INTENSIFYING STORMS, FLOODS AND CHANNEL CHANGE: SQUAMISH RIVER, BC (1956-2007)

by

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ABSTRACT

This study examines relations among hydroclimatic and channel changes on Squamish River in southwestern British Columbia (1956-2007).

Magnitude, volume and duration of extreme floods (Q≥1500 m^3/s) exhibit a 50, 450 and 300 percent respective increase with time and the annual-flood series is non-stationary with the largest floods being more recent. The increase in extreme floods is attributed to the intensification of late-season (Aug-Dec) Pacific storms that have produced increases in precipitation amounts, intensity and duration of respectively 340, 200 and 200 percent over the same period.

Changes in floodplain-surface area, calculated from GIS differencing of sequential large-scale aerial photographs, indicate that the rate of geomorphic change in Squamish River has accelerated between 1956-2007, a result of an increase in the magnitude and duration of the annual flood. Channel-change activity after 1980 has increased by a factor of 2 to 6 compared with the period prior to 1980.

Keywords: Channel change; climate change; flood regime

DEDICATION

This is for Papa, Bryan, my wife who I have yet to meet, Marbles and Hawaii.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 Introduction

It is generally accepted that climate is changing. Within Canada and more specifically British Columbia, southern regions are sensitive to shifts in the rainfall. The flooding regime of a river is one of many hydrologic variables intimately linked to precipitation type, intensity and frequency. Furthermore, the streamflow regime of coastal rivers, in particularly, is more sensitive to shifts in precipitation than in temperature.

Alluvial rivers, because of their easily transportable boundary materials, are likely to be the first type of rivers to respond to changes in streamflow; however, semialluvial rivers such as Squamish River, north of Vancouver, BC, are also likely to respond. Within Squamish River basin rainfall-driven extreme flooding events are known to rapidly reshape the river morphology in a number of reaches of varying planform (Sichingabula 1986). There is evidence to suggest that increases in precipitation are amplified through the hydrologic system yielding proportionally larger flood discharges. The effect that this will have on high-energy, steep coastal rivers remains unknown. Church and Ashmore (1998) state that, “Rivers are closely connected to landscape and climate [and that] river morphology and dynamics constantly adjust to the delivery of water and sediment from the watershed which controls the stream flow quantity and sediment load.” Thus, if there is a localized hydrologic shift involving an increase in the duration, frequency and/or absolute magnitude of large-scale floods, we might expect there to be an accompanying measurable shift in the magnitude of channel response such as changes in channel geometry. It is my hope that this case study of Squamish River may be used as an analogue to estimate the rate, magnitude and direction of change and overall stability of steep, gravel bedded coastal streams in response to hydrologic shifts in the southern Cordillera.

1.2 Hydrologic Responses to Climate Change

The precise response of a hydrological system to variations in climate is presently not predictable. Nevertheless, changes in the amount or intensity of rainfall, mean/maximum/minimum temperature, soil moisture, permafrost conditions, sediment yield, as well as streamflow, river freeze-up and run-off generation processes are likely involved. Environmental factors such as topography, surficial materials and land use may also exacerbate or moderate any such response. Since interactions of many physiographic factors influence the magnitude, frequency and sensitivity of the response, climatic-induced shifts in hydrology are rarely homogeneous between regions. Here I will limit the review of previous work largely to those based in coastal basins in British Columbia.

1.3 Hydrologic Shifts in Coastal Watersheds: Trends in precipitation, evidence from British Columbia

Although extensive studies of heavy precipitation events have been conducted for Canada (Mekis and Hogg 1999, Zhang et al. 2001) and for British Columbia as a whole (Whitfield 2001), due to the extensive spatial variability in orographic influence, continentality, annual temperature and precipitation regimes, hydrologic shifts will be only reviewed for coastal catchments of southwestern British Columbia.

There are two common ways in which to conduct numerical hydrologic surveys: using statistical methods and by hydrologic modelling. For a brief summary of the advantages and limitations of these two approaches refer to Loukas and Quick (1999). The majority of the studies reviewed here are empirical (statistical) in character.

Hydrologic shifts are commonly discussed in terms of rainfall characteristics (either mean annual amounts, rainfall intensity or storm duration) and often related to changes in temperature characteristics or large-scale climatic patterns. There are no long-term hydroclimatic studies of Squamish River valley. Sichingabula (1986) described the basic hydrology of the basin in terms of average monthly rainfall, but accurate year-by-year analysis of rainfall data was not a goal of his study. However, heavy or high-intensity rainfall studies have been conducted in areas proximal to Squamish River basin. An extensive rainfall-intensity study using nine spatially-distributed rain gauges was conducted by Jakob et al. (2003) in the densely populated Greater Vancouver Regional District (GVRD), located approximately 40 km south of Squamish. They found little evidence to suggest that short-duration (5 minutes to 2 hours) rainfall intensities have increased in the late 1950s to the early 2000s; only one of the nine stations show a statistically significant upward trend in rainfall intensity. Dunkley (2000) also analyzed GVRD rainfall-intensity data. He found that, for the years 1961-96, there is an increasing trend in the occurrence of storm events in which rainfall intensities greater than 10 mm/hr were registered for storm durations of less then one hour. Anthropogenic influences on rainfall-intensity data are not explored by either Jakob et al. (2003) or Dunkley (2000).

Loukas and Quick (1993) investigated the spatial distribution of hourly rainfall-intensity for Jamison Creek, a tributary of Seymour River located in the Coast Mountain Range, 40 km east of Squamish. This area is sparsely populated and therefore direct anthropogenic influence is likely minimal. Although this study did not focus on long-term trends in rainfall and rainfall intensity, it did find that, for medium to large rainfall events (20-40 mm and >60 mm of rain respectively), hourly rainfall-intensity decreased with elevation, a finding first reported by Hall (1989) within Jamison Creek for less intense events. However, maximum rainfall-intensity was found to be relatively constant with respect to elevation. Furthermore, storm rainfall for each event increased to mid-elevation of the watershed and then decreased at higher elevations.

Heavy precipitation events have also been documented by season. Zhang et al. (2001) investigated, among other things, the proportion of rainfall falling in “heavy” and “non-heavy” events. By regionally analyzing their results, they found that, for autumn (September to November) for the period 1950-1998 in the coastal regions of BC, the proportion of rain falling in heavy events versus non-heavy events has remained constant. Correlations between the precipitation amounts of heavy versus non-heavy events for the three coastal stations were significant at the 5% level.

Cunderlik and Burn (2004) also analyzed seasonal rainfall amounts in southern BC. Over an 80-year period from 1920-1999, the authors found that autumn precipitation has decreased over the study period, a result that is suggested to be linked to increased summer air temperatures and decreased autumn streamflow.

Hydrological modelling has also been employed to investigate the relationship between carbon dioxide-forced climate change and its affects on precipitation trends for a single coastal watershed located on eastern Vancouver Island. Simulated rainfall data of the Canadian Climate Centre General Circulation Model (CCC GCM) under a $2xCO_2$ scenario generated a 7.5% increase in mean annual precipitation in the Upper Campbell River watershed, Vancouver Island (Loukas and Quick 1999). The majority of the precipitation fell as rain from October to February, the so-called seasonally 'wet' period.

1.4 Hydrologic Shifts in Coastal Watersheds: Discharge Trends in British Columbia

Within British Columbia three annual flood regimes represent all river systems: a snowmelt-driven regime occurring in the spring or summer depending on basin size; a rainfall-driven flood regime occurring in fall or early winter, or; a combination of the previous two regimes (Melone 1986), often referred to as a 'mixed' or 'hybrid' regime. Of the three annual regimes, rainfall-driven floods and their possible relation to changing localized hydrology are of particular interest to this study.

Little attention has been given to investigating possible links between changing hydrologic regimes and trends in flood flows of rivers in Canada, especially in coastal British Columbia. Studies of flood flows in British Columbia have been concerned with the scaling and regionalization of flood flows (Eaton et al. 2002) rather than with trends within flood flows. Most of the literature concerning shifts in streamflow is focused on the timing and magnitude of discharge associated with meltwater production. For example, Cunderlik and Burn (2002) examined the spring (March-May) maximum annual-flow record of southern British Columbia. It was found that annual maximum flows, on average decreased by 0.5% of the mean annual flood per year for a thirty-year period from 1960-1999. Moore (1991) and Moore and McKendry (1996) found that annual peak-flow of nival-dominated discharge regimes has decreased in magnitude and duration since 1976, an occurrence likely associated with a shift in phase of the Pacific Decadal Oscillation (PDO).

Similarly, the timing and volume of one-third of the Fraser River annual flow, which is heavily dependent on the spring freshet, was found to advance at a rate equivalent of 11 days per century (Indicators of Change for British Columbia 2002). Whitfield (2001) also investigated temporal changes in meltwater release in five spatially similar regions of British Columbia by documenting, among other things, the relative length of what he referred to as the hydrologic summer. Comparisons were drawn between 5-day average discharge of two decadal periods 1976-1985 and 1986-1995. In coastal catchments, based on average differencing between the two decades, the hydrologic summer was found to begin later and end later within the year. The result is a shorter hydrologic winter. This fact, in combination with lower observed precipitation in the fall, results in lower-than-average fall flow. These finding are in agreement with Whitfield and Taylor (1998) who noted a decrease in the spring and summer flows when comparing averages from 1946-1955 against 1986-1995.

No data-based study has investigated the possible affect of climate change on flood magnitude or frequency. Loukas and Quick (1999) have employed hydrological modelling to investigate flooding trends in the coastal Upper Campbell River watershed in response to carbon dioxide-induce warming. The authors found that the University of British Columbia (UBC) Watershed Model (Quick 1995), under 2xCO_2 simulated scenarios for the period 1983-1990, predicted significant increases in the number of flood episodes, flood days, flood volume, mean-flood flow, mean-peak flow and annual maximum flood peak.

The UBC Watershed Model was also used by Loukas et al. (2002) to simulate the impacts of CO_2 -induced warming on the flood regime for Upper Campbell River in the same time period examined by Loukas and Quick (1999). These climate simulations, based on current (1900-1995) and predicted (1% increase per year, 1996-2100) atmospheric CO_2 found that mean annual precipitation increased 3.5%. However, this increase in precipitation is not distributed equally among rain and snowfall. The amount of precipitation falling as rainfall increased 35%, the majority of which was recorded between November and March. As a result, the magnitude and frequency of rainfall-generated peaks also increased.

Hydrologic modelling has also been employed by Whitfield et al. (2003) to predict extreme streamflow for rainfall-driven, snowmelt-driven and hybrid-driven (mixed rainfall- and snowmelt driven) streams in Georgia Basin. Using the same model as Loukas and Quick (1999) with climate data downscaled from the Canadian Coupled General Circulation Model as input data, in a warming climate scenario, the hydrologic characteristics of hybrid streams will begin to resemble those of rainfall-driven streams. This increased degree of rainfall domination of the hydrologic regime will increase winter-flood frequency, duration and magnitude of hybrid streams in the future. The shift in the characteristics of extreme flows predicted in both Loukas and Quick (1999) and Whitfield et al. (2003) studies is surprising since the watershed model frequently underestimates rainfall and rain-on-snow peaks.

Further work employing the UBC Watershed Model has shown the importance of rainfall run-off, represented as a percentage of peak flows, for Upper Campbell River (Loukas et al. 2000). Two types of peak flow analyses were performed on model output for the years 1983-1990: the first considers annual maximum peak flows and the second considers peak flows above a certain threshold. It was found that for rainfall and rain-on-snow driven peaks the rainfall run-off constituted 78-94% and 53-97% of the total discharge for the first and second analyses respectively.

1.3 Channel Changes: Squamish River

Sichingabula (1986) documented channel changes on Squamish River for a 38-year period using areal photography. This was done, in part, to determine the “Character and causes of channel planform changes in a high energy fluvial environment at a short time scale of decades.”

In order to achieve his aim, Sichingabula (1986) documented channel changes for five study reaches consisting of single-channel meandering, wandering gravel-bed and braided planforms. Since the documented channel changes provide a baseline for the present study it is important to summarize his findings. The following discussion is limited to the five major types of channel change identified on Squamish River and includes a brief summary of sediment transfers in Squamish River in relation to distance downstream.

1.31 Five Major Types of Channel Change Identified on Squamish River

The following five types of channel change were documented from 1947-1984 for five study reaches of varying planform: meandering (2x), wandering gravel-bed, partially braided and braided. A detailed description of each reach is presented in Chapter 2. Channel changes span multiple flood events but of particular interest here are the channel changes observed by areal photography taken in September 1984 and December 1984. These capture the effect of the then flood of record (in October 1984).

A) ***Bank Erosion*** rates of 2.4-11.5 m y^{-1} were measured from 1947-1984 in meandering and wandering gravel-bed reaches. Varying flood magnitudes produced similar amounts of erosion. The rates of bend migration resulting from bank erosion were found to not be significantly influenced by planform or period of record.

B) ***Intense Bank Erosion*** was predominantly observed at the heads of two major islands located in a partly braided and wandering gravel-bed reach. Downstream migration of banklines occurred at 12.2-18.3 m y^{-1} during the years 1947-1976 followed by a period of lower erosion rates from 1977-1984. Floods of all magnitudes produced intense bank erosion, however, comparably higher rates of intense bank erosion were observed for the island located in the partly braided reach following large floods in 1980, 1981 and 1984. Intense bank erosion is also associated with channel widening, especially in bends. Again, all ranges of floods produced channel widening, but the most rapid changes occurred following high-magnitude floods. Within two bends in the meandering reaches, 75 m and 200 m increases in channel width were observed for the periods 1980-1982 and Sept-Nov.1984 respectively.

C) ***Island formation*** and D) ***Destruction*** were observed in wandering gravel-bed and braided reaches and viewed as a reflection of the local reach stability. Floodplain growth can be propagated by the formation and subsequent attachment of an island to the floodplain. The rate of deposition onto these redefined point bars is comparable to the rate of maximum bank erosion experienced within bends.

E) ***Channel Reactivation*** was observed only in the braided reach. Reactivation was initiated by the 30-year flood of 1984. This same flood dissected the previously single main-channel system into a series of major channels and islands characteristic of a braided planform. This finding illustrates the way in which an extreme flood can rapidly change channel form, a change which persists today, 23 years later.

1.3 Objectives

Changes in streamflow regime is one response to a climatic shift. Often, when attempting to generalize the effects of climate change for large regions (for example, British Columbia), rivers are grouped according to their dominant streamflow regime: rainfall, snowmelt or hybrid (rain and snowmelt driven; rain on snow driven). The literature concerning coastal rivers in BC is dominated by streamflow data analyzed for the spring and summer months. In other words, the majority of research identifying streamflow responses to climate change have focused on the relation between snowfall, snowmelt and its subsequent influence on streamflow regime. In general, trends in low flows have been of more interest than those in flooding. When floods are a primary focus of research (such as Cunderlik and Burn 2000), more often it is exclusively summer floods driven by meltwater production, rather than isolated storm-driven floods, that receive the most attention. This despite the fact that recent evidence suggests that the greatest fluctuations in streamflow regime are associated with shifts in precipitation rather than temperature (Karl and Reibsame 1989). Possible linkages between variations in the hydrologic regime and extreme rainfall-driven floods occurring in the coastal regions of BC are, at present, unexplored. This is surprising since rainfall-driven floods can have a dramatic affect on short-term sediment transport and channel geometry (Sichingabula 1986; Hickin and Sichingabula 1988).

In this study I attempt to discern if a change in climate and hydrology, represented by changes in late-season rainfall-driven extreme floods, is reflected in the geomorphic record in terms of the rates and patterns of channel change. Sichingabula (1986) attempted to answer this question but concluded that the study period 1947-1984 was too short. His 38-year observation period was inadequate to determine the effects of any given flood event in relation to its magnitude and frequency. However, Sichingabula (1986) hypothesized that, “most channel changes in Squamish River are caused by infrequent high-magnitude floods regardless of the initial planform.” This leads me to hypothesize that if the frequency and/or magnitude of rainfall-driven extreme floods is increasing overtime, it might be expected that the rate of channel change for Squamish River is also accelerating. It is my hope that, by extending the observation record by another 25 years, I will be able to document a set of observations of adequate length to answer the question raised by Sichingabula (1986).

To achieve my general objective I address three specific research questions:

1. Is there evidence of a local shift in hydrology within Squamish River basin for the period 1955-2006?
2. Are there differences in the type and magnitude of channel change among the study reaches following an extreme flood and is there a difference in the rate of channel change before and after 1984?
3. Does a relationship exist between the type and magnitude of channel change and extreme flooding such that an empirical model can be constructed to estimate future channel changes?

My objective will be met by (i) analyzing Water Survey of Canada and British Columbia climate station hydroclimatic records; (ii) mapping and digitizing channel changes on sequential aerial photographs of Squamish River and (iii) analyzing rates and patterns of channel change.

CHAPTER 2: STUDY AREA

2.1 Study Area

Squamish River, located approximately 40 km north of Vancouver (Figure 1), is one of many gravel-bed rivers located within the Coast Mountain Complex of southwestern British Columbia. Squamish River drops approximately 2700 m to its sea-level terminus in the fjord-head of Howe Sound. It is a high-energy multi-planform river composed of braided, structurally confined and single-channel meandering reaches. Inter-planform transitions are in places abrupt and in others gradual. Most of the 150 km-long coastal river is flanked by steep mountain slopes composed primarily of granitic rocks with some gneiss and schist (Woodsworth 1977) formed during the Late Cretaceous (Mathews 1958). Twenty per cent of the contemporary drainage area (3200 km^2), is glacier covered (Paige and Hickin 2000). On the floodplain of Squamish River, which is partly dyked, the towns of Squamish and Brackendale represent two main areas of residential development (Jakob and Jordan 2001). Although Squamish River is free of man-made flow-controlling structures they are present on smaller tributaries of Squamish River. However, the flow-regulated tributaries enter Squamish River below the main gauging station and are considered to have minimal affects on the mainstem flow regime, sediment input and channel geometry.

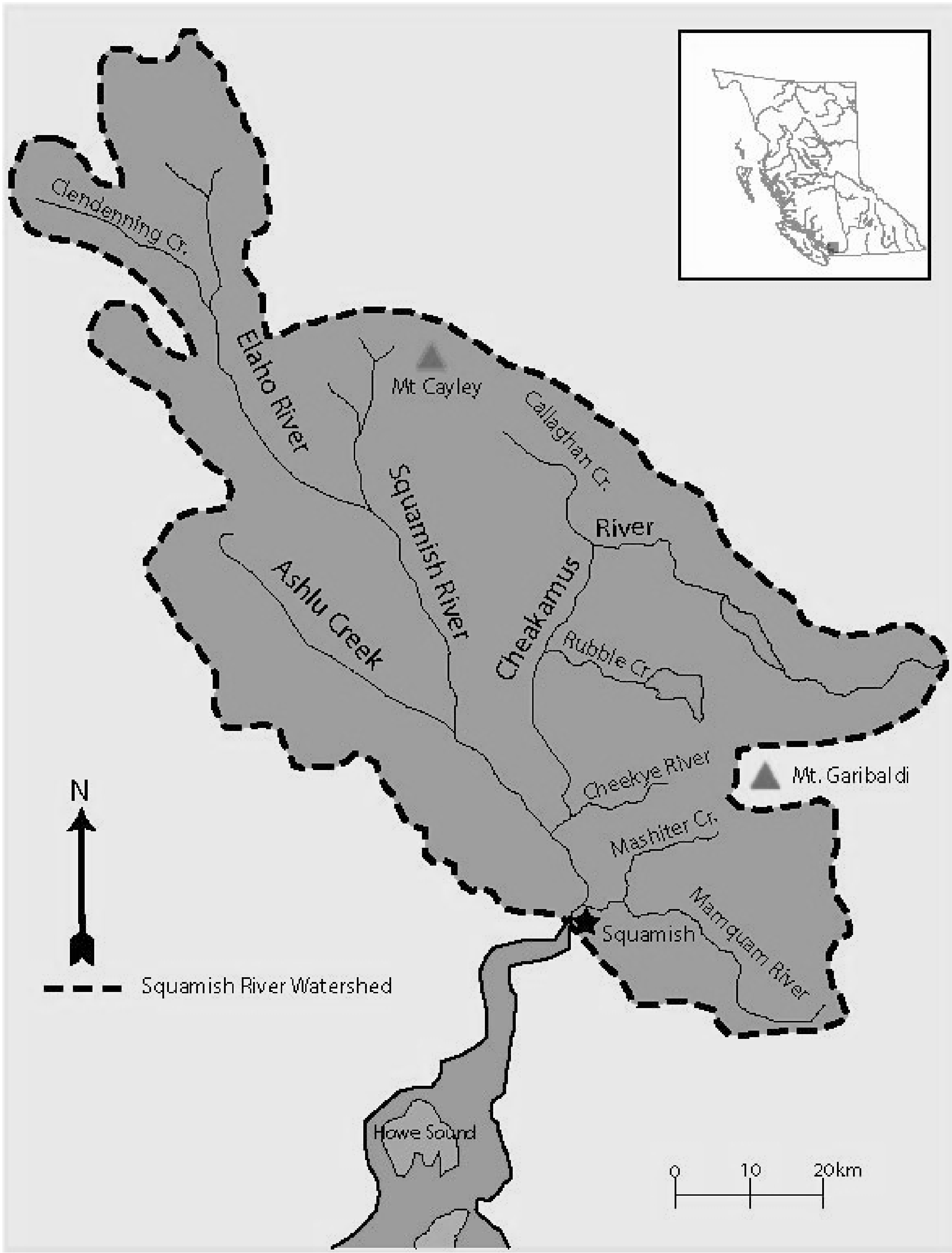


Figure 1: **Squamish River and its tributaries.**

Sediment sources of Squamish River are the moraine veneers situated on the steep mountain slopes (Brooks 1994) as well as vesicular volcanics forming Mount Cayley and Mount Garibaldi. Sediment is contributed to lower Squamish River by three main tributaries: Cheakamus, Cheekye and Mamquam (Brooks and Hickin 1991). Hickin (1989) observed that the sediment from Cheekye River has built a fan that has pushed Squamish River to the western wall of its valley. The fan is large enough to "exercise considerable upstream control on Squamish River".

Mass wasting events such as debris avalanches and debris flows originating from weathered vesicular volcanic andesitic lavas and tuff also produce significant but temporally localized sediment supply inputs. Some of these mid-late Holocene events (~4800 BP, 3200 BP, 1100 BP and 500 BP) have temporarily dammed Squamish River (Brooks and Hickin 1991). More contemporary evidence of mass wasting events temporarily damming Squamish River have been documented for Turbid Creek, which is the main western drainage of Mount Cayley (2393 m asl) (Jakob and Jordan 2001), and for Cheakamus River which drains the west side of the Mount Garibaldi (2678 m asl) volcanic complex (Moore and Mathews 1978) to Squamish River.

From bathymetric differencing Hickin (1989) estimated that 1.29×10^6 m^3 of sediment is deposited in Howe Sound each year. The sediment flux causes Squamish Delta to prograde downfjord at a rate of 3.86 m a^{-1} and vertically accumulate at an average rate of 0.2 m a^{-1} in the zone proximal to the delta front.

2.2 Climate and Vegetation

Wet mild winters and dry warmer summers characterize the maritime climate of Squamish River Valley. Monthly average temperature ranges from 0 to 18°C. As a result, annual snowfall only accounts for approximately 11% of the total precipitation at lower elevations (46 m asl) (Environment Canada climate stations 2007). The bulk of snowfall accumulates between December and February and usually melts by the end of July. Snowfall amounts at higher elevations are unavailable because of the scarcity of climate stations, or poor quality of the annual records.

The majority of the precipitation captured by Squamish River Basin is generated by cyclonic frontal systems that typify the fall and winter months. They develop over the North Pacific Ocean and track eastward (Loukas et al. 2000) or south-southwest (Loukas and Quick 1993). Due to the north/south orientation of the coastal catchment, Squamish River valley is an efficient interceptor of precipitation events. Average annual rainfall amount is 2246 mm but can be as high as 2880 mm (Environment Canada climate stations 2007). Similarly, rainfall intensities during the fall events commonly exceed 40 mm/day with larger storms producing rainfall rates greater than 100 mm/day. Approximately 75% of all precipitation is delivered during October-March.

The vegetation of Squamish River basin is located within the Western Hemlock bioclimatic zone. The abundant moisture of the Pacific Coast supports dense growth of conifers and deciduous trees. Besides western hemlock, amabilis fir, yellow-cedar, Douglas fir, grand fir, western white pine, big leaf maple, red alder, logdepole pine and Sitka spruce are known to inhabit the valley floor and slopes in this bioclimatic zone. Woody-debris is often incorporated into the floodplain of Squamish River from the undercutting of banks as the river migrates into its floodplain and from debris flows. The build up of woody-debris is a significant influence on channel form. Collections of logs and forest litter can promote in-channel sedimentation and form the nucleus of bars and islands (Hickin 1984) as well as causing channel abandonment. Accumulation of logs along channel banks, extending approximately 100 m in length and 20 m in width, were observed by this author in May of 2007.

2.3 Hydrology

The annual discharge regime of Squamish River is meltwater driven (Figure 2) with precipitation events producing localized spikes in the annual hydrograph (Figure 3). At Brackendale the average annual discharge is 240 m^3/s and typically ranges from an average-monthly low of 100 m^3/s from (Dec- Feb) to a high of 500 m^3/s in August). The mean annual flood is 600 m^3/s but intense and prolonged storm events can produce floods with mean daily discharge twenty times greater than that of average seasonal base flow, which often exceed bankfull-stage ($Q > 1000\ m^3/s$).

2.4 Study reaches

The character of channel changes will be documented for five study reaches (Figure 4). I have selected the five reaches outlined by Sichingabula (1986) for detailed investigation. Doing so enables the morphologic record of Squamish River to be extended to 60 years (1947-2007).

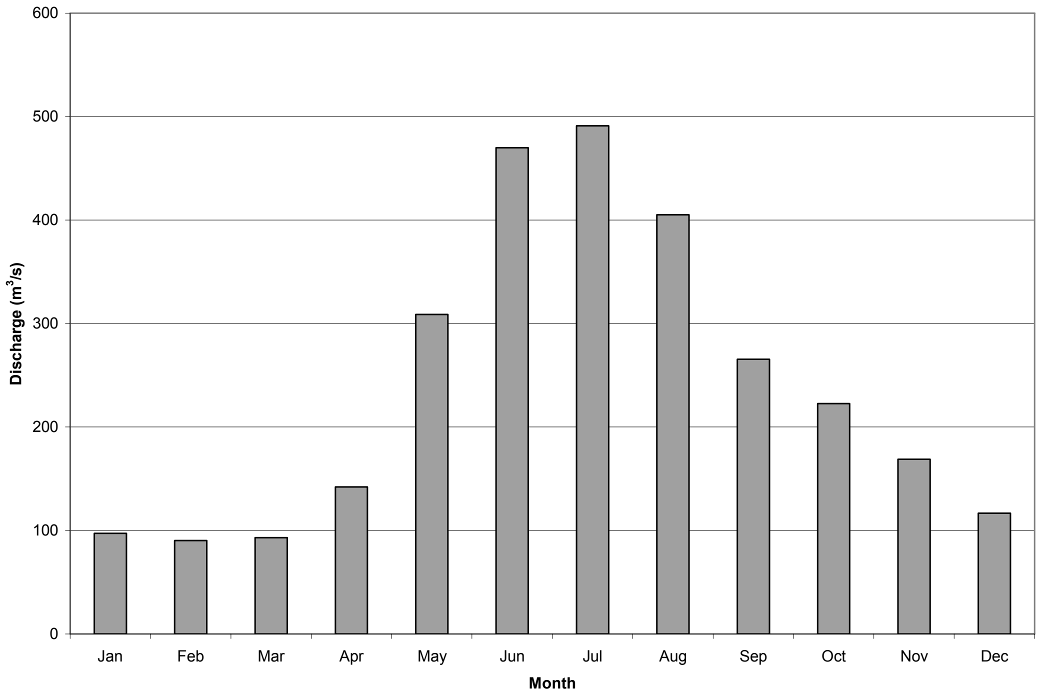


Figure 2: Average monthly discharge recorded at Squamish River Near Brackendale gauging station for the years 1956-2005.

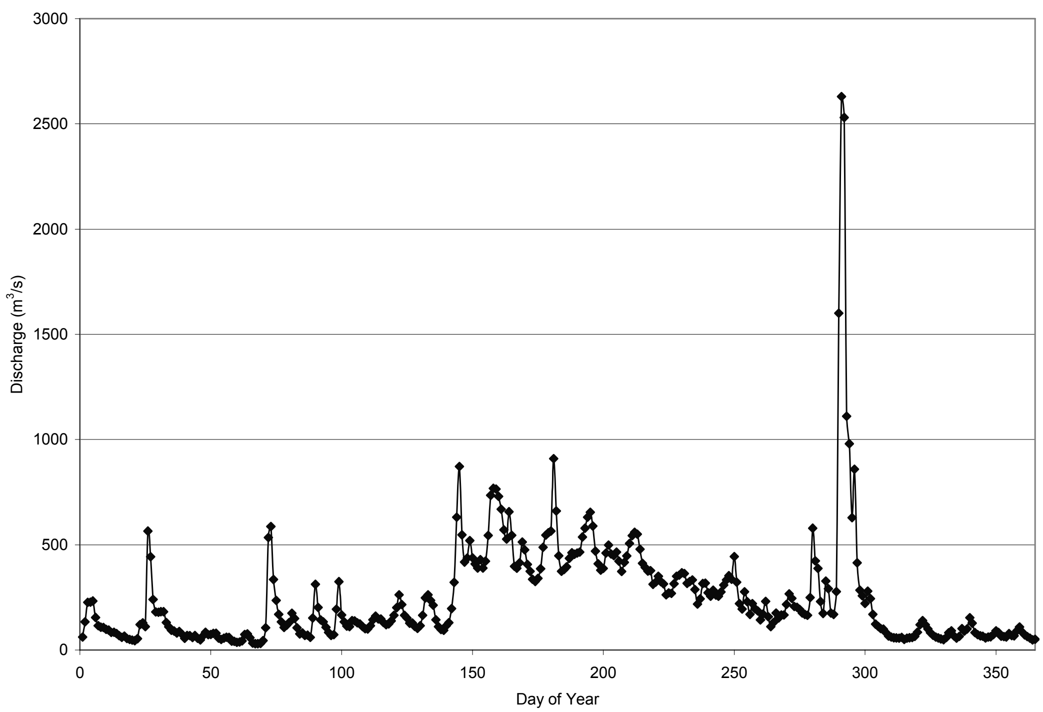


Figure 3: Mean daily discharge record 2003 at Squamish River Near Brackendale.

This long record facilitates comparative analysis of the behaviour of all reaches for given years, and also provides a basis for examining long-term change for given reaches.

The initial reaches were selected by visual inspection of aerial photographs and represent channel segments where the greatest amount of change has occurred (Sichingabula 1986). Locations of the five study reaches are displayed in Figure 4.

2.4.1 The Cheakamus-Mamquam Reach (Reach A)

Cheakamus-Mamquam Reach (Figure 8) is named for the major sediment supplying tributaries located directly upstream and downstream respectively. The high sediment input from these tributaries has caused Squamish River to partially braid through this reach. Approximately 5 km of the eastern bank is dyked to protect the municipality of Brackendale from flooding. Sichingabula (1986) chose this reach to study the effects of gravel deposition in a confined straight channel. This reach is located approximately 5 m above sea level and 10 km upstream of Howe Sound.

2.4.2 The Meandering Reaches: Upper and Lower (Reaches C and B)

The meandering reaches (Figure 7) are predominantly single thread and freely meandering. These two reaches are directly downstream of the Squamish-Ashlu Bend Reach and immediately upstream of the sole gauging station on Squamish River. Elevation ranges from 50 to 80 m above sea level in these reaches. These reaches were chosen to assess lateral migration rates, meander-train propagation and changes in channel sinuosity.

2.4.3 Squamish-Ashlu Bend Reach (Reach D)

The Squamish-Ashlu Bend Reach (Figure 6) is located 20 km downstream of Braided Reach, approximately 100 m above sea level. The planform of this reach is a wandering gravel-bed channel with a multi-threaded nature about a series of relatively stable bars and islands. This reach will be used to make inferences about the stability of bars and islands and their behaviour within a transitional planform.

2.4.4 Braided Reach (Reach E)

This reach is located 300-400 m above sea level in the headwaters of Squamish River basin, directly downstream of Squamish Canyon and Turbid Creek (Figure 5). The abundant gravels, which are not readily transportable by low flows or low-velocity flow, cause the channel to braid directly downstream of the faster-flowing canyonized reach of Squamish River. This reach was originally selected by Sichingabula (1986) on the basis of its planform alone.

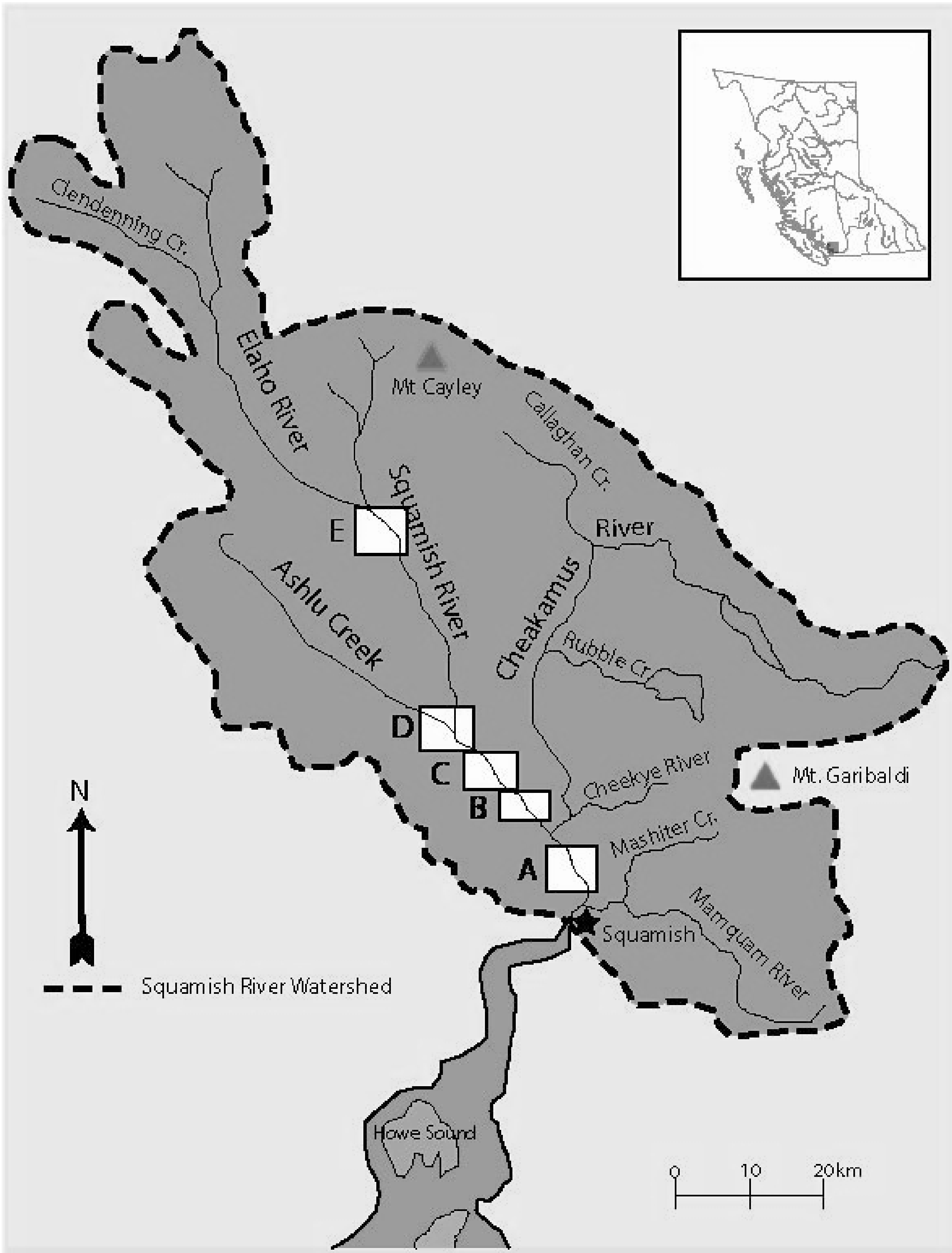


Figure 4: **Location of the five study reaches on Squamish River as previously defined by Sichingabula (1986). Bolded letters indicate study reach designation used in the text.**

Figure 5: **Aerial photograph of Braided Reach (Reach E) 1996. North is to the top of the photograph. (Provincial air photo 15BCB96099 No.123). Approximate scale: 1:52000.**

Figure 6: Aerial photograph of Squamish-Ashlu Bend Reach (Reach D) in 1990. North is to the top of the photograph (Provincial air photo 30BCB90053 No.95). Approximate scale: 1:25400

Figure 7: **Aerial photographs of Upper (above) and Lower Meandering Reach (in 1991 (below) (Reach C and B). North is to the top of the photographs. (Provincial air photo 15BCB91080 No.162). Approximate scale (top): 1:43000; (bottom) 1:28000.**

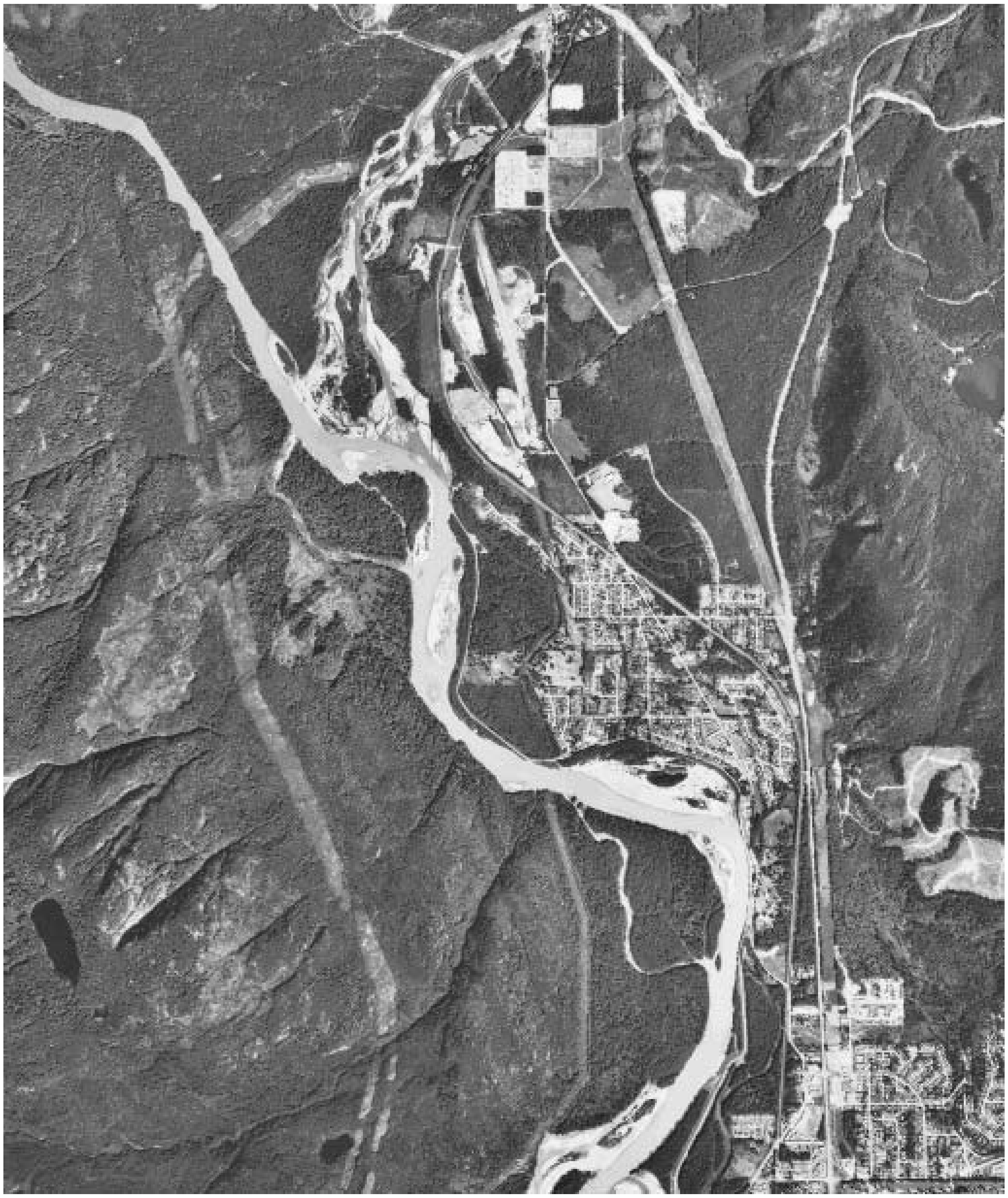


Figure 8: Aerial photograph of Cheakamus-Mamquam Reach (Reach A) in 1996. North is to the top of the photograph. (Provincial air photo 15BCB96037 No.216). Approximate scale: 1:45160.

CHAPTER 3: DATA COLLECTION AND METHODS

The goal of this thesis, as outlined in Chapter 1, is to determine if linkages exist between climatic variables and the rate and/or magnitude of channel change, and to determine if those linkages are quantifiable. This requires the collection of climatic data and aerial photography, and the establishment of procedures for accurately measuring the rate of channel change. This chapter outlines the data sources and the methods and techniques adopted in order to address my research objectives.

3.1 Hydroclimatic Data Collection

Hydroclimatic data, consisting of river discharge, precipitation and temperature records, are used to evaluate possible shifts in hydrology. These records (mean daily discharge, daily precipitation and mean daily temperature) were assembled from the archives of Hydrologic Survey of Canada gauging stations and Environment Canada climate stations. From these compiled data sets, continuous daily records for all hydroclimatic variables were produced for the years 1956-2006. Gaps within records were filled by extrapolating daily values using linear regression equations derived from relationships between the main (primary) and secondary stations. Regression estimates between stations required at least two years of daily data recorded for the same period of time by each station and coverage of a secondary station must overlap the gap in the primary record. R^2 values for these relations (>0.92) indicate strong statistical associations between the primary and secondary data sets for all hydroclimatic variables. Regressed daily values represent approximately 15% and 45% of the total daily data for the hydrometric and climatic records respectively. A map of the locations of all gauging and climate stations is shown in Figure 9.

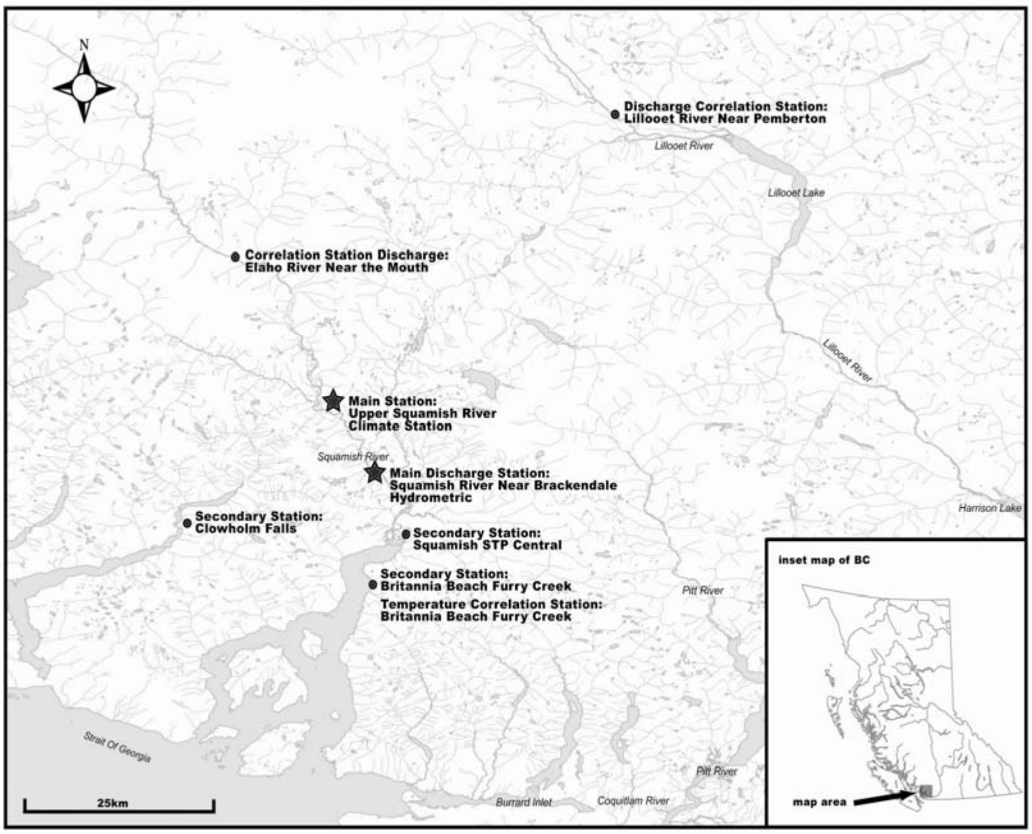


Figure 9: Locations of all hydrometric and climatic stations used in this study.

3.2 Discharge Data

The continuous mean daily discharge record is constructed from one primary gauging station (Squamish River Near Brackendale 08GA022) and two secondary gauging stations (Elaho River Near the Mouth, 08GA071 and Lillooet River Near Pemberton, 08MG005) for the years 1956-2006 (Table 1).

Table 1: Hydrometric stations used to construct a continuous mean daily discharge record for the years 1956-2005.

Station Name	Identification #	Primary or Secondary Station	Period of Record
Squamish River Near Brackendale	08GA022	Primary	1956-1995, 1997-2006
Elaho River Near the Mouth	08GA071	Secondary	1996
Lillooet River Near Pemberton	08MG005	Secondary	Monthly: 1960, 1972, 1974-76, 1978, 1981-82

The Brackendale gauging station is the only hydrometric station on Squamish River. It has a long continuous record since 1955 and was used by Sichingabula (1986) and Hickin and Sichingabula (1988) when they documented Squamish River channel change for the period 1947-1984. The Brackendale gauging station represents flow derived from approximately 72% of the Squamish River catchment (the remaining 28% is added downstream of this station).

A continuous mean daily discharge record is needed to identify and assess the characteristics of extreme-flood hydrographs produced by late-season storm events. The continuous discharge record also enables the extraction of other flow characteristics for the period of record such as trends in low flows, annual discharge volume, seasonal discharge and time taken for a specific proportion of the annual flow to pass the Brackendale Station.

3.3 Extreme-Flood Data

Extreme-flood data are extracted from the continuous mean daily discharge record. In order to document all extreme-flood events on Squamish River for the period 1956-2006 it is necessary to first define these.

Sichingabula (1986) estimated bankfull discharge in the field to be approximately 1000 m^3/s near the Brackendale gauging station. The record indicates that 48 floods in the study period have exceeded bankfull flow at Brackendale gauging station. An extreme flood is defined here as any flood in which the mean daily discharge is such that it is capable of doing a large amount of work in any one of the five channel reaches during its passage. Sichingabula (1986) and Hickin and Sichingabula (1988) did not quantify this definition directly but here a mean daily discharge equal to or exceeding 1500 m^3/s is arbitrarily chosen to represent an extreme flood. Extreme floods occurring as a result of prolonged or intense rainfall in August-December are of specific interest to this study. This particular group of floods is referred to as extreme or high-magnitude late-season floods.

Using this definition, 14 floods qualify as extreme. Of these, three flood events have been disqualified from the analysis. In one case, a 1700 m^3/s flood on June 27, 1968 occurred outside of the study months. Because it was caused by rapid snow melt or rainfall on snow, it is not part of the hydrologic population being considered. In the other case, the remaining two disqualified flood events, the 1620 m^3/s extreme flood of September 26, 1957 and the 1560 m^3/s flood of October 11, 1967 exhibit hyetographs that display no definitive onset or terminus.

Therefore, defining the storm precipitation and storm intensity inducing the extreme floods is not possible. The remaining eleven extreme flood events used for this study are shown in Table 2.

Table 2: Extreme floods (maximum discharge rate ≥ 1500m^3/s) occurring on Squamish River in the months of Aug-Dec, 1956-2005.

Large Scale Flood Date	Max. Daily Discharge of the Event (m^3/s)	Event Discharge (km^3)	Flood Duration (Days)	Storm Precipitation (mm)
Sept 6, 1957	2230	0.28	5	62.2
Oct 12, 1958	1580	0.22	6	136.6
Oct 31, 1967	1610	0.19	5	94.6
Oct 29, 1968	1570	0.11	4	97.2
Nov 4, 1975	1800	0.43	9	150.9
Dec 27, 1980	2020	0.41	7	203.2
Nov 1, 1981	2110	0.35	6	226.2
Oct 8-9, 1984	2150	0.68	13	305.6
Nov 11-12, 1990	1720	0.50	13	285.6
Aug 30, 1991	2120	0.40	8	259.2
Oct 17-19, 2003	2630	0.86	15	329.6

Two attributes in addition to the maximum daily discharge per event are determined for each extreme flow: flood duration and flood volume.

Flood duration is defined as the time taken, in days, for mean daily discharge to return to that flow magnitude recorded on the day prior to the initial, steep rise in the flood hydrograph (Figure 10).

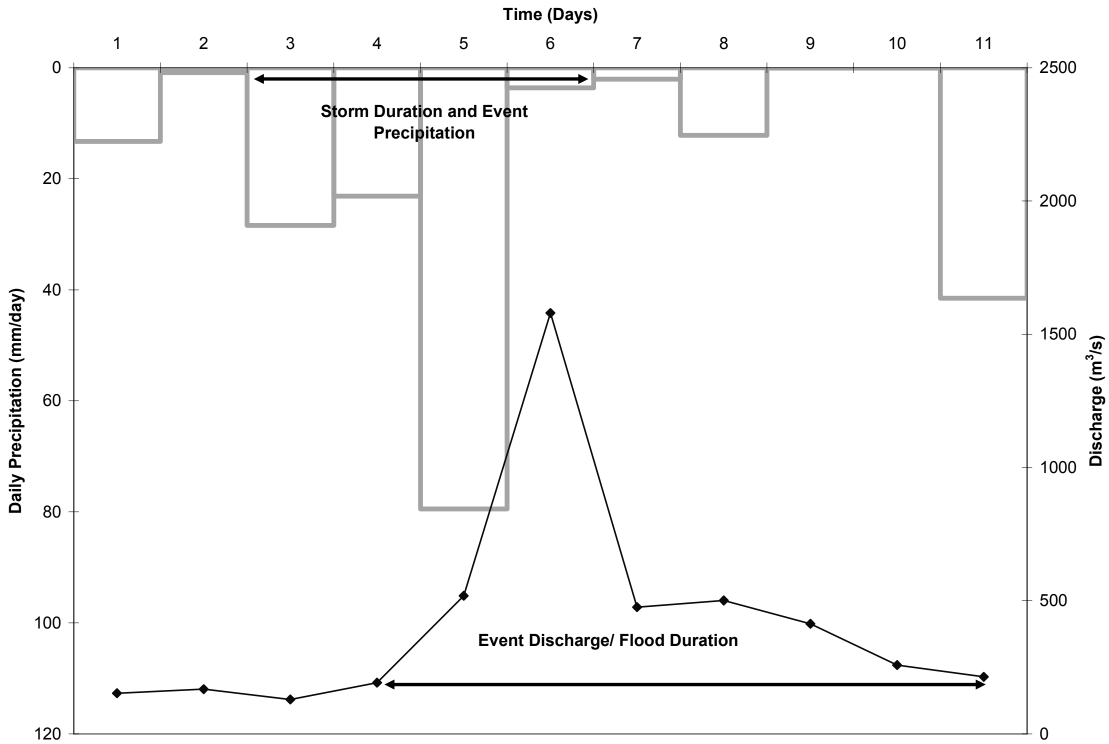


Figure 10: An example showing event discharge, flood duration, total event precipitation and storm duration of a flood (12 October, 1958) on Squamish River at Brackendale.

Flood volume is defined as the total flow of an individual flood calculated by summing the mean daily discharge for the flood event and multiplying by the number of seconds in a day.

3.4 Precipitation Data

Daily precipitation data used in this study were collected from one primary and two secondary climate stations (Table 3). The primary climate station, Upper Squamish (1047672), was selected because of the length of its nearly continuous daily precipitation record and because of its close proximity to the gauging station on Squamish River near Brackendale.

Table 3: **Climate stations used to construct a continuous 50-year precipitation record (1956-2005).**

Station Name	Identification #	Primary or Secondary	Period of Record
Squamish Upper	1047672	Primary	Jan 1980-Mar 1987, Mar 1988-July 1992, Dec 1992- May 1993, Jul 1994- May 2002, July 2002-Dec 2005
Squamish STP Central	10476871	Secondary	Apr. 1987-Feb 1988, Aug-Nov. 1992, Jun 1993-1988, Jun 2002
Clowhom Falls	1041710	Secondary	1956-1979

Two secondary climate stations, Squamish STP Central (10476871) and Clowhom Falls (1041710) were used to fill gaps in the daily precipitation record of the primary station based on regression equations derived from a two-year relationship of daily precipitation.

3.5 Storm Precipitation Data:

A storm is defined here as an intense, continuous precipitation event driving a late-season extreme-flood event. Storm data are used to determine if the characteristics of storms driving extreme floods have varied over time. Three attributes of an individual storm are determined: storm duration, event rainfall, and rainfall intensity (maximum-daily and average-daily).

Storm duration is defined as the period of time, in days, from the storm onset to terminus, a transition described by the storm hyetograph (see Figure 10). The onset of a storm is characterized by an initial steep rise from zero or near-zero daily precipitation and the terminus of a storm is marked by the next successive day in which no precipitation is recorded.

Event rainfall is defined as the total amount of rainfall recorded over the storm duration and is an indicator of the magnitude of a storm.

Rainfall intensity is defined as the time-rate of rainfall. It is often common practice to work with hourly rainfall intensities, as there is often significant variation in rainfall intensity over greater periods of time. However, due to the current lack of automated recording stations, coupled with the long period of record which pre-dates the use of such recording devices, measures of rainfall intensity are restricted to daily intensities.

Two rainfall intensities of different time scales are calculated for each storm: maximum single-day intensity (maximum daily intensity), and; average rainfall intensity for a given storm.

3.6 Temperature Data

The mean daily temperature record was derived from one primary (Squamish Upper, 1047672), and three secondary (Britannia Beach Furry Creek, 1041050; Squamish STP Central, 10476871; and Clowhom Falls, 1041710); Environment Canada climate stations (Table 4). These stations were chosen based on the longevity of their records and because of their close proximity to the gauging station on Squamish River near Brackendale.

Table 4: Climate stations used to construct a continuous 50 year precipitation record (1956-2005) in Squamish River catchment.

Station Name	Identification #	Primary or Secondary	Period of Record
Squamish Upper	1047672	Primary	Jan 1980-Mar 1987, Mar 1988-July 1992, Dec 1992- May 1993, Jul 1994- May 2002, July 2002-Dec 2005
Squamish STP Central	10476871	Secondary	Apr. 1987-Feb 1988,Aug-Nov. 1992, Jun 1993-1988, Jun 2002
Clowhom Falls	1041710	Secondary	1956-1979

3.7 Hydrologic Data Analysis

To determine if shifts in any of the hydrologic variables of interest have occurred within Squamish River basin over the 50-year study period, time series analyses of the continuous discharge, precipitation and temperature records were conducted over a variety of time scales including annual, seasonal and specific extreme-flood events.

The relationship between storm characteristics and extreme-flood events receives the most attention of all the time scales. Extreme-flood maximum daily discharge and flood duration are plotted against storm characteristics such as event rainfall, maximum daily rainfall-intensity and average rainfall-intensity per storm in bivariate graphs. Regression analysis is employed to determine the strength of various relationships among storm and flood characteristics.

3.8 Aerial Photography Data

Aerial photography provides an accurate, efficient and inexpensive basis for mapping changes in river channels. For these reasons, the history of

Squamish River channel morphology is based on an analysis of sequential aerial photography. Standardization of the spatial coordinates of air photographs within a geographic information system (GIS), allows for identification and absolute differencing of changes to channel morphology among sets of photographs.

Using a series of aerial photographs in conjunction with a GIS to deduce planimetric channel changes and estimate bed-material transfer rates has many advantages over alternative methods. Ham and Church (2000) note that, this method can be applied to much larger scales and over longer periods of time than studies involving direct field measurements; the calculation of morphological changes can be accomplished at a greater speed and accuracy; and morphological changes can easily be graphically represented within a GIS. Furthermore, the longer, more robust photo-data may reveal variations in bed-material transport rates that are not observable in shorter-term field survey studies.

This ‘morphological approach’ to estimating sediment budgets or areal change has been used for steep mountainous streams of British Columbia including Squamish River (Sichingabula 1986), Vedder River (Martin and Church 1995) and Fraser River (Ham and Church 2000).

Six sets of aerial photography, covering five channel reaches, are used in this study to document channel form in the years 1984, 1990, 1991, 1994, 1996 and 2007. The details of all photo images are specified in Table 5.

Sichingabula (1986) documented channel changes for the five Squamish River reaches for the years 1947-1984. Therefore, extending the photographic record required only air photos taken from 1985 to 2007, although the 1984 photos are used here to provide a common geomorphic reference point.

The majority of the aerial photographs (1990, 1991, 1994, 1996) are in the form of contact prints and were obtained through the British Columbia Crown Registry and Geographic Base. The 1984 and 2007 photographic data were obtained through custom Remote Sensing Unit lines (Department of Geography, Simon Fraser University) and are captured on 35 mm and large-scale positive film respectively.

3.9 Aerial Photography Analytical Procedures

In order to identify changes in the channel form of Squamish River over the photographic record, and to quantify those changes, each individual image is scanned, georeferenced/geocoded and annotated. The result of this process is a series of geometrically corrected overlays that, when superimposed on each other, visually display channel changes for each reach, with respect to time. The calculation of changes due to erosion and deposition are calculated in the GIS. This section details this three-step procedure.

Scanning of the aerial photographs employed one of two methods depending on the raw form of the photographic images. Those photos in the form of contact prints (1990, 1991, 1994, 1996) and positive-film (large-scale, 2007) were digitally scanned at 1200 dots per square inch (dpi) using an Epson Expression 10 000XL scanner.

Table 5: Air photographs used in this study.

Year	Provincial Roll #	Frame #	Scale 1:	Flight Height (ft)	Photo Date
1984	N/A	N/A	10000		Nov-05
1990	30BCB90053	95	15000	6096	Jul-16
1990	30BCB90053	53	15000	6096	Jul-16
1990	30BCB90103	247	15000	6096	Aug-16
1990	30BCB90103	228	15000	6096	Aug-07
1990	30BCB90103	202	15000	6096	Aug-07
1990	30BCB90103	151	15000	6096	Aug-07
1990	30BCB90103	128	15000	5791	Aug-07
1991	15BCB91080	162	40000	9144	Sep-05
1991	15BCB91080	158	40000	9144	Sep-05
1991	15BCB91157	110	40000	9129	Sep-09
1991	15BCB91157	30	40000	9129	Sep-09
1994	30BCC94116	164	15000	6248	Jul-28
1994	30BCC94116	126	15000	6096	Jul-28
1994	30BCC94121	35	15000	6096	Aug-01
1994	30BCC94121	61	15000	6096	Aug-01
1994	30BCC94121	86	15000	5791	Aug-01
1994	30BCC94121	127	15000	5791	Aug-01
1994	30BCC94121	113	15000	5791	Aug-01
1994	30BCC94121	178	15000	5791	Aug-01
1994	30BCC94122	31	15000	5791	Aug-01
1994	30BCC94144	183	15000	6096	Aug-30
1996	15BCB96099	123	40000	8665	Sep-27
1996	15BCB96099	62	40000	8589	Sep-27
1996	15BCB96037	250	40000	8577	Aug-09
1996	15BCB96037	216	40000	8577	Aug-09
1996	15BCB96100	19	40000	8613	Aug-09
2007	N/A	N/A	20000	11000	Nov-22

The remaining set of photos (1984), captured on 35 mm colour positive film, were imaged using a Minotla Dimage Scan Duall III AF- 2840 scanner, at 2820 dpi.

All scanned images were geocoded/georeferenced in order to rectify them so that absolute calculations of channel changes from photo to photo could be made. Using the cartographic program ER Mapper 7.1, one air photo per reach is geocoded and represents a reference image. A minimum of seven and average of ten ground-control points are selected per photo for the geocoding process. The spatial coordinates of the ground control points were obtained through Arc Mapper 7.1 using Cam Map DMTI streetfiles data, a Universal Transverse Mercator (UTM) projection and NAD83 datum. Once an image is geocoded, all other photos within a given reach are georeferenced to the geocoded image.

Outlines of the channel form for the rectified images were then manually drawn in ER Mapper 7.1. These outlines are referred to as annotations. To keep the analysis simple and manageable, annotations consist of only two features: channel boundaries, represented as vectors, and; vegetated islands/bars represented as polygons.

Channel boundaries are defined as the boundary between permanent vegetation or hard points and unvegetated channel sands/bars or the river itself. This definition obviates any problem of defining channel boundaries from year to year when discharge, and therefore river stage and width of the water surface, are not constant. Within a given reach, for the photographic record, discharge fluctuations range from 100-364 m^3/s, with no discharge exceeding bankfull.

Based on the outlines of channel boundaries, islands are thereby defined as any accumulation of sediment supporting sub-areal vegetation, separated from a channel boundary by a distinct filament of flow. Woody-debris dams that initiate the deposition of alluvial material are also recognized as islands. It should be noted that changes to unvegetated gravel bars are not incorporated into the areal measurements. These features are constantly reworked, as indicated by the lack of bar-top vegetation which make them difficult to characterize. Furthermore, bars are generally of low relief so they constitute a small proportion of the total sediment transport.

Once all of the annotations were completed in ER Mapper, they were exported as overlays into Arc Mapper (Version 9.2). They are organized by reach displaying channel morphology with respect to time.

3.10 Sediment Erosion and Deposition

Sediment transport for Squamish River is expressed using an areal change approach. By superimposing two overlays of different time periods, changes in channel morphology are identifiable. Through mapping and then calculating the area of channel changes within Arc Mapper, the magnitude and rate of change were quantified. In this study, positive values represent areal deposition, while negative values represent areal-erosion.

The difference in the total erosional and depositional area reflects the net change and dominant process for a given period. This net value is then divided by the number of years between air photographs to obtain the mean magnitude of change. It should be noted that calculations of the mean magnitude of change underestimate the actual change. The long (yearly) time periods between successive sets of air photos only captures channel change at two points in time.

The channel changes occurring between these points in time cannot be measured and thus the calculated changes in floodplain surface-area are minimum values. This problem is exacerbated as the time period between air photos increases. For example, if an large island underwent an annual cycle of destructive and re-emergent events during the 1996-2007 period, and its dimensions remained constant, then the calculated net change would be zero and the erosive and depositional channel changes would be underestimated by a factor of twelve. No correction factor has been applied to the data sets.

All areal changes are presented in two-dimensional units. Other authors determining sediment budgets from air photographs have presented their results in volumetric units. This requires some method of defining and measuring the average depth of the mobile bed-material layer as well as adjusting the areal extent of channel change to account for variations in water level (Ham and Church 2002). These 3D measures were not considered for this study. Furthermore, channel change measurements were presented in two-dimensional form by Sichingabula (1986) and in order to make useful comparisons between those and my findings a 2D approach is adopted here.

3.11 Measurement Error

Errors associated with the annotations arise from the inaccuracy of the source data used in the geocoding process and from the operational error associated with manually geocoding the images.

The accuracy limits of the source data constitute by far the largest amount of error in the analysis presented here. An associate from CanMap DMTI Spatial, from which the source data are obtained, states "… the positional accuracy of CanMap streetfiles will vary depending on the region being examined. For example, major urban centres have been aligned to satellite imagery with a 60 cm resolution, while rural areas have been aligned to Landstat 7 imagery which is a 15-30 m resolution." Based on this information, the error measurements are not equal for all five reaches. Although no study reach is located near an urban centre, two reaches (Cheakamus-Mamquam, Ashlu Bend) are located near suburban development. For these reaches a positioning error of +/-5 m is estimated to represent an upper limit. The remaining three reaches (Lower and Upper Meandering and Braided Reach) are located in rural areas. There is a gravel road, however, that runs along the length of all three reaches in close proximity (within~10 m) to the east bank of Squamish River. A reasonable estimate of positional error for these reaches is +/-20 m.

The error associated with the manual geocoding process is taken as +/-1.5 m after Ham and Church (1999). They state that, "An experienced operator can digitize points with an absolute error that is commonly less than 2 m r.m.s." This statement is based on the digitization of air photos of scale (1:70 000) with a stereoplotter with a resolution of 20 μm. The maximum scale of air photos used in this study is 1:40 000, but the most common is 1:20 000. If the resolution of the stereoplotter is assumed to be approximately equal to a computer cursor, an upper-limit operational error of +/-1.5 m is indicated.

Therefore, the total positional error for the suburban and rural reaches are conservatively estimated as +/-7 m and 22 m, respectively.

CHAPTER 4: THE HYDROCLIMATIC RECORD

This chapter presents the results of the time-series analysis of the climatic and hydrologic variables.

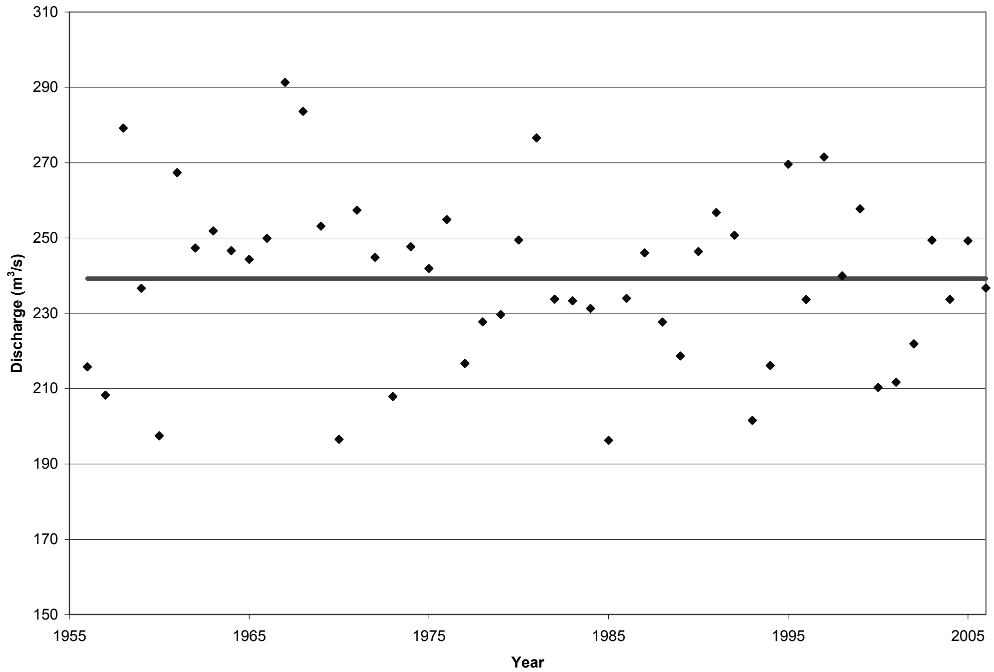
4.1 Hydrologic Data Analysis: Annual Records

Long-term data sets are useful in that they average out any short-term fluctuations or 'noise', and highlight the overall behaviour or nature of a system. In the following sections, the 50-year continuous record of hydroclimatic variables is analyzed as a whole and in terms of large periods of time (decades).

4.1.1 Discharge Analysis

The annual series of mean daily discharge for Squamish River does not show any evidence of a long-term trend. The entire record is characterized by often dramatic changes in mean daily discharge between successive years. The long-term record is best described in terms of periods of higher-and lower-than-average discharge. Periods of higher-than-average discharge occur in 1961-1969 and 1995-1999 while a prolonged period of lower-than-average discharge occurs in 1977-1989.

The August-December annual-maximum flow record also does not show evidence of a long-term trend and does not appear to be related to the mean daily discharge record (Figure 11).



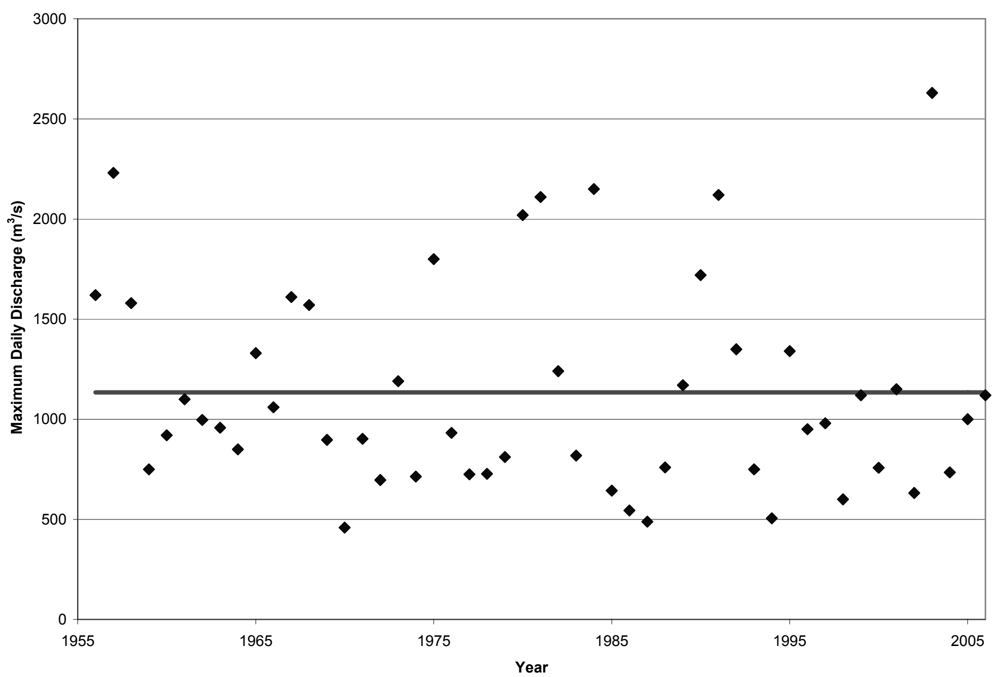


Figure 11: Mean-daily discharge (above) and annual maximum late-season (Aug-Dec) discharge (below) for Squamish River recorded at Squamish River Near Brackendale gauging station (1956-2006). The horizontal lines represent the annual average value for each data set.

4.1.2 Precipitation Data

Like the mean-daily discharge record, the precipitation record (Figure 12) is characterized by fluctuations in the data set which in places are large. For example, between 1984 and 1985 annual precipitation decreased by 1268.8 mm. There is no significant trend to the data set but there are several periods of pronounced precipitation increase. Positive trends are most evident in the years 1956-1968 (R^2 =0.31, P=0.09) and 1985-1999 (R^2=0.36, P=0.02). The former period precedes a period of lower-than-average annual precipitation.

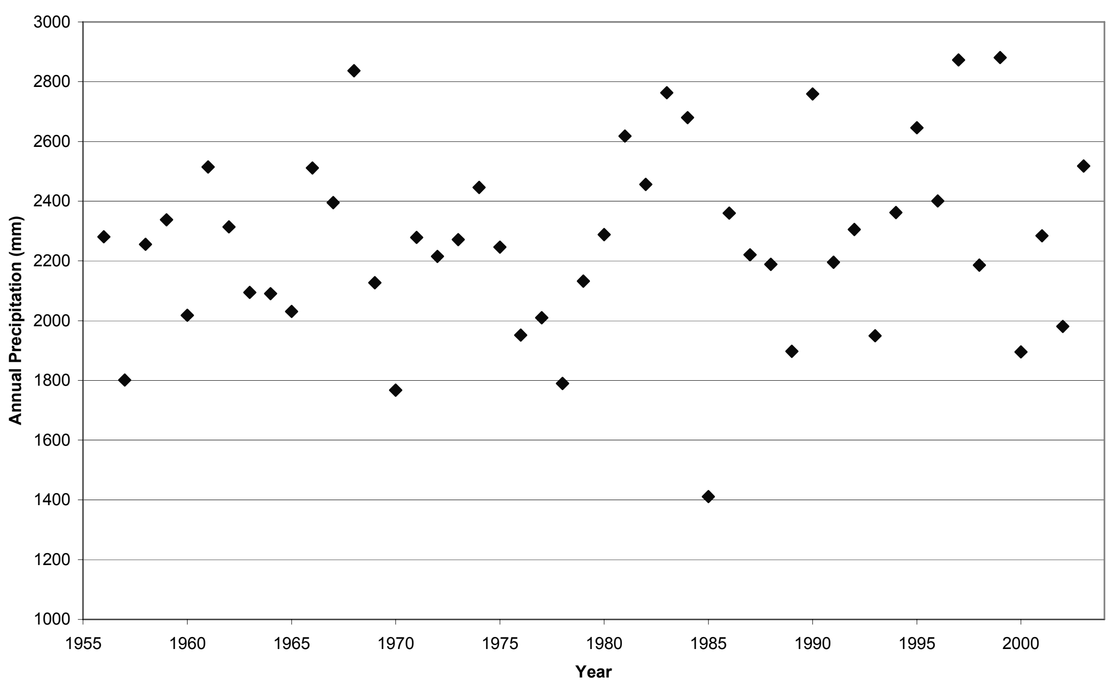


Figure 12: Annual precipitation in Squamish River basin recorded at the Squamish climate station (1956-2004).

4.1.3 Temperature Data

The absence of data points for the years 1964-1965 weakens generalizations on the long-term nature of the mean-daily temperature record within Squamish River Valley. However, it is apparent that the period of 1986-2004 was warmer than 1956-1985 (Figure 13). The warming after 1985 was rapid: mean-daily temperature increased from 7.5-9.1° and has remained relatively high since. The average difference in mean daily temperature between the two periods is 1.1°.

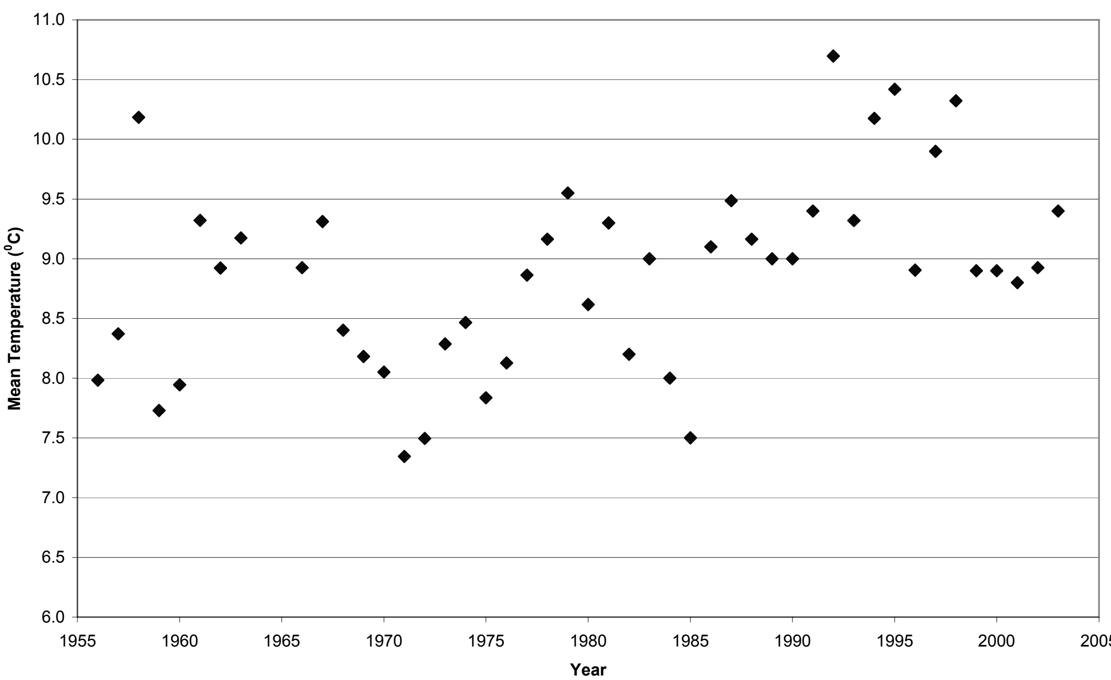


Figure 13: Mean-daily temperatures for Squamish River valley. The period 1986-2004 is significantly warmer than the period 1966-1985.

Furthermore, the 1986-2004 period, includes four years with the highest mean-daily temperatures and five out of the warmest six years recorded over the entire

50-year record. Note that, although correlated temperatures between the primary and secondary climate stations are used to construct a continuous mean daily temperature record, these synthetic data are not the basis of the trends within the record.

4.2 Hydrologic Data Analysis: Seasonal Record

Shifts in climate are rarely spatially or temporally continuous, and atmospheric phenomena often vary with time scale. For example, the average temperature of southwestern BC was found to increase by 0.5°C over the years 1895-1995 (Indicators of Climate Change for British Columbia 2002). However, the seasonal record for the same period shows increases in average temperature of different magnitude or no trend whatsoever. Furthermore, Zhang et al. (2001) have shown on a national scale that long-term trends in mean annual streamflow are not always representative of their seasonal components. Averaging of seasonal streamflow data can potentially conceal trends in streamflow generation processes. For example, a dramatic increase in flow derived from spring snow melt could be offset by an equivalent decrease in flow generated from fall storms for a given year.

To make sure that possible seasonal trends are not obscured by the annualized data, the 50-year continuous annual discharge, precipitation and temperature records are partitioned into three hydrologic seasons based on distinct streamflow periods: river-stage drop associated with the majority of precipitation falling as snowfall (January-April), the spring freshet associated with sustained high discharges (May-August), and late-fall, early winter with its storm-driven rapid changes in discharge (August–December).

4.2.1 Discharge Data

There are no strong long-term trends in the proportion of discharge being discharged during the three hydrologic seasons: Jan-Apr, May-August, Sept-Dec (Figure 14). There is a weak positive trend, however, in the proportion of water discharged in the Jan-Apr period. It appears that years which have an extreme flood are associated with an above-average proportion of flow being discharged in the Sept-Dec period.

4.2.2 Precipitation Data

The Jan-Apr precipitation data set is the only hydrologic season that displays any evidence of a long-term trend: a slight upward shift. The highest seasonal precipitation total of 1444.2 mm also occurred near the end of the Jan-Apr data set in 1999. Records for the other two hydrologic seasons are stationary but characterized by highly fluctuating data. Despite the magnitude of the fluctuations, the average seasonal precipitation for any decadal period produces a similar value for the two data sets. Thus, it appears that the upward trend exhibited in the 1985-2004 period of the annual precipitation time series (see Figure 12) may reflect the weak positive trend in the Jan-Apr seasonal hydrologic record.

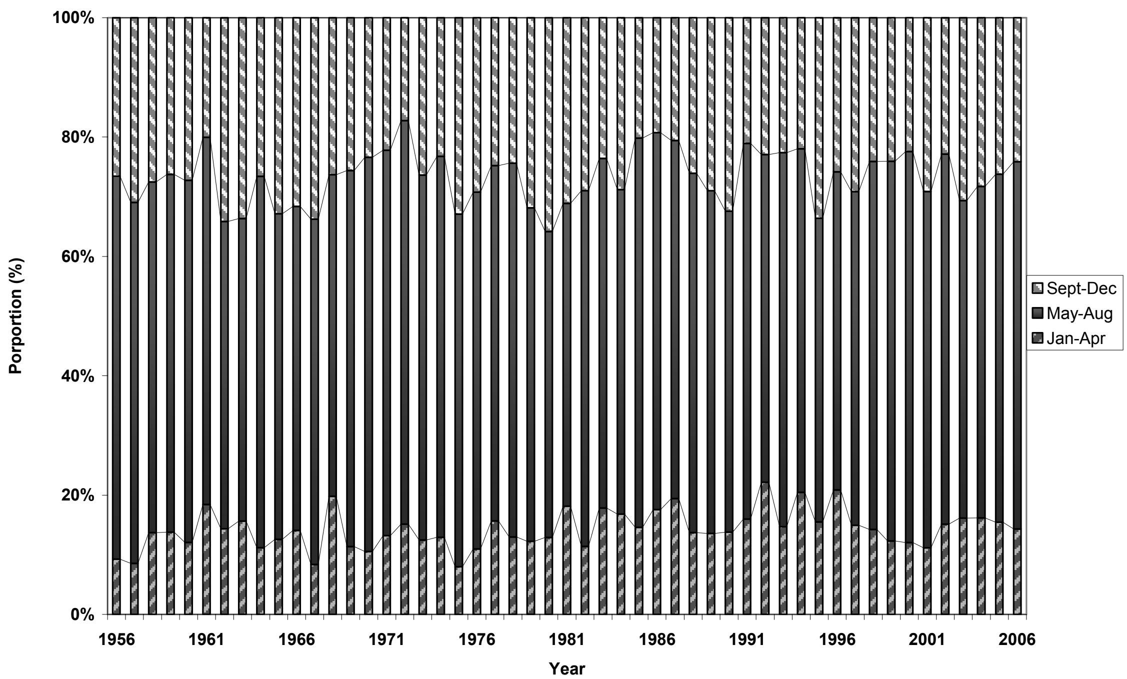


Figure 14: Proportion of Squamish River annual discharge flowing in the three hydrologic seasons (January-April, May-August and September-December), 1956-2005.

Extreme floods tend to coincide with years of above-average precipitation in the Aug-Dec hydrologic season but there are some notable exceptions. The 1991 extreme flood occurred in the sixth driest Aug-Dec period, a year after the 1990 extreme flood during the wettest year of the record.

4.2.3 Temperature Data

The mean-daily temperature time-series for the Jan-Apr hydrologic season displays an upward trend since 1969 (Figure 15). Although the fluctuations in seasonal temperature for the Jan-Apr period can exceed 3°C from year to year, the average mean-daily temperature in the 1970s is 0.9°C lower than the 1990s.

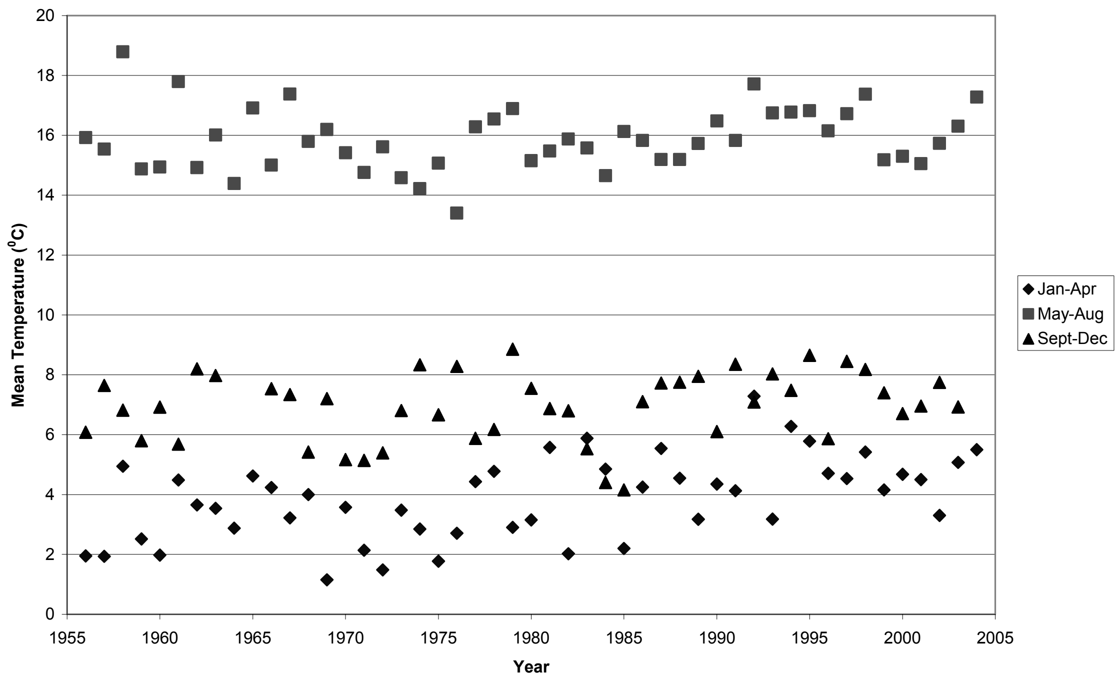


Figure 15: Mean temperature by hydrologic season for Squamish River, 1956-2004. A slight warming trend is exhibited by the Jan-Apr hydrologic season.

The May-Aug mean-daily temperature record appears to exhibit two trends: a negative trend from 1956-1975 followed by a positive trend thereafter (1976-2004)

The temperature record for Sept-Dec does not exhibit any trends for the study period.

4.3 Hydrologic Analysis: Late-Season Extreme Flood and Storm Data

Late-season extreme floods are those floods primarily driven by intense rainfall events that occur between August and December. This specific type of flood has a duration of <14 days and occurs, on average, only twice a decade. However, they produce rapid and sustained channel changes, which in one instance, has produced a shift in channel planform from meandering to braided (Hickin and Sichingabula 1988).

4.3.1 Hydrologic Analysis: Late-season Extreme Flood Data

There is a positive trend in the magnitude of late-season extreme floods with respect to time (Figure 16). Although the trend is relatively weak statistically (R^2 =0.34), the strength of the relationship suffers primarily from an outlying flood (circled value in Figure 16).

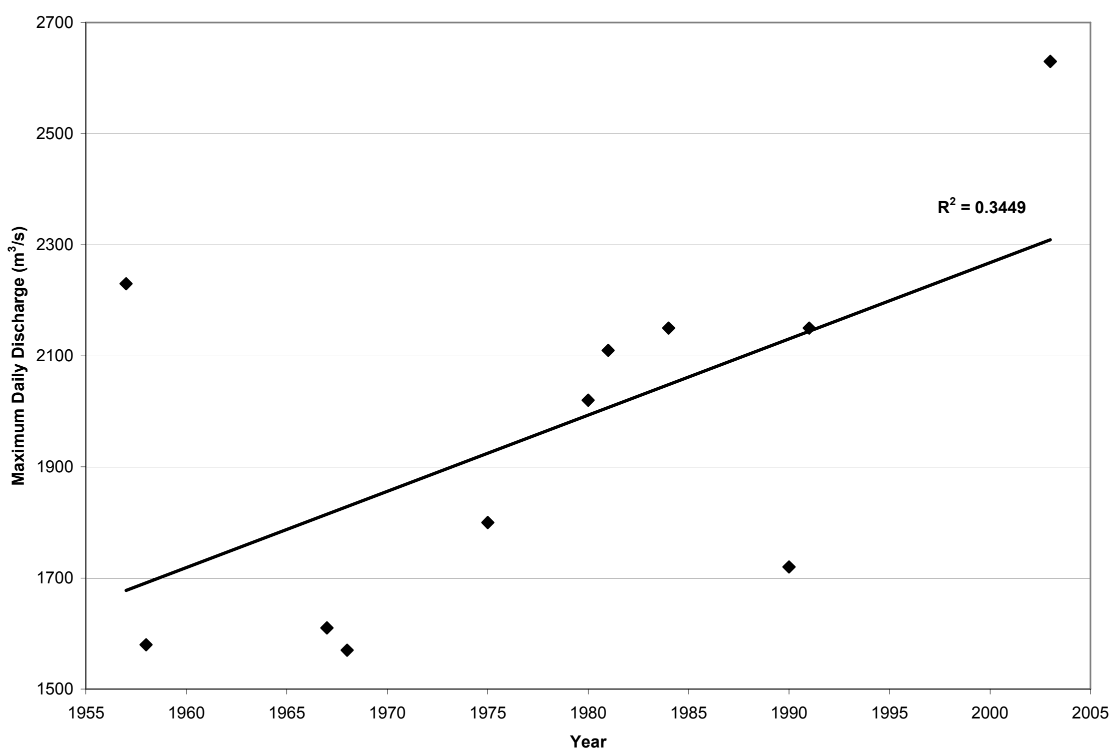


Figure 16: Maximum daily discharge for all extreme, 1956-2005. The 1957 extreme-flood outlier is discussed in the text (P=0.06).

The Sept. 6th, 1957 flood lies above the trendline by approximately 600 m^3/s. The large variance of the floods about the trend line can partially be explained by discrepancies in data collection.

According to the Water Survey of Canada the hydrometric data for Sept 6, 1957 is denoted as a 'partial day' which is probably a result of the hydrometric gauge being damaged as river stage rapidly increased. Nonetheless, it is not known if the mean daily discharge for Sept 6, 1957 was taken as the mean of the 'partial day' flow measurements or was extrapolated from the 'partial day' flow measurements. Whatever method was used, it is clear that the mean daily discharge value for Sept 6, 1957 is inaccurate. If the 1957 extreme flood is omitted from the regression relation, the recalculated R^2 value is 0.71.

The increasing trend in the magnitude of extreme floods with respect to time is paralleled by a positive trend (R^2=0.64) in flood duration (Figure 17). Over the period of record this trend implies that extreme-flood duration has increased by a factor of 3 to 4.

The extreme-flood volume, calculated as the sum of the mean daily discharges for the duration of the flood multiplied by the number of seconds in a day, also displays a positive trend with respect to time (Figure 18). The degree of variance within the data (R^2=0.66) is similar to that within the flood duration data (R^2=0.64) indicating a strong relation between the two variables.

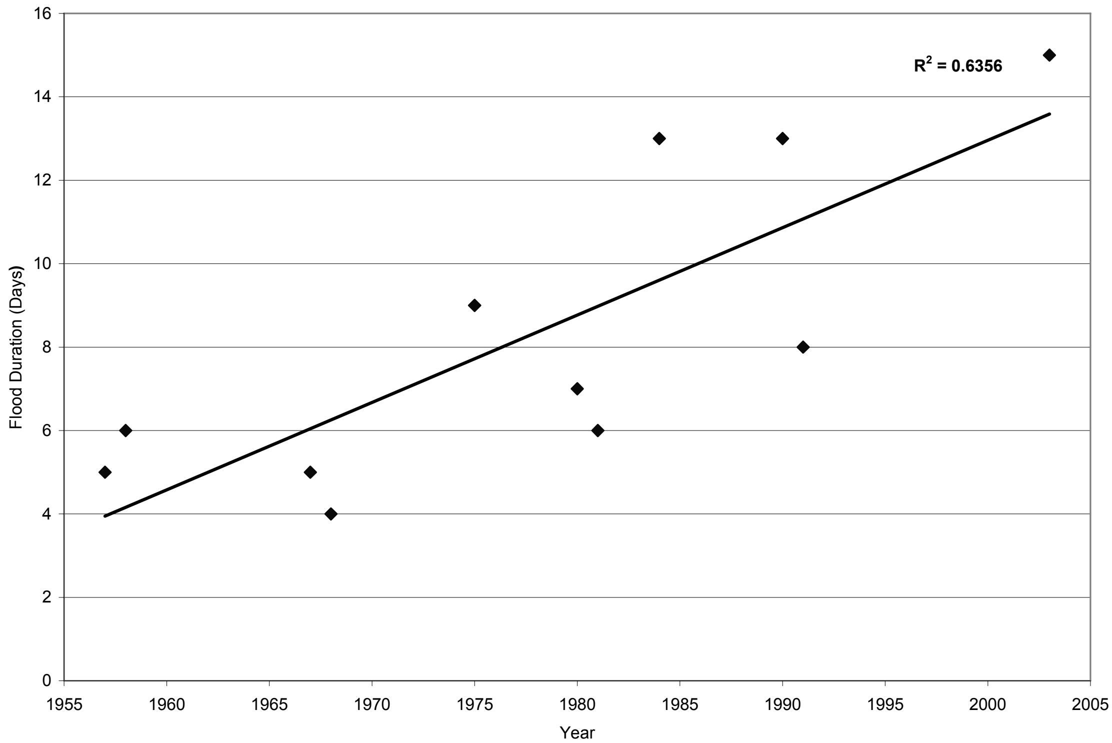


Figure 17: Duration of all extreme floods, 1956-2005, where the duration is measured from the day of the initial rise in the hydrograph to the day in which flow returns to its pre-flood discharge (P=0.003).

4.3.2 Hydrologic Analysis: Storm Data

Peaks in the flow regime of Squamish River in the months Aug-Dec are intimately linked to localized storm (rainfall) events. If the intensity or duration of a storm is great enough an extreme flood will be generated. Given the increasing trends in extreme-flood magnitude, duration and volume for the years 1956-2005 physical reasoning suggests that some aspect(s) of the climate of Squamish River basin are at least partly responsible for such hydrologic behaviour.

Indeed, the size of storms (defined as the total amount of rainfall driving an extreme flood) does increase linearly with respect to time (R^2 = 0.84) by a factor of about three (Figure 19) over the period of record.

Furthermore, within each storm the maximum daily rainfall-intensity and the average rainfall-intensity of the entire storm exhibit positive trends with respect to time (Figure 20), although the relations are not as strong (R^2 =0.55 and R^2 =0.50 respectively) as the storm-magnitude time series.

Although storm variables appear to increase linearly with respect to time, the lower R^2-values of the temporal relations may be an indication of a possible Pacific Decadal Oscillation (PDO) influence. If the 1975 flood is omitted from the temporal relation for the sake of discussion, the pre-and post 1975 floods could be interpreted as occurring in the opposing cool and warm phases characterizing the PDO. Nevertheless, within each sub-population, storm characteristics do appear to be part of a continuous trend.

Alternatively the strength of the temporal storm-intensity relations (Figure 20) likely suffers from an inconsistency in climatic conditions prior to the 1975 storm which is not exhibited by any other storm-flood event to any significant degree. In both the maximum rainfall-intensity per storm and average rainfall-intensity of the entire storm, the 1975 storm lies well below the trendlines. This is because six days previous to the onset of the storm that produced the extreme flood, another storm dropped 127.0 mm of rain. This amount was insufficient to produce an extreme flood but did produce a higher-than-average seasonal baseflow. Thus, by the time the second more prolonged yet less intense storm occurred, less precipitation was needed to exceed the 1500 m^3/s flood threshold.

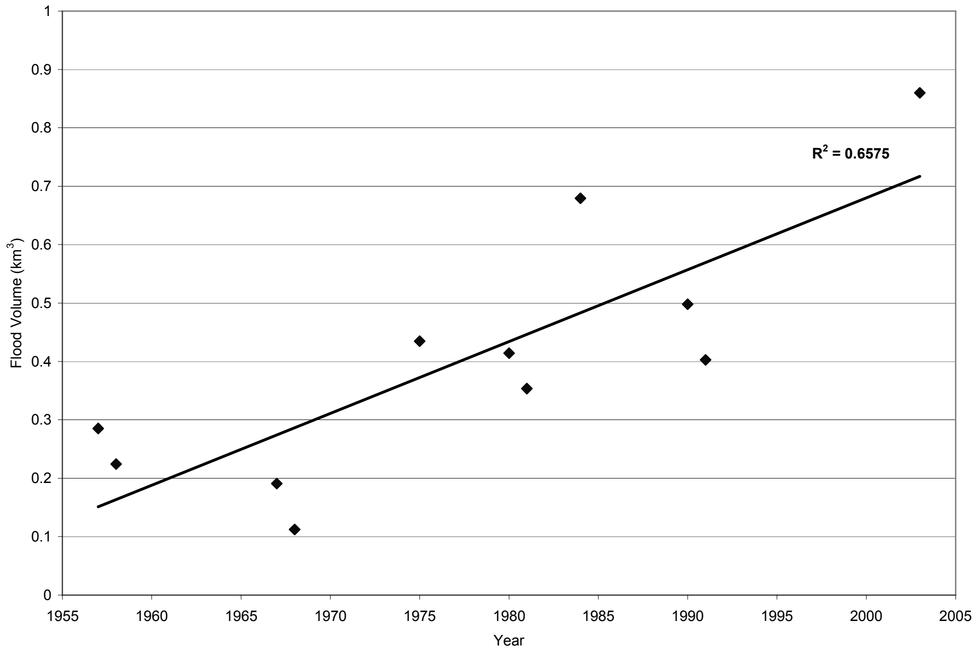


Figure 18: The volume of discharge recorded for extreme flood events 1956-2005. Event discharge is calculated by multiplying the sum of the mean daily discharges by seconds per day (P=0.002).

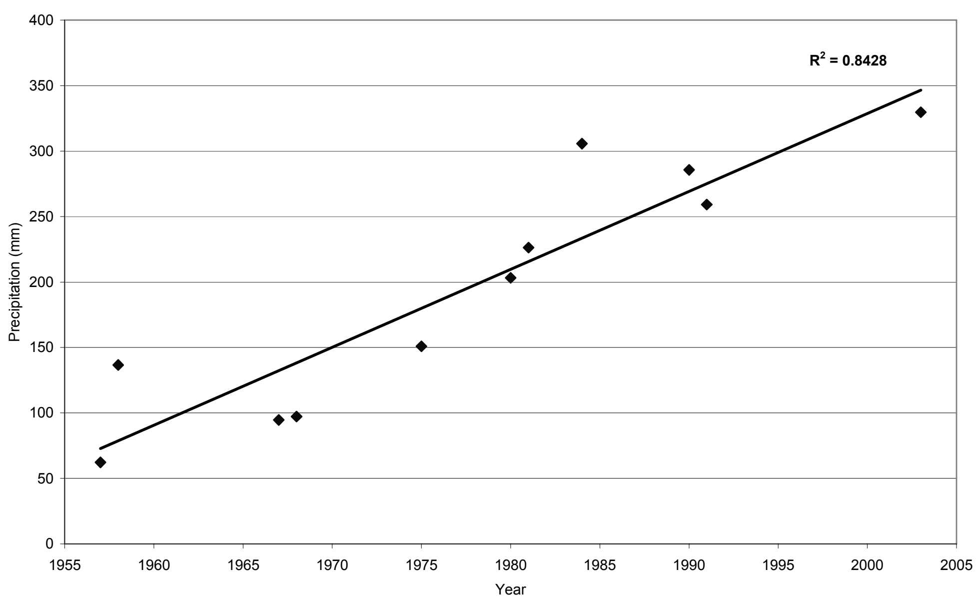
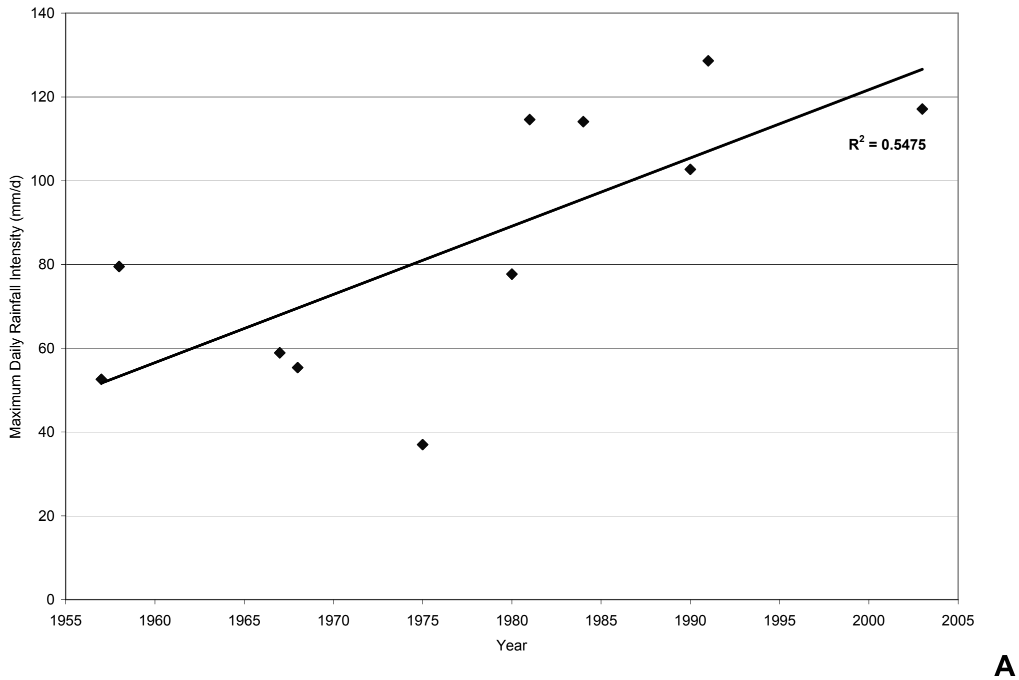


Figure 19: Magnitude of storms driving extreme floods with respect to time (1956-2004) display a strong upward trend (P=0.00007).



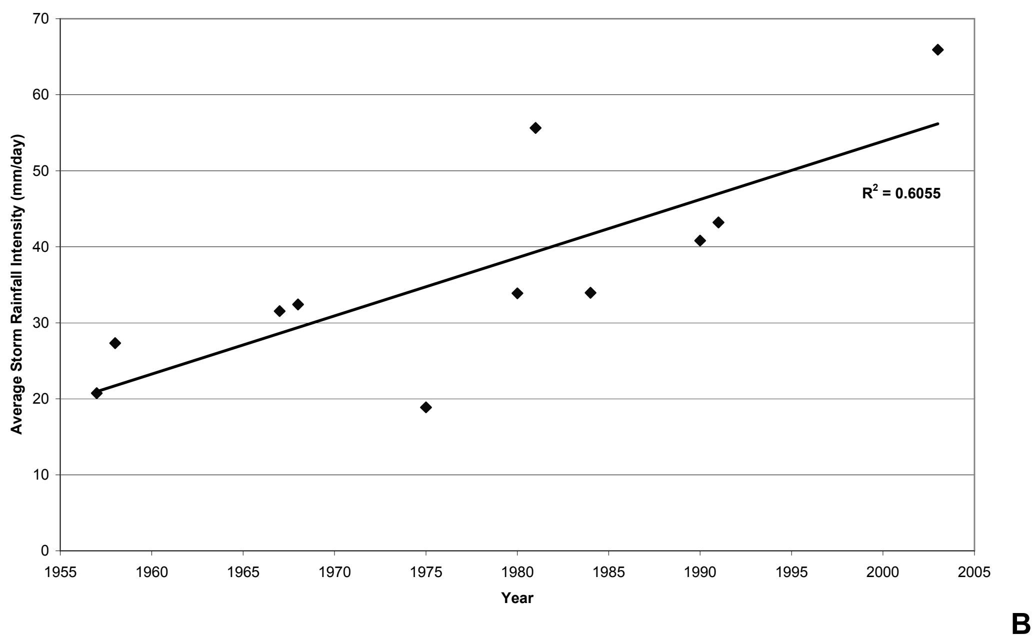


Figure 20: The maximum daily rainfall intensity (A) (P=0.001) and average rainfall intensity of storms driving extreme floods (B) (P=0.005), 1956-2004.

4.3.3 Hydrologic Analysis: Relation Between Extreme Floods and Storms

Extreme-flood magnitude and storm precipitation have been shown to both exhibit positive trends with respect to time. However, when these two variables are regressed, one against another (Figure 21), the variance is large (R^2=0.31). The strength of the relation is severely affected, however, by the 1957 and 1990 data points. In an attempt to clarify the relationship between extreme flood magnitude and storm precipitation several possible explanations are explored.

Based on the trend line in Figure 21, the 1957 flood appears to have produced a discharge far greater than the precipitation driving it would suggest. When regressing between data sets, as was done for the 1957 precipitation data, there is always a risk that values derived from the regression equation may be inaccurate. However, the relation between primary and secondary climate stations is very strong (R^2 =0.98) and so this does not seem to be the main cause of the anomalous 1957 value.

Another possible source of the variance may relate to the location of the regressed climate stations. Squamish Upper (primary) and Clowhom Fall (secondary) climate stations are situated in adjacent catchments. It is possible although highly unlikely, that a storm dropped significantly different amounts of precipitation in each basin. To check this possibility the precipitation record of an alternative climate station located within Squamish River basin was examined.

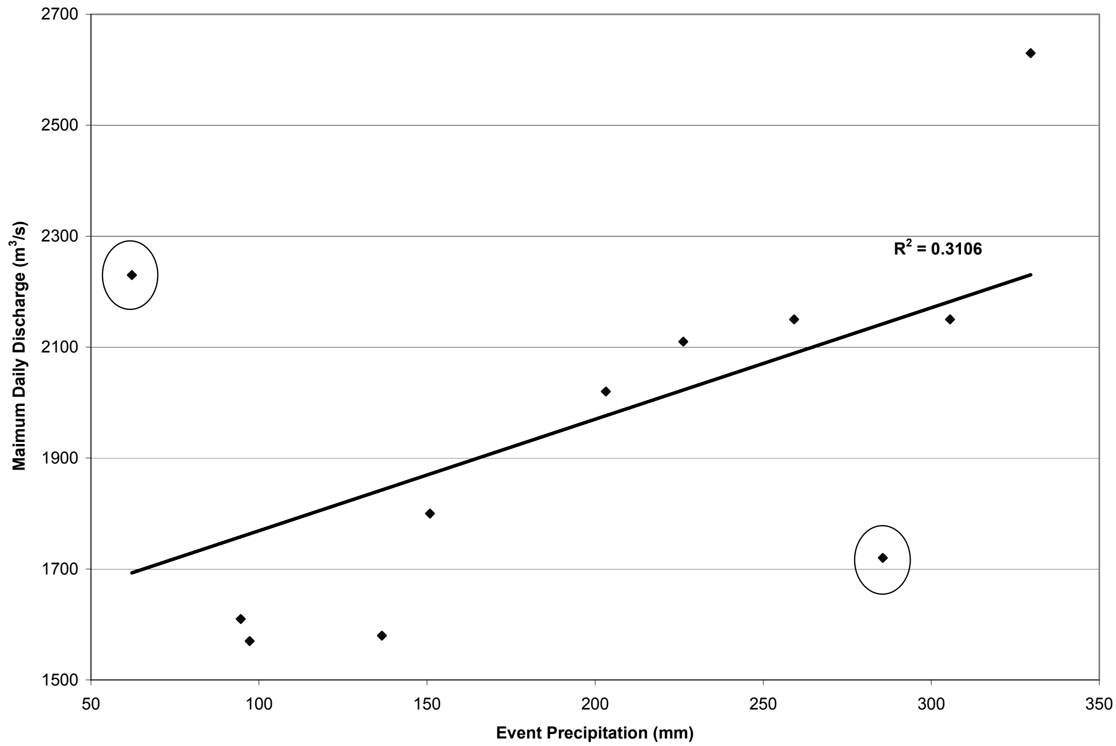


Figure 21: The relation between the maximum daily discharge per flood event and event precipitation driving the extreme flood, 1956-2004 (P=0.07).

On September 5-6, 1957 the Garibaldi climate station (1043060) recorded a total precipitation of 39.1 mm; which is comparable to the 62.2 mm recorded by Squamish Upper station. Therefore, it appears that the irregularity of the 1957 data point is not a rainfall-related problem but rather a flow-related problem.

The Squamish River and Garibaldi Volcanic Belt are prone to debris avalanches (Evans 1990). Could the relatively large discharge value be the result of a debris impoundment and subsequent release? Two small-scale historical debris avalanches originating from the western flank of Mount Cayley located in north Squamish River in 1963 have been documented (Clague and Souther 1982) and 1984 (Evans 1986; Jordan 1987; Lu 1988). Based on further research on prehistoric debris avalanches from Mount Cayley, Evans and Brooks (1991) "… believed [that the debris avalanches] are part of a series of small-scale events that occur relatively frequently (25-100 years?) between much rarer, large events." However, there is no evidence of temporary damming of the river. Sichingabula (1986) analyzed air photographs of Squamish River taken on Oct 24th, 1958 and would surely have noted the remnants of a debris avalanche incised by the river at that time.

A late summer snowmelt, producing higher-than-average seasonal baseflow, in conjunction with a medium magnitude/intensity storm could produce an extreme flood but the mean daily discharge record reveals no such evidence. Nor is there significant rainfall occurring before the onset of the storm producing the extreme flood which might have enhanced the extreme flood signal.

The most likely explanation for the anomalous 1957 flood/storm event relates to the simple sampling discrepancy discussed earlier in section 4.3.1. Since the discharge recorded on Sept 6, 1957 is denoted a 'partial day' it is possible that only the peak-portion of the daily hydrograph was sampled resulting in a higher mean-daily discharge than would have been recorded over the full day.

In contrast to the 1957 flood, the 1990 flood plots well below the trend line in Figure 21 indicating that the flood has generated a discharge far less than would seem likely to occur given the relatively large amount of storm precipitation. Of the above possibilities to account for anomalous 1957 data, only two are relevant to the 1990 extreme flood. That is, there are no errors associated with regression equations or location problems. All the data were collected from one station. Second, the 1990 flood occurred in November, thus there is no possibility of a summer snowmelt occurring that late on which a medium-magnitude precipitation event could be superimposed. Third, this study utilizes aerial photography taken one week after the flood occurred, so any channel obstruction would be visible.

However, since the flood occurred in November it is possible that some of the precipitation, especially at higher altitudes, fell as snowfall. Therefore, it may be possible that the decrease or delay in streamflow contribution from the upper elevations of the basin may have produced a lower-than-expected discharge peak. Although there are no climate stations in Squamish River basin recording minimum temperature data, the neighbouring Whistler climate station (1048898), located 657 m above sea level, recorded minimum daily temperatures of 0.0, 1.4 -0.8 and -0.5ºC in the four days prior to the storm onset. Thus, it is likely that precipitation fell as snow at elevations greater than 657 m above sea level and remains the most likely explanation of the anomalous Nov. 11-12 data point.

The strong relationships between flood and storm characteristics suggest a local shift in climate. But before such a statement can be made with a high degree of certainty, other factors that affect the conveyance of rainfall to a channel must be considered. The antecedent moisture conditions of soil affect the storage capacity and the hydraulic conductivity and thus the rapidity with which rainfall reaches a channel. A high antecedent-moisture level can reduce the amount of infiltrated precipitation which can result in a shaper rise in the hydrograph and larger peak discharge. In the absence of soil-moisture data, the antecedent moisture conditions are defined as the total precipitation recorded 14-days prior to the onset of a storm (Antecedent Moisture Index (API). API was plotted with respect to time (Figure 22) and to maximum daily discharge of an extreme flood (Figure 23). API shows no relation to either of the variables. However, it is interesting to note that extreme floods can be generated under relatively dry soil conditions (1984, 1991). Of course soil-moisture conditions become largely irrelevant if there is snow on the ground or if the ground is frozen.

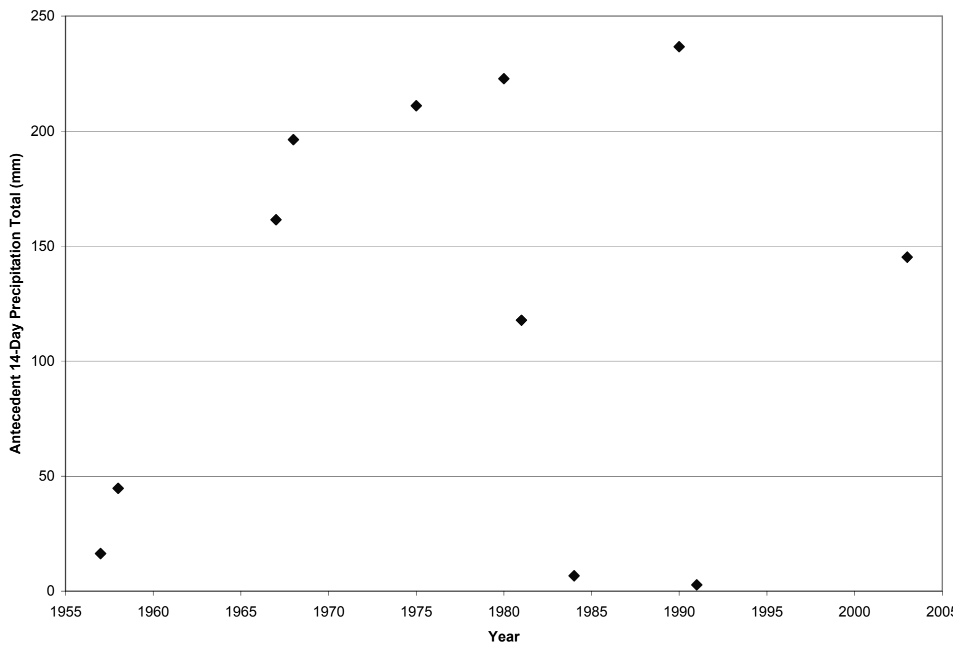


Figure 22: Antecedent precipitation index (API) (measured as the total precipitation recorded 14-days previous to the onset of a storm) for extreme floods.

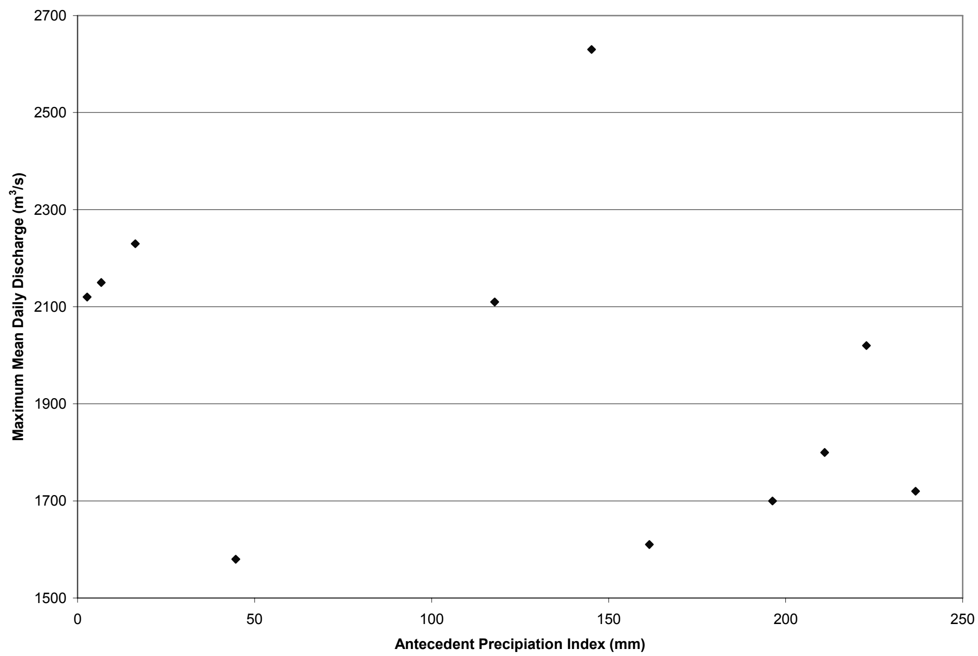


Figure 23: Antecedent precipitation index (API) (measured as the precipitation total of 14-days previous to the onset of a storm) versus the maximum mean daily discharge of extreme floods.

4.4 Flood-Frequency Analysis

By dividing the Squamish River flood record into sequential decadal periods and then performing Gumbel Analysis on each, shifts in the magnitude of floods of a given recurrence interval can be evaluated (Figure 24).

Clearly estimates of flood magnitude, which were extrapolated from logarithmic best-fit lines based on these decadal subsamples, significantly increase over time. In the case of the 10-year flood, for example, it has increased 600 m^3/s or 30% over the period of record. This result has significant implications for predicting flood probabilities in the future, a matter that will be revisited in Chapter 7.

Because the non-stationarity in the annual flood series is almost certainly driven by regional storm-climate changes, this apparent increase in flood magnitude over time likely is regional. Certainly the adjacent Lillooet River appears to be exhibiting similar behaviour (see Figure 25) perhaps to an even more striking degree.

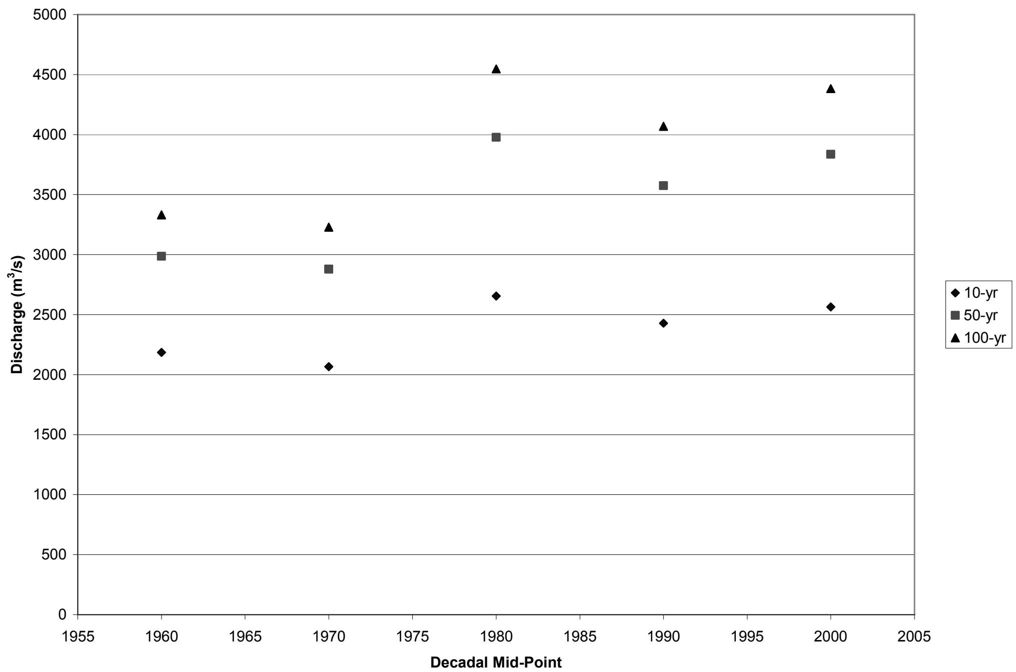


Figure 24: Estimates of the 10, 50 and 100-year flood magnitudes on Squamish River using magnitude-frequency analysis based on decadal periods, 1956-2006.

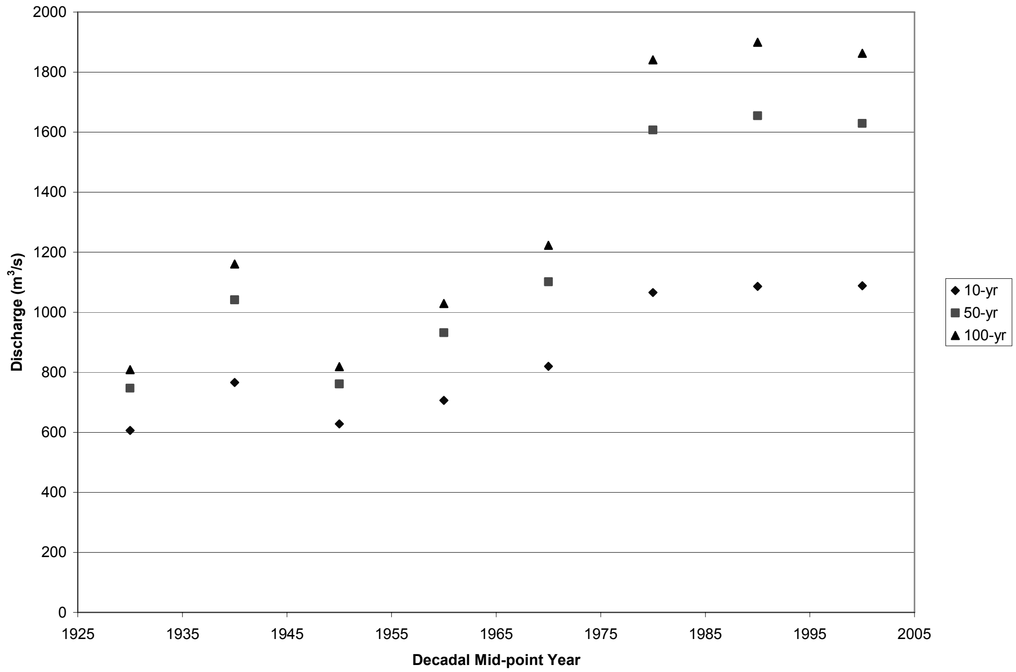


Figure 25: Estimates of the 10, 50 and 100-year flood magnitudes on Lillooet River using magnitude-frequency analysis based on decadal periods, 1925-2005

CHAPTER 5: CHANNEL CHANGE RESULTS

5.1 Channel-Change Analysis

This chapter presents a reach-by-reach description of channel changes documented for Squamish River over the photographic record (1984-2007). The most common adjustments include bank erosion/deposition, island erosion/deposition, downstream and lateral migration of river bends, while less common occurrences include chute-channel formation/abandonment, island accretion and division by medial channels.

Channel changes are quantified in terms of gains and losses (positive or negative changes) of surficial area, as well as rates or channel migration. Specific sites of interest are denoted by letters or number. These reference labels were primarily defined by Sichingabula (1986) but additional areas of recent activity have been added here. Thus, these labels may be alphabetically or numerically discontinuous. Possible explanations of the observed channel changes are also discussed within each section.

5.1.1a Cheakamus-Mamquam Reach

Sichingabula (1986) documented three major channel changes in the Cheakamus-Mamquam Reach for the years 1947-1984: downstream migration of the Squamish-Cheakamus confluence; downstream migration of Brackendale Island (A) from 1976-1984 and of Baynes Island (C) from 1947-1984; and growth of Brackendale Island (A) from 1947-1984.

Although change has continued at each of these three sites during the period 1984-2007, it is not as linear as that described by Sichingabula.

The Cheakamus-Squamish confluence, in general, continued to grow downstream (Figure 26). From 1984 to 1990 the apex of the confluence migrated 97 m, however, the development of a lateral (east-west) channel connecting both rivers divided the floodplain separating the confluence into northern and southern triangular-shaped portions.

This confluence configuration persisted until 1996 following which the second, and most extensive, downstream advancement occurred. The island extended 300 m downstream and grew in the cross-stream direction, reducing the effective channel width of the Cheakamus-Squamish system. The confluence growth is attributed to the coalescence of smaller islands as a result of sedimentation of channels separating islands located primarily at the head of Cheakamus River.

Evolution of Baynes Island (C) has been characterized by two distinct periods of change. The first period of change is distinctly erosional in nature and spatially dispersed. From 1984-1991 (Figures 26-27), Island (C) experienced erosion to the island head (1984-1991), to the eastern bank (1984-1990) and to the downstream end of the island group (1984-1990). The number of major islands within the Island (C) group was reduced from four to two over the same time period (1984-1991). These two islands persisted until 2007 (Figures 28-29). The change in alignment of the islands relative to the dominant upstream flow trajectory defines the start of the second period of change.

Between 1996 and 2007 (Figure 29), the width of the medial channel bisecting the islands grew from 32 m to 124 m at its greatest dimension and adopted a straighter, less meandering course. The change in alignment appears to be a reaction to the change in flow trajectory of Squamish River imposed by the lateral growth of the island separating Squamish and Cheakamus River as it exits the confluence area. The island, which has constricted Squamish River against the western bank, has likely shifted the focus of river attack to the head of Island (C) and to the medial channel. It is likely that some of the eroded bed materials from Island (C) and from the islands near the confluence were deposited and formed the nucleus of the elongated bar located approximately 0.25 km downstream of Island (C).

Immediately downstream of Island (C), the western channel bank experienced significant erosion between the years 1984-2007. This bank lies adjacent to a training dyke which extends from just north of Judd Slough to beyond the southern extent of the study reach.

At this location it was suggested by Sichingabula (1986) "… that stream stabilization on one bank of Squamish River would have caused increased erosion on the unstabilized bank." However, increased erosion on the opposite bank was not identified by Sichingabula in the period following the construction of the dike (1976-1984). Erosion of the unstabilized bank following 1984 could represent a lag effect in the adjustment of the channel to the dyke that is only recognizable beyond, at least, six years. The erosional rates between periods at this location have steadily decreased with respect to time following the 1991 extreme flood. This may indicate that the river is achieving a new equilibrium in response to the building of this structure.

The downstream migration of Brackendale Island (Island A) documented by Sichingabula from 1976-1984 has not persisted although since 1984 it has undergone other changes. The southern portion of the island and accompanying back channel to the west have translated upstream towards the northwest. The southeastern region, which has been characterized by multiple secondary satellite islands from 1984-1991, attached to the main isle through sedimentation and establishment of vegetation by 1994. Between 1996 and 2007 an additional satellite island located along the northeastern edge of the island experienced a 243 m extension in a flow-parallel direction.

Major depositional changes also occurred within the Brackendale Bend (1). Within the concave bank, steady and persistent deposition has reduced the effective width of the channel by 258 m at its greatest breadth between 1996-2007. The source of this deposited material is most likely derived from erosion of islands at the Squamish-Cheakamus confluence or from the extensive erosion of the western bank located below Island (C).

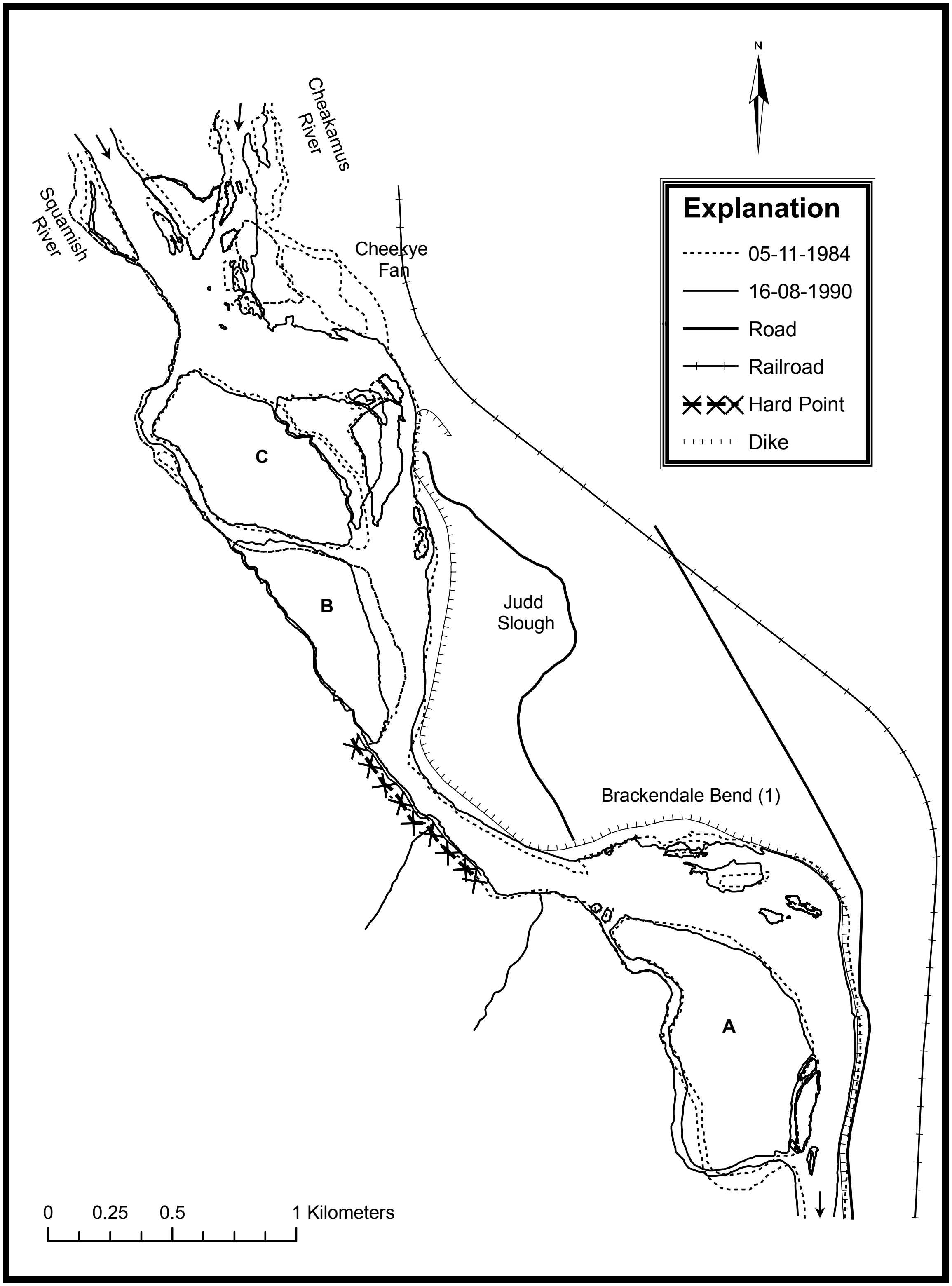


Figure 26: Channel changes in Cheakamus-Mamquam Reach, 1984-1990.

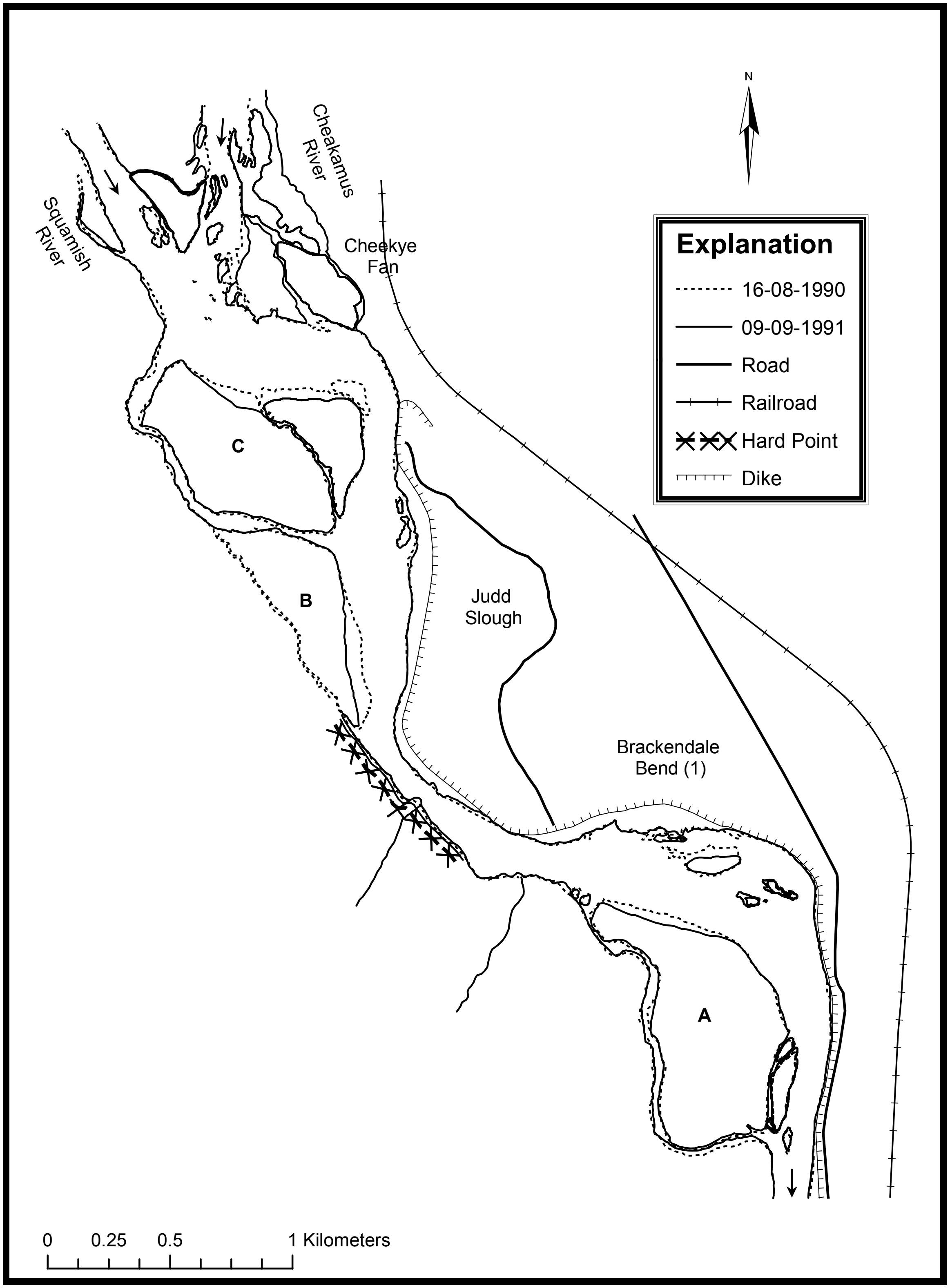


Figure 27: Channel changes in Cheakamus-Mamquam Reach, 1990-1991.

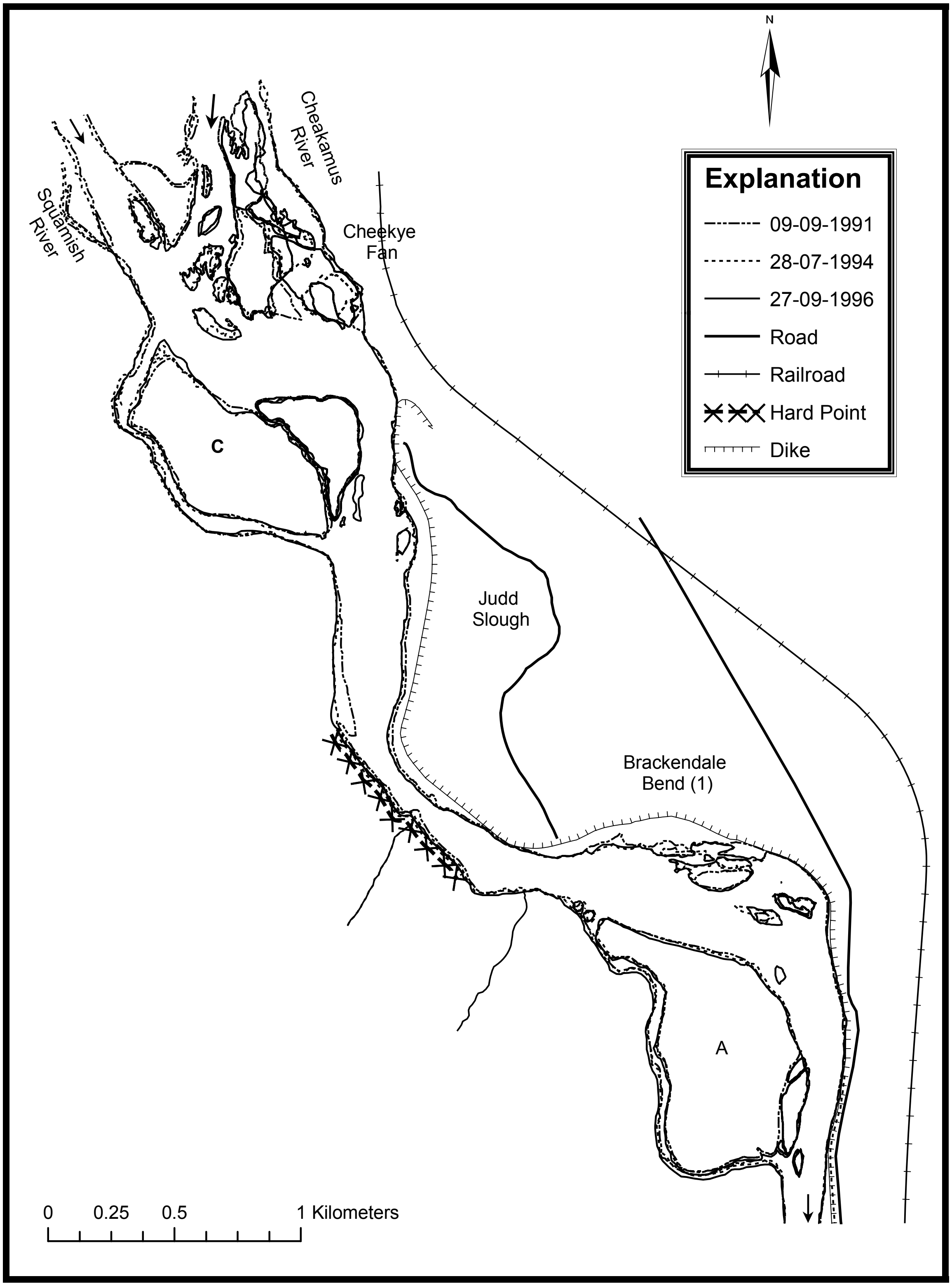


Figure 28: Channel changes in Cheakamus-Mamquam Reach, 1991-1996.

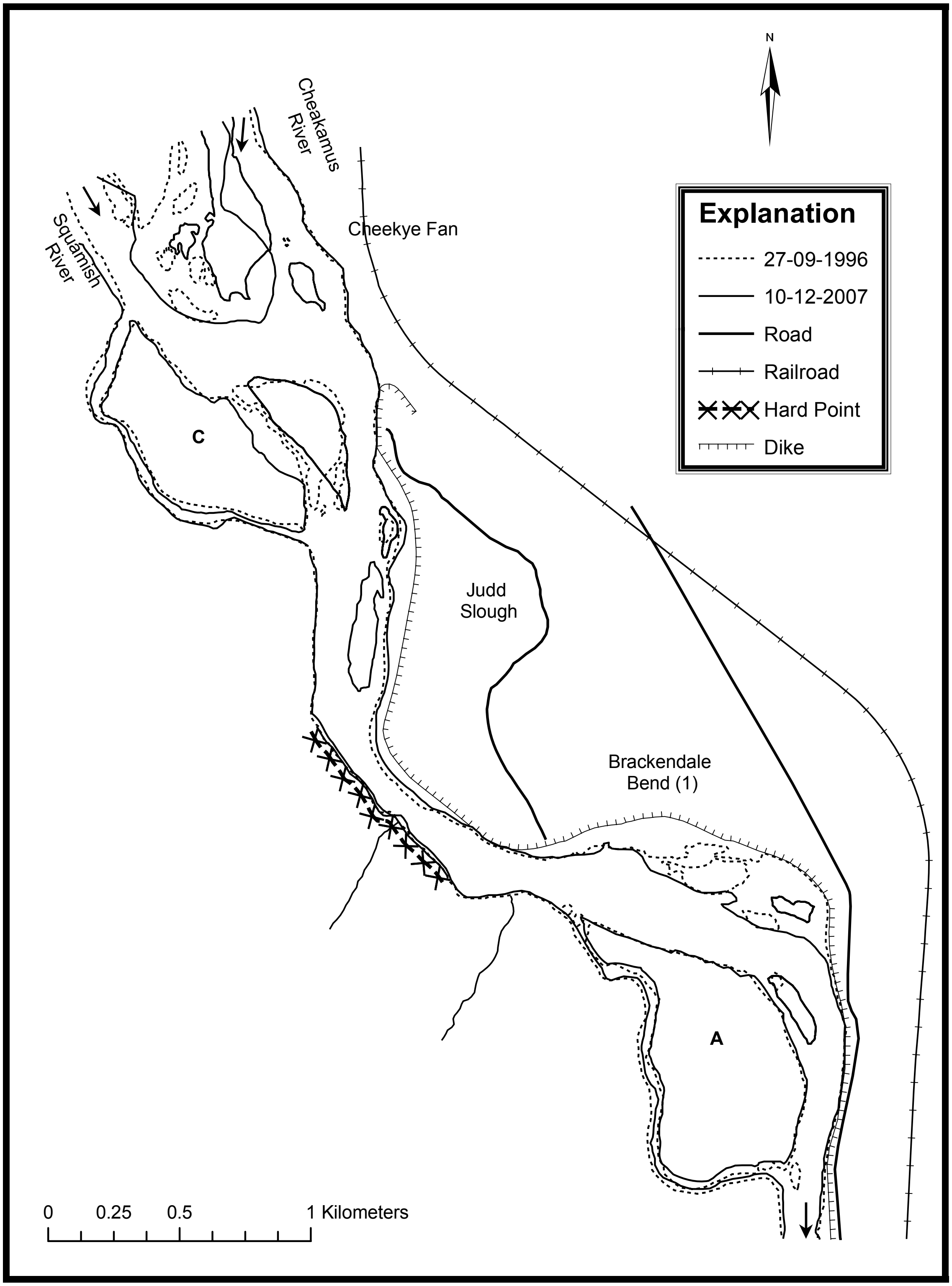


Figure 29: Channel changes in Cheakamus-Mamquam Reach, 1996-2007.

5.1.1b Effect of the 1990 and 1991 Extreme Floods on Cheakamus-Mamquam Reach

The 1990/1991 extreme floods (mean daily discharge of 1720 m^3/s and 2120 m^3/s; maximum instantaneous daily discharge of 2060 m^3/s and 2460 m^3/s, respectively) produced extensive geomorphic change within Reach A (Figure 27). Along the eastern bank of Cheakamus River near its mouth, the channel bank retreated 470 m at its maximum and dissected the previously coherent floodplain/Cheekye Fan into a group of three large islands. Net erosion associated with the bank retreat is 107.67 x 10^3 m^2. Within the same area during the years 1984-1990 (Figure 26), a period without extreme floods, the boundary of the eastern bank moved 445 m westward, likely through the process of channel infilling and island coalescence. This history suggests that extreme floods can rapidly rework this particular section of the floodplain and that the channel bank can return to its coherent nature in approximately seven years. However, recovery time will vary with the amount of material being deposited on the Cheekye Fan. Considering the morphologic changes in this area over the 1996-2007 period, recovery time may be even less than four years. In 1996 the area at the mouth of the Cheakamus had a multiple island morphology. By 2007 the eastern bank once again displays its coherent nature. The flood of record occurred between these sets of photographs (in 2003). Thus it is possible that the extreme flood introduced another source of instability to the area, leading to the dissection of the eastern bank and reorganizing the islands configuration of 1996. If the channel bank progressed cross-stream again by 2007 the channel recovery time would be less than about four years. It is difficult to discern if this behaviour is in agreement with the pattern of change documented by Sichingabula. The timing of extreme floods in relation to the timing of the photographic record is such that extraction of such detail is unfeasible. However, there is evidence that this area has been subject to a cycle of floodplain dissection and island coalescence to varying degrees in the years 1947-1969.

The head of Isle (C) experienced significant erosion in response to the 1990/1991 extreme floods. Maximum bank retreat was 48 m and a satellite island of 9.13×10^3 m^2, located off the northeast bank of the larger island, was excavated. The head of Island (A) was similarly eroded; maximum bank retreat equalled 40 m.

No major deposition in Reach A was recorded following the 1990/1991 extreme floods. However, infilling of the back channel located to the west of Island (B) promoted the accretion of the isle to the floodplain where it has remained for the rest of the photographic record. Concurrently, the downstream bank of Island (B) was significantly eroded, in places up to 67 m. Based on calculations of the net change in areal extent, it is apparent that in Reach A the dominant process associated with extreme floods is erosion.

Sichingabula (1986; see his Fig 4.3) found similar changes in the Cheakamus-Mamquam Reach following the Oct 8-9, 1984 extreme flood but channel changes were not extensive. Island head erosion observed following the 1984 flood was of similar magnitude to that of the 1991 flood. No changes, however, were noted in the more active regions documented for the 1990/1991 extreme floods: the northeastern section of the reach near the confluence and Island (B).

5.1.2a Lower Meandering Reach (Reach B)

The most noticeable change to the Lower Meandering Reach (Reach B) is its significant straightening, as a result of the reduction in curvature of Bends 2, 2a and 3.The most pronounced straightening occurred in Bends 2 and 2a. From the earliest study period (1984-1990) deposition throughout the outer concave bend in combination with erosion along the inner convex bend have reduced the curvature of Bend 2 (Figure 30). Similarly, erosion of the apex of the convex bank on Bend 2 has locally reduced channel curvature though the apex of the bend. Due to the lack of photo coverage, the outer bank of Bend 3 could not be mapped. Upstream, minor erosion to the convex bank of Bend 3 further reduced the curvature of the bend, a process active since 1947. The convex bank experienced its greatest retreat (225 m) following the Nov 1, 1981 extreme flood (Figure 31).

All three bends (2, 2a, 3) experienced further straightening between 1990-1991 as a result of the 1990/1991 extreme floods (a detailed summary of the effect of the extreme floods on Reach B is described in the following section).

The passage of the 1990/1991 extreme floods seems to have marked a distinct shift in the process by which channel straightening is accomplished. For the period 1984-1991, channel straightening was dominated by erosion of convex banks in Bends 2, 2a and 3.

Following the extreme flood, deposition became the dominant process influencing channel sinuosity. Minor convex bank erosion is identifiable in the depositional period (1994-2007) on the upstream bank of Bend 3 (1994-1996; Figure 32); on the downstream bank of Bend 2a (1994-2007) and at the apex of Bend 2 (1996-2007). Deposition in the concave banks of Bends 2 and 3, however, constitute the most significant source of straightening. Large islands (2.86×10^4 m^2 and 2.13×10^4 m^2) relative to the size of the Bends 2 and 3, respectively, formed during the period 1991-1994. The island in Bend 2 eventually accreted to the floodplain and extended upstream (1994-1996). Between 1996 and 2007 (Figure 33) the newly created floodplain grew 102 m predominantly in the cross-stream direction.

Unlike the Bend 2 island, the island in Bend 3 did not accrete to its floodplain during the latter period, presumably due to the constant influx of water from the tributary in the northwest corner of the bend. However, the island did grow by 6.35×10^3 m^2 from 1994-1996 before being divided by 1996. Between 1996-2007 the northern portion of the island accreted to the upstream bank of the concave bend and extended the bank downstream by a maximum of 95 m. The southern portion, consisting of two other islands, offers some bank protection from river attack to the downstream bank of the concave bank in Bend 3. Both topographic elements contribute to straightening the channel by directing the main filament of flow more directly downriver.

The appearance of vegetation on bars is closely related to the aggradation of concave-bank benches which are defined as fine-grained fluvial materials deposited in the concave banks of tightly curved bends (Woodyer 1975). Hickin (1979) identified two such benches in Squamish River, which were thought to be at different stages of development: a mature bench in Bend 2 and a youthful feature located in Bend 3. Hickin (1979) suggests that bench formation is a product of the generation and shedding of vortices at the flow separation boundary. The vortices then advect into the separation zone, mostly near the downstream limit of the flow structure, where the concave-bank bench forms due to rapid energy dissipation and deposition of the suspended load from the coherent flow structures.

In the Lower Meandering Reach extreme floods appear to indirectly influence the development and lifespan of concave-bank benches. If the separation zone were to grow, say by the translation of the main filament of flow toward the convex bank as a result of convex bank erosion and channel widening, then it likely would produce or reinitiate concave-bank bench growth. The recent behaviour of the concave-bank benches located in the Reach B (see Figures 32-33) may be attributed to this phenomenon.

Hickin (1979) estimated that the concave-bank bench in Bend 2 was in a mature state of development due the observance of [then] recent erosion (2000 m^3) causing a bank retreat of 25 m at its maximum width. This erosive period is probably a combination of the bench extending streamward, allowing the river to access the sediments of the fore edge and the growth of the point bar on the opposing convex bend which caused the river to shift toward the opposite bank (see Sichingabula 1986, Fig 4.5). This assumption is supported by Hickin (1979) who noted the absence of a separation zone on the concave bank of Bend 2, although a weak separation zone occurred just upstream of the feature (Hickin 1978). Erosion of the fore edge may have continued if a similar channel configuration persisted but the extreme flood of 1981 drastically eroded the convex bank of Bend 2.

Following Hickin’s work the concave-back bench has continued to grow from 1984 to 2007. This consistent growth is visible on the areal photography but not shown on the annotations. This is merely a result of how permanent vegetation is used as a proxy for channel stability. Thus the concave-bank bench in Bend 2 first appears as islands separated from the concave bank before accreting to the floodplain in 1996. Based on the recent history of the concave-bank bench in Bend 2, it likely is in a state of reinitiated growth as a consequence of the development of a flow separation zone which in turn is a product of channel straightening. The concave-bank bench located in Bend 3 provides an estimate of how long this growth period will persist.

Since 1979, the size and morphology of the Bend 3 concave-bank bench has varied little. It was hypothesized by Hickin (1979) that the fore edge of the bench is a 5 year (?) equilibrium feature that fluctuates about a streamward boundary. If the streamward boundary of the separation zone is a function of the inflection of the convex bank under an approximately constant discharge, then the stability of the bench can be explained. The morphology of the convex bank of Bend 3 and location of the concave-bank bench fore edge has not varied from that observed by Sichingabula (1986) from 1980-1982, although the upstream bank of the convex bank eroded 41 m at its maximum following the 1990/1991 extreme floods. Therefore, it can be assumed that the location of the main filament of flow and width of the separation zone have also experienced little change. In these terms Bend 3, initially described as a developing feature, has reached a state of maturity. The present morphology of the bench likely will persist until there is a change in the general pattern of river migration or bank concavity.

The age of the concave-bank bench in Bend 2, if 1964 is taken as an initiation date based on Hickin's (1979) observations and 1979 is taken as an upper-limit stability date before deposition resumed, is approximately 15 years. The age of the concave-bank bench in Bend 3, if 1979 is taken as an initiation date and 2007 is taken as the lower-limit stability date, is approximately 29 years. Therefore the estimated age of concave-bank benches, from initiation to a stable form, is about 15-30 years.

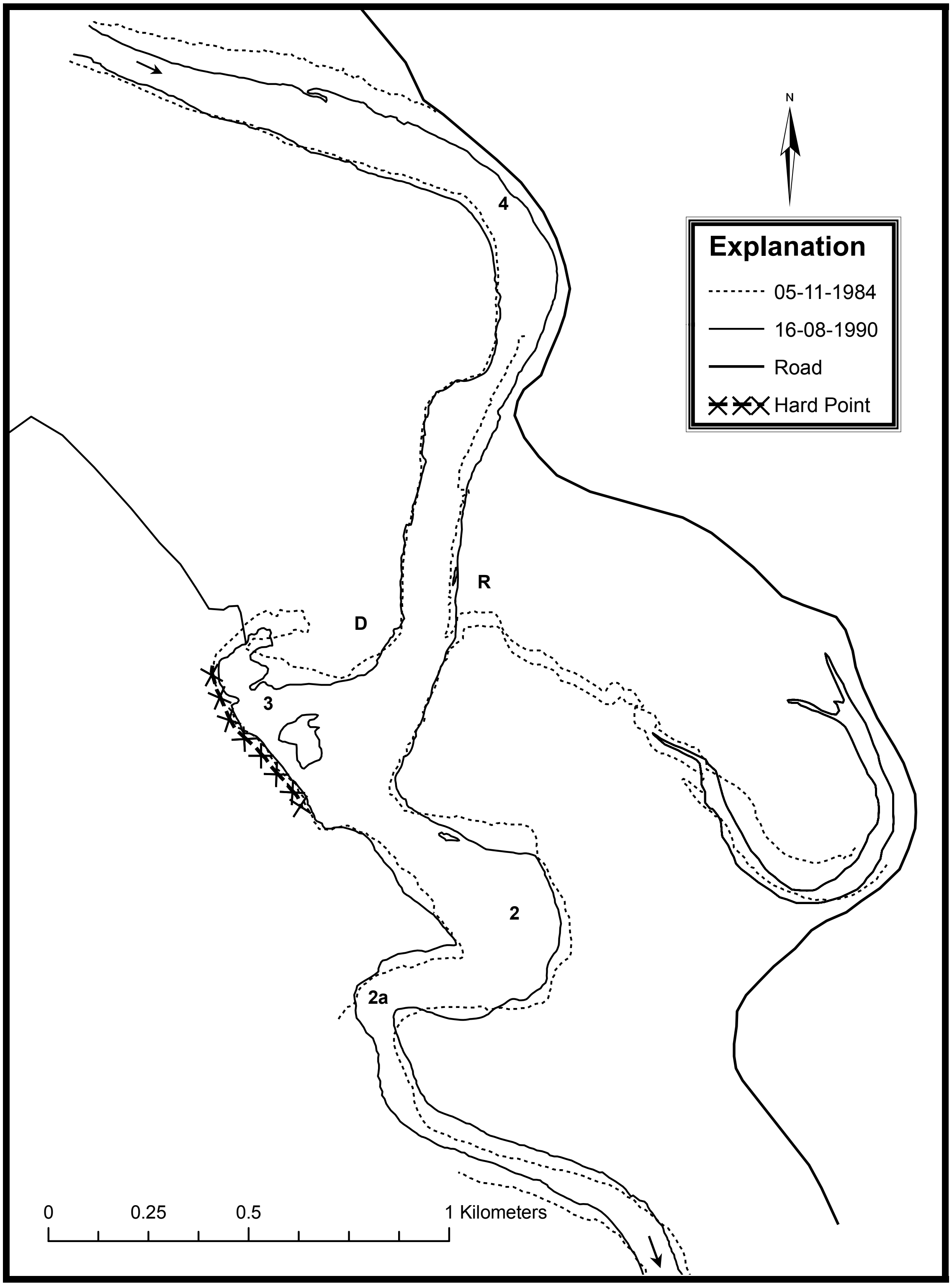


Figure 30: Channel changes in Lower Meandering Reach, 1984-1990.

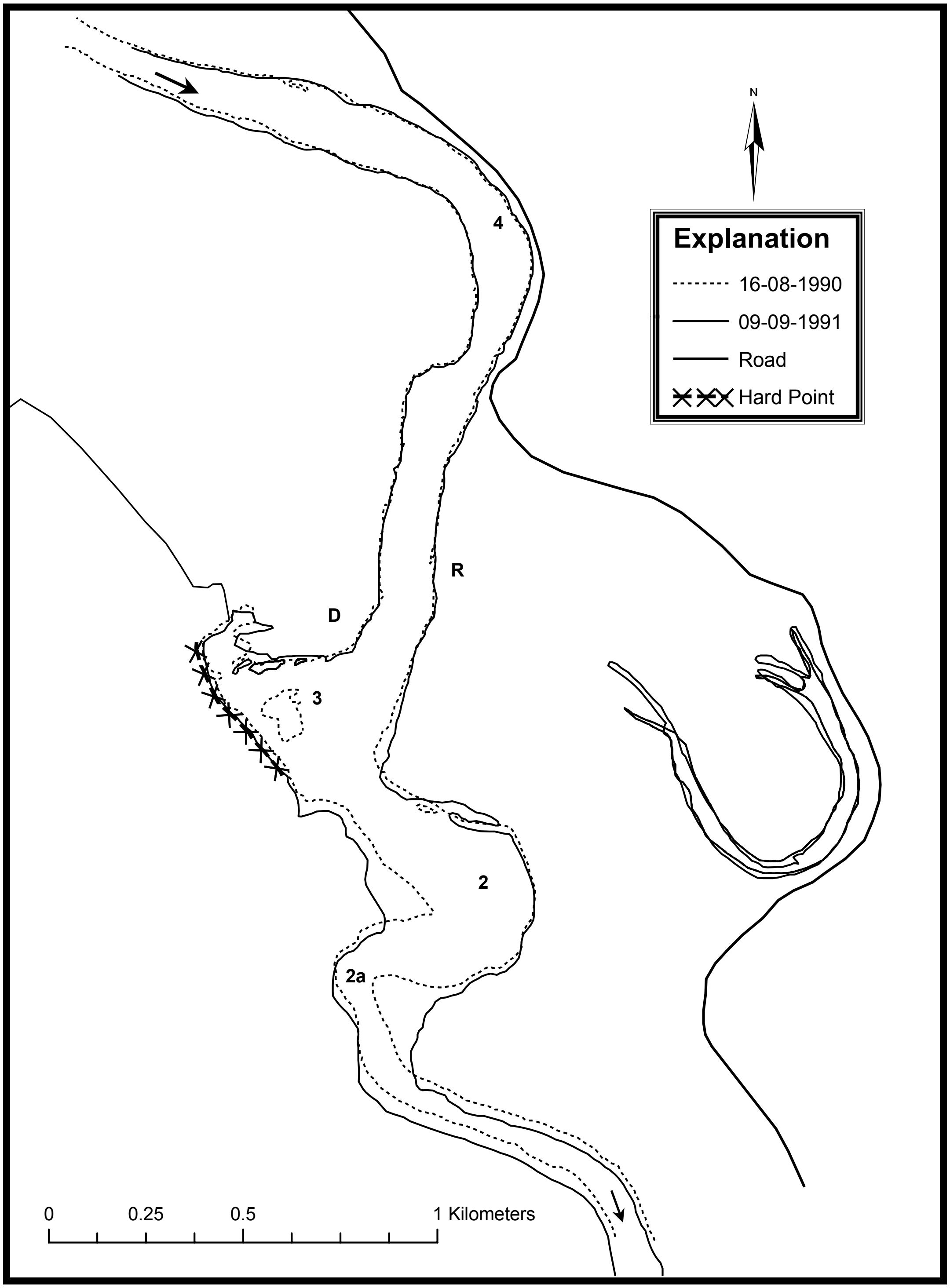


Figure 31: Channel changes in Lower Meandering Reach, 1990-1991.

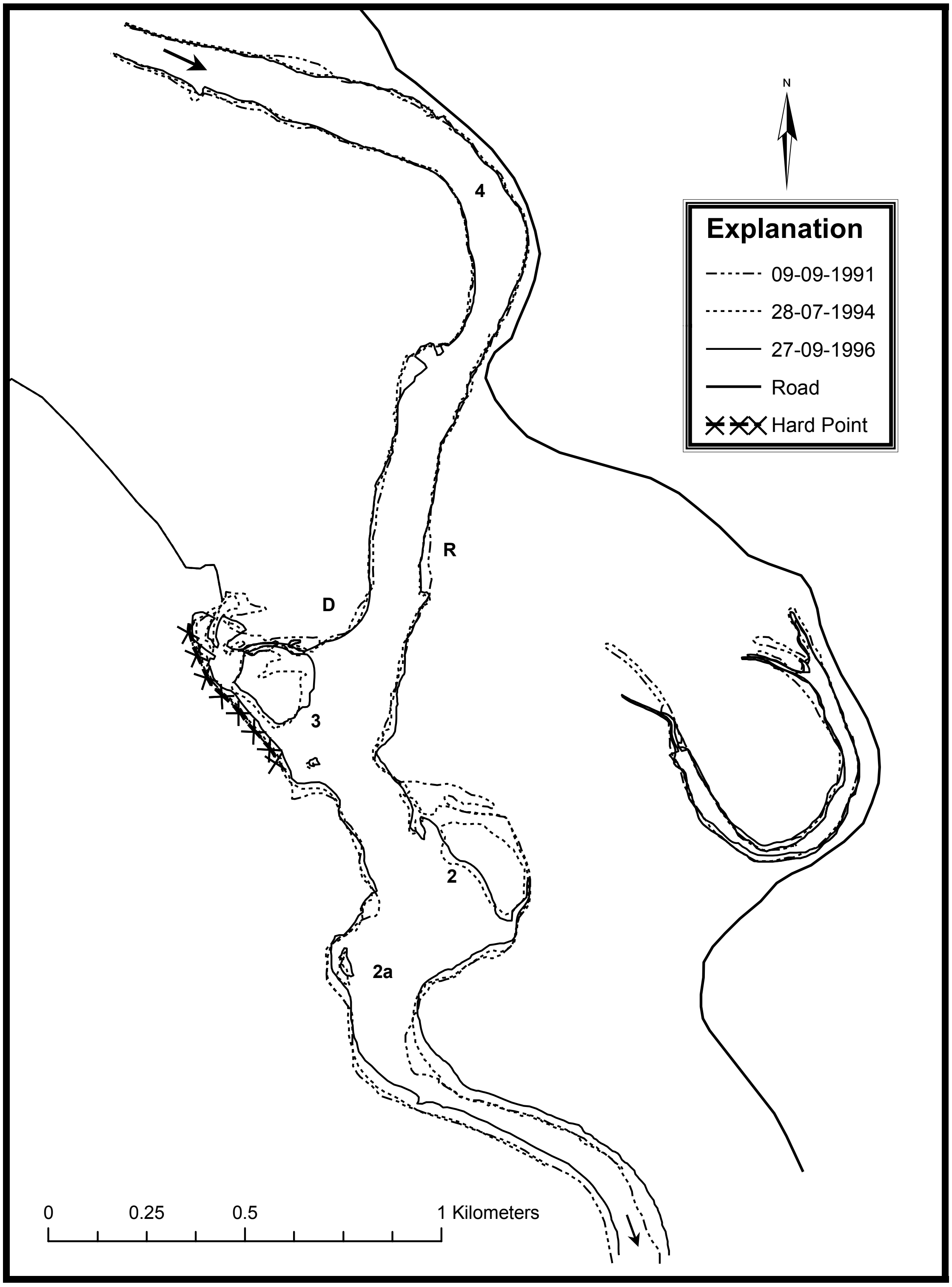


Figure 32: Channel changes in Lower Meandering Reach, 1991-1996.

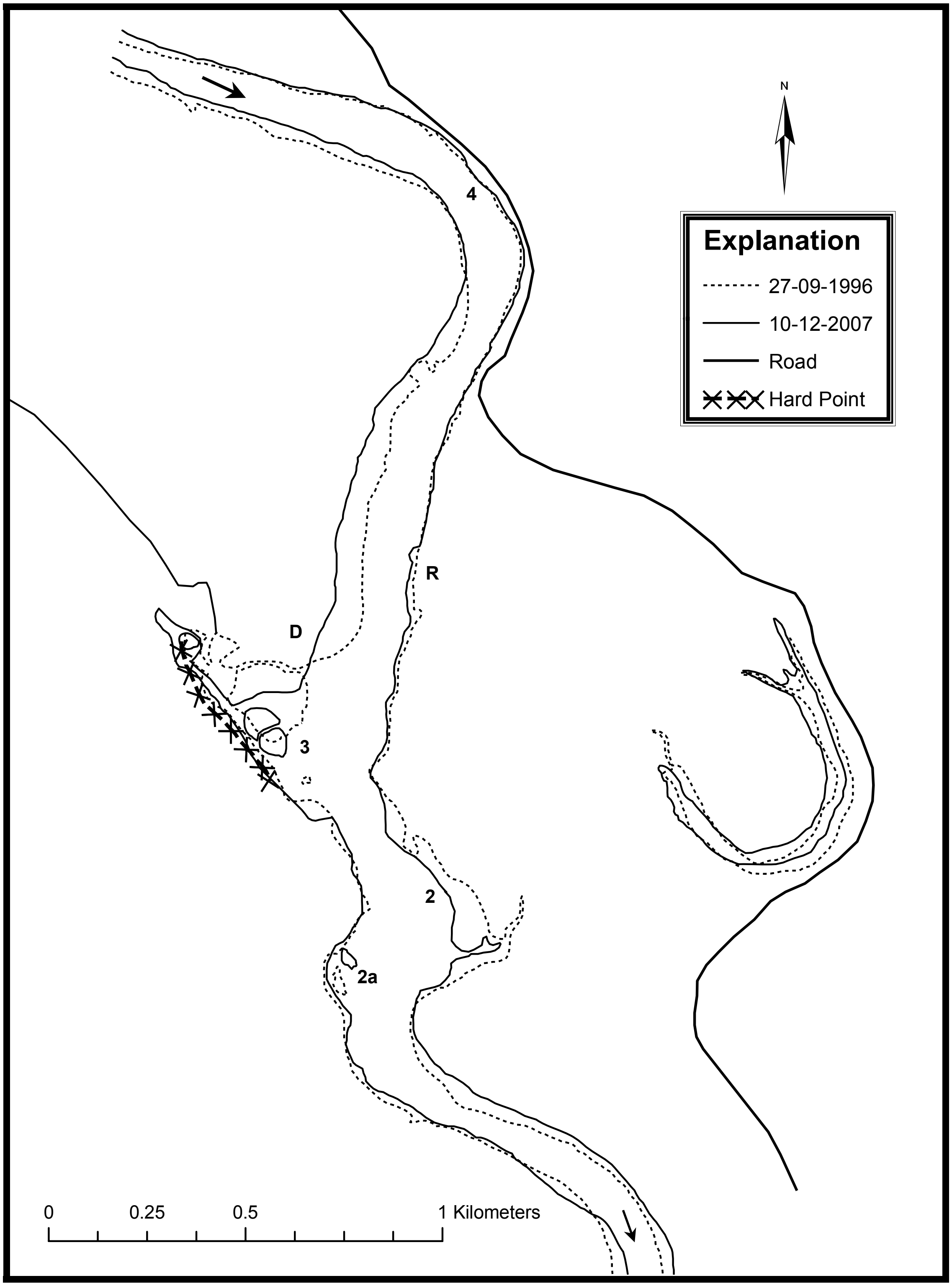


Figure 33: Channel changes in Lower Meandering Reach, 1996-2007.

5.1.2b Effect of the 1990/1991 Extreme Floods on the Lower Meandering Reach (Reach B)

The 1990/1991 floods had a dramatic effect on the straightening the Lower Meandering Reach, primarily in Bends 2, 2a, and 3 (Figure 31). Bend 4 remained stationary, presumably because of the bank protection offered by the training structure on the concave bank.

Sichingabula (1986) noted that, due to the existence of a hard point, downstream migration of Bend 3 has been halted as the meander remains ‘hung up’. Thus the convex (inner) bank of Bend 2 is exposed to direct attack by the river. This bank attack appears to be accelerated during large floods. The convex bank of Bend 2 retreated 132 m at its maximum and destroyed 2.94 $x10^4$ m^2 of floodplain. The magnitude of change experienced during the 1990/1991 flood in the convex bank of Bend 2 is comparable to that of 1984 in which 75 m of bank retreat and 1.7 $x10^4$ m^2 of bank destruction occurred (Sichingabula 1986). The straightening of Bend 2 coincidently focused the river’s attack on the upstream concave bank of Bend 2a. Further downstream, the convex bank of Bend 2a experienced the greatest change in terms of bank retreat, 179 m at its maximum, and areal destruction of 2.94 $x10^4$ m^2. Further yet downstream the un-named section of channel below Bend 2a migrated downstream following the 1990/1991 floods. The southern bank was displaced 43 m with concomitant deposition of 28 m on the northern bank.

Overall it appears that channel straightening in Reach B is operating as a feedback mechanism that progresses in a downstream direction. The encounter between the downstream migration of Bend 3 and the hard point, rather than hydrologic conditions, appears to be the dominant control. Although significant channel straightening continues on the convex bank of Bend 3, since the 1984 extreme flood and on Bends 2 and 2a following the 1990/1991 extreme floods, other extreme floods have produced little change in these bends. To summarize, the largest changes in Lower Meandering Reach are associated with the passage of extreme floods but not all extreme floods produce large changes. If the observed pattern of convex bank destruction leading to subsequent river attack on the convex bank of the meander located directly downstream persists, then it is likely that the bend below Bend 2a is the next target of river attack.

If extreme floods do not initiate the straightening process then a more pertinent question may be, “What control do extreme floods impose on channel sinuosity?” Although this question deserves more time than I can provide, within my analysis there is no evidence to suggest that the straightening process active from 1984-2007 is going to reverse in the near future. This leads me to conclude that extreme floods help preserve the straightened course of Squamish River by mobilizing any accumulations of in-channel sediment before they can be colonized and stabilized by vegetation.

The southern channel boundary below Bend 2a thus is likely a further illustration of this erosional feedback mechanism, in this case set in motion by Bend 3 being ‘hung up’ on the hard point of the western channel bank.

5.1.3a Upper Meandering Reach (Reach C)

The most dramatic channel change to Reach C in the years 1984-2007 is the cut-off of Bend 7 whose concave bank had previously been retreating for approximately 50-years (Sichingabula 1986). Straightening of the channel by erosion of the western edge of Island E and of Point J (convex bank) from 1984-1990 (Figure 34) likely decreased the amount of flow around the island, through Bend 7. The reduced volume of flow around the island would decrease the competence of the flow (all other flow variables considered constant) and would lead to deposition of suspended material within the bend. Extension of the eastern bank of Island (E) by 160 m at its maximum between 1984-1990 supports this notion. By 1994 Bend 7 had completely cut itself off from the main body of flow. A back channel persisted in the downstream portion of the concave bend but by 1996 this too had infilled. The cut-off most likely would have occurred earlier had it not been for the 1990/1991 extreme floods that, due to their large transport capacity, probably prevented further deposition and stabilization by vegetation growth within the bend. The straightening of Squamish River through Bend 7 seems to have initiated meander growth in Bend 6 by directing erosion downstream at the concave bank.

It is difficult to determine if Bend 8, further upstream, will behave in the same fashion as its downstream counterparts. There is some indication that Squamish River will straighten through Bend 8 in the near future (20-30 years?). Extensive erosion of the head of Island (F; maximum of 225 m from 1984-2007) and of the western channel bank just upstream of the entrance to the back channel (maximum of 150 m from 1996-2007), in conjunction with deposition on the northern bank of the river adjacent to the entrance of the back channel (Bank F8; maximum of 143 m from 1996-2007) have acted together to change the flow trajectory so that a greater proportion of flow is being carried through the back channel. Should this back channel develop into the main channel, it would be a more direct flow route than around Island F.

However, the behaviour of the concave bank of Bend 8 is contrary to the straightening trend. Although the width of the back channel mouth has generally increased over time, seemingly to accommodate a larger proportion of flow past Bend 8, the concave bank is still retreating (eastward). These observations suggest the whole of the bend is undergoing some sort of re-adjustment rather than changes being confined to the back channel.

Meander growth in Bend 8 follows a rather orderly pattern. The focus of meander growth (extension) has translated along the perimeter of the concave bank in a downstream direction. Initial extension (1984-1991) (Figures 34-35) occurred at the apex of the bend. For the next six years (1991-1996) (Figure 36) the maximum bend extension was just downstream of the apex and from 1996-2007 (Figure 37) the point of maximum growth moved to the downstream bank of the bend. This non-continuous pattern of meander growth in Bend 8 was also noted by Sichingabula (1986; Figures 4.8 and 4.9) and differs from the more symmetric, uniform pattern of meander growth observed in Bend 7 (1947-1984). This may be related to the orientation of Squamish River relative to the entrance of the meander. All the recent activity (1996-2007) is probably related to the point bar growth at Bank F8 which has shifted the flow toward the southern bank.

Bend 8 is the only bend in Upper Meandering Reach that is in an apparent state of growth although Bend 6 currently is translating downstream. After a period of initial growth to the northeast (1984-1991) erosion in Bend 6 has been focused in a downstream direction at rates ranging from 4-17 m/yr. Bend 5, located immediately downstream of Bend 6, has remained approximately fixed over the entire period of record, a result of bank training associated with road construction along the concave bank. If Bend 6 continues to migrate downstream, it will cause over-tightening of Bend 5.

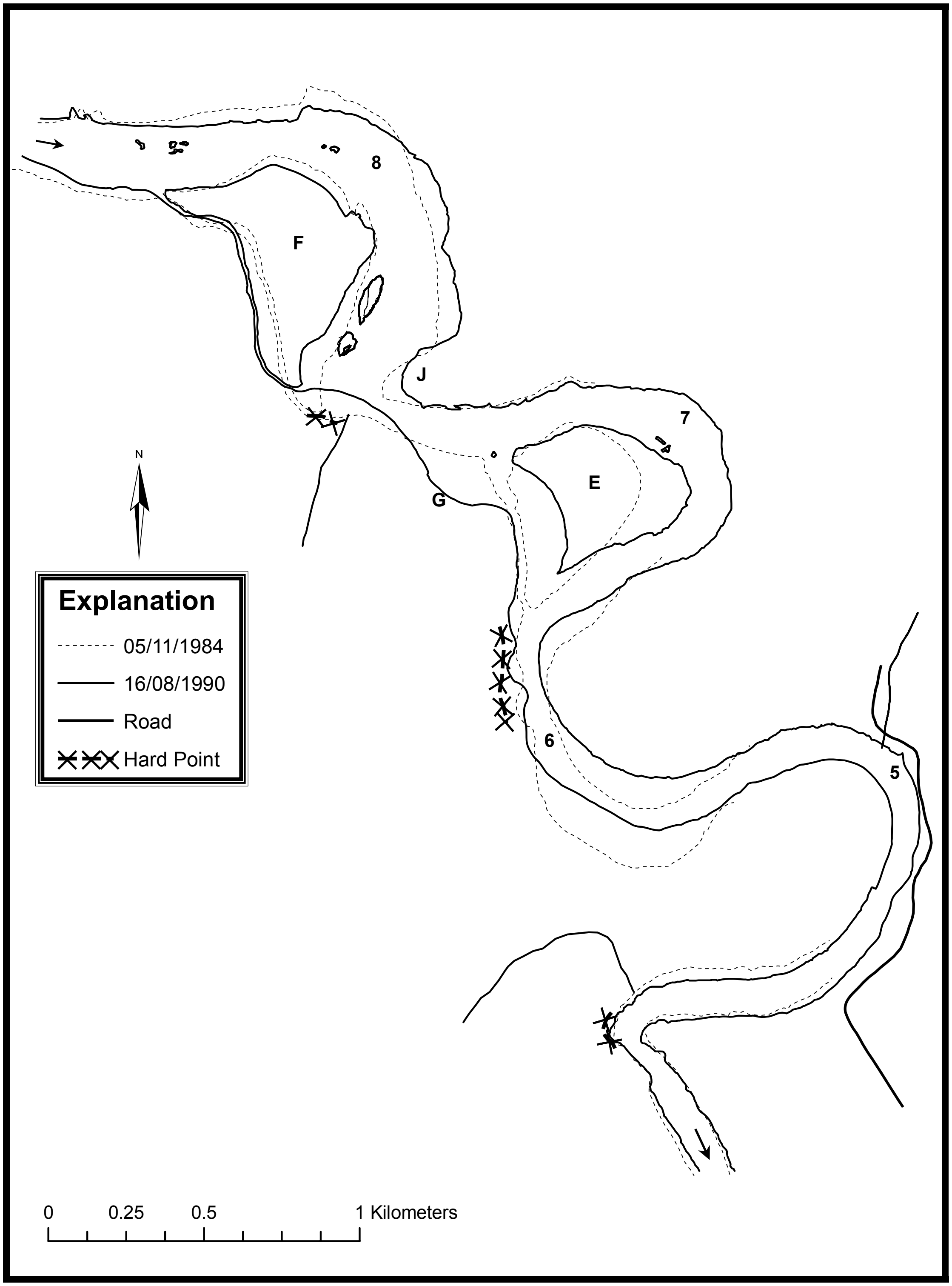


Figure 34: Channel changes in Upper Meandering Reach, 1984-1990.

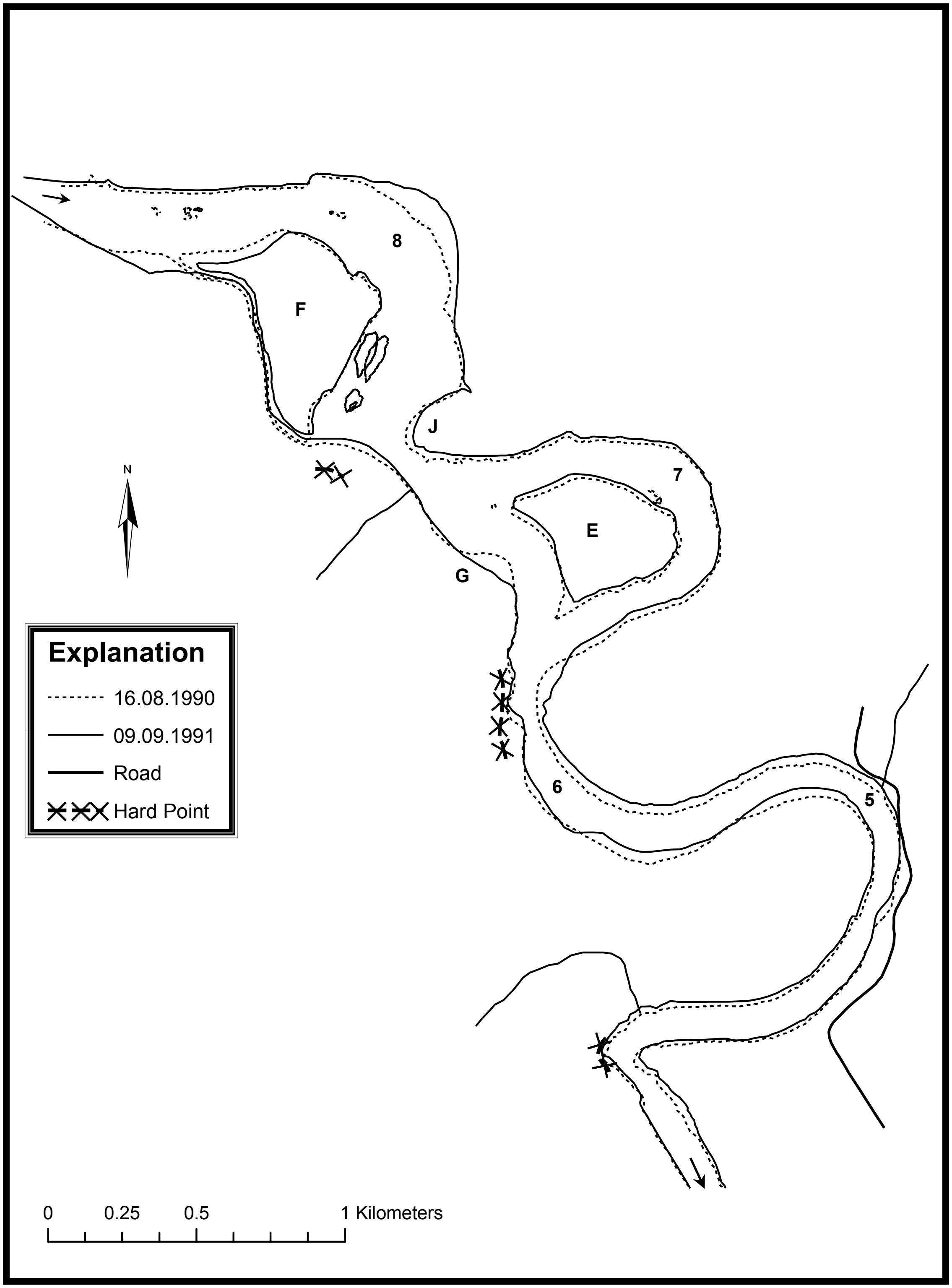


Figure 35: Channel changes in Upper Meandering Reach, 1990-1991.

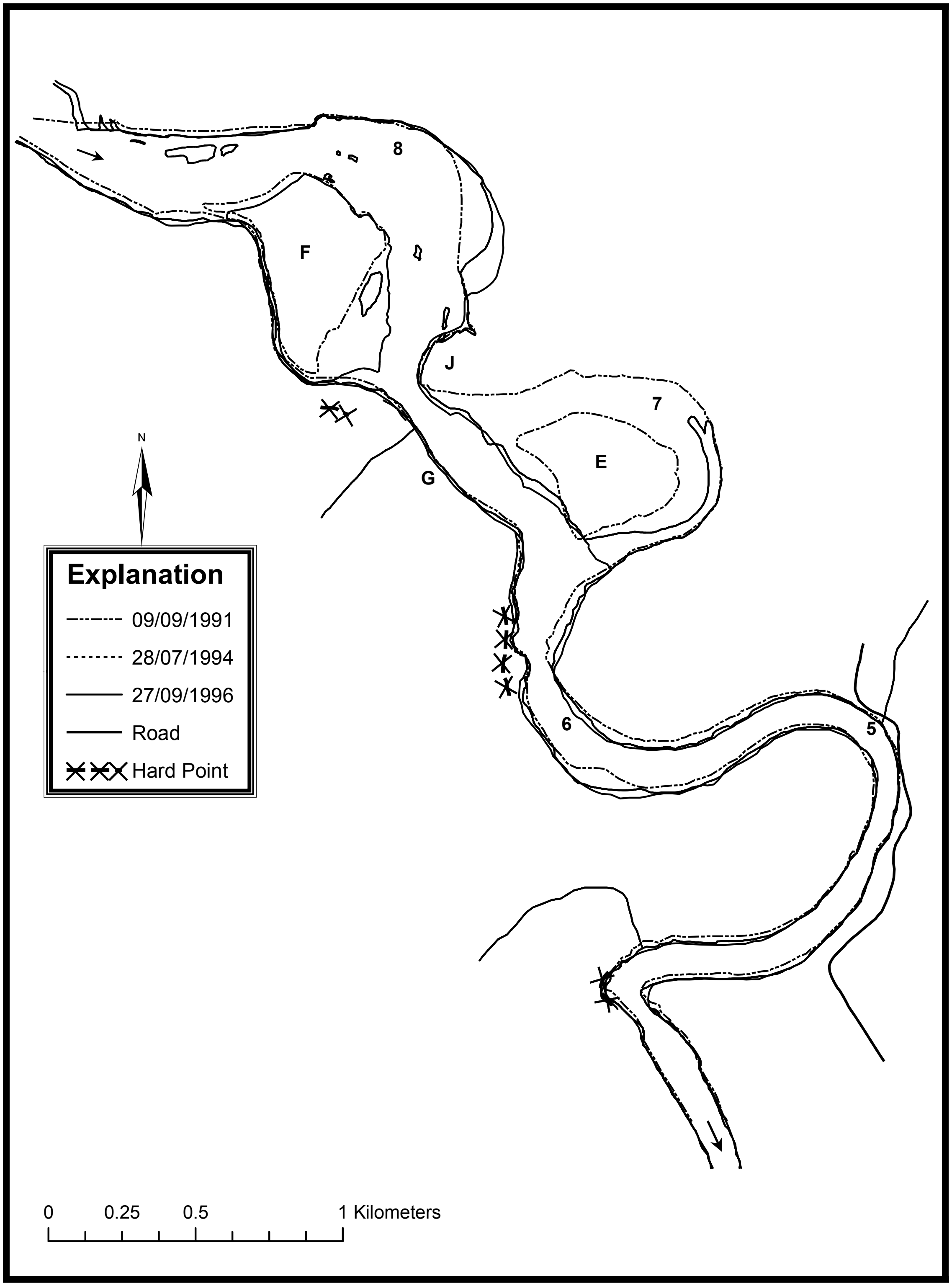


Figure 36: Channel changes in Upper Meandering Reach, 1991-1996.

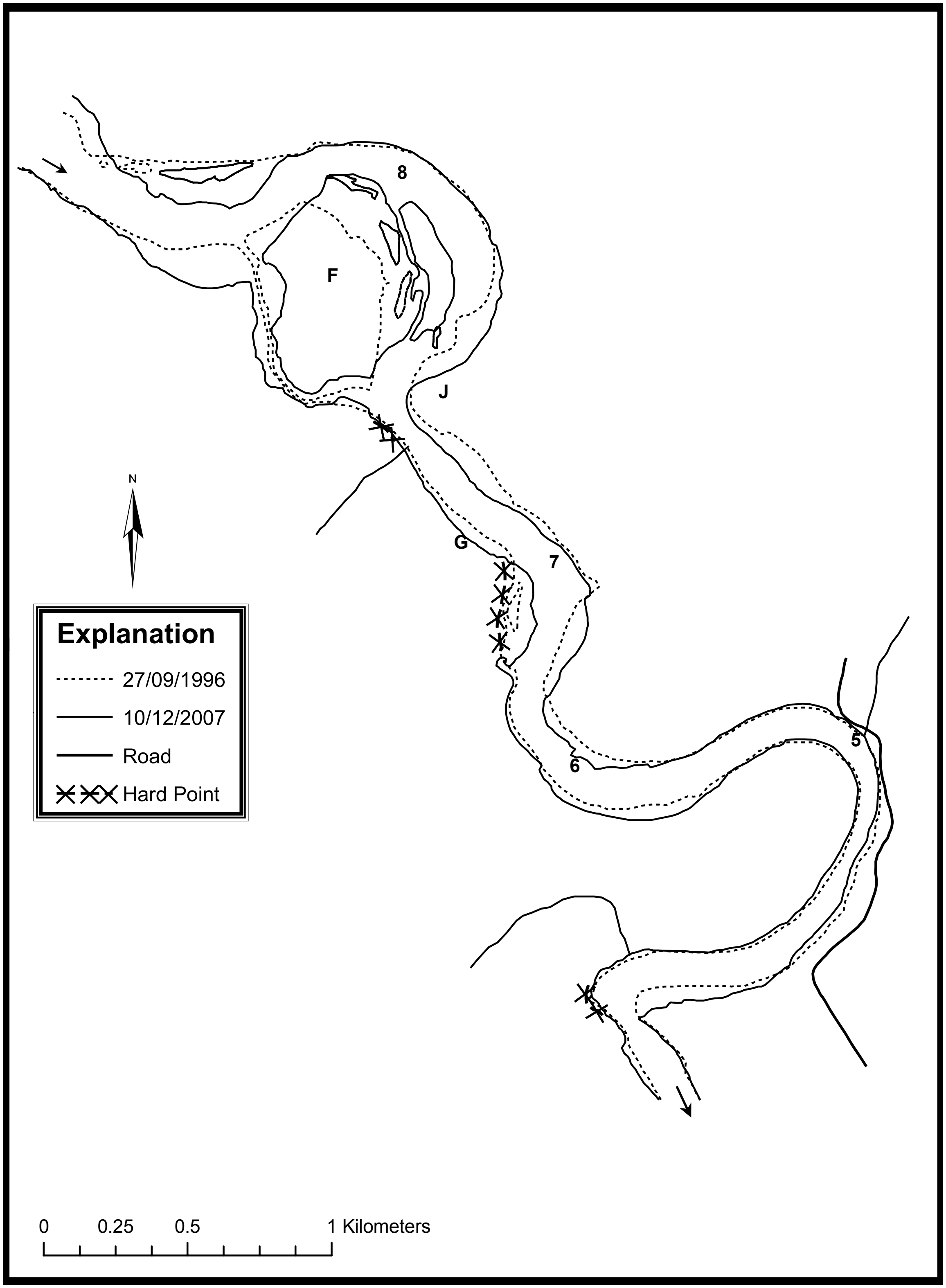


Figure 37: Channel changes in Upper Meandering Reach, 1996-2007.

5.1.3b Effect of the 1990/1991 Extreme Floods on Upper Meandering Reach

In comparison with Reaches A and B, the Upper Meandering Reach experienced little geomorphic change in response to the extreme floods (Figure 35). The most intense change to channel banks occurred in the concave bank of Bend 8 where a maximum of 94 m of bank were eroded.

The significant straightening characterizing Reach B was not documented in Reach C, which is surprising since the two reaches adjoin each other. Moreover, the islands of Reach C experienced only minor change in contrast to those in Reach B. Island (E) migrated upstream on the order of 20 m. The western and northwestern margins of Island (F) were eroded a maximum of 65 m near the entry to the back channel. Overall the net change in area to the Island (F) group of 2.5 $x10^4$ m^2 is relatively minor. Although erosion to convex banks is not observed in Upper Meandering Reach, systematic erosion is observed on protruding channel-banks near the entrance to the Island (F) back channel and on the western bank opposite Island (E), together acting to ‘smooth’ out local channel irregularities. The extreme floods also produced a systematic bank translation of approximately 32 m from the apex of Bend 5 to the apex of Bend 6.

Similarly, the 1984 extreme flood accomplished minimal change to Upper Meandering Reach: slight bank erosion to concave banks (Bends 5, 7 and 8) and convex bank (Bend 6) and erosion to the head of Island (E). The most noticeable change to the reach following the 1984 flood is the development of a back channel to the east of Point J which acts as a flow conduit between the concave banks of Bends 7 and 8.

5.1.4a Squamish-Ashlu Bend Reach (Reach D)

Throughout the study period (1984-2007) the only consistent channel change in Reach D is erosion of the western bank above the Ashlu-Squamish confluence (Bank K1). Although bank retreat has been consistent over all study periods, the greatest erosion coincides with periods of extreme floods (1990-1991; 1996-2007). In all, the bank has retreated approximately 450 m at its maximum over the 24-year period with the most extensive bank retreat occurring in the 1996-2007 period.

Like Bend 8 in Reach C, the focus of maximum retreat here has translated downstream with respect to time. From 1984-1991 (Figures 38-39) the focus was located cross-stream from the medial point of Island (K). From 1991-2007 it had shifted downstream closer to the mouth of the Ashlu River (Figures 40-41).

Continuous erosion at this point on the western bank of Squamish River has been documented since 1947 (Sichingabula 1986). He noted that bank erosion at this location is a response to the growth of Island (K) in a cross-stream direction which caused Squamish River to increase channel width. This observation is in general agreement with my analysis of channel change along Bank K1. The only exception is the 1990-1991 period in which proportionally larger erosion in relation to the deposition on the stream-wise edge of Island (K) is observed. Similar circumstances were observed on the Beatton River by Nanson and Hickin (1984) who found that the resultant channel widening lead to a decrease in subsequent channel migration rates.

Following 1991, the configuration of islands located south of the confluence noticeably changed. By 1994 erosion to the head of Island (I) initiated the development of a medial channel that divided Island (I) into two smaller, unequally sized islands. In the following study period, the smaller of the two islands was sub-divided. Intense erosion along the margins of the medial channels expanded the conduit further from 1996-2007.

When the geomorphic record of Reach D is analyzed in its entirety, the post-1991 changes to Island (H) give the impression that the channel is straightening. As in the Lower Meandering Reach, channel straightening has not been initiated by an extreme flood but is a product of an incremental history. Island (H) is a remnant of extensive and prolonged erosion (1947-1984) to the convex bank of the Ashlu-Bend. The pattern of convex bank erosion excavated the island so that it was positioned transverse to the dominant flow direction, a characteristic not shared by any other island in the reach. Since its creation the river has attempted to create an avulsion channel across the B-axis (north-south axis) of Island (I) which was accomplished by 1994. Although a medial channel previously existed, the river was ineffective in removing a large log-jam at its mouth. So channel straightening may be linked to, but is not caused by, extreme floods. Rather, the inherent nature of the wandering gravel-bed reach in Squamish River is to achieve a streamlined morphology by aligning channel islands parallel to the dominate flow direction. The activity of the H2 island group appears to support this interpretation. From 1996-2007 (Figure 41), after the subdivision of Island (I), the islands coalesced, vegetation established and spread upstream parallel to flow in a curvilinear fashion about Ashlu Bend. The majority of the material on which vegetation established itself is a large sheet of gravel deposited following the 1990/1991 extreme floods that connected the H2 island group with the western boundary of Island (I) (not shown on Figure 39). As a result of these changes the majority of flow either travels around the concave bank or through the more direct medial channel bisecting Island (I). The change in flow pattern as a result of the re-organization of islands located below the confluence had little impact on migration rates of Ashlu Bend itself.

This is due to the fact that migration of Ashlu Bend is highly dependent on the rate of sediment delivery from three tributaries that terminate within Ashlu Bend. Erosion or stabilization of their alluvial fans through vegetation growth can result in rapid fluctuations in the position of the concave bank boundary, as can be seen from Figures 38 and 40. The delivery of sediment to the channel may have promoted or initiated infilling of the Island (G) back channel. The island accreted to the floodplain by 1990 where it has remained until the end of the photographic record. The influence of alluvial fans on providing island stability to newly accreted islands is also noted by Sichingabula (1986).

Other common channel changes in Reach D are island formation/growth and island destruction/erosion. The growth behaviour of islands can often be erratic and exhibits no obvious direct relation to general flow characteristics. For example, Island (J) has experienced periods of growth, retreat, division and re-growth over the last 24 years. In this case, extreme flood periods were responsible for both minor erosion and major deposition. The cause of the abrupt appearance of islands at the Ashlu mouth remains unknown. However, it may be related to debris flows originating within the Ashlu River valley. The sporadic nature of debris flows could account for the sudden appearance of islands following an absence at the mouth of the Ashlu for approximately 53 years. The movement of debris material to the alluvial fan could have provided enough material for vegetation to establish above the bankfull river stage. The stability of the islands after 1990 may be due to the inability of Squamish River to access the material due to the protection offered by the southern limit of Bank K1. The exposure of the islands following the rapid bank retreat between 1996-2007 likely will result in significant erosion of it in the near future.

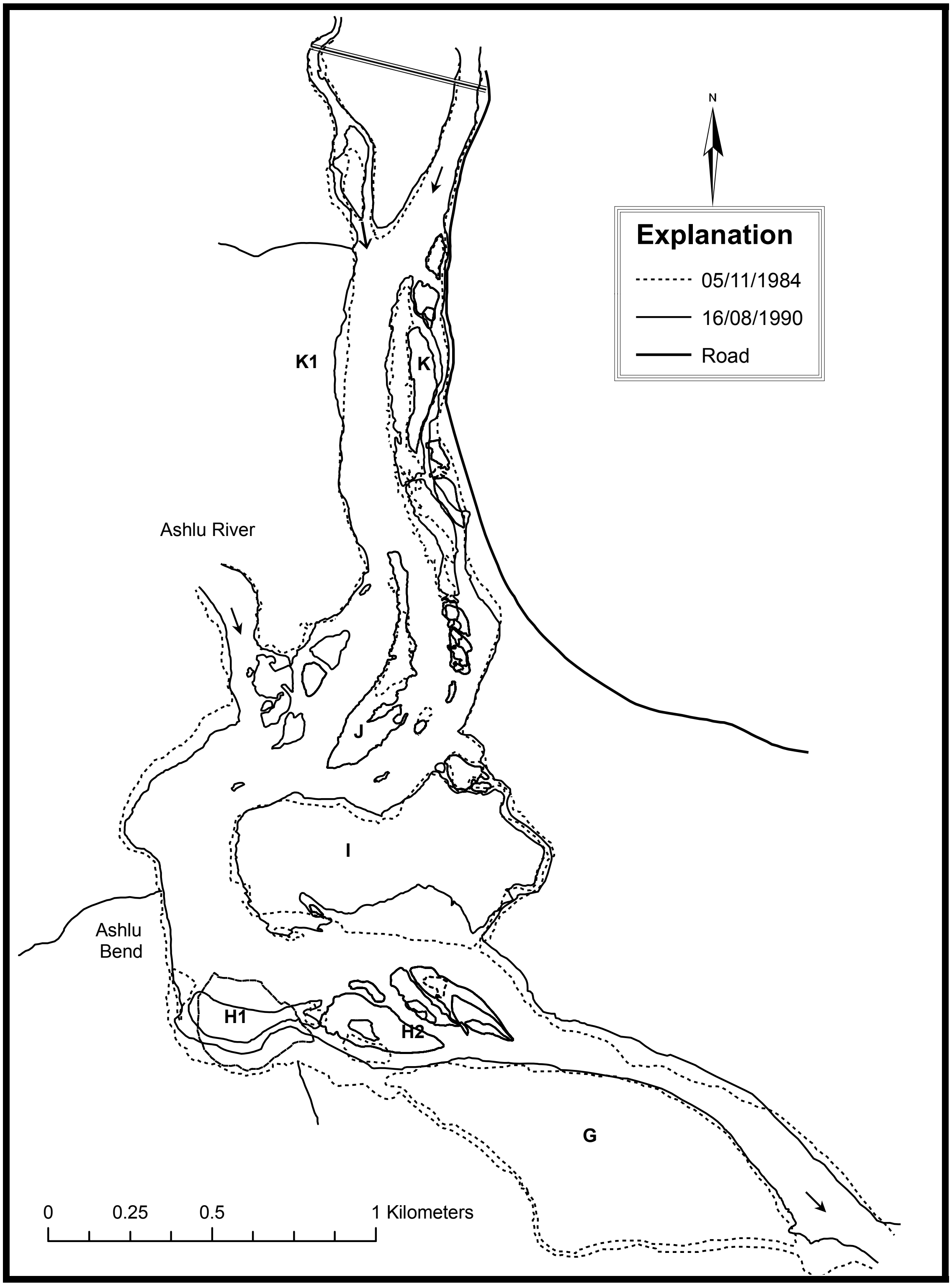


Figure 38: Channel changes in Squamish-Ashlu bend reach, 1984-1990.

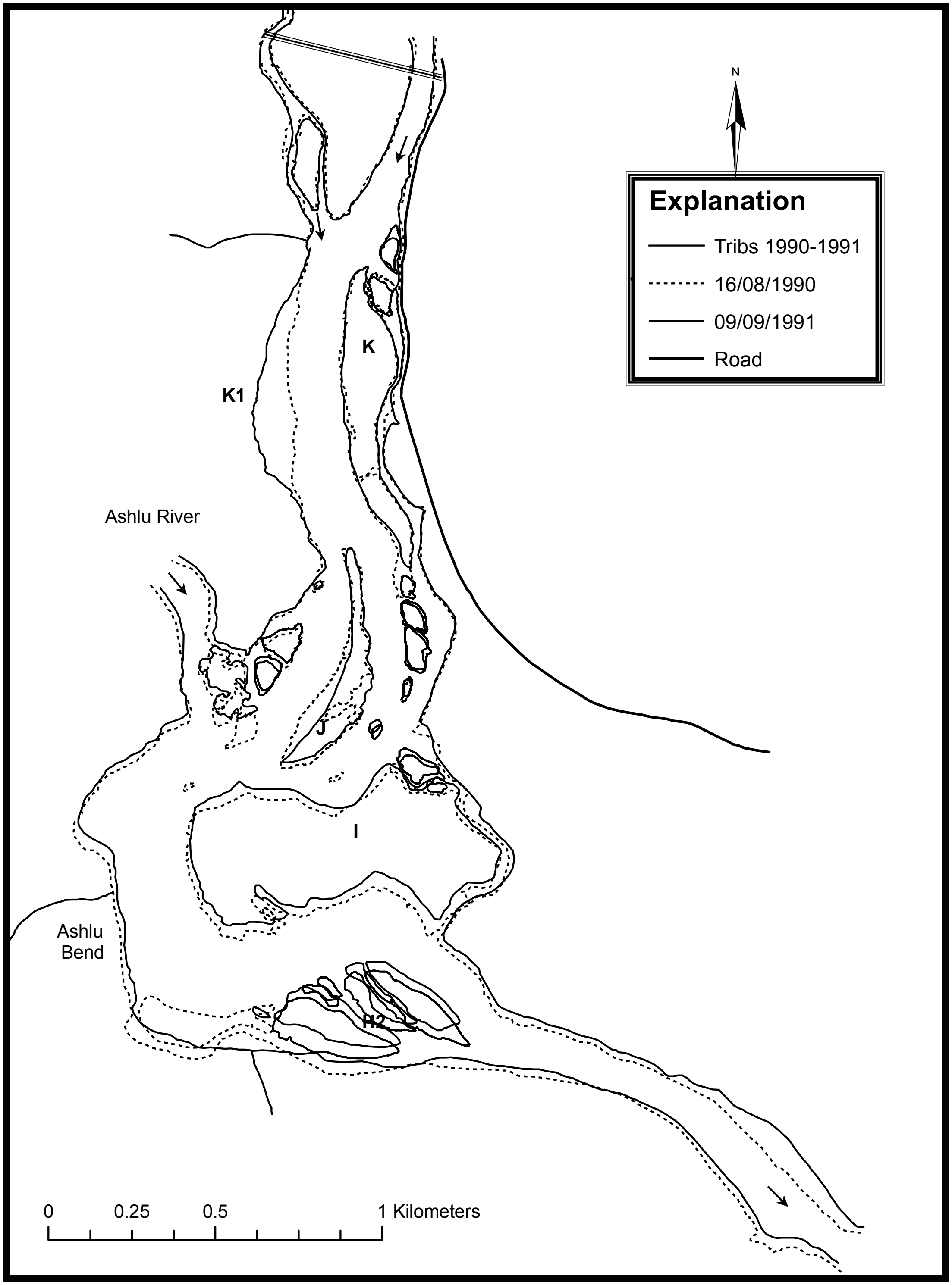


Figure 39: Channel changes in Squamish-Ashlu bend reach, 1990-1991.

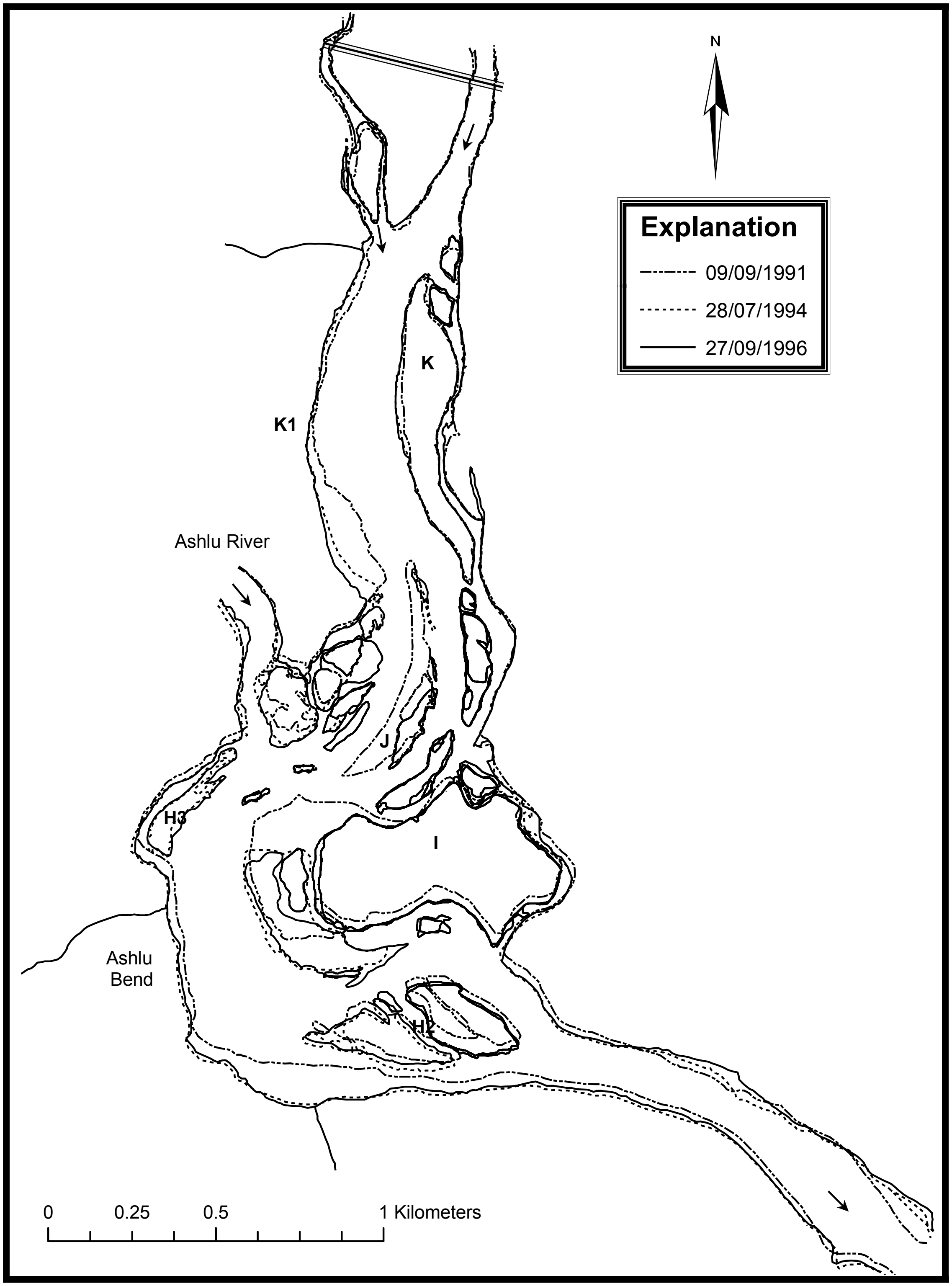


Figure 40: Channel changes in Squamish-Ashlu bend reach, 1991-1996.

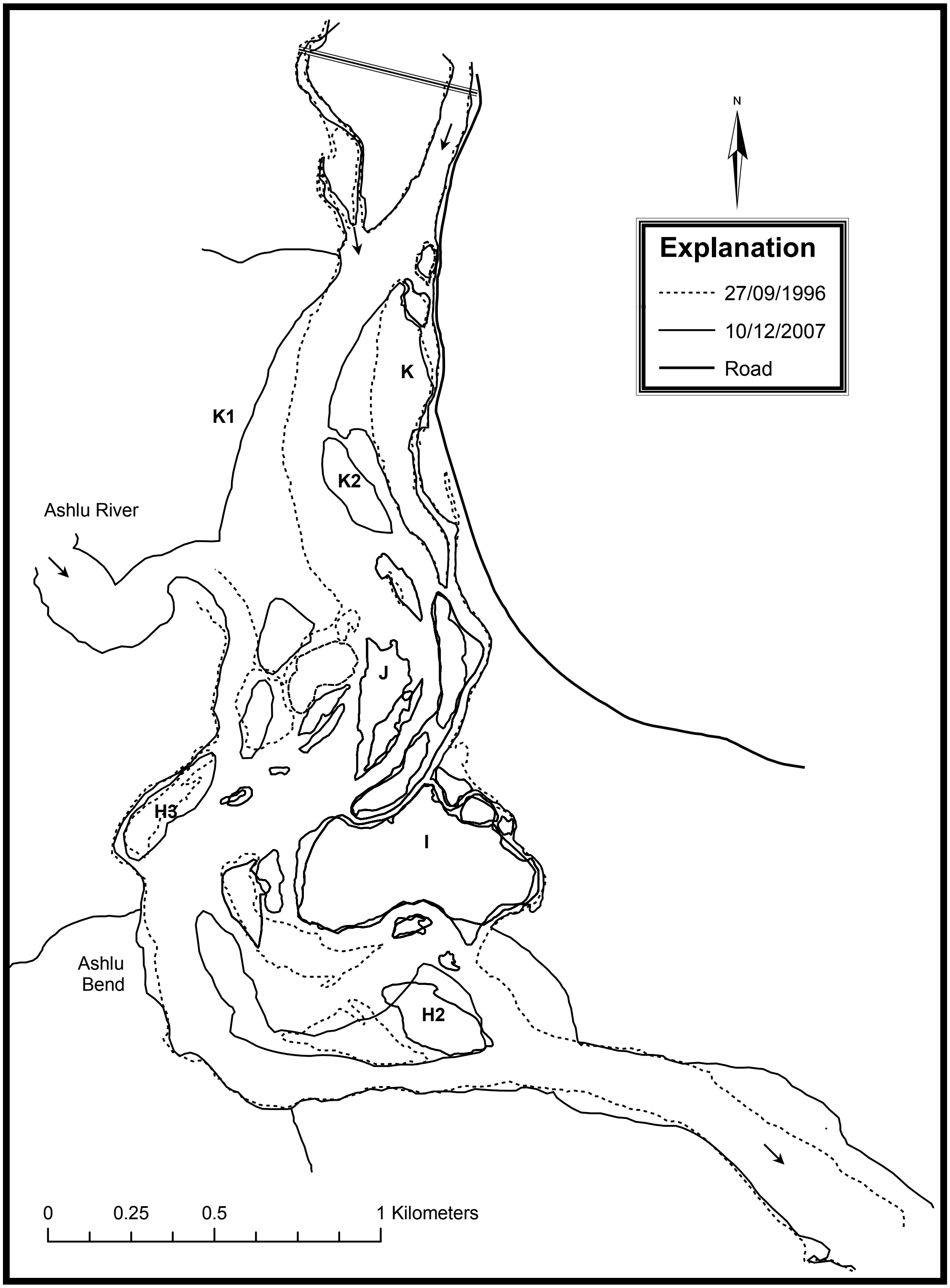


Figure 41: Channel changes in Squamish-Ashlu bend reach, 1996-2007.

5.1.4b Effects of the 1990/1991 Extreme Floods on Ashlu-Bend (Reach D)

The channel changes resulting from the 1990/1991 extreme floods are complex. For example, massive bank erosion occurred on the western bank upstream of the confluence in which 4.38 $x10^4$ m^2 of floodplain surface area were removed and maximum bank retreat was 130 m. However, approximately 400 m downstream of the Ashlu-Squamish confluence a near-continuous 20 m-wide band of deposition extended the concave bank of Ashlu Bend.

The response of islands to the extreme floods is more uniform than channel banks but can be divided into two groups based on their relative position to the Ashlu-Squamish confluence. The majority of the islands located upstream of the confluence (J, J2 and K) underwent extension or coalescence, while the islands located south of the confluence predominantly experienced migration, either upstream (Island I) or towards the southern bank (Island H2 group). The only exception is the destruction of Island (H1) (3.08 $x10^4$ m^2) located near the concave bank of Ashlu bend.

The only significant geomorphic change that resulted from the 1984 flood is the erosion of 1.1 $x10^4$ m^2 from Island J, although the flood did knock down the bridge that crosses Squamish River in the north of the reach. Extreme floods in 1980 and 1981 also had little impact on Reach D (Sichingabula 1986).

5.1.5a Braided Reach (Reach E)

Since no photographic coverage of Braided Reach is available for 1990, the impacts of the 1990/1991 extreme floods cannot be directly identified. Instead the channel change record of Braided Reach is discussed as a whole.

Although Braided Reach has experienced island formation and destruction, bank retreat, bank extension and channel abandonment from 1984-1996 (Figures 42-44) the degree of channel changes is relatively minor in comparison with the previous four reaches.

The largest change to the reach occurred during the years 1984-1991. The channel retreated a maximum of 152 m and 19.2 $x10^4$ m^2 of material was eroded from Bank (M1) (Figure 42). It is assumed that this change was achieved by the 1990 and 1991 extreme floods, however, due to the lack of photographic coverage in 1990 this is speculation based upon Sichingabula's (1986) observations. He found that the processes of island destruction and bank erosion were associated with periods characterized by a high frequency of extreme floods (1980-1984). In contrast, while processes such as floodplain construction, channel abandonment, stabilization of gravel bars and alluvial fan deposits by vegetation, are associated with periods characterized by a low frequency of extreme floods (1969-1980). Therefore, the 1990 and 1991 extreme floods, the latter of which is comparable in magnitude (2020 m^3/s) to the largest flood that occurred between 1980-1984, are the likely cause of the majority of the erosive change seen in Figure 42.

Extreme floods have occurred in the low-activity period (1969-1980) but did not result in significant channel change. Sichingabula suggests that this is the result of one of two processes. Either the photographic period is too long to distinguish potential changes, or these floods are simply not overtopping the banks. The maximum mean-daily discharge registered for any extreme flood during this period is 1800 m^3/s. A flood of this magnitude would surely overtop banks of any of the four other study reaches. However, the large channel width of Braided Reach, as well as its comparably smaller catchment can effectively carry these large discharges within the channel banks. If it is assumed that bankfull discharge is achieved at some value between the largest flood of the low-activity period and the smallest flood of the high-activity period. Flow data from the Brackendale gauging station located approximately 45 km downstream, suggests that the bankfull discharge of Braided Reach is between 1800 and 2020 m^3/s. That is, the minimum discharge at which significant change will likely occur in Braided Reach lies between these two values.

The largest flood, (Oct 1984 mean daily discharge 2150 m^3/s) of the high-activity period of the early 1980's produced the most dramatic channel changes. Hickin and Sichingabula (1988) observed that a drastic shift in channel planform occurred in the northeastern section of the reach. Reactivation of old channels created islands that were part of the floodplain from 1947-1984 and shifted the predominantly single channel reach prior to 1984 into a system dominated by two channels. Erosion of the eastern bank was severe enough to demolish approximately 1 km of adjacent gravel road. From 1947-1996, this remains the only flood event to produce a major channel change in Reach E. Unfortunately, the impact of the flood of record in 2003 (mean daily discharge 2630 m^3/s; maximum instantaneous discharge 3140 m^3/s), whose mean daily discharge is 480 m^3/s greater than the extreme flood of 1984, cannot be analyzed due to absence of photographic coverage. Recently (1996) the reactivated channels have started infilling.

Based on the photographic information available, extreme floods (1968, 1969, 1975 and 1991) have the ability to change the morphology of Braided Reach, drastically at times, but once the change occurs, periods with a low frequency of extreme floods do very little to alter the resultant flow configurations. That is, periods of lower-than-average flood magnitude, more or less, maintain the new channel morphology.

This pattern of stability reflects the fact that extreme floods are the only mechanism that can effectively transport the bed-calibre materials as well as promote floodplain dissection via channel avulsions.

The majority of large clasts supplied to Braided Reach originate from alluvial fans that line the steep valley slopes adjacent to Squamish River and from mass movements such as the 1963 Dusty Creek debris flow that originated from Mt. Cayley (Clague and Souther 1982). Sichingabula attributed the high degree of braiding in this reach to the large influx of bed-calibre material from Dusty Creek debris flow.

Cruden and Yu (1988) suggested that one such debris flow which was not mentioned in Hickin and Sichingabula (1988), was the actual cause of the dramatic change in channel planform. The 3 Mt of sediment deposited in Squamish River from the Turbid Creek debris flow located upstream of the area of “massive organization” was said to only be redistributed by the extreme flood not the mechanism of change itself. However, Hickin and Sichingabula (1989) noted that Cruden and Yu failed to recognize that the earlier of the two sets of 1984 photographs were taken in September, after the debris flow (June) but before the extreme flood (October). These photos show no major channel alignment in Braided Reach following the debris flow. Thus, Hickin and Sichingabula argue that their original interpretation is valid and that the flood is the primary agent of the major channel reorganization in 1984.

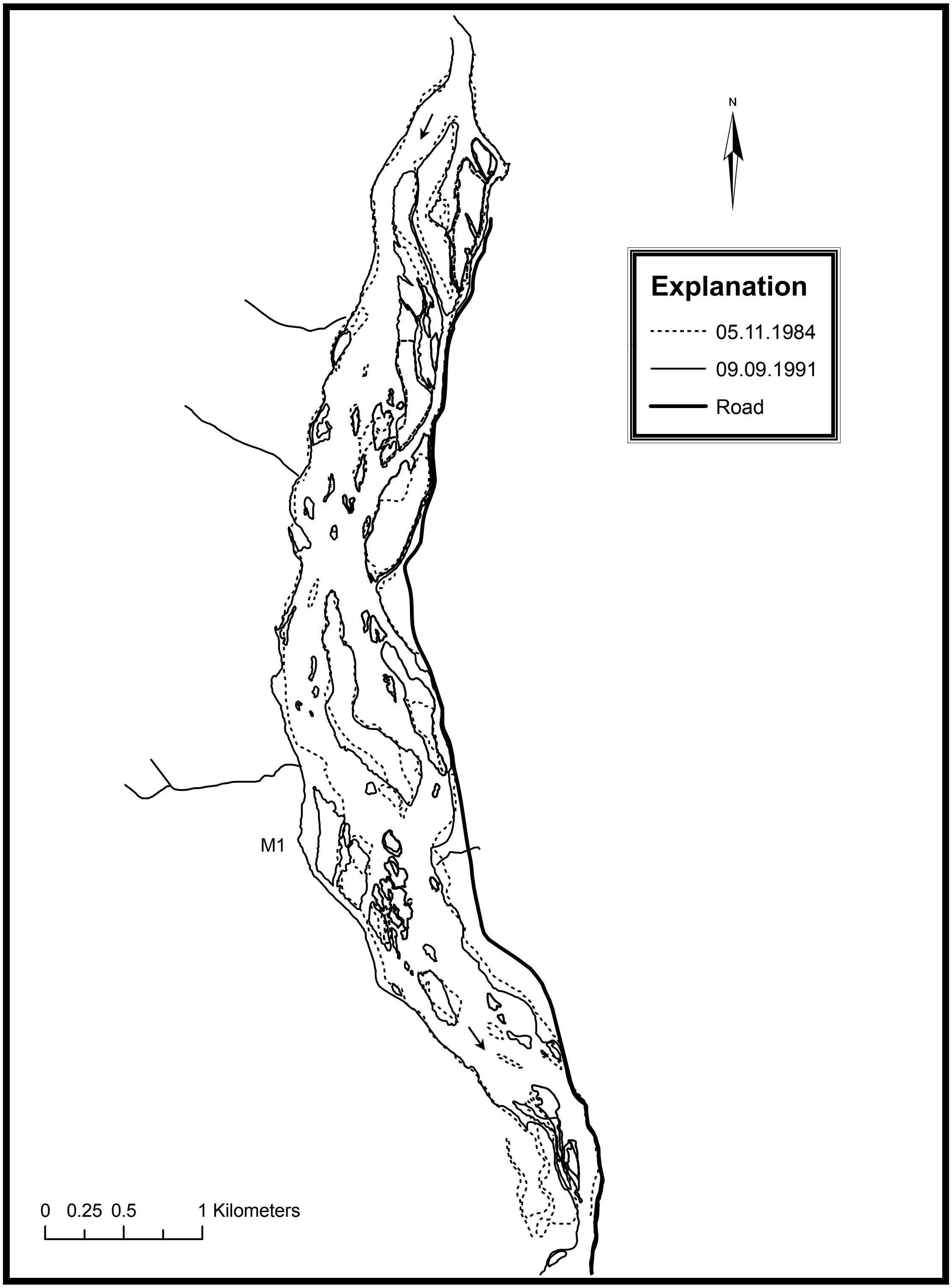


Figure 42: Channel changes to Braided Reach, 1984-1991.

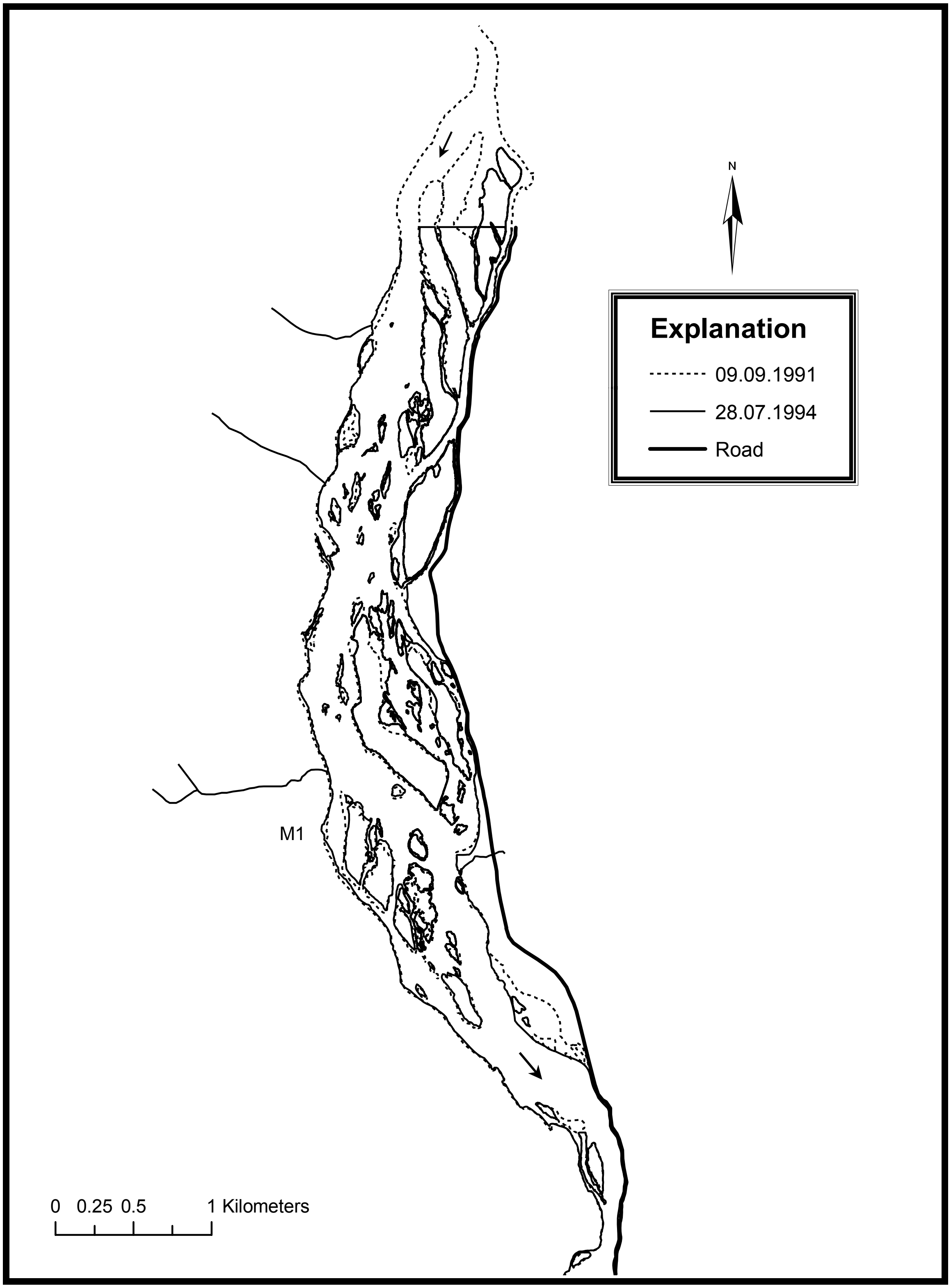


Figure 43: Channel changes to Braided Reach, 1991-1994.

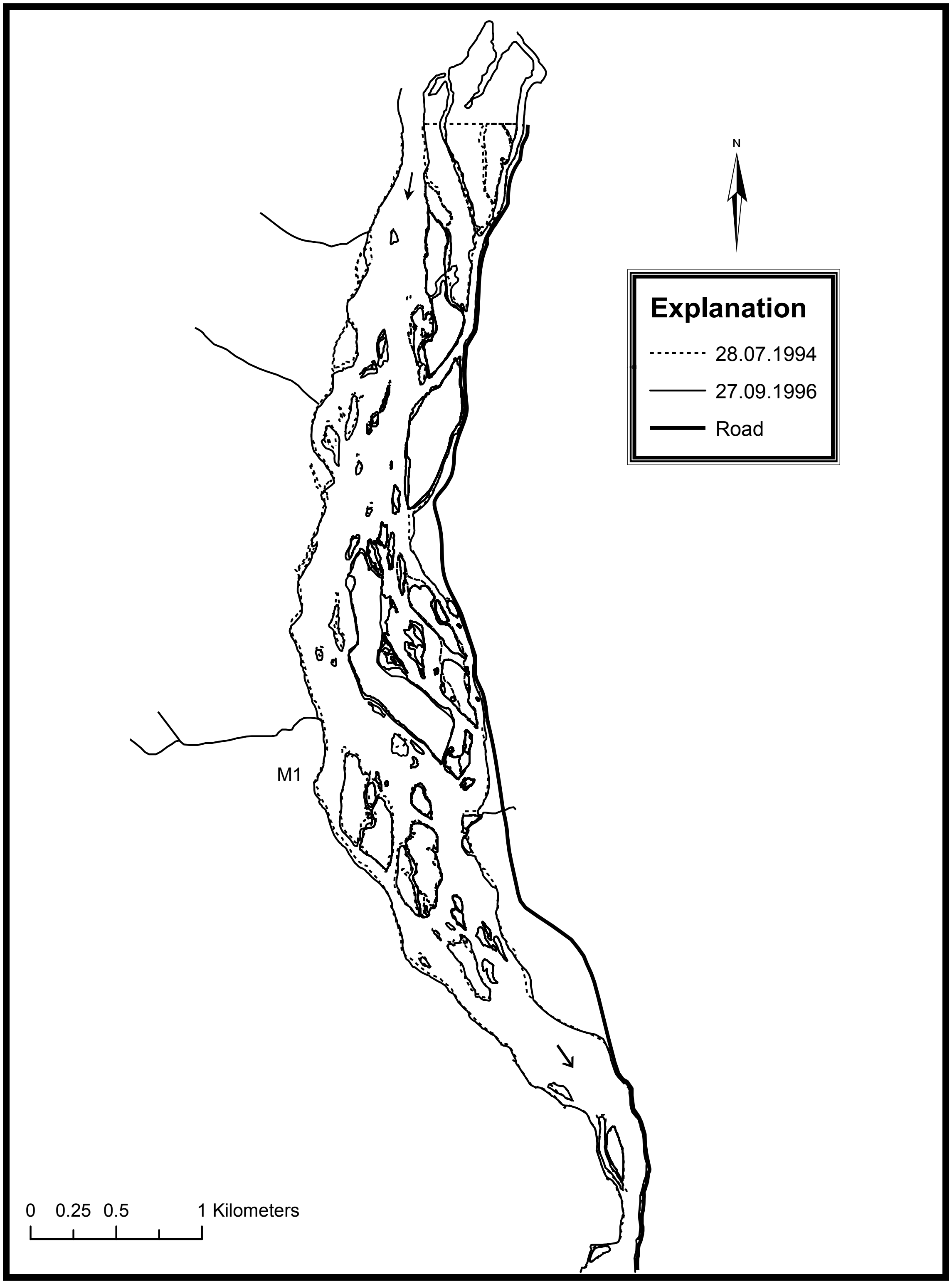


Figure 44: Channel changes to Braided Reach, 1994-1996.

CHAPTER 6: QUANTITATIVE ANALYSIS OF CHANNEL CHANGE

This chapter summarizes the reach-by-reach channel changes from 1984-2007 in quantitative terms, places these changes in the context of the complete period of record (from 1947-2007) and relates individual channel changes to the frequency of discharges.

The main goal of this thesis is to investigate the role of extreme floods in shaping the geomorphology of Squamish River. The main hypotheses, based on intensifying hydrometeorlogic trends is that, from 1984-2007, extreme floods have resulted in more intense and extensive geomorphic changes and exhibit more control on the overall behaviour and alignment of the river channel than in the years 1956-1980.

To test this hypothesis of accelerating channel change, the amount and intensity of geomorphic change is quantitatively expressed as two-dimensional surface-area changes and maximum bank-retreat rates. The distinct and contrasting magnitude/frequency relations exhibited by the study periods of varied length provide a simple basis to assess the geomorphic impacts of floods on Squamish River under a variety of flow conditions. For example, the Aug 1990- Sept 1991 period is relatively short and brackets two extreme floods, while the Jul 1994-Sept 1996 period is also relatively short but brackets no extreme floods. This provides a simple means of isolating the geomorphic effect to

Squamish River of a variety of flow conditions. By averaging the total areal change and maximum bank-retreat values on an annual basis, comparative analysis may reveal that extreme floods have a distinct effect on the channel change on a yearly timescale, that may not be present in periods without an extreme flood(s).

6.1 Floodplain Surface-area Change

Floodplain deposition (FD), floodplain erosion (FE), total change in floodplain surface-area ($\Delta A_1 = |FD| + |FE|$) and net change in floodplain surface-area (ΔA_2 = FD-FE) constitute the variables used to assess channel change. The four variables are presented as cumulative-mass plots organized by reach in Figures 45-48.

The shape of the cumulative mass-plot curves indicate the nature of change over time. A linear plot implies a constant rate of change while concave and convex plots imply acceleration or deceleration in the respective rates of change. Additionally a step-wise curve may indicate a series of coupled high and low activity period, possibly associated with flood events.

From the late-1950's to 1970 the rates of erosive, depositional and total channel change in all reaches remained moderate and relatively constant. This period was followed by extremely low rates of channel change extending in the early 1980's. However, from approximately 1982 until 1996 the four non-braided study reaches (Braided Reach is not shown due to a lack of data) enter a period of heightened geomorphic activity. From 1996-2007 the rate of geomorphic change appears to decrease, but as discussed below, this may be a statistical and methodological artefact rather than a real decline in geomorphic activity.

In some of the cumulative mass-plots (e.g. Reach A) the geomorphic acceleration commences following 1984; the year which marks the end of Sichingabula's (1986) study period and the beginning of my original research. This acceleration is not the result of differential survey techniques because the methodology used to determine channel changes in both studies is identical. There may be minor operational differences but these are assumed to exercise minimal influence on the long-term channel change record.

The significant concave-upward profile of the FE, FD and ΔA_1 cumulative-mass plots of all reaches indicate that the rate of erosion, deposition and total channel change have accelerated in the last 50-years. The magnitude of total change (bottom left graphs in Figures 45-48) are approximately equal among Reaches A, C and D, while Reach B has only experienced approximately half that of the more active reaches.

The greatest average annual rate of increase in FD, FE and ΔA_1 between individual measurement periods, can be attributed to the passage of extreme floods (1980-1982; 1982-Oct 1984; Oct 1984-Nov 1984; 1990-1991). In general study periods that closely bracket extreme floods are predominantly characterized by erosive changes. More specifically, in non-braided reaches the total surface-area change recorded in the 1990-1991 period is approximately two times greater than any other prior average rate of change recorded within their respective reaches (Figures 49-50).

It is important to note that the isolated effect of the flood of record on channel change cannot be resolved because of the long duration of the bracketing aerial photographs. Nevertheless, the behaviour of past floods suggests that significantly large change likely did occur in response to the 2003 flood. But if the average annual changes are interpolated from the cumulative mass-plots, the 1996-2007 period registers below-average accumulation rates. This could be a result of the inability of lower-than-average flood discharges to institute channel change, while low prolonged transport rates offset the large changes accomplished by the extreme flood. Furthermore, it is possible that many channel changes occurred but, due to the limitation associated with aerial photographic differencing, went undetected (see Section 3.10).

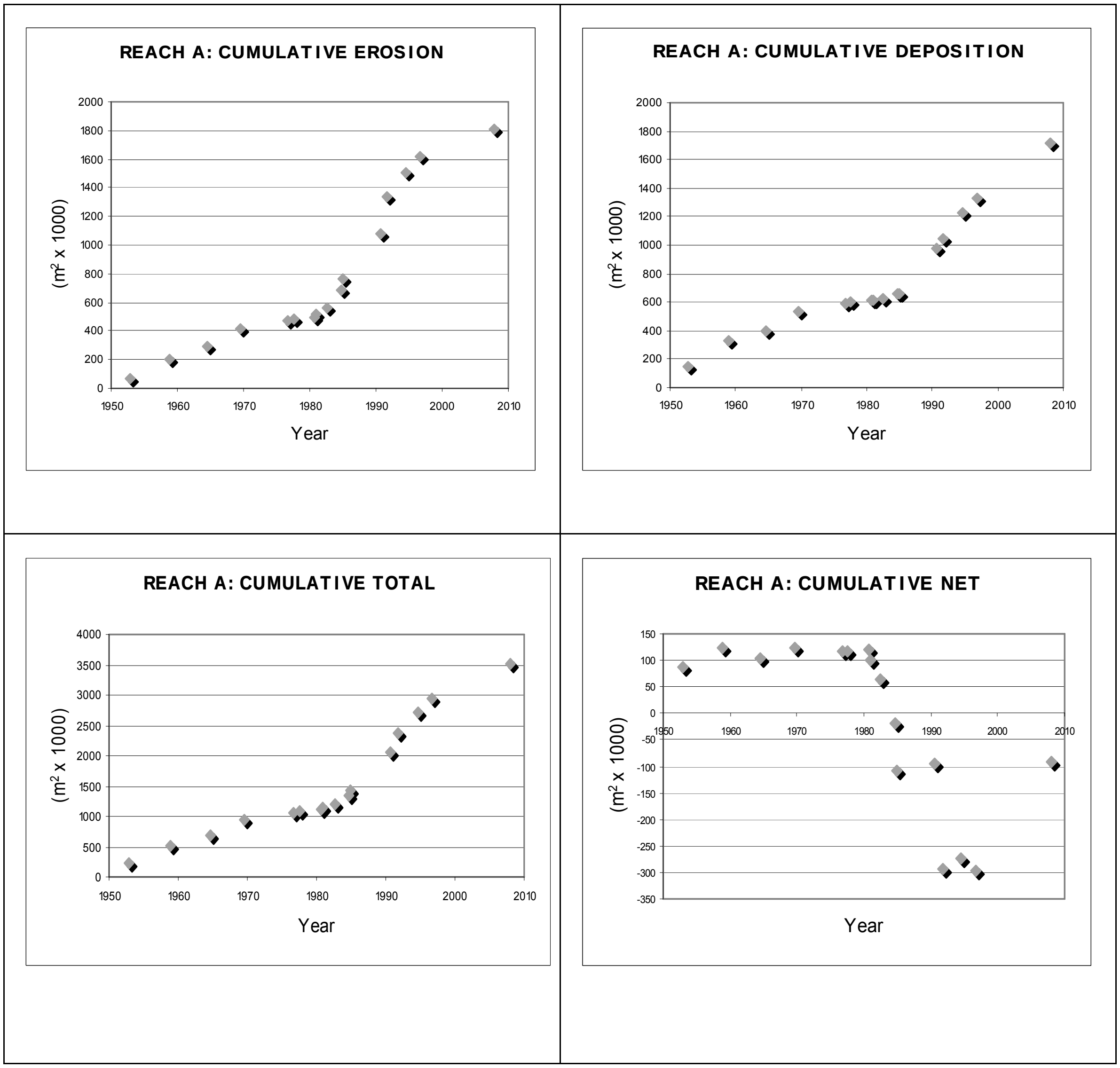


Figure 45: Cumulative-mass plots of floodplain erosion (FE), floodplain deposition (FD), total surface area change (│FE│+ │FD│) and net surface-area change (FD-FA) for Cheakamus-Mamquam Reach (1947-2007). Each data point represents the end of a photographic period. Data from 1947-1984 are from Sichingabula (1986).

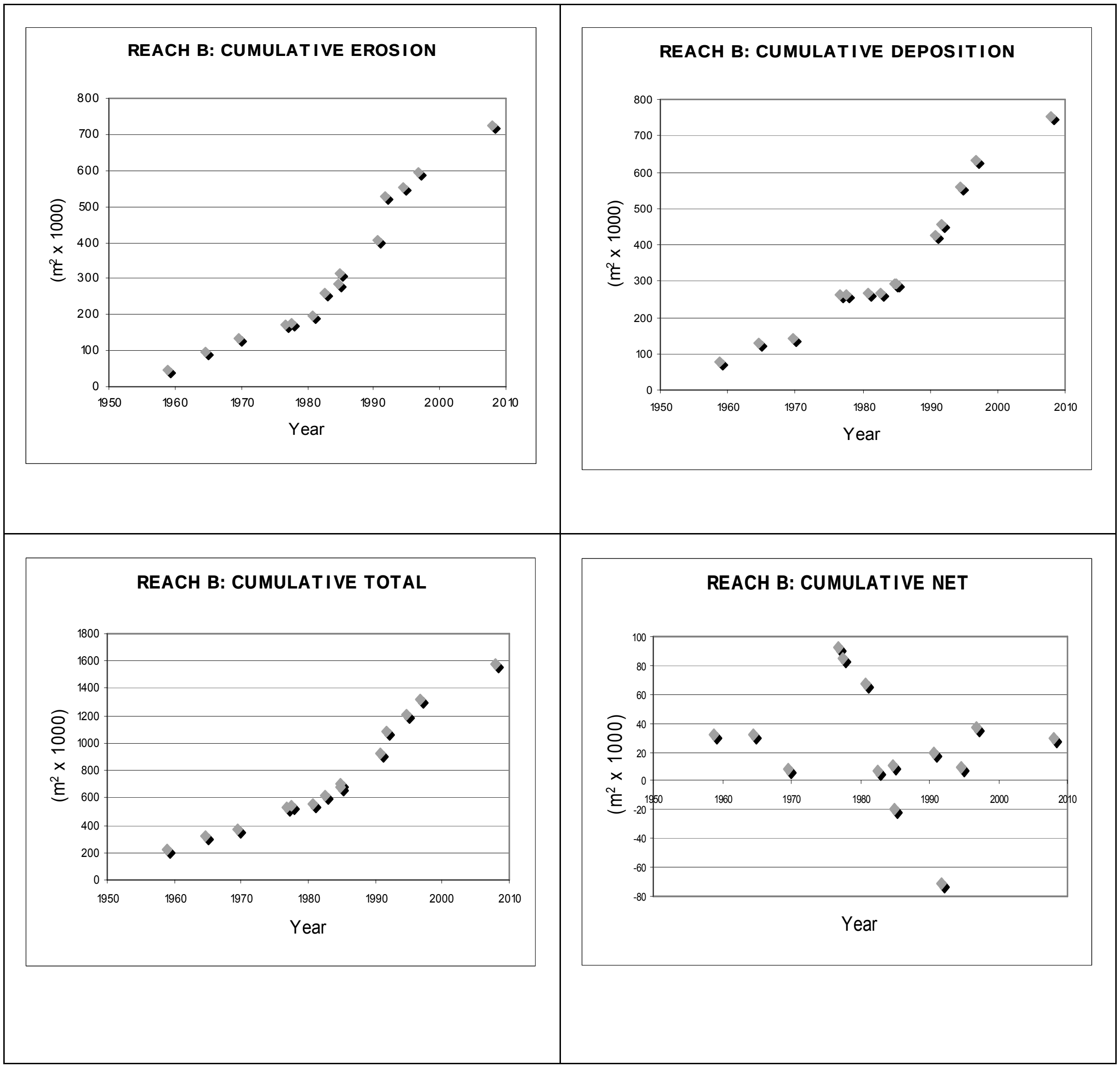


Figure 46: Cumulative-mass plots of floodplain erosion (FE), floodplain deposition (FD), total surface-area change ($\Delta A_1 = |FE| + |FD|$) and net surface-area change (FD-FA) for Lower Meandering Reach (1947-2007). Each data point represents the end of a photographic period. Data from 1947-1984 are from Sichingabula (1986).

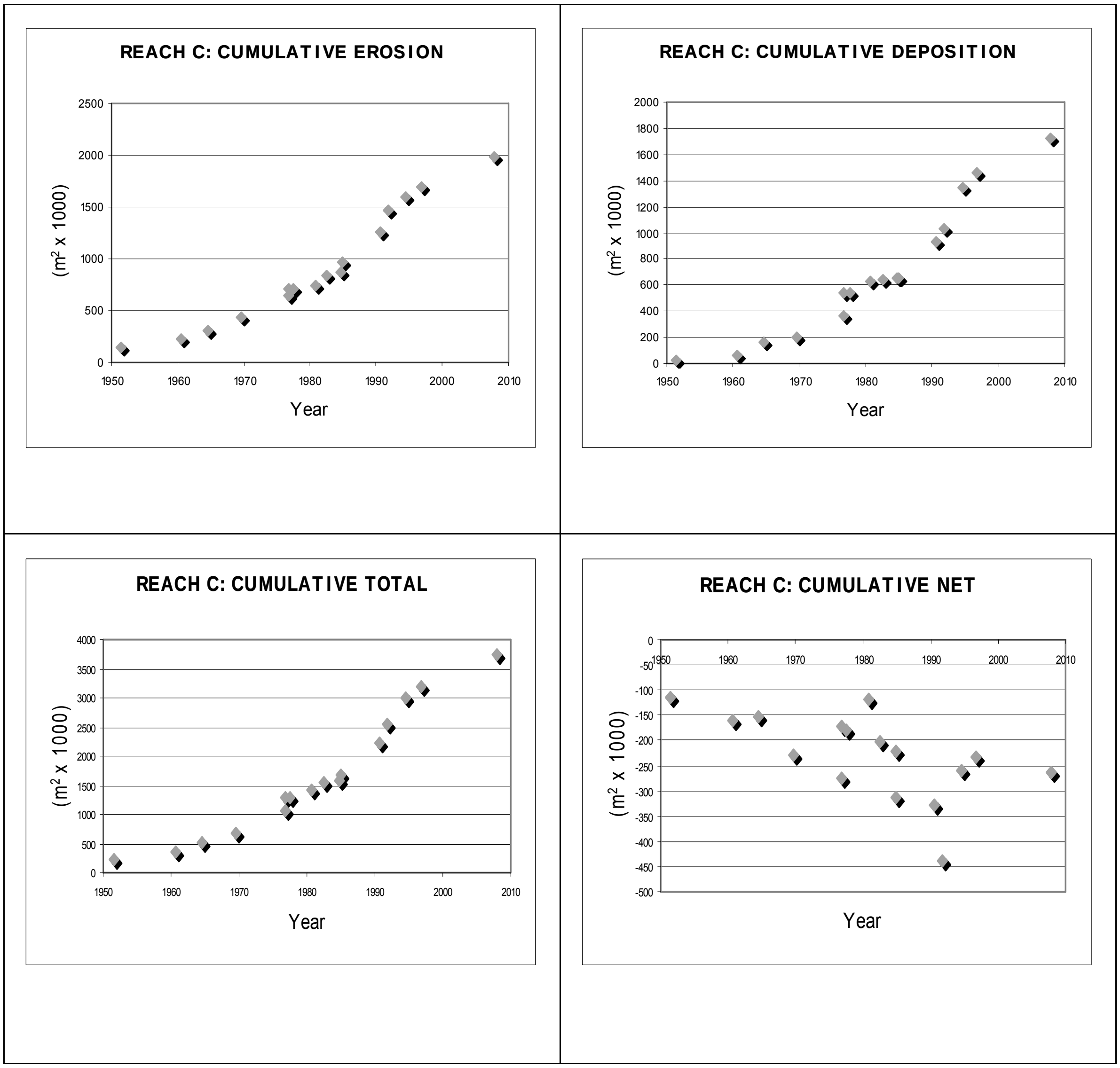


Figure 47: Cumulative-mass plots of floodplain erosion (FE), floodplain deposition (FD), total surface-area change (│FE│+ │FD│) and net surface-area change (FD-FA) for Upper Meandering Reach (1947-2007). Each data point represents the end of a photographic period. Data from 1947-1984 are from Sichingabula (1986).

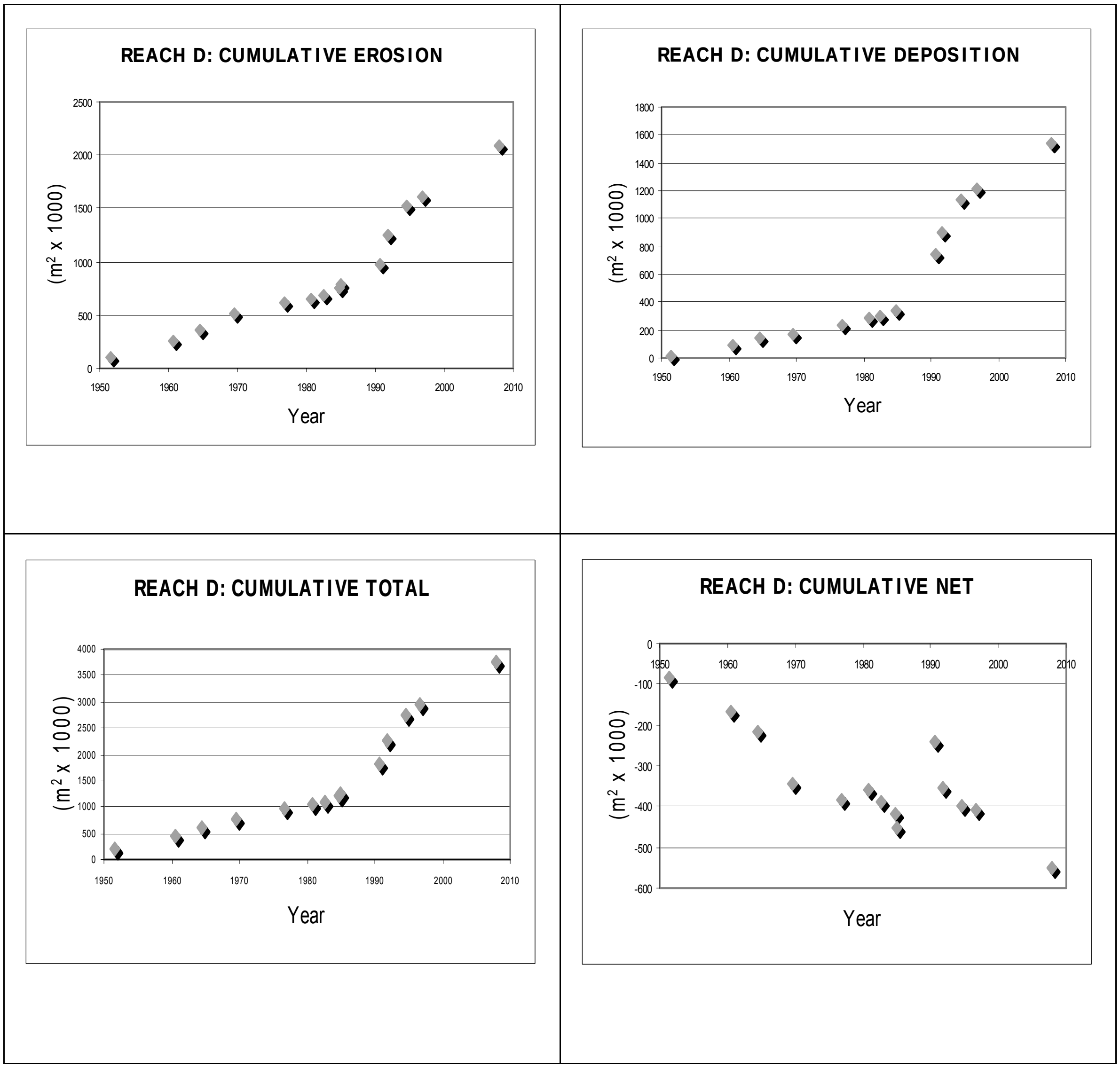


Figure 48: Cumulative-mass plots of floodplain erosion (FE), floodplain deposition (FD), total surface-area change ($|FE| + |FD|$) and net surface-area change (FD-FA) for Squamish-Ashlu Reach (1947-2007). Each data point represents the end of a photographic period. Data from 1947-1984 are from Sichingabula (1986).

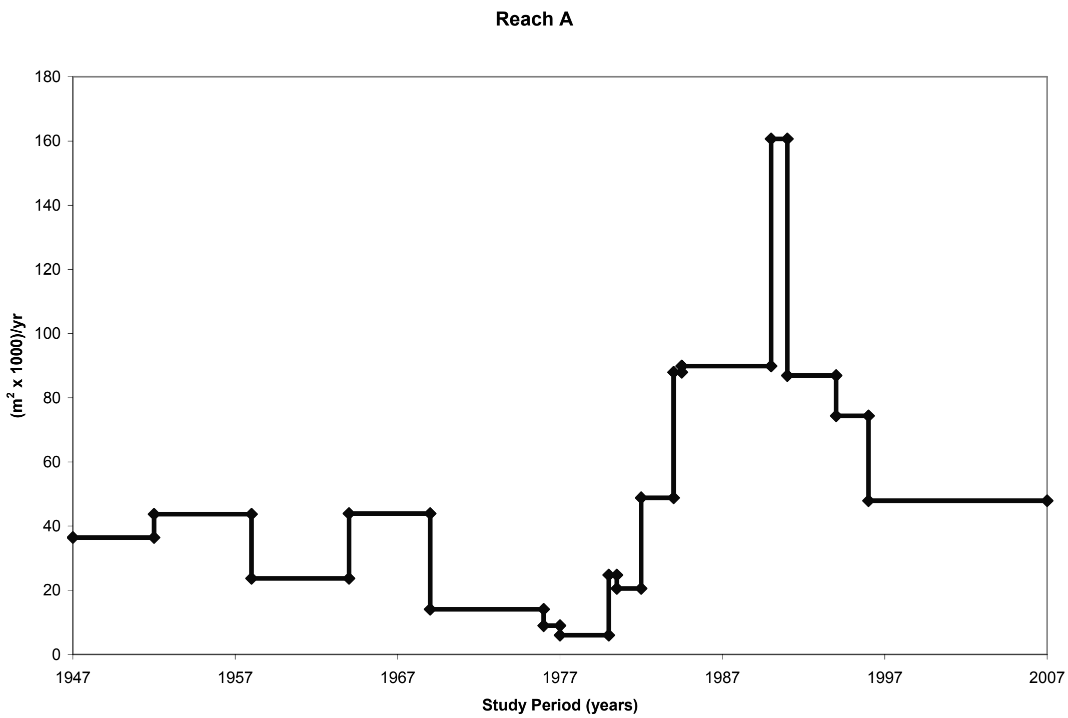
Thus the annual average areal change calculated for the 1996-2007 period could be an underestimate of the actual change. From Figure 51 it can be seen that the longer the time period between air photos, in general, the lower the apparent annual-average rate of change.

Although the increase in ratios of floodplain surface-area erosion and deposition are approximately equal, the absolute rates of increase vary considerably. The cumulative-net channel change graphs (lower-right, Figures 45-48) indicate which of these two processes is the dominant mechanism of channel change. The cumulative-net change in floodplain-surface area indicates that, with the exception of Reach B, floodplain erosion always (Reaches C and D), or recently (since 1980) has out-paced deposition (Reach A). In a few cases erosion may *appear* to be the dominant process because the time interval between aerial photographs is too short for vegetation to establish (Oct 1984-Nov 1984) so that the measurement protocol does not recognize the deposition.

If cumulative erosion and deposition mass-plots are compared for each reach, the erosion plots are noticeably ‘smoother’. The more step-wise nature of the deposition is difficult to explain. Perhaps enhanced deposition occurs after an extreme flood. A large flood event could mobilize a large amount of sediment that eventually could be colonized by vegetation, thereby temporarily increasing the rate of deposition before achieving a more steady state. However, this notion is contradicted by the fact that large and small amounts of deposition are recorded by periods that proceed extreme floods in 1984-1990 and 1980-1982, respectively.

Table 6: The average rate of cumulative floodplain erosion, floodplain deposition and total floodplain change before and after 1980. In each reach, the ratio is positive indicating a recent acceleration in geomorphic change in Squamish River.

Period	Cumulative Floodplain Erosion (m^2 x 1000/ yr)	Cumulative Floodplain Deposition (m^2 x 1000/ yr)	Cumulative-Total (m^2 x 1000/ yr)
Reach A			
1947-1977	16.7	17.6	34.3
1977-2007	55.6	43.9	99.5
Increase Ratio	**3.3**	**2.5**	**2.9**
Reach B			
1947-1977	6.9	10.2	17.2
1977-2007	20.4	20.4	40.8
Increase Ratio	**3.0**	**2.0**	**2.4**
Reach C			
1947-1977	23.3	19.6	42.9
1977-2007	49.9	46.7	96.6
Increase Ratio	**2.1**	**2.4**	**2.2**
Reach D			
1947-1977	21.6	8.9	30.6
1977-2007	58.1	53.5	111.6
Increase Ratio	**2.7**	**6.0**	**3.7**



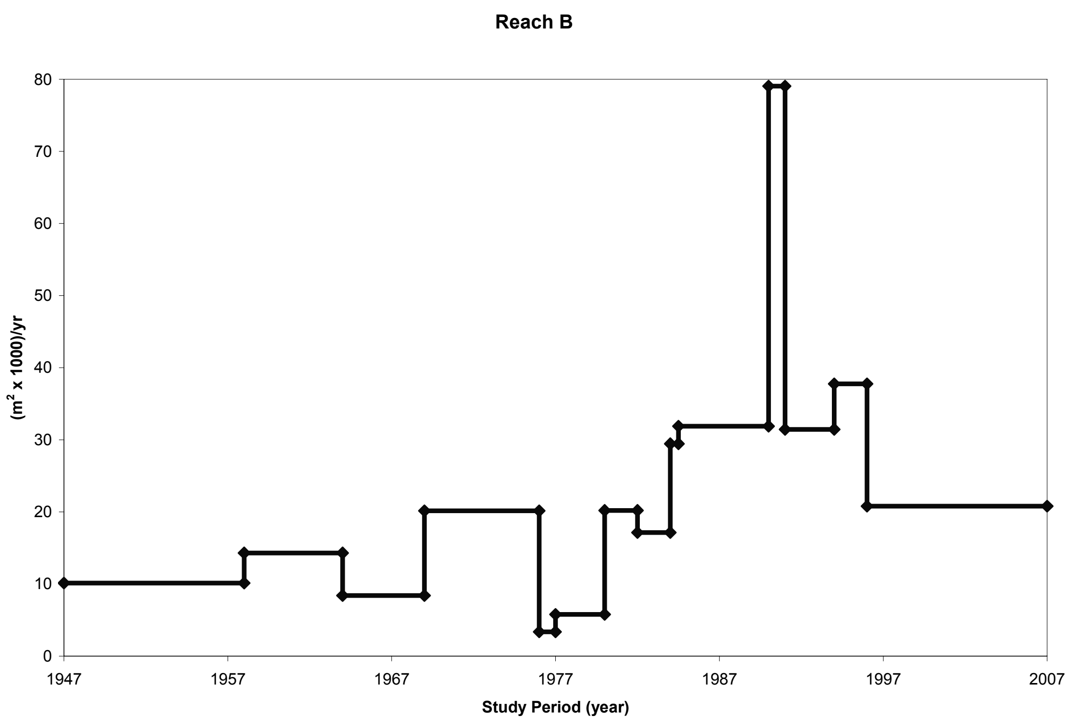
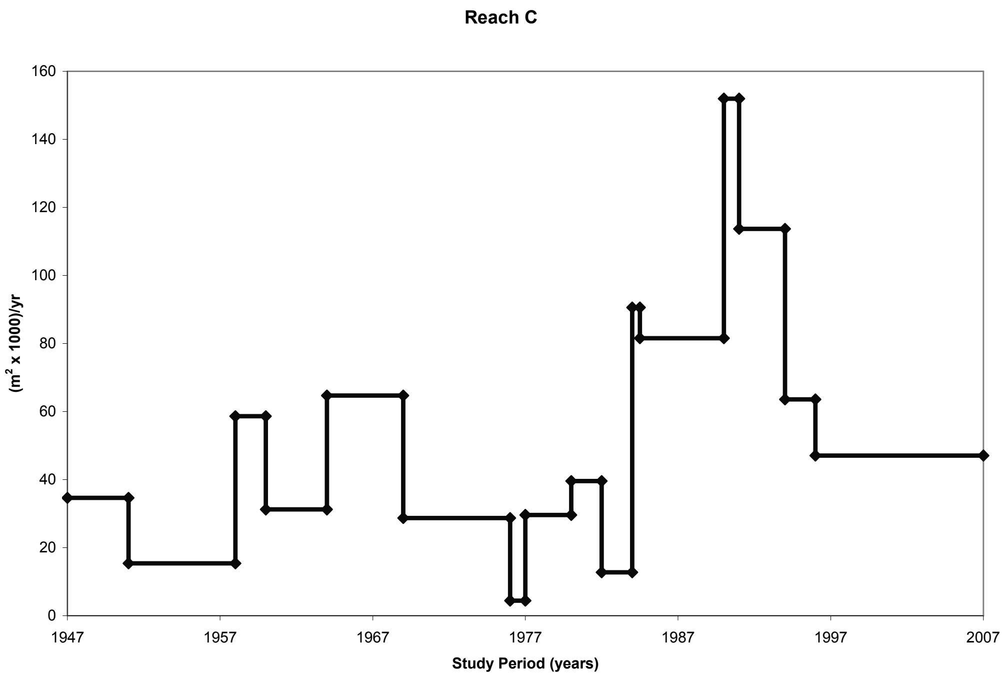


Figure 49: Average-annual rate of channel change by study period for the Cheakamus-Mamquam (Reach A) and Lower Meandering Reach (Reach B) (1947-2007).



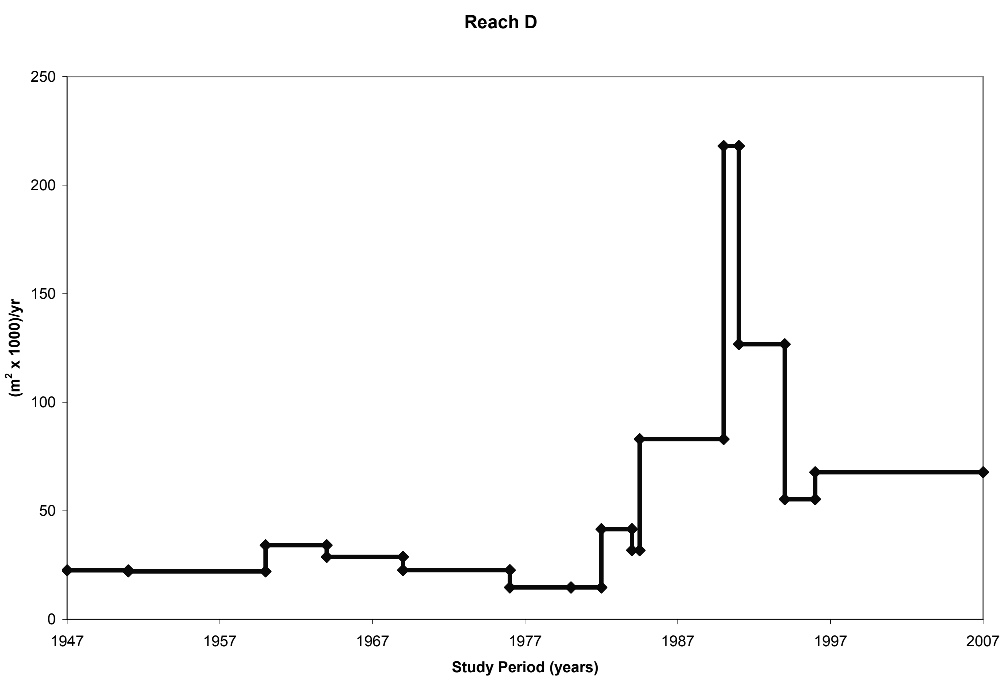


Figure 50: Average-annual rate of channel change by study period for the Upper Meandering (Reach C) and Ashlu-Bend Reach (Reach D) (1947-2007).

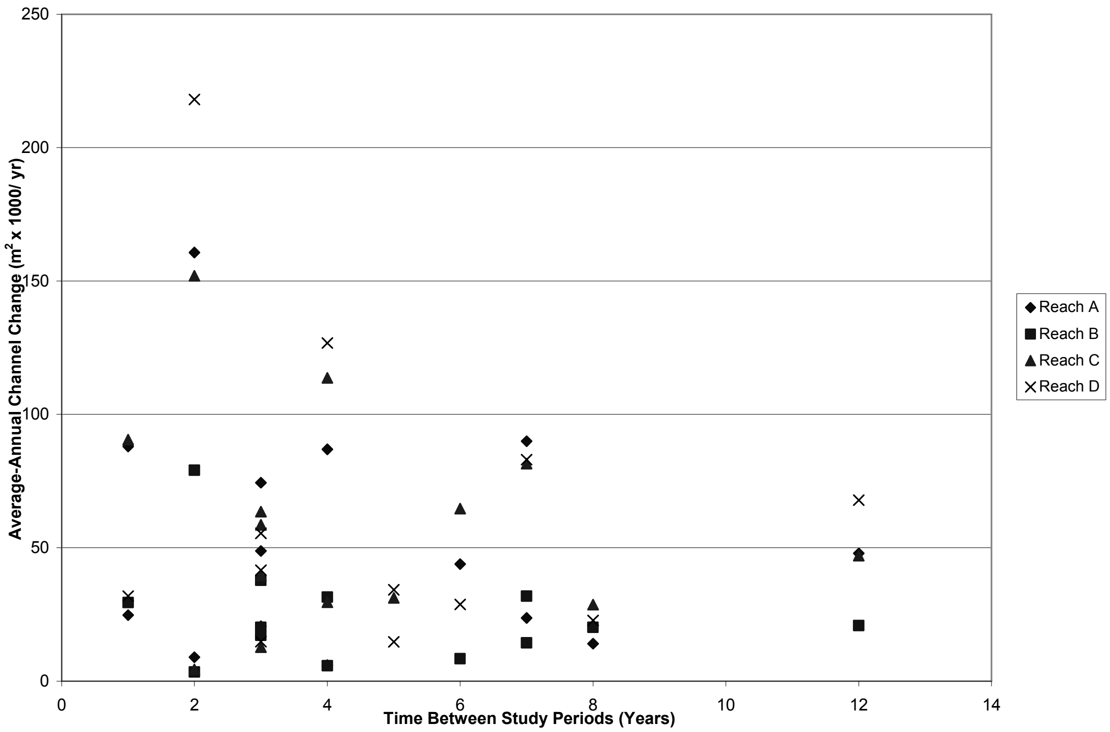


Figure 51: Relation between the average-annual rate of channel change and the length of study periods (1947-2007). The decreasing trend of the upper envelope likely reflects the increasing amount of channel change that goes undetected as the study period increases.

Regardless of the shape of the cumulative mass-plots, the average rate of channel change is calculated for the pre-and post-1980 channel change data and is shown in Table 6. The average rate at which the post-1980 period accumulated mass is at least twice the rate in the earlier period. Reach D experienced the largest relative change, while the smaller magnitude of change is about the same for the remaining three reaches.

6.2 Bank Retreat

Maximum and average bank-retreat rates for selected freely-migrating bends were determined for each study period. Although simultaneous erosion and deposition in banks may occur within a bend, bank retreat is the dominant process associated with extreme flooding on Squamish River.

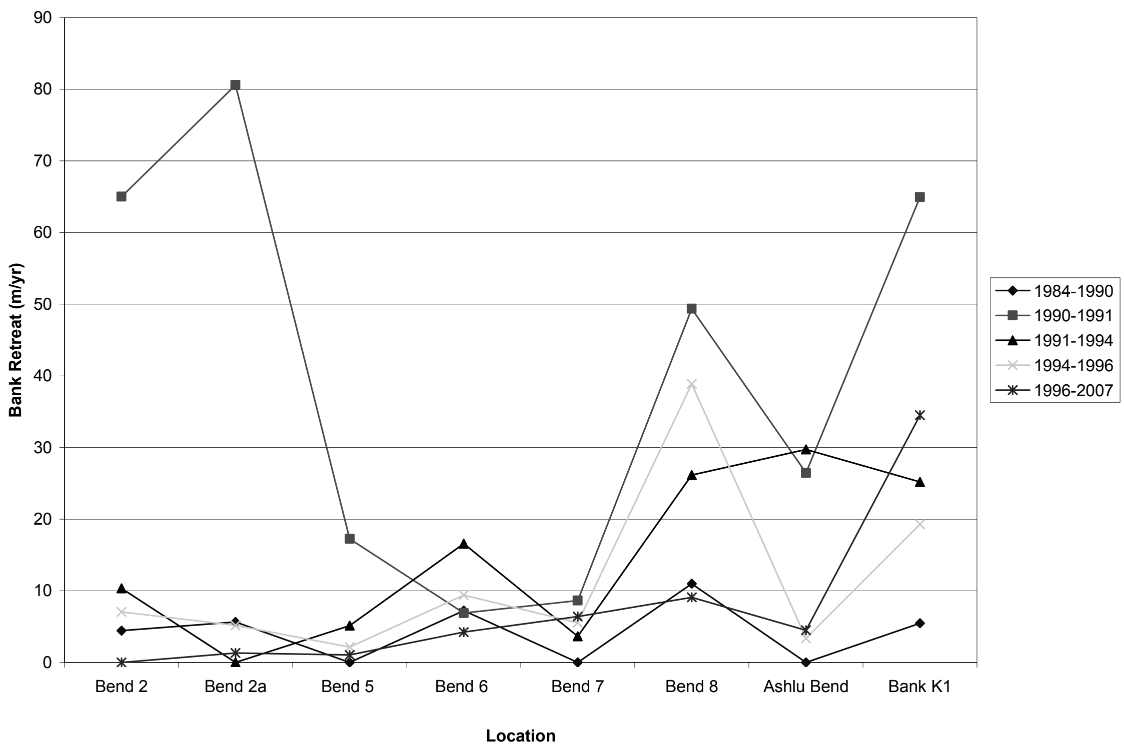


Figure 52: Average annual bank-retreat for several periods in selected freely-migrating bends and banks located in Reaches B, C and D. The greatest bank retreat rates are associated with the extreme floods of 1990-1991 with the exception of Bend 6 and Ashlu Bend. Locations are arranged in an upstream order from left to right (x-axis).

Bank erosion is viewed as the more relevant bank-specific measure for comparing the degree of channel change within a bend for periods with hydrologically distinct flow regimes. Whereas deposition rates are affected by sediment supply (which may differ from year to year) and by vegetation establishment times, bank erosion is primarily a response to discharge if all other variables affecting bank stability are considered spatial constant.

Like the total areal channel change (ΔA_1), bank retreat rate appears to be significantly affected by extreme floods (Figure 52). Rates for the 1990-1991 period are the greatest on record at each location except for Bend 6, which may partially have been influenced by a hard point upstream of the bend. Average-annual retreat of approximately 60 m/yr or greater were recorded for two bends (2 and 2a) and Bank (K1), with the largest rate of 80.5 m/yr observed in Bend 2a during this period. In comparison, during the flood-free period between 1994-1996, the average annual bank-retreat rate was approximately 10 m/yr.

Sichingabula (1986) did not record maximum bank-retreat rates in his earlier inventory of Squamish River channel change. Therefore, the long-term relation between bank retreat and the increasing trend in extreme flood magnitude cannot be determined. However, since 1984, not taking the 1990-1991 period into consideration, there is no temporal or spatial trend in the migration rates at each location (Figure 53). Rather, retreat rates generally are closely clustered within each location (with the exception of Bend 8).

Given the behaviour of the selected bends during extreme flood events, it is somewhat surprising that, despite bracketing the flood of record in 2003, the 1996-2007 period did not register average-annual retreat rates on the approximate order of the 1990-1991 period. One possible explanation is that significant change did occur, but deposition and vegetation establishment in concave bank zones during the period following the flood (2004-2007) concealed or muted any previous erosive changes. Another explanation may relate to the recent development in the reduction of channel curvature. For example, growth of concave banks in a streamward direction is noted in Bends 2 and 3 (see Figures 31-33) and Bend 7 (see Figure 36). This possibility is closely linked to the process of channel straightening which might have acted to reduce river attack in concave bends, while convex bends increasingly became the erosional focus within the bend. However, this would only explain the behaviour of selective bends in Reaches B and C.

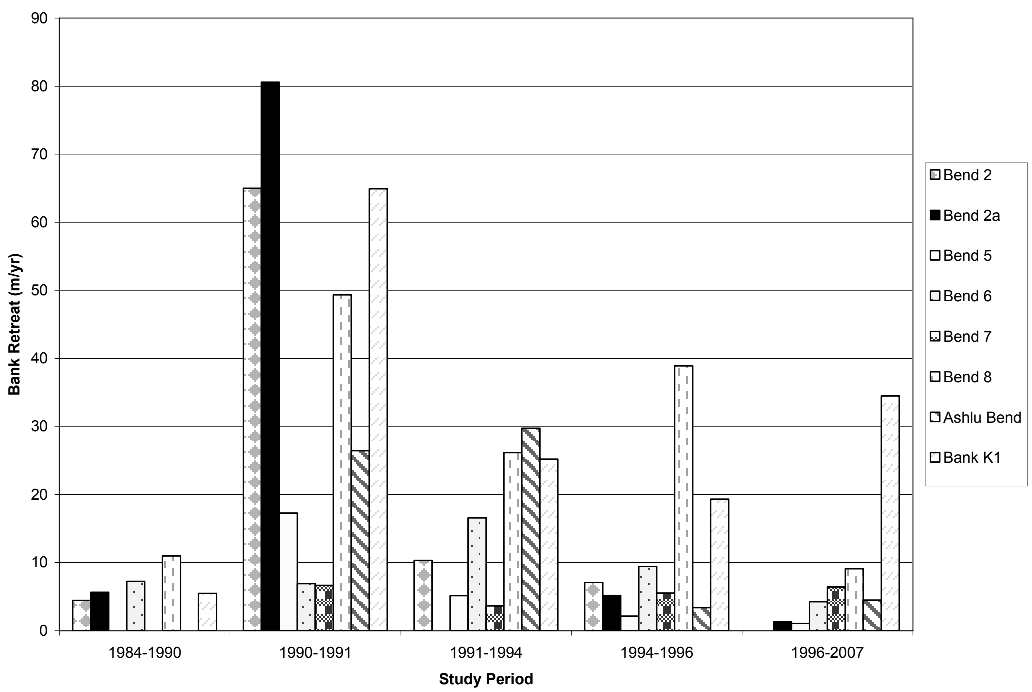


Figure 53: Average-annual maximum bank-retreat for selected locations averaged by year for all study periods. The greatest bank-retreat at each location, except Bend 8 and Ashlu Bend, are closely related to the passage of the 1990/1991 extreme floods.

The lower than expected retreat rates of Bank K1 in the non-meandering Reach D is more certainly related to the length (12-years) of the photographic interval than to any straightening process. The reach did experience a massive absolute bank retreat (>400 m) but averaged by year this amounts to a relatively low retreat rate. Whether all the erosion was predominantly accomplished by the extreme flood of 2003 remains unknown but is certainly possible and even likely.

The relatively low retreat rate for Bend 8 of Reach C likely relates to the fact that, from 1996-2007, the river became more adjusted to its new configuration as a result of the point bar growth of Bank F8 (see Figure 37). Therefore the aforementioned growth and translation of the focus of erosion may have dampened the rate of bend erosion. The reasons for the low retreat rates in the remaining bends (5 and Ashlu Bend) between 1996-2007 are unknown.

CHAPTER 7: DISCUSSION AND CONCLUSIONS

7.1 Discussion: What caused the acceleration of channel change on Squamish River?

The findings of Chapter 4 clearly indicate that, although some general measures of average annual climate for Squamish River basin are stationary over the last half-century (for example, annual precipitation), others exhibit modest increases (for example, mean daily temperature) and still others are characterized by pronounced increases (such as those in rainfall magnitude and intensity associated with extreme floods). Similarly, although the mean annual-discharge record is relatively stationary, the absolute magnitude, volume and duration of rainfall-driven extreme floods ($Q \geq 1500$ m^3/s) have increased markedly with respect to time. Indeed, physical reasoning suggests strongly that the accelerating record of channel change reported in Chapter 5 is likely caused by the increasing volume of water generated by the intensification of these fall rain storms over time.

The accelerated geomorphic change appears to be related to extreme floods generated by increasingly bigger storms rather than by more frequent ones. The yearly occurrence rates of three lesser, yet geomorphically significant, discharges were also examined as potential sources of the rapid increase in geomorphic change.

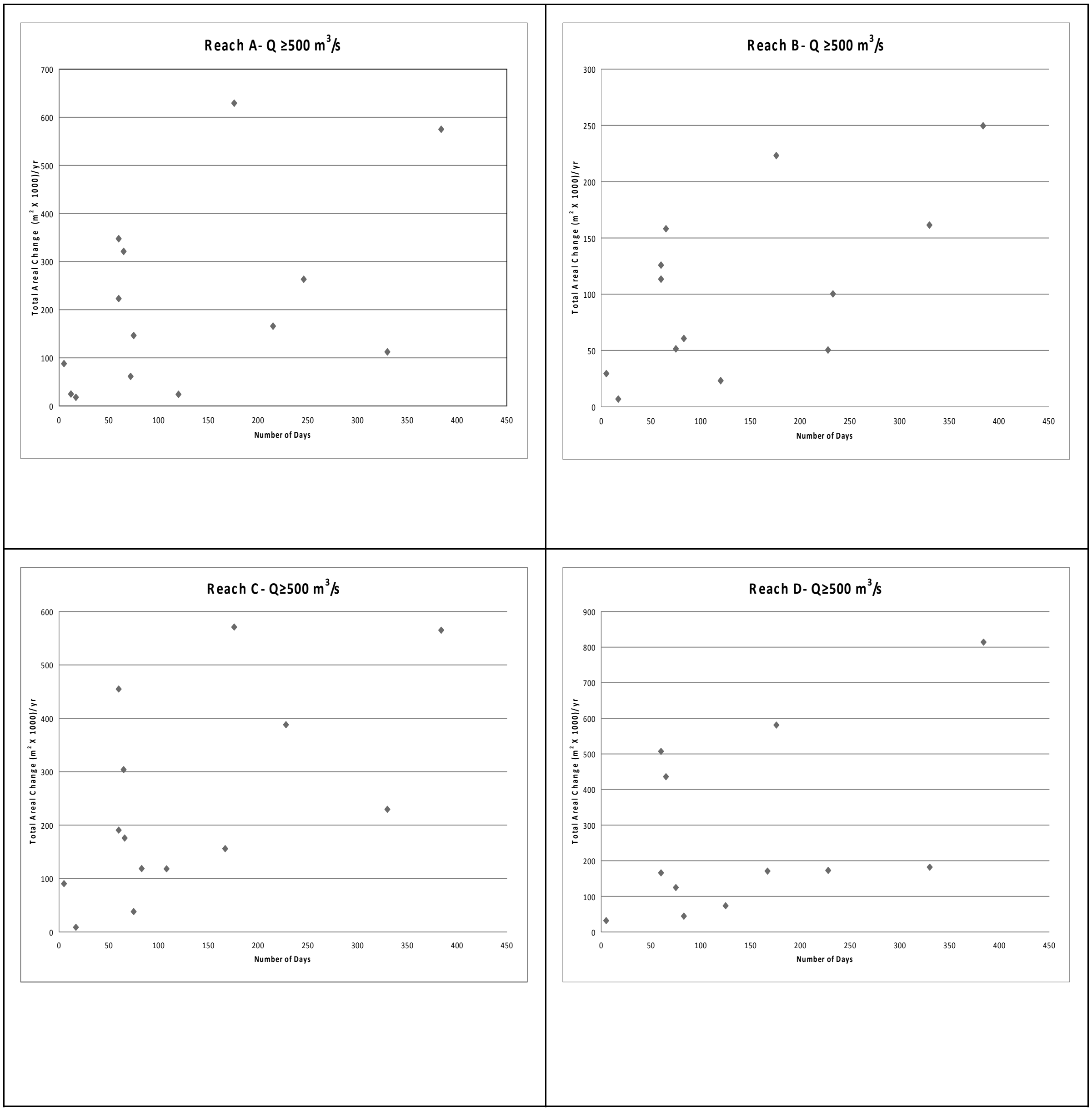


Figure 54: Total channel change plotted against the number of days in which mean daily Q≥ 500 m^3/s for all study periods (1956-2007). Data from 1958-1984 are from Sichingabula (1986).

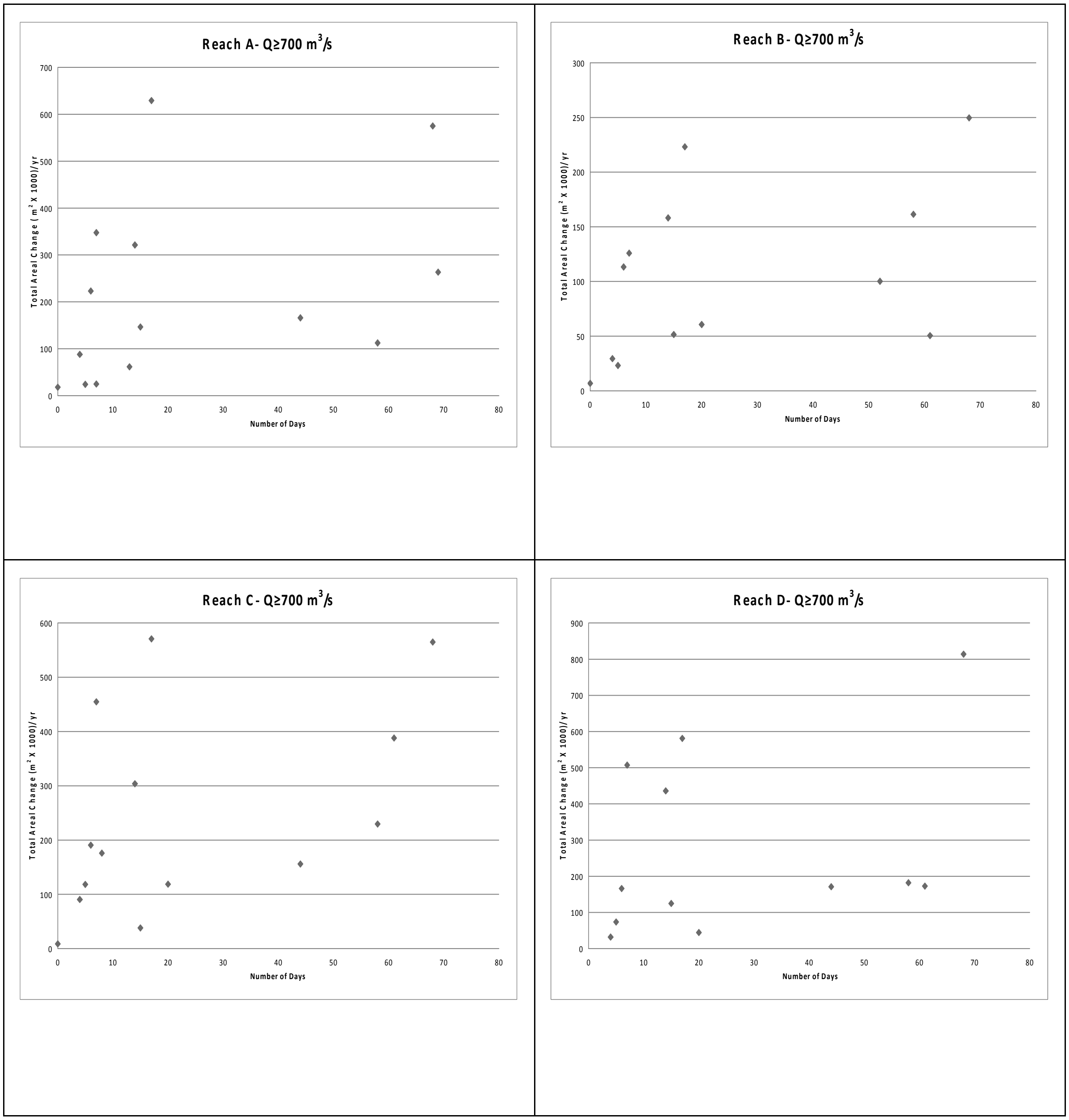


Figure 55: Total channel change plotted against the number of days in which mean daily Q≥ 700 m^3/s for all study periods (1958-2007). Data from 1956-1984 are from Sichingabula (1986).

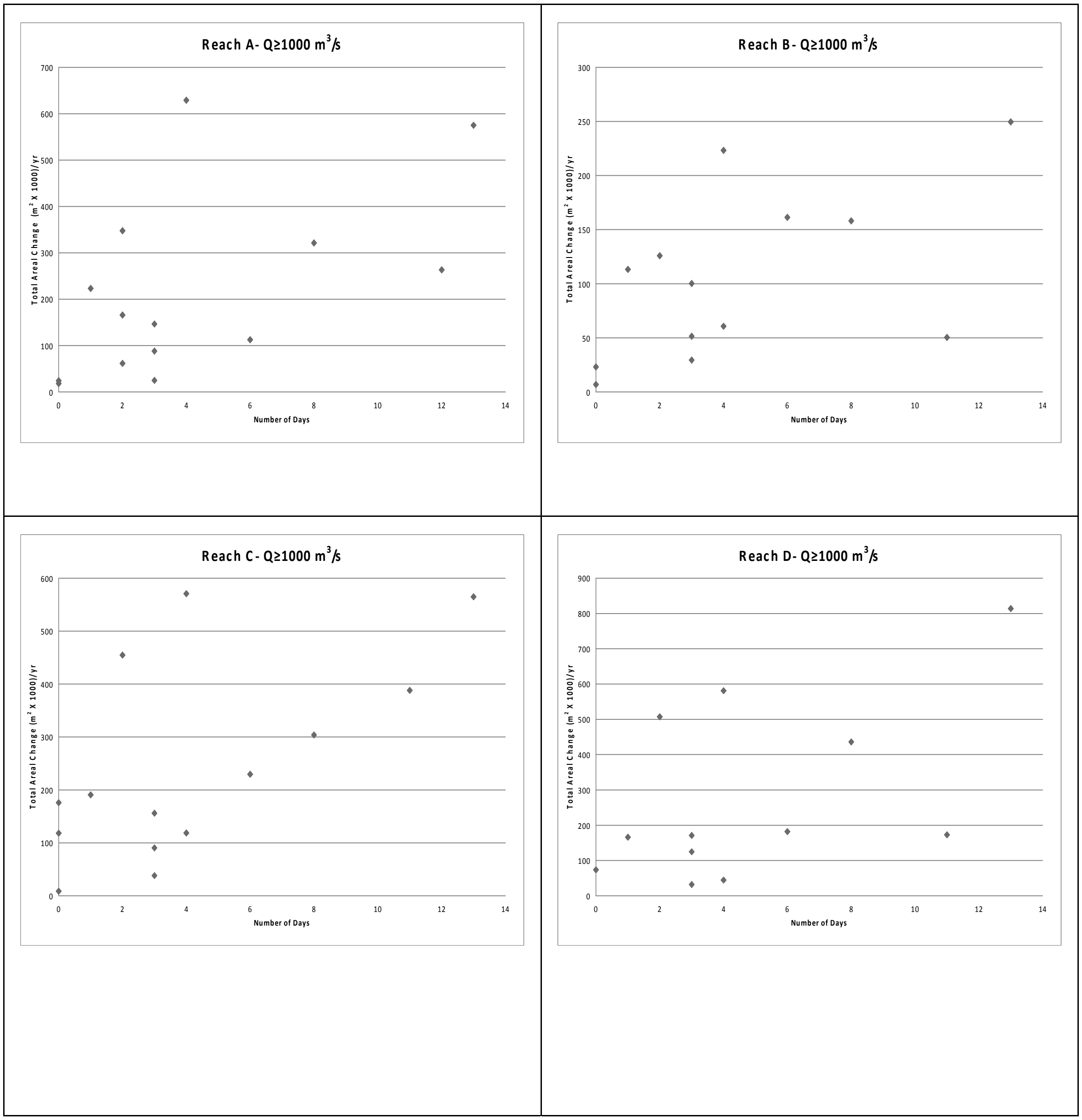


Figure 56: Total channel change plotted against the number of days in which mean daily Q≥ 1000 m^3/s for all study periods (1956-2007). Data from 1958-1984 are from Sichingabula (1986).

Mean-daily Q≥ 500 m^3/s is the magnitude of flow during the spring freshet; Q≥ 700 m^3/s floods were shown by Hickin and Sichingabula (1988) to have a strong statistical correlation to changes in floodplain surface-area, and Q≥ 1000 m^3/s represent bankfull flow in single-channel reaches. Although the general trend suggests that a greater degree of channel change is associated with higher occurrence rates of the three geomorphically significant discharges (Figures 54-56), there is no temporal trend to the relation that mirrors that of the extreme flood data. This total channel change-flood frequency relation is also affected by relatively short time periods that bracket extreme floods (Sept 24, 1984- Nov 5, 1984; Nov 11, 1990-Aug 30, 1991) and by the fact that channel change can be accomplished by discharges less than 500 m^3/s. Thus, the frequency of Q≥500, 700 and 1000 m^3/s does not explain the recent geomorphic acceleration.

Stratified linear regression analysis was also attempted to determine if the variance in channel-change variables between the two periods could be explained by the variation in extreme-flood occurrence but the limited data set and related lack of statistical significance in the relations limit its usefulness. The results are displayed in Appendix 30 in the interest of completeness.

7.1.1 The role of debris flows

Although the changing fall rain-storm regime is the most likely candidate explanation for the accelerating channel changes on Squamish River, two competing explanations - debris flows and forest harvesting – deserve further discussion.

In Chapter 5 it was noted that a large debris flow occurred in Turbid Creek, immediately upstream of Braided reach in 1984. Despite the assertion made by Hickin & Sichingabula (1988) that the majority of debris-flow materials likely was flushed out of Braided Reach and did not cause the major reorganization of the reach at that time, the debris flow could have influenced the total change in floodplain surface-area as the materials were transported downstream. Indeed, elsewhere Pelpola and Hickin (2003) suggested that a debris flow is the likely explanation for a period of above-average annual bed-material transport rate in Fitzsimmons Creek, Whistler BC and this secondary effect could be relevant to the Squamish River case. Paige and Hickin (2000) found that bedload in Squamish River moves in coherent waves or pulses in the downstream direction at an average rate of 15.5 m/d. This process, defined as pulse scour and fill, is detectable on sonar surveys. Should the increase in bed-material transport affect the amplitude or downstream celerity of the bed-wave, shoaling or temporary storage of a bed-wave on the streamward edge of a point bar or island head, for example, could provide a stable environment for vegetation to establish. The net result, given the protocol adopted in this study, would be an increase in net areal deposition.

Average rates of areal deposition presented in Table 7, however, provide no clear evidence that Turbid Creek debris flow left such a depositional signature. In Braided Reach the decrease in areal depositional over the three study periods may represent the initial arrival and rapid exhaustion of the debris-flow materials. Nevertheless, areal deposition appears to respond more readily to extreme floods. The greatest average areal-deposition for each reach was recorded between 1990-1991, following which all reaches recorded a reduction in depositional rates (1991-1994).

Table 7: Total deposition of all reaches averaged per annum.

Period	**Reach A (10^3 m^2/yr)**	**Reach B (10^3 m^2/yr)**	**Reach C (10^3 m^2/yr)**	**Reach D (10^3 m^2/yr)**	**Reach E (10^3 m^2/yr)**
05/11/1984-16/08/1990	45.8	18.7	39.5	56.4	
16/8/1990-09/09/1991	60.6	33.5	97.0	161.0	124.8[1]
09/09/1991-28/07/1994	45.9	25.7	79.5	57.7	114.9
28/07/1994-27/09/1996	33.7	23.6	36.1	26.6	79.2
27/09/1996-10/12/2007	32.4	10.1	22.3	28.0	

[1] Total recorded for the period 1984-1991 due to missing imagery

7.1.2 The Role of Forest Harvesting

Squamish River basin has been progressively logged and although the cut is neither large nor at elevations much above the valley floor, potential impact on Squamish River hydrology is certainly possible. It will be argued here, however, that for the reasons outlined below, the impacts likely are relatively small.

It is argued that forest harvesting affects a number of basin-scale hydrologic processes (Table 8). Here the discussion of the influence of forest harvesting on streamflow regime is limited to the most important variable in the present context: the response of peak flows. The discussion is also restricted to studies conducted in the Pacific Northwest (Rothacher et al. 1967; Rothacher

1973; Harr et al. 1979; Harr and McCorison 1979; Harr 1980; Harr et al. 1982; Jones and Grant 1996; Thomas and Megahan 1998; Beschta et al. 2000).

The majority of studies attempting to decipher the effects of forest harvesting on hydrologic processes are conducted using a paired watershed methodology, whereby one basin represents a control (i.e. natural forest) and the other represents the treatment response (i.e. forest harvesting). For small basins with unchanged control basins the paired watersheds can be compared directly. For large basins where the control basin has undergone changes as well, an index is selected to represent the degree of magnitude of forest harvesting (independent variable) and an index is selected to represent the treatment effect on flow (dependent variable).

Jones and Grant 1996; Thomas and Megahan 1998; and, Beschta et al. 2000 all used data collected primarily from paired-watershed studies conducted in the H.J. Andrews Experimental Forest located in the western Cascades. These studies have the most robust data sets, indicated by their long post-treatment study period, and they examine the behaviour of hydrologic responses operating within two spatial scales, small (60-101 ha) and large (60-600 km^2) basins, separately. The total clearcut area of the two small basins were 31% and 100% while the cumulative clearcut area of the large basins ranged between 12-25%. Although these studies share the same data sets, they differ in how and why experimental variables were selected, and how statistical analyses were used and have produced different results among the three studies. This has generated much discussion and debate in the literature.

For example, Jones and Grant (1996) concluded that forest harvesting has increased peak discharges by as much as 50% in small basins and 100% in large basins. However, Thomas and Megahan (1998) argue that Jones and Grant's use of analysis of variance (ANOVA) was inappropriate and gave an inflated measure of actual change in peakflow Q. Thomas and Megahan (1988) suggested that considering the objective of the original study, an analysis of covariance (ANCOVA) is more appropriate and therefore applied this analysis to Jones and Grant's data. The re-analyzed data produced partially contrasting results. Peak flows in small watersheds still displayed a treatment effect (increases up to 90%) but their analysis gave no indication of a harvesting effect in large basins.

When interpreting these results it is important to note, as Beschta et al. (2000) indicate, that although both Jones and Grant (1996) and Thomas and Megahan (1988) addressed peak-flow magnitude, large floods were not the primary focus of their studies. Defining large-event peakflows was the result of stratifying the data set rather than physical reasoning. For large basins Jones and Grant (1996) defined three event-size categories by dividing the cumulative distribution of flow events into thirds.

Table 8: Summary of hydrologic processes and measures that have been identified or proposed to be responsive to forest harvesting.

Hydrologic Process	Reference
Interception and peak throughfall intensities	Hicks et al. 1991; Ziemer 1981; Keim and Skaugset 2003
Transpiration	Adams et al. 1991
Fog and cloud drip	Harr 1982, 1983
Snow accumulation rates	Toews and Gluns 1986; Troendle and King 1987; Storck et al. 2002; Winkler et al. 2005
Sensible and latent heat inputs on exposed snow surfaces	Berris and Harr 1987, Adams et al. 1998
Hydraulic conductivity and soil infiltration capacity	Startsev and McNabb 2000
Infiltration via macropores	deVries and Chow 1978
Generation of infiltration excess overland flow	Luce and Cundy 1994
Hydrophobicity of soils	Henderson and Golding 1983; McNabb et al. 1989
Subsurface storm flow	King and Tennyson; Dhakal and Sidle 2004
Annual water yield	Bosch and Hewlett 1982; Trimble et al. 1987; Stednick 1996
Extreme low flows	Harris 1977; Harr et al. 1982; Heatherington 1982; Keppler and Ziemer 1990; Hicks et al. 1991
Large wood recruitment rates to streams	Keller and Swanson 1979; Bisson et al. 1987; Andrus et al. 1988; Carlson et al. 1990; Hartman and Scrivener 1990; Woodsmith and Buffington 1996; Benda et al. 2002
Fine sediment delivery to channels	Beschta 1978; Hartman et al. 1996
Simplification of stream channels from forest related changes in sediment supply	Lisle 1982; Lyons and Beschta 1983; Ryan and Grant 1991; Dose and Roper 1994

But due to the fact that small discharges occur much more readily than large flows, 70-75% of the total events in large basins have a recurrence interval <1-year so they indirectly exercise considerable control on the predictor variable for larger size classes. Setting the minimum value of large-event peakflows at recurrence intervals >1-year is below the typical definition of bankfull flow (Leopold et al. 1964; Richards 1982). However, defining peakflows by a geometric measure (e.g. bankfull flow) would produce a population size too small to make statistically significant inferences. Although Beschta et al. (2000) realize the limitations of lowering the minimum magnitude of large-event peakflows, in their re-analysis of Jones and Grant's discharge data, they begrudgingly accept this underestimated definition in order to produce comparable results with the previous two studies.

Another experimental inconsistency that makes it difficult to determine the treatment effect on peak flows in paired-basin experiments is related to the size of large basins. An unaltered, pristine, readily accessible watershed of significant size to use as a control basin is difficult to locate in the Pacific Northwest due to its extensive logging history. More precisely, Fohrer et al. (2005) have suggested that the paired-basin approach is not feasible for watersheds >1000 km^2. In the studies conducted in the western Cascades, the three-paired large-basins have all been logged. Therefore, the 'control' basin is defined as the basin with the least amount of area logged at the end of the data collection period. It should be mentioned, however, that each control basin was more heavily harvested than its corresponding treatment basin for part of the study period. Nevertheless, in absence of a true control, an index, such as the percentage difference in land area harvested, is designated to reflect the differences in forest harvesting between a matched-pair of basins (Jones and Grant 1996). Thomas and Megahan (1998) and Bechta et al. (2000) have criticized this index as a weak treatment variable because it is not unique in the sense that the predictor variable does not account for vegetation recovery time, even though treatment effects have been demonstrated to decrease with time (Hicks et al. 1991), and does not account for spatial variability in harvested areas. Other factors such as the spatial heterogeneity of rainfall distribution (Surfleet 1997), and the elevation distribution of a basin (i.e. percentage of basin below the snow-line) could dramatically effect hydrologic response.

There is also the problem of determining the synchronicity of the observed hydrologic changes that are being related to the shape of a hydrograph. For example, the removal of trees will reduce the amount of rainfall intercepted and, therefore, potentially increase the amount of water reaching streams. But soil compaction associated with the initial tree removal could hinder preferential subsurface water flow through macropores and thus reduce the hydrologic efficiency and timing in which flow is transferred to the stream. This problem is exacerbated as the number of altered hillslope processes increase, which is often the case as basin size increases. For example, within large basins, topographic features such as wetlands, ponds and lakes can temper the effects of land use change (Robinson et al. 2000). Furthermore, synchronization effects from forest harvesting in non-uniform, steep watersheds are typically weaker than relatively uniform flat watersheds (Lin and Wei 2008).

Isolating the treatment effect or effectively demonstrating that any observed change in peak flows is solely a response of the treatment (harvesting) effect is nearly impossible. As Moore and Wondzell (2005) summarize, “ [The] hydrologic effect of forest harvesting and logging roads at the site, stand, or hillslope scale are reasonably well understood at a qualitative level. However, a lack of appropriate tools and concepts has limited the ability to make quantitative extrapolations to catchment scale response.”

I am therefore hesitant to assume that a scaled up version of Jones and Grant (1996), Thomas and Megahan (1998) and Beschta et al. (2000) findings would be representative of the actual net response operating in Squamish basin. The fact that the flow response exhibited by their small and large study basins are often contradictory, and basin size is defined as a relative rather than an absolute term leads me to believe this assumption is unwise. The drainage area of Squamish River is at least six-times larger than any basin examined by the aforementioned authors. Furthermore, these studies are also focused on a wide range of flows, whereas this Squamish River study is focused on true peak flows, a population which has previously been identified as being too small to conduct tests of significance.

Attempts to obtain quantitative data on forest harvesting history of Squamish River basin were not successful. From visual inspection of the air photographs, however, no more than 10% of the basin appears to have been harvested. This fact alone, suggests that forest harvesting is not likely to be important in explaining the increase in extreme flood magnitude on Squamish River.

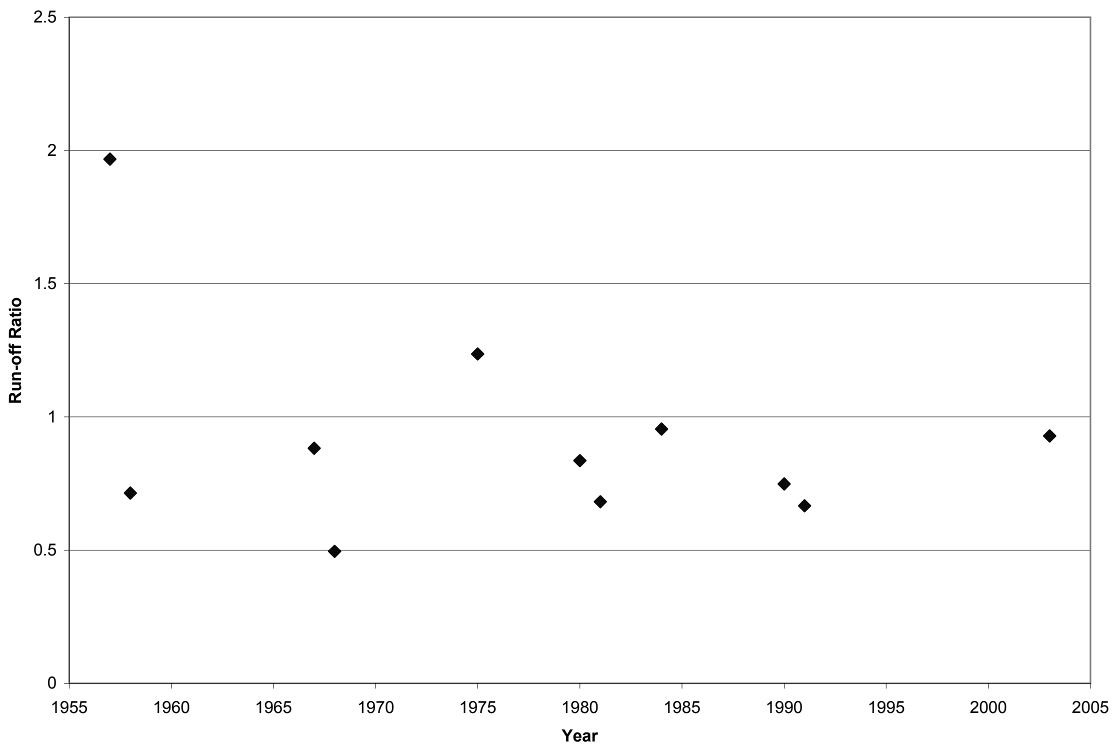


Figure 57: The run-off ratio (event discharge/ event precipitation) of extreme-flood events (Q≥ 1500 m^3/s; 1956-2004). Run-off ratio >1 are a result of discharge produced from additional rainfall received by the basin prior to the onset of the storm.

This conclusion from general principles is supported by the runoff ratio (event discharge/event precipitation) for large-scale storms in Squamish River basin (Figure 57). It is highly variable but has remained approximately constant over time indicating that the amount of discharge produced by a given amount of precipitation for large fall events remains relatively constant across the study period. In instances when the run-off ratio is greater than one (1957 and 1975), it is assumed that rainfall of storms occurring prior to the designated onset of the storm attributed to producing the extreme flood has been incorporated into the discharge response. This is not to say that the run-off ratio for smaller, more frequently occurring storms or that the runoff ratio associated with glacial melt have also remained temporally constant.

This is an important distinction to make because Troendle and King (1985) and King (1989) have demonstrated that the treatment effect decreases with event magnitude. If a change in the effectiveness of water conveyance to the river is noticeable for more commonly occurring storms and during prolonged discharge events (spring freshet), it could have a dramatic effect on in-channel sediment transport and thus channel change. But even if the accelerated geomorphic response in Squamish River were attributed to this phenomenon, it would still require a noticeable change in forest cover. Again, there is no reason to believe that any rapid increase in forest harvesting occurred around the early 1980's.

In summary, sediment delivery to the channel via a large debris flow in 1984 and forestry-related alterations of the flood regime likely are insignificant influences on the long-term behaviour of floodplain surface-area change of Squamish River. Increasing extreme flood magnitude, driven by intensifying Pacific storms remains the most likely explanation of the geomorphic acceleration of Squamish River from 1956-2007.

7.2 The Nature of Channel Change

The behaviour of the channel change displayed in the cumulative mass-plots (Figures 45-48) can be interpreted in one of two ways. The first interpretation is that the 50-year record of geomorphic change can be divided into two distinct periods: a period of low geomorphic activity (1957-1980) and a period of high geomorphic activity (1980-2007). The quantitative analysis of channel change shown in Table 6 is based on this temporal division. These geomorphic activity ratios provide a simple means of demonstrating that the rate of channel change between the periods is quite striking. But there is not a single event to suggest a dramatic shift in the rate of channel change occurred around the year 1980. This essentially arbitrary division and the implied interpretation, however, may obscure how Squamish River fluvial system actually works. Perhaps equally valid is the view that the data plots are more indicative of a smooth transition, rather than a sharp contrast in the cumulative mass-plots.

Thus, a second interpretation is that from 1956-2007 geomorphic change has undergone a progressive acceleration. This progressive change is likely more realistic than the first interpretation with its partitioning of the long-term record into two linear segments. But it is also important to recognize that the channel-change data sets, particularly the cumulative change (bottom left; Figures 45-48) may not be as orderly as they appear. The long intervals between photographs may have ‘smoothed out’ geomorphic detail embedded in the cumulative mass-plots that only are detectable with yearly data. For example, the profile of the channel change may actually look like that shown in Figure 58.

Here a steep slope represent the stress of an extreme flood event (rapid cumulative change) while the subsequent plateau represents periods of system relaxation with declining level of channel change until the next event occurs and the pattern of channel change is repeated. In fact, the shape of the cumulative erosion and deposition mass-plots exhibit hints of this behaviour (Figures 45-48).

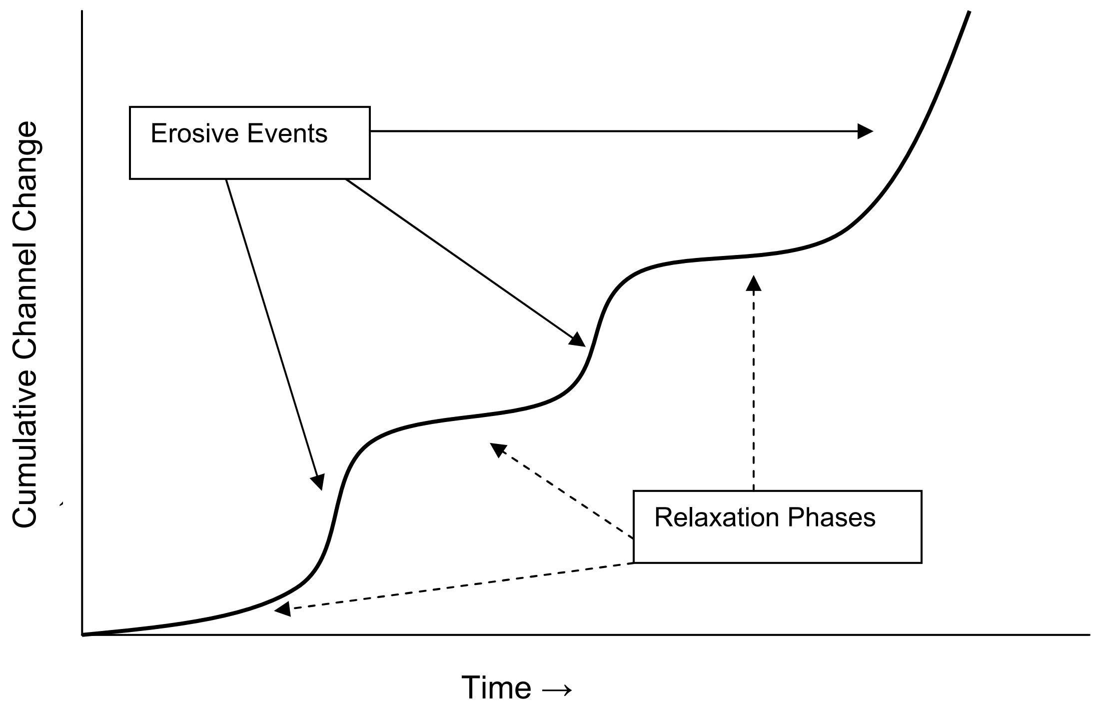


Figure 58: Hypothetical cumulative mass-plot that might result from a series of dramatic erosive events associated with extreme flood events, followed by channel relaxation periods associated with periods of lower discharge.

7.3 Conclusions

As I indicated in Chapter 1, in this study my objective is to answer the general question:

Have there been changes in hydroclimatology over the last half-century that are reflected in the historical morphodynamics of Squamish River?

This general question is explored by seeking answers to three specific questions:

1. Is there evidence of a local shift in hydrology within Squamish River Basin for the period 1955-2006?

2. Are there differences in the type and magnitude of channel change among the study reaches following an extreme flood; and is there a difference in the rate of channel change before and after 1984?

3. Does a relationship exist between the type and magnitude of channel change and extreme flooding such that an empirical model can be constructed to estimate future channel changes?

The answers derived from this study are briefly reviewed below:

Question 1: Shift in hydrology within Squamish River Basin for the period 1955-2006.

The principal findings of this study that relate to Question 1 are as follows.

- Analysis of long-term averaged hydroclimatic data sets (see Chapter 4) reveal many stationary records over a variety of time scales (annual, decadal and seasonal).
- Two variables, mean-daily precipitation (Figure 12) and mean-daily temperature (Figure 13), have increased over partial periods of the

annual records, but do not appear to have affected the mean-daily streamflow record).

- The character of late-season (Aug-Dec) extreme floods (mean daily $Q \geq 1500\ m^3/s$) is the only aspect of the streamflow record that dramatically changes over the period of record. The magnitude, volume and duration of extreme floods significantly increased form 1956-2006 (Figures 16-18). The size of extreme floods appears to be driven by the intensification of Pacific storms, expressed in terms of maximum storm-rainfall intensity, average storm-rainfall intensity and storm duration (Figure 19 and 20).

7.2.2 Question 2: Squamish River channel response to extreme floods

The principal findings of this study that relate to Question 2 are as follows.

- In all five study reaches, the Oct 8-9, 1990 and Nov 11-12, 1991 rainfall-driven extreme floods were demonstrated to represent a period of heightened geomorphic activity in which erosion is the dominant type of channel readjustment (Figures 55-56). This finding is in agreement with Sichingabula's (1986) channel-change calculations for the Oct 8-9, 1984 rainfall-driven extreme flood. Thus, this relation likely holds for all extreme floods on Squamish River.

- Over the period of record there was a shift in the rate of geomorphic change but it is best described as a progressive change, rather than abrupt one centered on the year 1984.
- The rate of erosive, depositional and net channel change have collectively accelerated since 1956, with the most rapid increase occurring after the early 1980s (Figures 45-48). In the absence of any other correlative long-term averaged hydroclimatic trends, the acceleration of geomorphic change is attributed to the size, but not increased frequency, of late-season extreme floods.

7.2.3 Question 3: History as a guide to future channel response

The principal findings of this study that relate to Question 3 are as follows.

- The geomorphic acceleration relating to trends in extreme flooding, of Squamish River has not produced systematic channel change in all study reaches. Many individual channel changes were observed (bank erosion/deposition, island erosion/deposition, debris dam destruction/construction, channel avulsion, meander cut-offs) but none of these processes appear to be exclusive to any one planform type. Therefore, there is no basis for an empirical model to predict future channel change mechanisms for all reaches.
- However, two general morphological responses which are interpreted to result from extreme-flood intensification have been observed in multiple reaches: 1) the meandering reaches

experienced channel straightening and, 2) within one meandering, wandering gravel-bed and semi-braided reach, erosion has clearly outpaced deposition and thus constitutes the dominant type of channel change.

- Although the specific type of channel change in response to flood size is not predictable, the rate of general geomorphic change to Squamish River appears to be intimately related to extreme-flood size. Thus, the acceleration of geomorphic change should continue if the size of extreme floods continues to increase. However, predicting if this intensifying flood scenario is likely to occur is beyond the scope of the study. In this context, however, I note that extreme-flood magnitude must be bound by an upper-limit based on maximum storm-intensity and on floodplain/river channel geomorphic properties. The near linear increase in extreme-flood magnitude since 1956 culminating in the flood of record in 2003, does not indicate that Squamish River is approaching such a physical limit.

7.3 Implications For Society

The residents of Squamish are protected from flood-related property damage and loss of life by training dykes constructed along the eastern banks of the lower Squamish River in 1969 and 1976. These structures were built to contain the 100-year flood, which was calculated from the annual flood data available at the time. However, the extreme flood record (Figure 16) and decadal average flood magnitude (Figure 24) have not remained temporally stationary over the period of record.

Since the dykes construction, three extreme floods have overtopped their banks: Oct 8-9, 1984, Aug 30, 1991 and Oct 17-19, 2003. Thus, it may be more accurate to extrapolate the 100-year flood for future design purposes from the last 20-years or last 10-years of annual flood data. The difference in the 100-year flood calculated from the complete flood record (1956-2006) and the partial records may represent the current underestimation incorporated into the design flood (Figure 59).

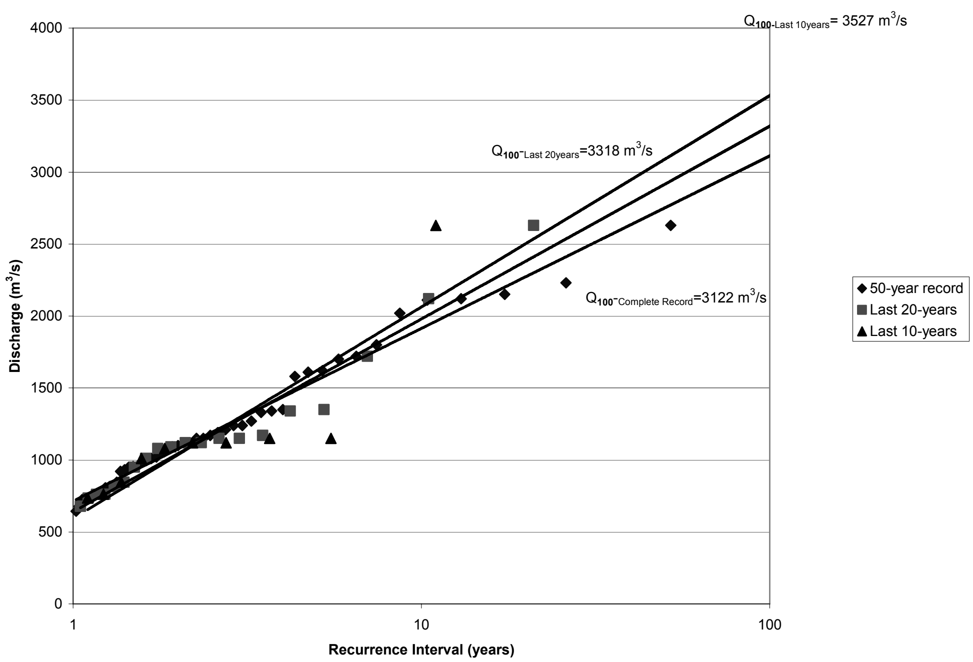


Figure 59: Estimates of the 100-year flood for Squamish River using the last 10, 20 and 50 years (1956-2006) of annual flood data. Estimates were extrapolated from semi-logarithmic best-fit lines through the discharge-recurrence interval plots. The difference in the Q_{100} reflects the non-stationary of the record which has implications for the construction of flood protective structures based on the design flood.

7.5 Future Research

This study has identified the intensification of high-magnitude, low-occurrence hydrologic events as the driving force behind the rapid acceleration of geomorphic change. Although this conclusion can be stated with a high-degree of confidence, to strengthen this argument further, estimating the influence of forest harvesting on the hillslope hydrology of Squamish River is essential and remains an attractive target of future research.

I think that the most intriguing question raised by my findings is ”How long will this state of geomorphic acceleration persist?” Clearly, there is a strong case for continuing a hydroclimatic and channel-change monitoring program on Squamish River. Any prospect of lengthening the discharge/channel change record by reconstructing the environment prior to the measurement record is also an attractive avenue for future research.

It is possible, for example, that two-dimensional channel-change is related to volumetric rate of sediment accumulation of deltaic materials. Menounos et al. (2005) found that varve thickness correlates with annual flood magnitude in five lakes in the southern Coast Mountains. Thus, analysis of the Squamish River deltaic sedimentary record may be used to reconstruct flow data from sedimentation rates. This relationship could be used to determine if the recent accelerated geomorphic change on Squamish River has occurred in the past.

APPENDICES

Appendix 1

Area measurements of Channel Changes Around Squamish River Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	16.94	2.42	118.34	16.91	101.39
16/8/1990-09/09/1991	107.67	107.67	4.05	4.05	-103.62
09/09/1991-28/07/1994	28.53	7.13	22.64	5.66	-5.89
28/07/1994-27/09/1996	9.98	3.33	13.35	4.45	3.36
27/09/1996-10/12/2007	15.93	1.33	143.97	12.00	128.04
Total/ Average	179.05	24.37	302.35	8.61	123.30

Appendix 2

Area Measurements of Channel Changes in Northern Islands Located Around Squamish-Cheakamus Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	36.11	5.16	19.68	2.81	-16.43
16/8/1990-09/09/1991	13.69	13.69	2.24	2.24	-11.45
09/09/1991-28/07/1994	59.70	14.92	66.08	16.52	6.38
28/07/1994-27/09/1996	44.27	14.76	29.28	9.76	-14.98
27/09/1996-10/12/2007	43.11	3.59	0.00	0.00	-43.11
Total/ Average	196.88	10.42	117.28	6.27	-79.60

Appendix 3

Area Measurements of Channel Changes in Baynes Island (C), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	75.95	10.85	23.36	3.34	-52.59
16/8/1990-09/09/1991	48.17	48.17	3.98	3.98	-44.19
09/09/1991-28/07/1994	13.27	3.32	19.85	4.96	6.58
28/07/1994-27/09/1996	13.91	4.64	17.91	5.97	4.00
27/09/1996-10/12/2007	59.75	4.98	26.23	2.19	-33.51
Total/ Average	211.05	14.39	91.32	4.09	-119.72

Appendix 4

Area Measurements of Channel Changes in Islands Located South of Baynes Island (C), Near Judd Slough, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	1.63	0.23	2.41	0.34	0.78
16/8/1990-09/09/1991	4.03	4.03	0.10	0.10	-3.93
09/09/1991-28/07/1994	0.38	0.09	4.07	1.02	3.70
28/07/1994-27/09/1996	1.41	0.47	0.30	0.10	-1.11
27/09/1996-10/12/2007	1.12	0.09	40.48	3.37	39.35
Total/ Average	8.58	0.98	47.36	0.99	38.78

Appendix 5

Area Measurements of Channel Changes Between the Southern Extent of Baynes Island (C) and Brackendale Bend 1, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	78.89	11.27	72.64	10.38	-6.25
16/8/1990-09/09/1991	41.59	41.59	21.12	21.12	-20.47
09/09/1991-28/07/1994	43.77	10.94	20.11	5.03	-23.66
28/07/1994-27/09/1996	12.80	4.27	11.72	3.91	-1.08
27/09/1996-10/12/2007	32.43	2.70	26.35	2.20	-6.08
Total/ Average	209.49	14.15	151.94	8.53	-57.54

Appendix 6

Area Measurements of Channel Changes Between the Head of Island (A) and the Southern Extent of Reach A, 1984-2007

Period	Type of Channel Change Erosion $10^3\ m^2$		Type of Channel Change Deposition $10^3\ m^2$		Net Change $10^3\ m^2$
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	58.63	8.38	30.54	4.36	-28.09
16/8/1990-09/09/1991	5.46	5.46	17.74	17.74	12.28
09/09/1991-28/07/1994	11.09	2.77	19.98	5.00	8.89
28/07/1994-27/09/1996	26.29	8.76	1.97	0.66	-24.32
27/09/1996-10/12/2007	0.83	0.07	130.37	10.86	129.54
Total/ Average	102.30	5.09	200.61	7.72	98.31

Appendix 7

Area Measurements of Channel Changes in Island (A), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	35.03	5.00	33.02	4.72	-2.00
16/8/1990-09/09/1991	25.54	25.54	10.31	10.31	-15.23
09/09/1991-28/07/1994	7.18	1.80	11.48	2.87	4.29
28/07/1994-27/09/1996	11.44	3.81	20.17	6.72	8.73
27/09/1996-10/12/2007	32.21	2.68	21.75	1.81	-10.45
Total/ Average	111.40	7.77	96.74	5.29	-14.66

Appendix 8

Area Measurements of Channel Changes in Islands located North of Island (A), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	5.22	0.75	20.92	2.99	15.70
16/8/1990-09/09/1991	14.58	14.58	1.06	1.06	-13.53
09/09/1991-28/07/1994	0.00	0.00	19.44	4.86	19.44
28/07/1994-27/09/1996	1.90	0.63	6.41	2.14	4.51
27/09/1996-10/12/2007	0.51	0.04	0.00	0.00	-0.51
Total/ Average	22.21	3.20	47.83	2.21	25.62

Appendix 9

Area Measurements of Channel Changes in Bend 2, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	12.34	1.76	2.77	0.40	-9.57
16/8/1990-09/09/1991	29.96	29.96	2.68	2.68	-27.28
09/09/1991-28/07/1994	5.44	1.36	3.42	0.86	-2.02
28/07/1994-27/09/1996	19.45	6.48	17.66	5.89	-1.80
27/09/1996-10/12/2007	15.48	5.16	9.53	3.18	-5.95
Total/ Average	82.67	8.95	36.06	2.60	-46.61

Appendix 10

Area Measurements of Channel Changes in Bend 3, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	15.20	2.17	24.07	3.44	8.87
16/8/1990-09/09/1991	33.35	33.35	4.51	4.51	-28.84
09/09/1991-28/07/1994	3.37	0.84	14.81	3.70	11.44
28/07/1994-27/09/1996	7.64	2.55	16.44	5.48	8.80
27/09/1996-10/12/2007	4.66	1.55	32.29	10.76	27.63
Total/ Average	64.21	8.09	92.12	5.58	27.91

Appendix 11

Area Measurements of Channel Changes in Bend 4, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	15.40	2.20	1.45	0.21	-13.94
16/8/1990-09/09/1991	5.75	5.75	1.95	1.95	-3.79
09/09/1991-28/07/1994	3.10	0.78	5.84	1.46	2.74
28/07/1994-27/09/1996	2.18	0.73	2.83	0.94	0.64
27/09/1996-10/12/2007	20.14	6.71	8.23	2.74	-11.91
Total/ Average	46.57	3.23	20.31	1.46	-26.27

Appendix 12

Area Measurements of Channel Changes to All Islands located in Reach B, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	0.00	0.00	8.76	1.25	8.76
16/8/1990-09/09/1991	8.76	8.76	2.33	2.33	-6.43
09/09/1991-28/07/1994	0.82	0.21	55.21	13.80	54.39
28/07/1994-27/09/1996	8.39	2.80	9.87	3.29	1.48
27/09/1996-10/12/2007	12.88	1.07	5.15	0.43	-7.74
Total/ Average	30.86	2.57	81.32	4.22	50.47

Appendix 13

Area Measurements of Channel Changes in All Banks of Reach B, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	92.06	13.15	122.36	17.48	30.30
16/8/1990-09/09/1991	115.84	115.84	31.21	31.21	-84.63
09/09/1991-28/07/1994	22.04	5.51	47.77	11.94	25.74
28/07/1994-27/09/1996	33.96	11.32	61.06	20.35	27.09
27/09/1996-10/12/2007	115.90	9.66	115.70	9.64	-0.20
Total/ Average	379.80	31.10	378.10	18.13	-1.71

Appendix 14

Area Measurements of Channel Changes in Bend 5, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	No Data	No Data	No Data	No Data	No Data
16/8/1990-09/09/1991	26.45	26.45	19.86	19.86	-6.59
09/09/1991-28/07/1994	9.79	2.45	19.57	4.89	9.79
28/07/1994-27/09/1996	5.46	1.82	5.46	1.82	-0.01
27/09/1996-10/12/2007	13.06	1.09	15.52	1.29	2.46
Total/ Average	54.76	7.95	60.41	6.97	5.65

Appendix 15

Area Measurements of Channel Changes in Bend 6, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	56.60	8.09	91.45	13.06	34.85
16/8/1990-09/09/1991	74.11	74.11	23.69	23.69	-50.42
09/09/1991-28/07/1994	31.51	7.88	13.00	3.25	-18.51
28/07/1994-27/09/1996	17.49	5.83	6.59	2.20	-10.90
27/09/1996-10/12/2007	92.87	7.74	39.40	3.28	-53.47
Total/ Average	272.58	20.73	174.13	9.10	-98.45

Appendix 16

Area Measurements of Channel Changes in Bend 7, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	42.16	6.02	24.66	3.52	-17.50
16/8/1990-09/09/1991	17.92	17.92	8.51	8.51	-9.41
09/09/1991-28/07/1994	4.23	1.06	188.26	47.07	184.04
28/07/1994-27/09/1996	15.56	5.19	51.15	17.05	35.58
27/09/1996-10/12/2007	52.98	4.42	58.25	4.85	5.27
Total/ Average	132.85	6.92	330.83	16.20	197.98

Appendix 17

Area Measurements of Channel Changes in Bend 8, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	71.88	10.27	33.14	4.73	-38.74
16/8/1990-09/09/1991	57.23	57.23	17.08	17.08	-40.15
09/09/1991-28/07/1994	51.77	12.94	15.99	4.00	-35.77
28/07/1994-27/09/1996	31.83	10.61	8.97	2.99	-22.86
27/09/1996-10/12/2007	97.07	8.09	56.50	4.71	-40.57
Total/ Average	309.78	19.83	131.68	6.70	-178.09

Appendix 18

Area Measurements of Channel Changes in Island (E), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	56.66	8.09	48.79	6.97	-7.87
16/8/1990-09/09/1991	14.36	14.36	8.63	8.63	-5.73
09/09/1991-28/07/1994	1.80	0.45	0.00	0.00	-1.80
28/07/1994-27/09/1996	N/A	N/A	N/A	N/A	N/A
27/09/1996-10/12/2007	N/A	N/A	N/A	N/A	N/A
Total/ Average	72.82	7.64	57.42	5.20	-15.41

Appendix 19

Area Measurements of Channel Changes in Island (F), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	48.22	6.89	36.21	5.17	-12.01
16/8/1990-09/09/1991	31.17	31.17	6.04	6.04	-25.13
09/09/1991-28/07/1994	11.68	2.92	60.57	15.14	48.89
28/07/1994-27/09/1996	12.34	4.11	15.77	5.26	3.43
27/09/1996-10/12/2007	41.02	3.42	118.38	9.86	77.36
Total/ Average	144.43	9.70	236.96	8.30	92.53

Appendix 20

Area Measurements of Channel Changes in Islands located in Reach C, Excluding Island E and F, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	0.00	0.00	1.35	0.19	1.35
16/8/1990-09/09/1991	1.35	1.35	0.00	0.00	-1.35
09/09/1991-28/07/1994	0.00	0.00	8.79	2.20	8.79
28/07/1994-27/09/1996	2.63	0.88	12.84	4.28	10.21
27/09/1996-10/12/2007	1.54	0.13	0.00	0.00	-1.54
Total/ Average	5.52	0.47	22.98	1.33	17.46

Appendix 21

Area Measurements of Channel Changes in All Banks of Reach C, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	189.32	27.05	190.24	27.18	0.93
16/8/1990-09/09/1991	160.12	160.12	82.28	82.28	-77.84
09/09/1991-28/07/1994	123.47	30.87	248.52	62.13	125.05
28/07/1994-27/09/1996	67.44	22.48	79.66	26.55	12.22
27/09/1996-10/12/2007	254.68	21.22	149.31	12.44	-105.37
Total/ Average	795.03	52.35	750.03	42.12	-45.01

Appendix 22

Area Measurements of Channel Changes in West and East Banks Located South of Squamish- Ashlu Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	38.65	5.52	157.35	22.48	118.70
16/8/1990-09/09/1991	70.89	70.89	69.72	69.72	-1.17
09/09/1991-28/07/1994	118.38	29.59	32.81	8.20	-85.57
28/07/1994-27/09/1996	22.14	7.38	19.70	6.57	-2.44
27/09/1996-10/12/2007	168.35	14.03	34.60	2.88	-133.75
Total/ Average	418.41	25.48	314.18	21.97	-104.23

Appendix 23

Area Measurements of Channel Changes in West and East Bank Located North of Squamish- Ashlu Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	22.65	3.24	33.56	4.79	10.91
16/8/1990-09/09/1991	65.48	65.48	15.98	15.98	-49.50
09/09/1991-28/07/1994	49.41	12.35	31.61	7.90	-17.80
28/07/1994-27/09/1996	15.36	5.12	4.67	1.56	-10.70
27/09/1996-10/12/2007	169.33	14.11	9.01	0.75	-160.31
Total/ Average	322.23	20.06	94.83	6.20	-227.41

Appendix 24

Area Measurements of Channel Changes in Island (I), 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	63.80	9.11	22.84	3.26	-40.96
16/8/1990-09/09/1991	39.21	39.21	24.90	24.90	-14.31
09/09/1991-28/07/1994	51.34	12.83	58.82	14.70	7.48
28/07/1994-27/09/1996	26.64	8.88	8.87	2.96	-17.77
27/09/1996-10/12/2007	63.06	5.25	17.25	1.44	-45.81
Total/ Average	244.05	15.06	132.68	9.45	-111.37

Appendix 25

Area Measurements of Channel Changes in Squamish-Ashlu Bend, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	0.00	0.00	64.41	9.20	64.41
16/8/1990-09/09/1991	13.09	13.09	28.25	28.25	15.16
09/09/1991-28/07/1994	67.81	16.95	5.17	1.29	-62.64
28/07/1994-27/09/1996	3.19	1.06	9.88	3.29	6.69
27/09/1996-10/12/2007	12.93	1.08	5.59	0.47	-7.34
Total/ Average	97.03	6.44	113.31	8.50	16.28

Appendix 26

Area Measurements of Channel Changes in Islands Located Upstream of Squamish-Ashlu Confluence Including the Confluence Islands, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	22.27	3180.92	113.83	16.26	91.56
16/8/1990-09/09/1991	39.16	39161.16	26.95	26.95	-12.21
09/09/1991-28/07/1994	34.97	8741.87	77.51	19.38	42.54
28/07/1994-27/09/1996	12.68	4227.89	36.54	12.18	23.86
27/09/1996-10/12/2007	65.89	5490.73	201.66	16.81	135.77
Total/ Average	174.97	12160.51	456.49	18.31	281.52

Appendix 27

Area Measurements of Channel Changes in Islands Located Downstream of Squamish-Ashlu Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	38.69	5.53	67.47	9.64	28.78
16/8/1990-09/09/1991	60.29	60.29	23.48	23.48	-36.81
09/09/1991-28/07/1994	21.99	5.50	30.21	7.55	8.22
28/07/1994-27/09/1996	9.34	3.11	10.16	3.39	0.82
27/09/1996-10/12/2007	11.65	0.97	73.05	6.09	61.39
Total/ Average	141.97	15.08	204.37	10.03	62.40

Appendix 28

Area Measurements of Channel Changes in Islands Located Near the Mouth of Squamish-Ashlu Confluence, 1984-2007

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-16/08/1990	0.00	0.00	33.55	4.79	33.55
16/8/1990-09/09/1991	11.12	11.12	7.49	7.49	-3.64
09/09/1991-28/07/1994	2.79	0.70	24.49	6.12	21.69
28/07/1994-27/09/1996	3.31	1.10	18.41	6.14	15.10
27/09/1996-10/12/2007	53.16	4.43	26.02	2.17	-27.15
Total/ Average	70.39	3.47	109.95	5.34	39.56

Appendix 29

Area Measurements of Channel Changes in Braided Reach- Islands and Channel Banks, 1984-1996

Period	Type of Channel Change Erosion 10^3 m^2		Type of Channel Change Deposition 10^3 m^2		Net Change 10^3 m^2
	Total	**Mean**	**Total**	**Mean**	**Total**
05/11/1984-09/09/1991	465.79	58.22396	873.82	109.2276	408.03
09/09/1991-28/07/1994	396.11	99.02733	459.77	114.9436	63.67
28/07/1994-27/09/1996	221.88	73.9606	237.70	79.23418	15.82
Total/ Average	1083.78	77.07063	1571.30	101.1351	487.52

Appendix 30

Table of root mean squares for relations among floodplain surface-area adjustments in Cheakamus-Mamquam (Reach A) and Lower Meandering (Reach B) Reaches and the duration of various flood-magnitude classes. Net Change (ΔA_1) is the sum of the absolute change of eroded and deposited areas while (ΔA_2) is the difference between eroded and deposited areas. Upper values in each cell are results for the years 1951-1984 derived from Sichingabula (1986), and lower values are calculated for the 1984-2007 period.

	Number of days when			
Reach A	**700≤Q< 1000m³/s**	**1000≤Q<1600m³/s**	**Q≥1600m³/s**	**Q≥ 700 m³/s**
Floodplain Erosion (FE)	0.33 0.00	0.41 0.09	0.11 0.01	0.36 0.00
Floodplain Accretion (FA)	0.82 0.64	0.74 0.33	0.09 0.09	0.85 0.59
Net Change in floodplain surface area (ΔA_1)	0.20 0.66	0.09 0.16	0.00 0.06	0.19 0.58
Net Change in floodplain surface area (ΔA_2)	0.68 0.39	0.69 0.35	0.12 0.08	0.71 0.38
Reach B	**700≤Q< 1000m³/s**	**1000≤Q<1600m³/s**	**Q≥1600m³/s**	**Q≥ 700 m³/s**
Floodplain Erosion (FE)	0.22 0.33	0.09 0.77	0.25 0.69	0.23 0.40
Floodplain Accretion (FA)	0.39 0.26	0.00 0.03	0.03 0.02	0.33 0.21
Net Change in floodplain surface area (ΔA_1)	0.19 0.01	0.00 0.30	0.00 0.49	0.15 0.03
Net Change in floodplain surface area (ΔA_2)	0.49 0.63	0.03 0.67	0.11 0.33	0.43 0.65

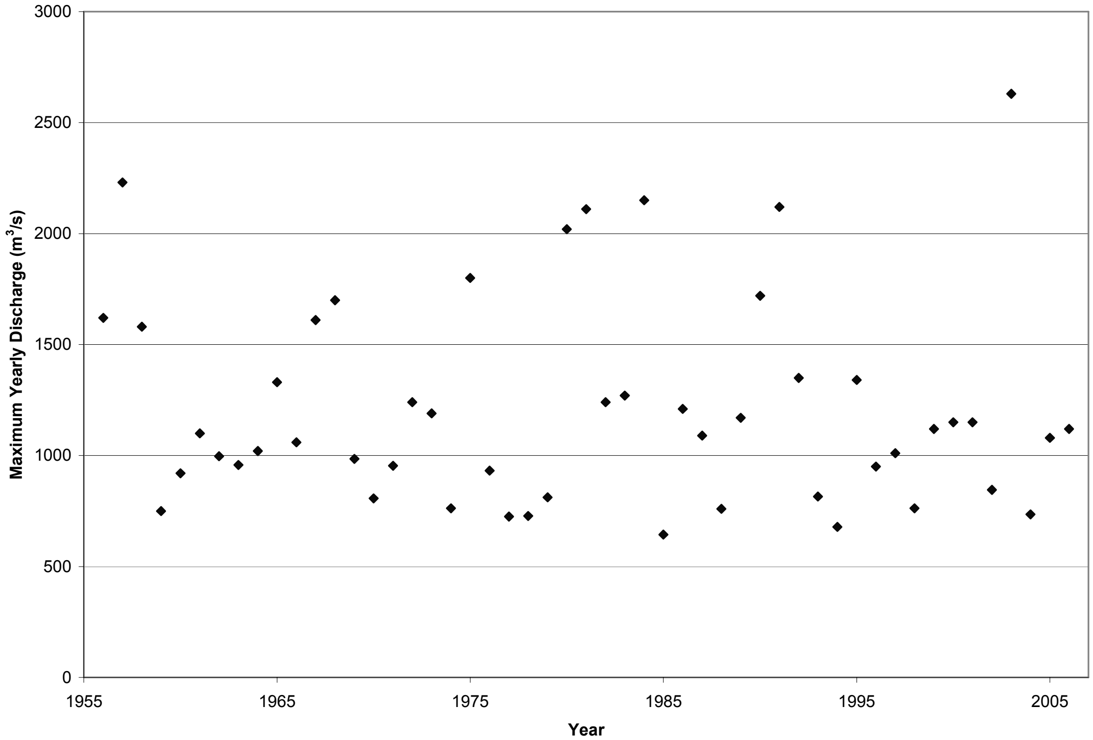
Appendix 31

Table of root mean square values representing the amount of variance in channel-change characteristics explained by the variation in extreme floods. The upper value in each cell is data derived from pre 1980 data and the lower values are derived from post 1980 data. Statistically significant relationships are in bold.

Number of days when $Q \geq 1500 m^3/s$				
Channel Change Variable	**Reach A**	**Reach B**	**Reach C**	**Reach D**
Floodplain Erosion (FE)	**0.42** **0.09**	0.06 **0.53**	**0.58** **0.18**	**0.78** **0.01**
Floodplain Accretion (FA)	**0.66** 0.01	0.00 0.02	**0.80** 0.02	**0.57** 0.12
Net Change in floodplain surface area (ΔA_1)	**0.54** 0.02	0.0 **0.59**	0.02 **0.47**	**0.67** **0.11**
Net Change in floodplain surface area (ΔA_2)	**0.56** 0.04	0.01 **0.08**	**0.85** 0.02	0.02 **0.06**

Appendix 32

Annual Maximum Flood Series for Squamish River 1956-2006



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