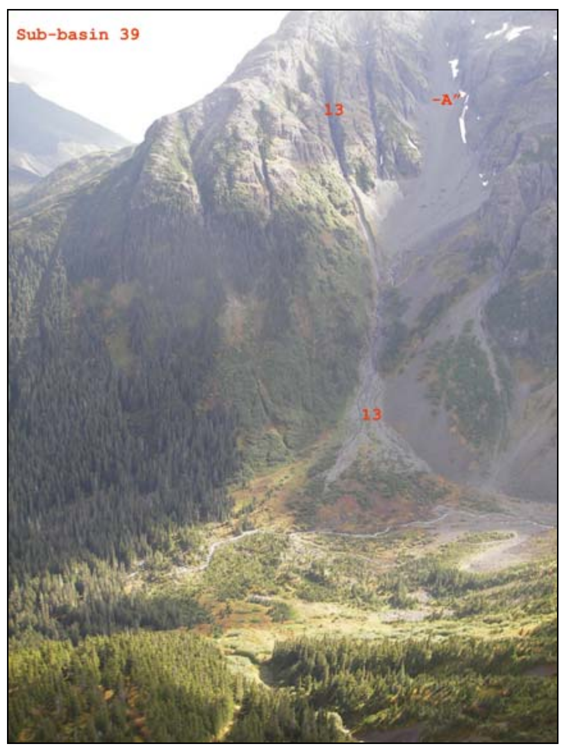

Figure 4-14. Subbasin 39, snow avalanche track and valley head basin.

flat-bottomed, slowly revegetating valley-head basin. Sediment from snow avalanche and debris flow track #39-13 was deposited on a valley floor cone (Figure 4-14), and did not enter stream 39. The channel in the valley head basin had a gentle gradient and appeared to be aggrading slowly, trapping a large proportion of the sediment that was generated on the valley walls and the hanging valley. Sediment output from sub-basin 39 to Williams Creek has been steady since 1949.

Sub-basin 40 (SB40, 828 ha): The sub-basin covered mostly subdued forested slopes, drained by several deeply incised streams. Sediment was generated from failing 15–20 m-high streamside escarpments in bedrock (#40-55 to #40-62) and in glacial till (#40-51 to #40-54, Figure 4-15). These sediment sources have been active with little change since pre-1949, producing a small amount of sediment annually due to weathering of the exposed rock and mineral soil surfaces. Sediment output to Williams Creek has been low and steady since 1949.

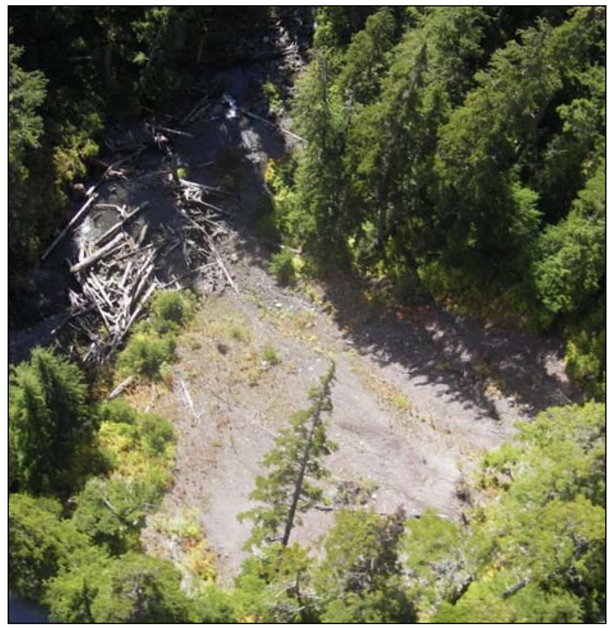

Figure 4-15. Subbasin 40, site #40-51. Stream side escarpment failure in glacial till.

4.2 Influence of Development Activities on Sediment Source Activity

Logging is the main development activity in Williams Creek valley. A small number of identified sediment sources appear to be related to logging, both along roads and in clearcuts. Sediment point sources along logging roads were concentrated along the Williams Creek mainline (#03-4, #00-16, #00-17, #00-32) and along a branch road on the west side of Llewellyn Creek (#16-11, #16-19, #16-13, #16-61, #16-62, #16-121 to #16-123). Most of these sources were active between 1968 and 1988, and were related to the period of extensive logging in the 1970s and early 1980s. The estimated total sediment output from the road-related sources in Llewellyn Creek was 11 852 m^3. These sources were located on steep gully walls in glacial till, and 50–70% of this volume was likely transported as suspended load. Several road-related sources along Williams Creek mainline did not reach Williams Creek, and the estimated output from the listed sources was 500 m^3. Road deactivation was undertaken in 1997-8 on roads in Llewellyn Creek drainage. A review of the deactivation measures in 2002 found that deactivation had been effective in reducing sediment delivery to the streams, and that newly constructed road segments typically had "no sedimentation issues" (Acer Resource Consulting Ltd. 2003).

Numerous small debris slides occurred in clearcuts along Williams Creek mainline, identified during field work in 1998 and during air photo interpretation. These narrow slides generally ran out on the open slope and were disconnected from the stream network. Between 1988 and 2001, sediment from debris slide #00-35 in sub-basin 00/2 ran to the valley floor, covered Williams Creek mainline, and may have deposited some sediment in Williams Creek (Figure 4-16).

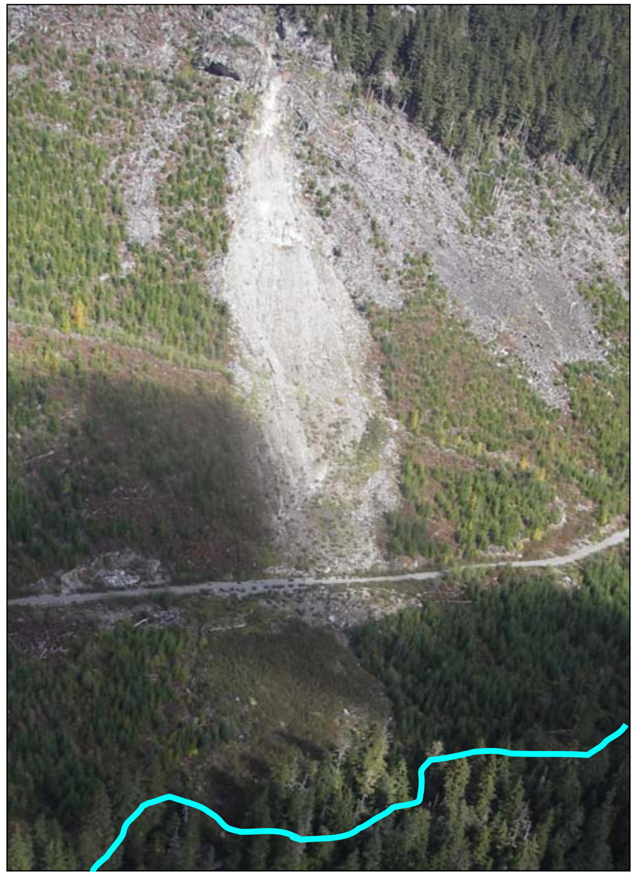

Figure 4-16. Debris slide initiating in a clearcut (site #00-35). The blue line marks the approximate location of Williams Creek

Road surfaces are known to potentially generate suspended sediment when used during wet conditions. The amount of sediment generated and delivered to the stream network depends on the texture and erodibility of the road surfacing material, the level of road maintenance, the amount of traffic on the road, and the density of stream crossings. With the exception of several road segments in Llewellyn Creek, surfacing material and road cuts seen during fieldwork in 1998 and 2006 were moderately coarse- to coarse-textured, and erodibility was considered low. Sections of Williams Creek mainline built prior to 1988 crossed numerous streams along the valley floor, generating a relatively high likelihood that any suspended sediment generated along roads would be delivered to a stream. Roads built during recent logging since 1997 have accessed settings on mid-elevation valley walls, and the density of stream crossings is lower.

5 CHANNEL CHANGES

5.1 Planimetric Channel Adjustment

The lower 6 km of Williams Creek flows across a low gradient fan and onto an unconfined valley bottom before reaching Lakelse Lake. The planimetric adjustment of the channel from 1949 to 2001 is shown in Map 1. The channel follows a wandering to irregular pattern amongst islands and wetlands. Reach 4 marks the apex of the fan and is largely confined by the valley walls (valley bottom width ≈ twice the undisturbed channel width) and channel gradient averages 0.013 (Table 3-2). The channel followed a relatively straight pattern in 1960 with few bars or islands. However, by 1975 the channel had widened from 37.6 to 53.1 m (Figure 5-1), and large side- and mid-channel bars had developed as the channel began to wander across the valley bottom, eroding the riparian area. By 1988, the reach had begun to recover, with relatively large portions of the active rtions of the active channel colonized by riparian vegetation (mapped as mixed vegetation and sediment). Channel width was 39.2 m, close to the value recorded for 1960. This recovery continued until 2001, although areas of mixed vegetation and sediment remained, suggesting that the channel had not completely returned to the form observed in 1960.

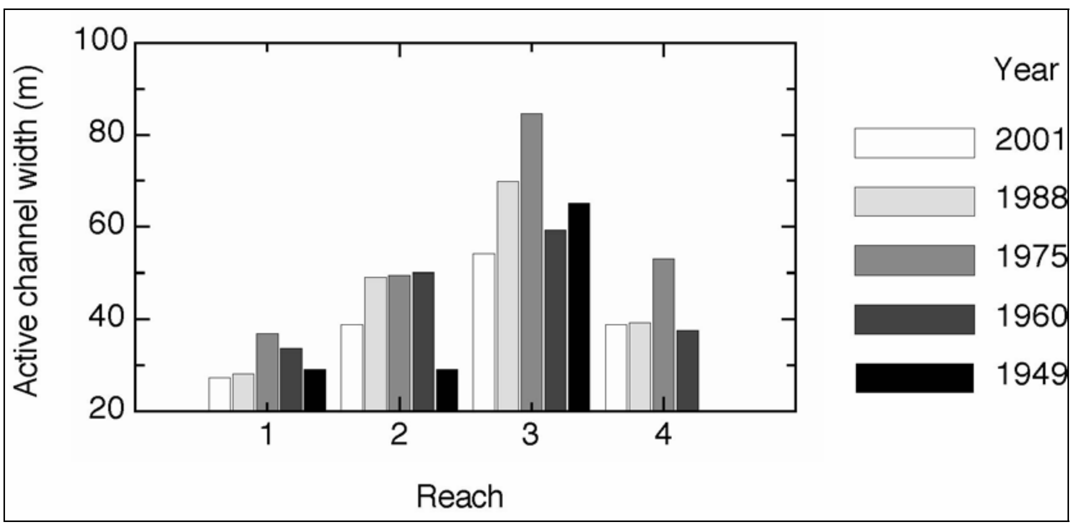

Figure 5-1. Active channel widths in lower Williams Creek: 1949 to 2001

Reach 3 is the uppermost unconfined reach on the fan, and was an active sedimentation zone throughout the period of study. Channel gradient averaged 0.0098. Large side-channel bars were observed in 1949, with small portions colonized by riparian vegetation. By 1960, mid-channel bars became more frequent and accumulations of woody debris (typically in the form of log jams) had developed. By 1975, relatively large mid-channel bars and log jams characterized the morphology. A mega-jam (Hogan and Bird 1998) developed in the lower portion of the reach as the channel avulsed and shifted laterally across the fan (the avulsion was first observed in 1960). Smaller avulsions were observed along the lower right bank as the channel began to scour several new channels through the riparian area and into the wetlands adjacent to reach 2. Channel width increased in 1975 from 59.3 m in 1960 to 84.6 m in 1975, and then gradually recovered to 69.9 and 54.2 m in 1988 and 2001, respectively (Figure 5-1). Most woody debris was absent from the reach in 1988, either transported downstream, buried by the channel, or covered by riparian vegetation growing on the fan surface. Active channel sediments were colonized by riparian vegetation as the channel width decreased through 1988 and 2001.

Reach 2 is the lowermost reach on the fan, buffered from reach 3 by a decrease in channel gradient (average gradient in reach 2 was 0.0082) and the development of a complex system of distributary channels (mapped as flood channels) that connect with adjacent wetlands, effectively reducing the transport capacity of the channel. Channel bars were generally absent from the reach in 1949 and 1960. Log jams and channel bars formed in the channel by 1975, but were relatively infrequent compared to reach 3. Channel width remained relatively stable between 1960 and 1988 and then decreased in 2001 (Figure 5-1). The presence of vegetated channel bars suggested that channel recovery processes may have begun before 1975, and by 2001 most of these features were completely revegetated and became part of the stable fan surface.

Reach 1 flows across an unconfined valley bottom, connecting the Williams Creek fan to Lakelse Lake. The channel has remained relatively stable between 1949 and 2001 as the channel is buffered from reach 2 by a reduced gradient (reach 1 gradient average 0.0016) that limits sediment transport. However, the pattern of widths adjustment follows that observed in other reaches, with relatively wide channels occurring in 1975 and 1988 (Figure 5-1). Islands and channel bars are infrequent throughout the reach, as the channel is essentially a transport reach moving sediments from the fan to the lake.

5.2 Net Storage Changes

Net changes in sediment storage in a reach were calculated by differencing DEMs for each period of observation (in the calculations, a positive value represents net deposition while a negative value represents net erosion). The results are given in Table 5-1 and Figure 5-2. Uncertainty in the data derived from comparison of DEMs was calculated after Lane et al. (2003). Generally, the channel aggraded from 1949 to 1975, with the largest change in storage occurring in reach 3 where 73,000 ± 6,000 m^3/yr of sediment was deposited between 1960 and 1975. Between 1975 and 1988, sediment stored in reaches 3 and 4 was eroded, again with the largest change in storage occurring in reach 3 where 104,000 ± 4,000 m^3/yr of sediment was eroded. Reach 2 followed a similar trend of erosion and deposition as reach 3, although the overall amount was nearly an order of magnitude less. Reach 1 remained relatively stable and experienced relatively small amounts net aggradation between 1949 and 1960 and between 1975 and 1988.

Table 5-1. Net change in sediment storage. Negative and positive values represent net erosion and net deposition, respectively.

Reach	Net change in sediment storage (m^3/yr)			
	1988–2001	1975–1988	1960–1975	1949–1960
1	300 ± 200	3,500 ± 100	-700 ± 200	12,500 ± 900
2	3,000 ± 200	-5,000 ± 200	13,500 ± 200	10,000 ± 1,000
3	29,600 ± 400	-103,600 ± 300	72,500 ± 400	31,000 ± 2,000
4	-8,200 ± 200	-6,700 ± 100	34,200 ± 200	–

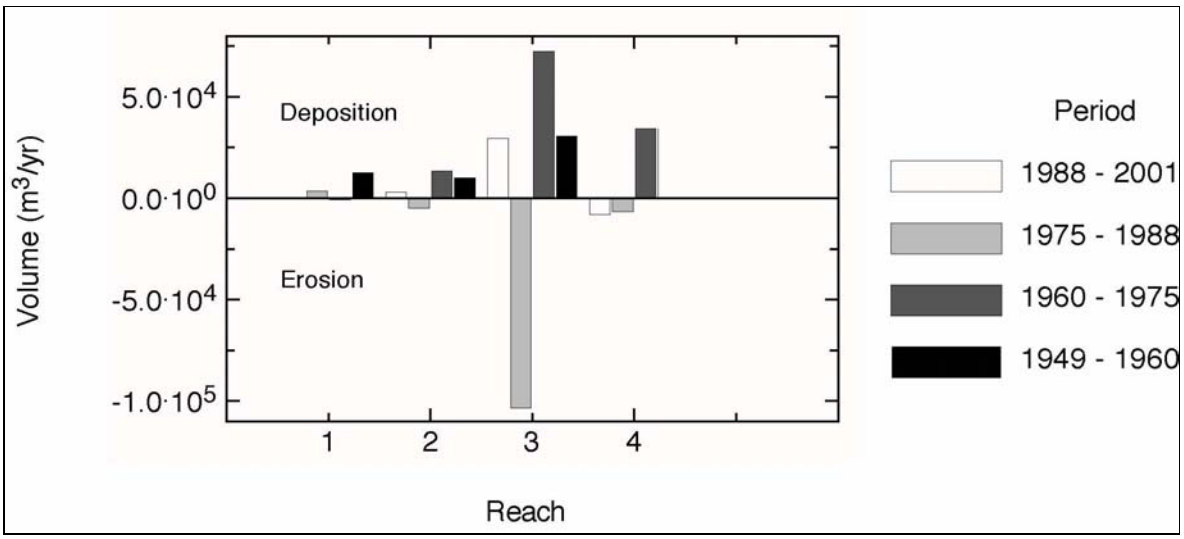

Figure 5-2. Change in sediment storage in lower Williams Creek

5.3 Bed Material Transport

Sediment transport was calculated for the lower 6 km of Williams Creek by measuring the three-dimensional changes in channel morphology from the planimetric maps and DEMs. The complete method is described in detail by Ashmore and Church (1998) with examples drawn from British Columbia given by Ham and Church (2000) and Martin and Church (1995). A reference transport rate (Q_r) was calculated for reach 3 as it was the most laterally unstable, thereby minimizing the negative bias introduced by compensating scour and fill. The estimate is given by:

$$Q_r = V_e(L_t / L_r) / t \tag{8}$$

where V_e is the volume of bed material sediment eroded (estimated from DEM differencing), L_t is the travel distance or step length of the eroded sediment, L_r is the reach length, and t is the number of years between successive air photo exposures. In this report, L_t was calculated for Q_{maf}, assuming this represented the effective discharge where significant amounts of bed material are mobilized (cf. Andrews and Nankervis 1995). Hassan and Church (1992) related L_t to excess stream power by:

$$L_t = 1.0(\omega - \omega_o)^{1.2} \tag{9}$$

Excess stream power is given by Bagnold (1980) as ω - ω_o, where:

$$\omega_o = 305D^{\frac{3}{2}} \log(12d/\,D) \tag{10}$$

and D is a representative grain size of the sediment (taken here as the D_{50}). An estimate of ω is given by:

$$\omega = \rho g d s v \tag{11}$$

where g is the gravitational constant (9.81 m/s^2), ρ is the density of water (1000 kg/m^3), and v is the water velocity through the reach, estimated by the Manning equation (Equation 2) with reference to data presented in estimates of Q_{maf} and channel geometry. The D_{50} of bed material mobilized at Q_{maf} is given by the boundary shear stress (τ):

$$\tau = \rho g d s \tag{12}$$

and the critical shear stress (τ_c) is:

$$\tau_c = \theta g(\rho_s - \rho)D \tag{13}$$

where θ is the Shields parameter (assumed here as 0.045) and ρ_s is the density of sediment (1000 kg/m^3). Assuming $\tau = \tau_c$ at Q_{maf}, Equations 12 and 13 can be rearranged to estimate the D_{50} of the mobilized sediment mixture as follows:

$$D = \frac{\rho d s}{\theta(\rho_s - \rho)} \tag{14}$$

The results are given in Table 5-2. In general, the D_{50} of sediments mobilized at Q_{maf} was about 150 mm and particles in this size fraction travelled approximately 400 m each flood event. Although larger particles may only move a few metres while smaller particles move several kilometres, the values presented here give an average L_t for the entire grain-size distribution of bed material sediment present in the reach. Generally, L_t varies with channel geometry, as a relatively wide and shallow geometry results in relatively low excess steam power (and vice versa). Step lengths standardized by w indicated that sediments typically move four to nine times *w*, or about the length of a single pool-riffle-bar unit as suggested by Neill (1987). Q_r was calculated for each air photo period (Equation 8) using an average L_t (with L_t values calculated at the start and end of each period). Each L_t was then multiplied by the number of discharge events exceeding $Q_{1.5}$ in each period to yield a total L_t (see section 2.3). The results are given in Table 5-3.

Table 5-2. Average particle step lengths in reach 3 for a single transport event at Q_{maf}

Year	τ_c (N/m^2)	D_{50} (mm)	v (m/s)	ω (N/ms)	ω_o (N/ms)	$\omega - \omega_o$ (N/ms)	L_t (m)	L_t/w (no units)
2001	113	156	1.7	205	37.5	167	466	8.6
1988	104	143	1.6	172	32.5	139	374	5.3
1975	99	136	1.5	152	29.3	123	322	3.8
1960	109	149	1.7	188	35.1	153	419	7.1
1949	106	146	1.6	179	33.6	145	393	6.0

Table 5-3. Reference transport rates in reach 3 for each study period. Q_r was calculated using an average reach length measured at the beginning and end of each period.Average L_t was calculated from L_t values marking the beginning and end of each period (see Table 3-4) multiplied by the number of flows $\geq Q_{1.5}$ in each period (see Table 2-1). Where the flood record was shorter than the air photo record, an average for the entire record was used.

Period	Flows $\geq Q_{1.5}$ (yr^{-1})	Average L_t (m)	t (yr)	Q_r ($\times 10^3$ m^3/yr)
1988–2001	1.4	6,596	13	24 ± 5
1975–1988	1.0	4,117	13	130 ± 30
1960–1975	0.9	3,692	15	10 ± 2
1949–1960	1.1	4,062	11	22 ± 8

A sediment balance was then constructed for the lower reaches of Williams Creek as

$$\Delta V = V_i - V_o \qquad (15)$$

where ΔV is the net change in bed material storage in a reach over the period of observation (erosion subtracted from deposition), and V_i and V_o are volumes of sediment input and output from a reach, respectively. Assuming V_o can be estimated by Q_r calculated for reach 3, V_o for reach 2 is solved by measuring ΔV, and using V_o from reach 3 as V_i to reach 2. These calculations were then extended to the remaining reaches. (Note that the method permits estimation of V_o for the reach immediately upstream of the study area in each period of study).

The results are given in Table 5-4 and Figure 5-3. Sediment transport through lower Williams Creek was relatively low between 1949 and 1960, with an average rate of 22,000 ± 4,000 m^3/yr (the range by reach was from < 8,000 to 52 000 m^3/yr). There is a general downstream decline in transport rates with a significant reduction of 50 000 ± 10 000 m^3/yr from reach 4 to reach 1. Transport rates were generally unchanged between 1960 and 1975, averaging 23 000 ± 1,000 m^3/yr in reaches 1 through 4 (but averaging 42 000 ± 1,000 m^3/yr when reach 5 was included in the estimate). However, a significant increase in transport of 30 000 ± 8,000 m^3/yr was observed in reach 4, and a decrease of 11 000 ± 8,000 m^3/yr was observed in reach 3. This spatial pattern in transport suggests that the increased sediment load transferred through reach 4 was deposited in the active channel and across the fan surface of reach 3 (given increased sediment storage in the reach during this period as shown in Figure 5-2). The relatively precise data from 1960 to 1975 reveal a general downstream decline in transport rates, suggesting reaches 3 and 4 are depositional in character, storing relatively coarse sediments in the upper fan, while transporting the remaining mobile fractions downstream. The analysis further suggests that most of these sediments were derived from upstream of the fan, given relatively high transport rates in reach 5.

Table 5-4. Sediment transport through lower Williams Creek. Note that a transport rate for reach 5 was calculated although no measurements were made in the reach (see text for explanation).

	Sediment transport (× 10^3 m^3/yr)			
Reach	1988–2001	1975–1988	1960–1975	1949–1960
1	20 ± 5	130 ± 30	< 2	< 8
2	21 ± 5	130 ± 30	< 2	12 ± 8
3	24 ± 5	130 ± 30	10 ± 2	22 ± 8
4	53 ± 5	< 50	83 ± 2	52 ± 8
5	45 ± 5	< 40	117 ± 2	–

The trend observed prior to 1975 is reversed in the period 1975 to 1988. Sediment delivery from reach 5 to the fan declined by 100 000 ± 30 000 m^3/yr compared to rates observed between 1960 to 1975, while transport in reaches 1 through 3 increased by an average of 120 000 ± 10 000 m^3/yr. Most of this sediment was derived from storage along reaches 3 and 4 (Figure 5-2), as sediments deposited prior to 1975 were remobilized as supply from upstream declined. Between 1988 and 2001, average transport rates in reaches 1 through 3 declined by 100 000 ± 20 000 m^3/yr but remained about 14 000 ± 4,000 m^3/yr higher than the average rates observed between 1949 and 1975. This suggests that the channel was still reworking sediments delivered to reaches 3 and 4 prior to 1975, and that channel recovery processes were still ongoing in 2001.

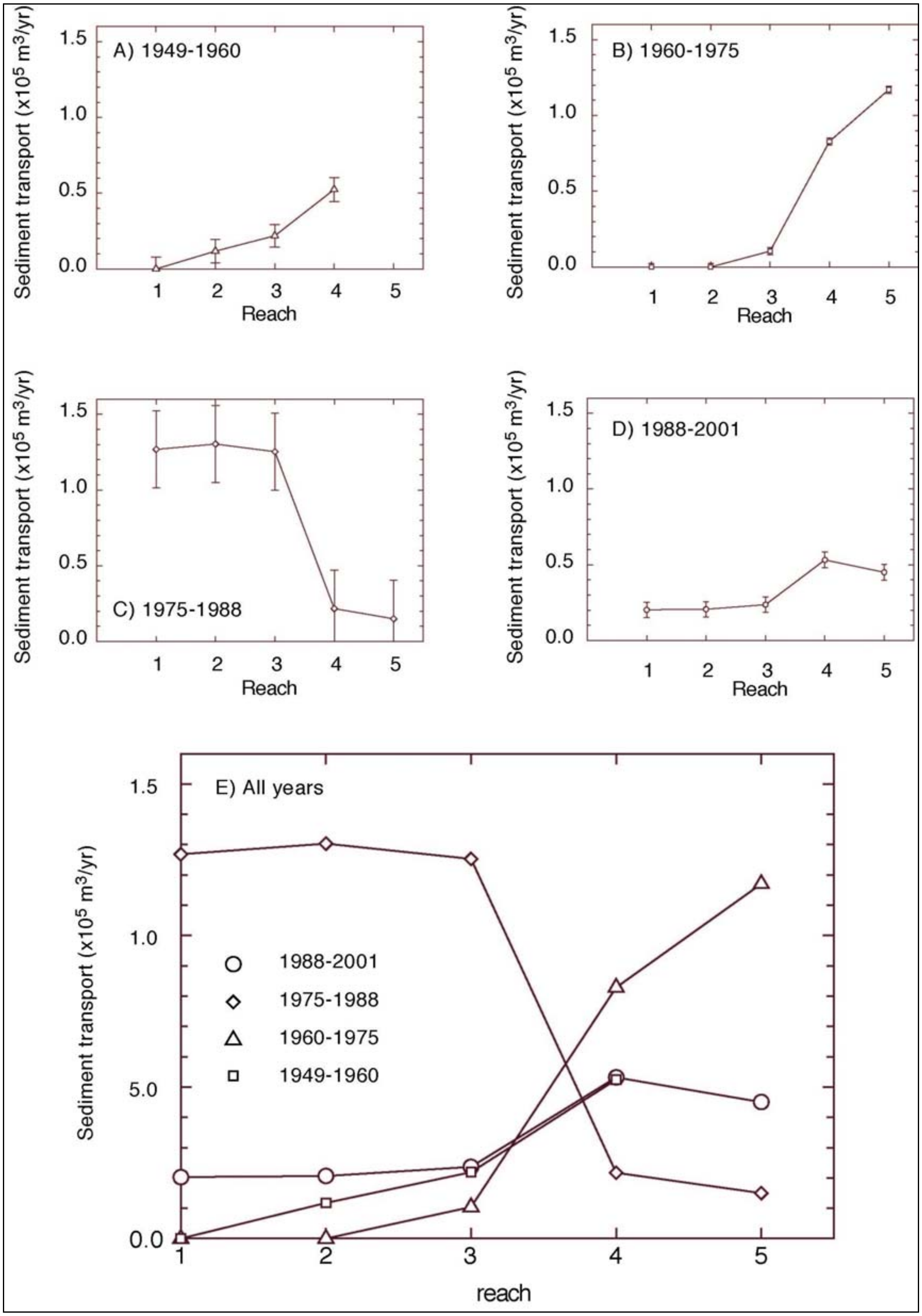

Figure 5-3. Sediment transport rates in lower Williams Creek

6 SEDIMENT TRANSFER HAZARD

6.1 Reconnaissance Sediment Budget

6.1.1 Estimated hillslope sediment source volumes

The estimated sediment output volume from the Williams Creek valley drainage area was 540 000 m^3 (Table 6-1). In Table 6-1 *Sediment input from sediment sources* refers to the sum of sediment volumes generated at each source, based on the measured length and width, and the assumed standard erosion depth at each site. *Sediment output from sub-basin* refers to the sediment volume that was entrained and transported to a valley bottom stream (Williams Creek, Myron Creek, Llewellyn Creek, SB38 Creek, and SB39 Creek).

High sediment volumes were contributed from Sub-basin 29 (82 500–183 800 m^3) and Sub-basin 16 (Llewellyn Creek: 56 300 –70 200 m^3), two tributary valleys with active headwater processes. Relatively high volumes of sediment were contributed from steep alpine basins along the north side of the mid-valley section of Williams Creek valley (SB20: 48 700–83 400 m^3; SB25: 44 900–74 800 m^3; SB28: 38 700–53 900 m^3). A third area of high sediment production comprised the neoglacial moraines in the headwaters of sub-basin 38 (76 300 m^3–88 000 m^3).

Sediment yield per sub-basin (Table 6-2) ranged from < 1 to 420 $m^3/km^2/yr$. Average sediment yield for the Williams Creek valley drainage area was 42 $m^3/km^2/yr$. This is within the order of magnitude of sediment yield for similar sized watersheds reported in the literature (Jordan and Slaymaker 1991).

6.1.2 Estimated hillslope sediment volume by time interval

Figure 6-1 shows an approximation of sediment production per observation period. Many small, long-term sediment sources were active prior to 1949, and the majority of the volume generated from these sources was assumed to have entered the stream network during the initial slope failure, prior to 1949. However, the sediment volume allocated to the pre-1949 period was probably overestimated as a result of applying standard reconnaissance scour depths to all sediment sources.

For the 52 years after 1949, total sediment output from all sub-basins was greatest between 1968 and 1988, compared to 1949 to 1968 or 1988 to 2001 (Figure 6-1, Table 6-2). This trend was driven mainly by increased sediment source activity between 1968 and 1988 in sub-basins 00/1, SB02, SB04, SB16, SB20, and SB25 (Figure 6-2). These sub-basins were steep, generating high sediment throughput to the Williams Creek valley floor. Colluvial fans on the valley floor have partially stored sediment delivered from these sub-basins, and have somewhat reduced the throughput to Williams Creek.

Table 6-1: Sediment production by sub-basin

Sub-basin	Sediment source input volume (m^3)	Sub-basin output volume (m^3)	Sub-basin area (ha)	Sediment yield[a] ($m^3/km^2/yr^a$)	Sediment yield[c] ($m^3/km^2/yr$)
00/1	23 784	11 284	2 000	8	16
00/2	17 869	13 190	2 313	8	10
01	125	125	179	1	1
02	36 160	21 696	140	206	344
03	1 585	1 585	445	5	5
07	10 301	9 270	50	249	277
08	8 889	4 945	114	58	104
12	15 783	8 355	145	77	146
13	4 685	1 511	90	22	70
14	5 575	5 018	299	22	25
15	5 573	5 015	377	18	20
16	70 165	56 293	1 553	48	60
17	3 840	384	178	3	29
18	450	270	157	2	4
19	4 806	811	150	7	43
20	83 422	48 709	364	179	306
21	125	13	165	0	1
25	74 848	44 909	348	172	287
26	27 149	19 628	989	26	37
27	0	0	90	0	0
28	53 885	38 721	407	127	176
29	183 786	82 527	2 086	53	117
30	21 377	10 951	86	169	330
31	30 128	18 077	158	152	254
32	19 083	11 450	111	137	229
33	25 508	15 305	48	428	714
35	0	0	127	0	0
36	9 087	2 726	360	10	34
37	2 846	1 708	264	9	14
38	87 969	76 273	1 017	100	115
39	42 079	26 976	980	37	57
40	2 243	2 221	829	4	4
Total	873 121	539 943	17 002	42	68

[a] Calculated based on estimated sub-basin output volume
[b] Calculation was based on a 75-year period, allowing for an 18–20 year sediment source activity period prior to 1949
[c] Calculated based on estimated sediment source input volume

Table 6-2. Estimated sediment output volume by observation period

Observation period	Estimated sediment output volume (m^3)	Estimated sediment output volume per year (m^3)	Estimated sediment input volume (m^3)	Estimated sediment input volume per year (m^3)
pre-1949	282 854		463 240	
1949–1968	67 370	3 546	104 704	5 511
1968–1988	123 682	6 184	205 809	10 290
1988–2001/5	66 037	4 402	99 368	6 625

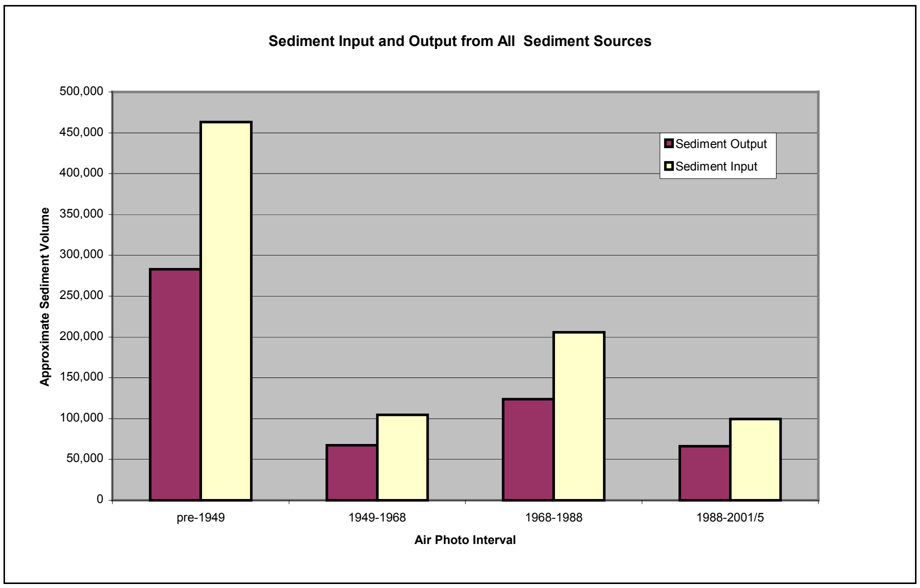

Figure 6-1. Sediment output and sediment input volume from all subbasins since 1949

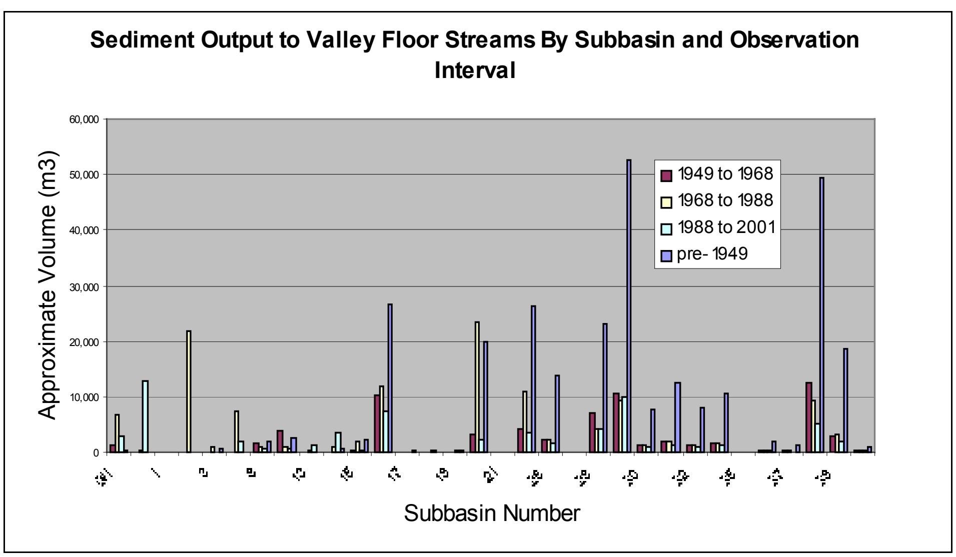

Figure 6-2. Sediment output by subbasin and observation period.

Sub-basin 38 showed a different trend (Figure 6-2). Estimated sediment output to the valley floor stream was greater between 1949 and 1968 than after 1968. This corresponds with significant aggradation and channel change on the gravelly fluvial fan at the mouth of sub-basin 38 during a flood event between 1949 and 1968.

Sediment production rate in Llewellyn and Myron Creeks (sub-basins 16 and 29) was relatively steady between 1949 and 2001. Sub-basins 16 and 29 are large tributary valleys, covering 9.1% and 12.3% of the Williams Creek valley, respectively. The greater sediment production (Table 6-1) from these sub-basins reflects the larger basin area.

Between 1988 and 2001, sediment source activity and estimated volumes were similar to estimates for the 1949 to 1968 period.

6.2 Channel Sediment Routing Hazard

Stream channels upstream of the fan were described from maps and field observations. The mainstream longitudinal profile is shown in Figure 6-3. Channel gradient averaged 3% along the lower profile to the 34 km mark. Air photo and field observations suggest that above the 24 km mark, the channel follows a riffle-pool morphology with zones of lateral channel instability and storage of gravel- to cobble-sized sediments. Downstream, the channel follows a rapid morphology (Church 1992) along the mainstem, transporting boulder size clasts in a series of long chutes to the fan. Opportunities for sediment storage in the channel or along the channel margin are limited (Grant et al. 1990; Montgomery and Buffington 1997), so that most sediment introduced to this section of the channel remains mobile and is transported downstream to the fan. The sediment transfer hazard in this portion of the watershed is considered high.

An estimate of the temporal link between an input of sediment to the rapid section of channel at km 24 of the longitudinal profile, and the time it takes to reach the fan, was made with reference to the analysis presented in Section 5. Assuming average channel conditions of D_{50} = 256 mm, d = 1 m, s = 0.03, θ = 0.06, and n = 0.08, the average L_t for the channel is about 2 km per flood event. Given that we assumed $Q_{1.5}$ was exceeded about 1.1 times per year in Williams Creek (Table 2-1), the D_{50} of sediment transferred to km 24 may take approximately 8 years to reach the apex of the fan at km 6 of the longitudinal profile. Finer-size fractions may require only a few years to reach the fan, while coarser fractions may take several decades.

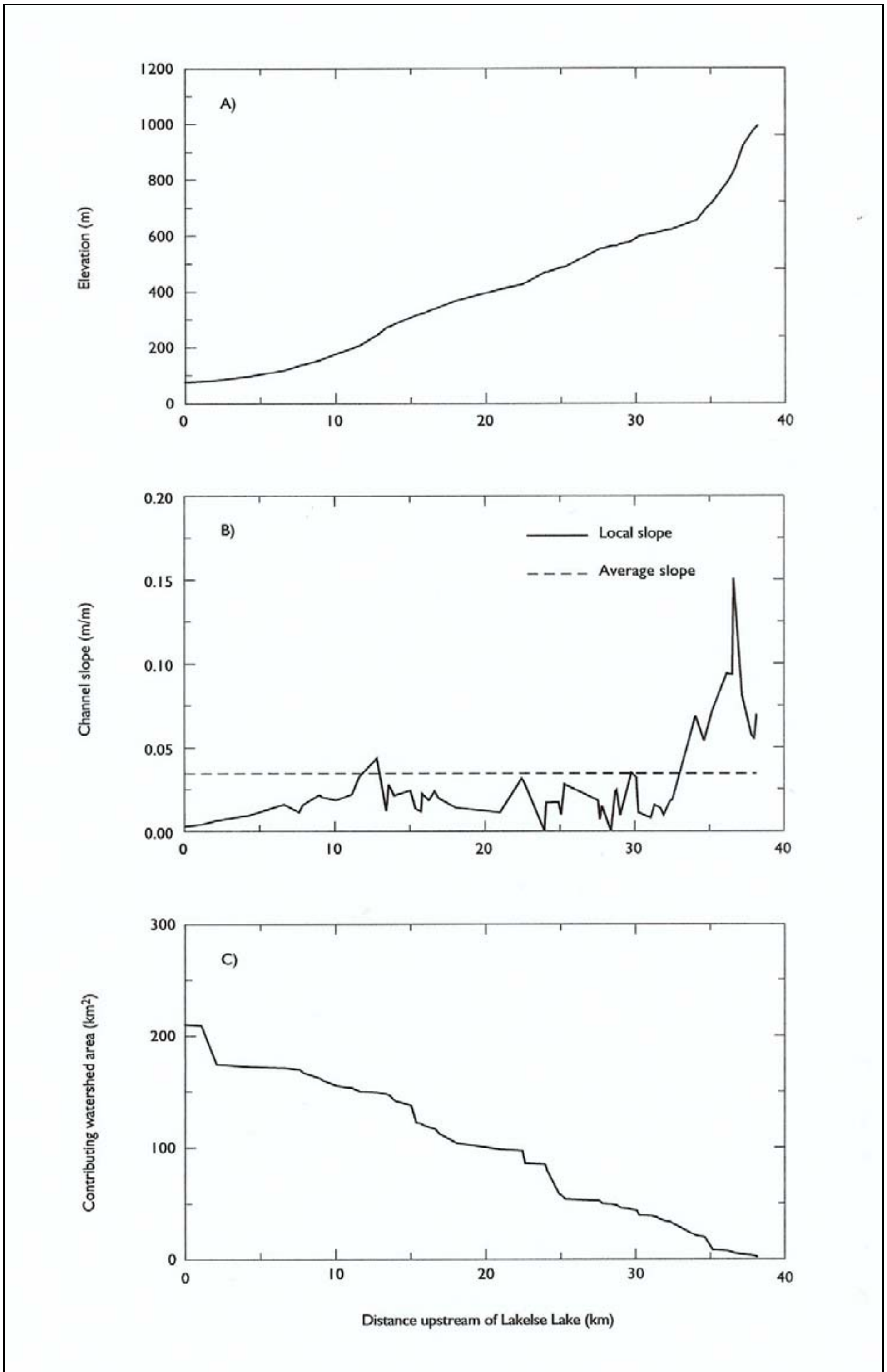

Figure 6-3. Longitudinal profile of the main channel of Williams Creek: A) channel elevation, B) channel gradient, C) contributing watershed area. Data was derived from 1:20,000 TRIM maps and 1:50,000 DEM.

7 CONCLUSIONS

The sediment regime in Williams Creek valley over the last 52 years is dominated by coarse-textured sediment, contributing to bedload and bedload movement in the channel network. Suspended sediment supply is limited, due to the relatively lower number and smaller size of fine-textured sediment sources. Turbidity in Williams Creek typically clears up within 1–2 days after a heavy rainfall event (Ken Fraser, pers comm., July 2006).

The Williams Creek valley produced sediment from natural hillside sources in three main areas of the watershed:

(1) Steep gully systems draining small alpine basins on the northern valley walls, approximately at mid-valley locations (SB20 to SB25, SB28, and SB33), subject to debris flow activity. Bedrock lithology is predominantly granodiorite, with a minor component of calcareous sedimentary rock. This area typically produced coarse-textured sediment (coarse sand, pebbles to cobbles with small boulders, with a few large boulders).

(2) The glaciated headwater valley section in sub-basin 38, subject to periglacial and neoglacial erosion. The lithology is dominated by rhyolithic to basaltic volcanic flows and breccias with a distinct green and maroon aphanitic appearance. This area typically produced pebble-size material, with a comparatively high component of silt and fine sand.

(3) headwater valley walls and stream banks in Myron and Llewellyn Creeks, subject to gully erosion, stream bank erosion, and debris slides. Bedrock lithology typically consists of volcanic rock similar to area (2). Typical sediment texture includes minor clay, silt, sand, pebbles, and cobbles, as well as occasional small boulders.

The lithologic composition on the fan apex suggests that sources in granitic bedrock (area 1) were equal to or slightly more productive with respect to sediment delivery to the alluvial stream reaches than sources in volcanic bedrock (areas 2 and 3).

The overall activity of sediment sources, and the number of sediment sources on the hillslopes in Williams Creek valley upstream of Williams Creek fan, started to increase before 1968, clearly increased during the period 1968–1988, and returned to approximately pre-1968 levels for the period 1988–2001.

During the period of increased sediment output from sub-basins between 1968 and 1988, numerous small, new sediment sources were generated throughout the Williams Creek valley. Sediment production increased, particularly in area 1. The most obvious event was a large debris avalanche/debris flow in sub-basin 20, which delivered 18 000 to 30 000 m^3 of sediment to Williams Creek. Sediment from the sub-basins in area 1 is typically transported to alluvial reach 4 and the fan apex in reach 3 within several years. Another zone of increased activity consisted of forested slopes in the lower valley, such as those in sub-basins 2 and 7. A debris flow in sub-basin 2 delivered 20 000 m^3 to 35 000 m^3 to Williams Creek. Given the proximity to the alluvial reach 4 and the fan apex, sediment delivery time was extremely short to immediate.

The increased sediment output from area 2, in particular from SB38, to Williams Creek between 1949–1968 was largely absorbed by the unconfined, gentle gradient stream reach in the upper Williams Creek valley. Sediment delivery to the Williams Creek fan was delayed by several decades.

Logging- and road-related sediment sources that impacted the stream network were relatively small and infrequent in comparison to the natural sediment sources in the valley. Logging-related sediment sources were typically point sources at stream crossings, or where cutblocks encroached on streamside embankments. These point sources generated in the order of 300–500 m^3 of sediment per site. Open-slope debris slides in cutblocks have typically not reached the stream network, with the notable exception of site #00-35. The highest density of logging-related sediment sources was in Llewellyn Creek sub-basin, dating back to the 1970s and early 1980s. These sites had started to revegetate by 2001.

The channel flowing across the fan was disturbed some time between 1960 and 1975. Channel width in reaches 3 and 4 increased by 41 and 43%, respectively, as sediment from the upper watershed was transferred to the fan (sediment storage increased in reach 3 by 73 000 ± 6,000 m^3/yr). Transport rates out of reaches 4 and 5 were relatively high (83 000 ± 2,000 and 117 000 ± 2,000 m^3/yr, respectively), indicating that the sediment was derived from upstream sources and not remobilized from the fan itself. This occurred despite relatively intense forest development adjacent to the channel during this period. Forest harvesting activities may have contributed to the observed channel instability, but it seems likely that increased sediment supply from upstream was the dominant process affecting channel stability.

Between 1975 and 1988, sediment stored in reaches 3 and 4 was remobilized and transported to the lower channel, eventually reaching Lakelse Lake. Net scour along reach 3 alone was 103 600 ± 300 m^3/yr. As a result, transport rates increased by an order of magnitude through reaches 1, 2, and 3, while transport through reach 4 returned to a similar rate to the average observed between 1949 and 1960. By 1988 to 2001, channel morphology had largely recovered along the lower channel. Channel widths were generally similar to those observed both in 1949 and 1960 as riparian vegetation colonized a portion of the active channel. However, transport rates through reaches 1, 2, and 3 remained relatively high, indicating that channel recovery processes are ongoing.

7.1 Synthesis

Increased sediment production started between 1949 and 1968 in undeveloped terrain in the upper watershed, with low sediment transfer rates along the main valley stream reaches. A separate, post-1968 event or series of events mobilized increased sediment volumes in gully systems located mid-valley, with rapid sediment transfer to alluvial reach 4 and the fan. The extent of the resulting channel changes in reach 4 peaked before 1975 in reach 4, and before 1988 in reaches 3, 2, and 1 downstream. Sediment supply to reach 4 dropped to pre-1960 rates after 1975. In the Williams Creek valley, reduced sediment mobilization was obvious only after 1988. This timing discrepancy may be partly due to the relatively long intervals between air photo series used for the sediment budget in the valley.

7.2 Discussion

The reconnaissance sediment budget determined the sediment yield from hillslope sources at 42 $m^3/km^2/yr$ between 1949 and 2001. However, peak sediment input between 1968 and 1975 in reach 4 was 117 000 ± 2,000 m^3/yr or 688 $m^3/km^2/yr$, and sediment yield received between 1975 and 2001 was approximately 235 $m^3/km^2/yr$. This discrepancy of an order of magnitude suggests that the reconnaissance sediment budget systematically underestimated the sediment volumes mobilized in the Williams Creek valley. In particular, other sources such as tree windthrow, sheet wash, and fluvial bed and bank erosion above the fan may represent important, relatively continuous sources of sediment to the drainage network not accounted for in this study.

Analysis of a single lake sediment core taken in 2002 in the north basin of Lakelse Lake suggests that sedimentation rates have steadily increased since 1950, peaking in 1991, with drastically reduced rates after that (Cumming and Laird 2002). This trend is generally consistent with the increased sediment yield seen in the Williams Creek valley between 1949 and 1988, and the channel changes affecting progressively downstream reaches on the fan between 1960 and 1988. However, sedimentation rates steadily increased in the south basin of Lakelse Lake during the same period. This suggests that Lakelse Lake sedimentation rates are controlled more by processes or developments throughout the Lakelse Lake watershed, rather than by processes in one large sub-basin.

The observed trend of hillslope processes since 1949 corresponds partially to the precipitation trend over the last 52 years. The period of elevated sediment production between 1968 and 1988 corresponds to a short period of above-average precipitation (1974–1978), which included the largest precipitation event recorded in the area (Terrace climate station, October 31, 1978). However, a similar precipitation trend between 1987 and 1993 was not reflected in elevated sediment production from hillslope sediment sources.

The channel changes on the alluvial reaches of lower Williams Creek appear to have been triggered by processes upstream of reach 4 and the fan, within the Williams Creek valley. However, they could not be tracked to specific hillside processes, events, or activities. Nor does the timing of channel changes (peak change in reach 4 prior to 1975) correspond well to periods of above-average discharge (1974–1978), although the rainstorm and corresponding flood of October 15, 1974 (recorded in nearby gauged watersheds) could have triggered at least some channel change. Land use changes and floodplain development also affected the extent of changes. In summary, multiple factors control channel changes on the fan, and appear to interact in a complex and possibly unpredictable manner.

7.3 Outlook and Recommendations

Fisheries and Oceans Canada is considering investing in sockeye habitat enhancement on the lower alluvial reaches of Williams Creek. This requires an understanding of the possible future sediment regime for the Williams Creek watershed. As a result of this study, no clear connection emerged between hillslope processes, precipitation, discharge trends, changes in land use, and the observed channel changes on the fan. However, sediment sources in the valley and sediment yield to Lakelse Lake have declined since the late 1980s or early 1990s, suggesting the watershed is in a period of relatively low geomorphic activity (corresponding to a period of relatively low extreme discharge and precipitation). During this period, channel morphology in the lower reaches has recovered (or is recovering) from disturbance or a series of disturbances that occurred before 1975. Despite these observations, predictions of the future extent of channel changes are subject to great uncertainty. Sediment transfer from unstable slopes in the upper watershed to the fan is relatively rapid, as the drainage network is relatively steep with little opportunity for storage. The channel changes since 1960 have shown that any changes to bedload volume or mobility in reach 4 will eventually affect channel stability in reach 2 below, as stored sediment on the fan is re-worked and transported downstream.

This study focused on the relationship between upslope sediment production and channel changes in the lower alluvial reaches, as they related to increased influx and throughput of bedload. The suspended sediment regime was not evaluated in detail. However, suspended sediment sources exist in the Williams Creek valley, and there may be a relationship between suspended sediment production in the valley and fine-textured sedimentation in important sockeye spawning habitat. We offer the following suggestions for information to be compiled in future studies that may clarify uncertainties identified here.

Field mapping the location of distributary channels in reaches 1 to 4 with an indication of:

- sockeye spawning habitat potential;
- proximity and exposure to channel changes as mapped out in this study;
- characterization of distributary channel bed textures;
- connectivity of sockeye spawning habitat to Williams Creek main channel and its exposure to inflow of suspended sediment during floods and overbank flooding.

This information would assist in determining the sensitivity of sockeye spawning habitat to channel changes as mapped in this study and to suspended sediment deposition.

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9 APPENDIX

9.1 Aerial Photos used in the Study

Table 9-1. Aerial photos used for stereoscopic sediment source mapping in the Williams Creek valley

	Flight line	Frame	Colour/B &W	Date of exposure	Flying height (m asl)	Nominal scale
1938	BC43 BC48	2-11 66-72 106-111	B&W B&W	June 21 June 23		1:17 000[a]
1949	BC1023	23-26 40-44 85-89 100-105	B&W	September 27		1:31 000
	BC1024	34-38, 55-60, 106-110	B&W	September 27		
1968	BC5303	107-110 143-147 155-158 194-198 208-212	B&W	August 3	6,096	1:32 000
1981	15BC81042	123-127 133-141 151-155	B&W	July 10	7,468	1:40 000
1988	30BCB88016	262-264	B&W	July 7	6,401	1:15 000
	30BCB88018	187-192 238-250	B&W	July 18	6,401	
	30BCB88019	39-52, 99-111 183-187 238-239	B&W	July 18	6,706	
2001	15BCB01002	15-19 64-72 103-110 148-151	B&W	August 8	5,800	1:30 000

[a] Enlarged from 1:40 chain (1:31 680) negative

Table 9-2. Inventory and description of airphotos used in photogrammetric mapping and DEM generation. Scale and pixel size (in ground space) were estimated for image area along the channel (average terrain elevation was 100 m asl).

Date	Nominal focal length (mm)	Average flying height (m asl)	Scale	Scanning resolution (μm)	Pixel size (m)	Flight line(s)	Frames
2001 8/8	152.7	5,823	1:37 475	10	0.37	BCB01002	110, 111, 112, 113, 114
1988 7/10	305.6	6,673	1:21 507	12	0.26	BC88019	180, 181, 182, 183, 184
1975 6/19	152.4	2,185	1:13 667	12	0.16	BC5664	243, 244, 245, 260, 261, 262, 271, 272
1960	82.55	2,681	1:31 261	12	0.38	BC2786	95, 96, 98, 99
						BC2787	42, 43, 44, 45
1949 9/27	82.55	5,418	1:64 421	12	0.77	BC1025	8, 9

9.2 Flood History in the Lakelse Lake Area

Table 9-3. Known and possible flood events in the Terrace-Kitimat area

Known and possible flood events, Terrace- Kitimat 1894-2004

Year	Only Historical records	Event Recorded	Precipitation mm/days Terrace A	Zymoetz	Max Daily Discharge (m3/s)	Williams	Max Daily Discharge (m3/s)	Hirsch	Max Daily Discharge (m3/s)	Kitimat	Max Daily Discharge (m3/s)
1894	Spring flood >1936	Septer & Schwab									
1898	Spring flood >1936	Septer & Schwab									
1903	Jan 4-5 1903	Septer & Schwab									
1905	Oct 1-3 1905	Septer & Schwab									
1909	Oct 24-30 1909	Septer & Schwab									
1913		Septer & Schwab	157/3 days							Nov 30-Dec 3	
1914		Septer & Schwab	147/4 days							Nov 20-25	
1917		Septer & Schwab	81.8/3days	19-Nov							
1926		Septer & Schwab	93.7/2 days	22-Nov						Nov 21-25	
1929		Septer & Schwab	134.9/2 days	12-Nov							
1933		Septer & Schwab	165.5/2 days	30-Nov							
1935		Septer & Schwab	234/4 days	Oct 21-26							
1936		Septer & Schwab		May 29-June3							
1936		Septer & Schwab	82.1/2days	Nov 9-19							
1940		Septer & Schwab				Oct 17-20					
1945		Septer & Schwab	99.3/2 days	02-Nov		02-Nov					
1950		Septer & Schwab		14-Jun							
1951		Septer & Schwab	119.1/2 days	Oct 26-28							
1952		Septer & Schwab				April 15-18					
1953		Septer & Schwab	76.9/3 days		776					Oct 10-14 25-27	
1954		Septer & Schwab	68.8/3 days	'an 30-Feb 3						Jan 30-Feb 3	
1954		Septer & Schwab	148/8 days		677					Sept 21-25	
1956		Septer & Schwab	168.2/2 days							Nov 2-3	
1958		Septer & Schwab	170.9/6 days							Oct 27-Nov2	
1959		Septer & Schwab	225.7/6 days							Nov 30-Dec 5	
1960		Septer & Schwab	68.3/3 days							Oct 14-16	
1961		Septer & Schwab	121.2/2 days							Feb 4-5	
1961		Septer & Schwab	60.6/2 days	Oct 29-30	1050					Oct 12-14	
1962		Septer & Schwab	49.2/2 days	Oct 15-17	850					Oct 15-17	
1964		Septer & Schwab	104.7/3 days	Oct 16-20	323					May 31-June 8	892
1965		Septer & Schwab	168.4/ 6days		646					Oct 16-21	1100
1966		Septer & Schwab	120.7/6 days	Oct 21-24	1250	Oct 21-24			187	Oct 21-24	1120
1967		Septer & Schwab	60.6/3 days		428				128	Sept 20-24	886
1969		Septer & Schwab	129.3/3 days		459	Nov 26- Dec2			282	Nov 26- Dec2	1300
1974		Septer & Schwab	120.9/ 4 days	Oct 13-16	1470	Oct 13-16		Oct 13-16	566	Oct 13-16	1650
1978		Septer & Schwab	203.9 2 dys	)ct 29-Nov	1980	Oct 29-Nov 1		Oct 29-Nov	541	Oct 29-Nov 1	2410
1979		Septer & Schwab	151.4/3 days						110	Dec 25-27	794
1983		Septer & Schwab	51.8/2 days						124	Sept 23-26	931
1986		Septer & Schwab	34.8/3 days						112	Oct 26-28	575
1987		Septer & Schwab	162.6/3 days	Sept 17-21	819	Sept 17-21			343	Sept 17-21	1530
1988		Septer & Schwab	106.6/1 day	Sep 26-29	1280	Sep 26-29		Sep 26-29	320	Sep 26-29	1300
1989		Septer & Schwab	55.4/2 days						283	Nov 15-18	1020
1990		Septer & Schwab	71.4/1day						159	Nov 11-12	500
1990		Hydat Env. Can	-102.6/1day							Nov 28-Dec 8	1090
1991		Septer & Schwab	148.3/3 days	Oct 6-14	1810	Oct 6-14		Oct 6-14	467	Oct 6-14	2500
1992		Hydat Env. Can	180.6/2 days	Sept 28-30	1380	Sept 28-30		Sept 28-30	510	Sept 28-30	2820
1993		Hydat Env. Can	95.8/3 days							02-Nov	1610
1998		Hydat Env. Can	104.8/3 days							06-Oct	1370
2002		Hydat Env. Can	58.6/2 days					Nov 18-21	317	Nov 19-22	1520
2004		Hydat Env. Can	51.8/2 days							Nov 4-5	1260

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