CHARACTER AND CAUSES OF CHANNEL CHANGES ON THE SQUAMISH RIVER, SOUTHWESTERN BRITISH COLUMBIA

by

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B.A., University of Zambia, Lusaka, Zambia 1981

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ABSTRACT

This study utilizes a graphical approach to investigate the character and causes of channel changes on the Squamish River from 1947 to 1984.

Patterns and magnitude of channel changes have been identified and measured from sequential photography. Planimetric measurements of channel displacement and areas of erosion and deposition from compiled isochrone maps show complex channel response related to flood magnitude and frequency complicated by local scale geomorphic effects.

Qualitative analysis and characterization of channel changes revealed that major types of changes observed on Squamish River in the last four decades were: bank erosion and bend migration; island formation and destruction; flood plain construction; channel widening and reactivation of old channels by exceptionally high floods. Quantitative analysis of stream channel displacement and measurements of areas of erosion and deposition occurring in the observation period, have shown that stream banklines migrated for distances of up to 550 m in the thirty-seven year period. Meander bends were found to have migrated at annual average rates of between 2.4 and 11.5 m y^{-1}.

Erosion and deposition of sediment in the braided and meandering reaches of the Squamish River correspond with floodplain surface transfers ranging from 5.2×10^2 m^2 y^{-1} to 9.5×10^3 m^2 y^{-1}; sediment movement generally declines in the downstream direction.

This study concludes that local-scale variability in channel changes dominates the effects of flood magnitude and frequency for flows less than the four year flood. More extreme events such as the thirty year flood of record (in 1984), however, can cause more general and abrupt changes in channel character.

DEDICATION

To my Late sister Blandina

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CHAPTER 1: INTRODUCTION

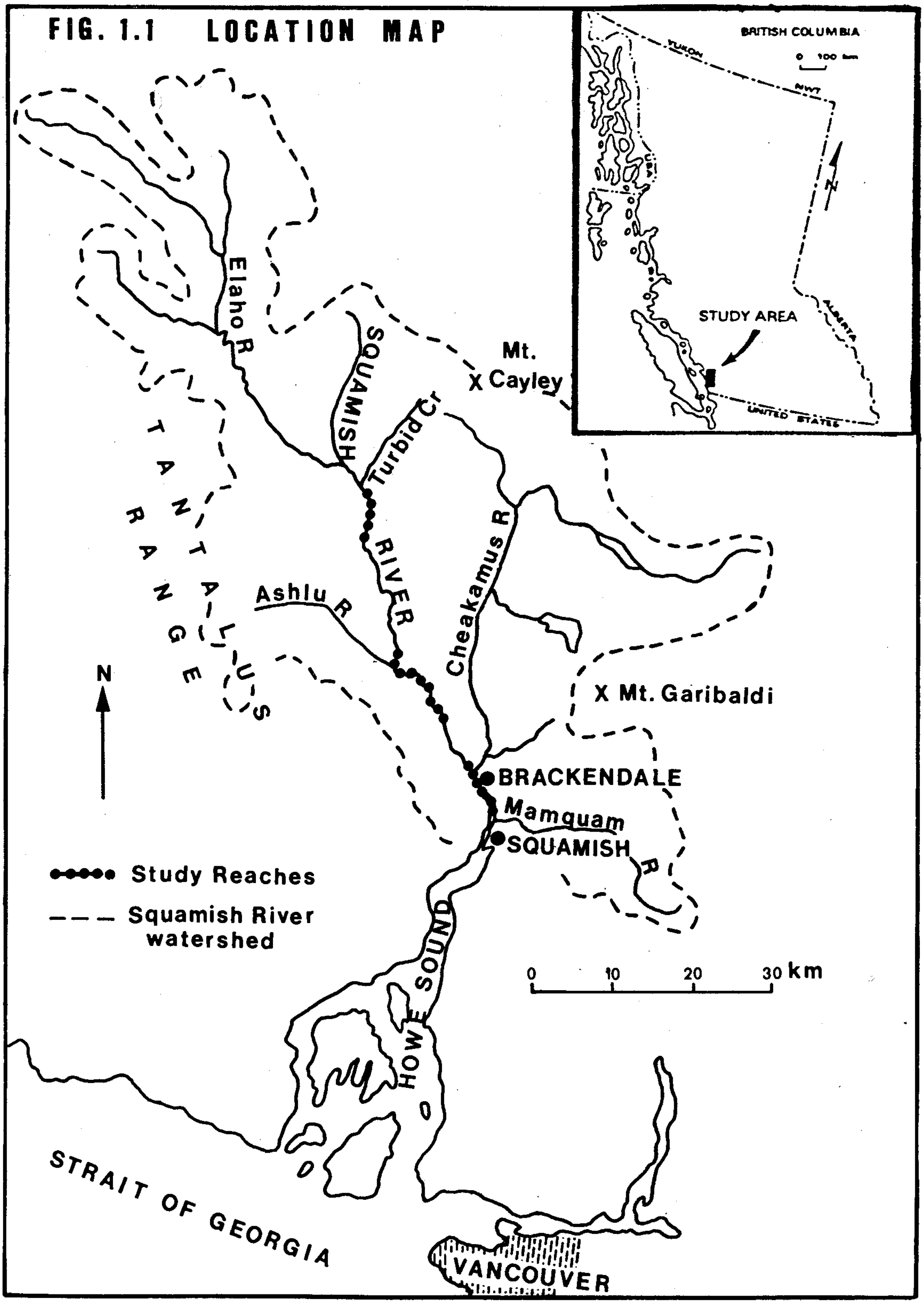
1.1 Introduction

The topic of channel change recently has attracted the attention of a variety of river scientists concerned with the lack of both theory and empirical data base on which to found principles of morphodynamics (Hickin, 1983). There is a particular need to understand the nature of channel planform changes and of channel alignment shifts, the rates at which these occur and their causes.

For many years fluvial geomorphologists have been guided by the notion that most work in rivers is done by flows of moderate magnitude and frequency and not by more common flows and the rarer major floods (Wolman and Miller, 1960). But the notion is not well tested and is increasingly being challenged by a new generation of "catastrophists" (Baker, 1977). Also, there has been little discussion of the relative effects of floods of given magnitude and frequency on channels of meandering as opposed to braided reaches. Indeed there are many other similar questions about channel changes in need of answers.

This study attempts to address some of these questions by documenting channel changes on the Squamish River, southwestern British Columbia, Canada (Figure 1.1), during the last four decades. It is an appealing candidate for this study because it is a high-energy mountainous channel that exhibits readily

FIG. 1.1 LOCATION MAP



measurable change at this timescale and it has both braided and meandering reaches.

The remainder of this chapter will be restricted to a discussion of the role of flood events in fluvial geomorphology. The objectives and scope of the study are outlined while methodological matters are the subjects of later chapters.

1.2 Frequency and Magnitude of Geomorphic Processes

Wolman and Miller (1960) have shown that, on many rivers the largest portion of the total sediment load is carried by flows that occur once or twice each year on the average and are thus related to the bankfull discharge. The concept of frequency and magnitude of geomorphic processes currently is the focus of a debate among geomorphologists concerned with its meaning and with the effects of events of different frequency and magnitude (Patton, 1977). There is wide disagreement on the effects of floods of different magnitude and frequency and resolution will have to await research. Wolman and Miller (1960) stated that the relative importance of geomorphic processes resulting from events of different frequency and magnitude may be measured in terms of either the relative amounts of work done or the creation of specific landforms. Thus, by assessing the amount of work done by events of different magnitude and frequency, knowledge of the effectiveness of different events on geomorphic processes should enhance our understanding of the aforementioned geomorphic concept.

Wolman and Gerson (1978) defined effectiveness in terms of the ability of an event or combination of events to affect the shape or form of the landscape. The effectiveness of flood events in creating specific landforms will vary from place to place as certain climatic and physiographic regions may experience different flood intensities (Baker, 1977). Generally, however, erosion or the destruction of a landscape should increase with the magnitude of the flood event. In underlining this point Wolman and Gerson (1978) stated that:

> "Exceedingly rare floods of extreme magnitudes estimated at recurrence intervals of 500 years or longer, may exceed thresholds of competence otherwise unattainable in the 'normal' record resulting in 'irreparable' transformations of valley landforms."

However, Dury (1973) has reported on a 1000-year flood event, on Nene River in England, which produced insignificant geomorphic effects on the landscape. Similarly, the effects of a 100-year flood on the Grand River in Ontario, reported by Gardner (1977), had only minor geomorphic impact on the landscape. Elsewhere, Gupta and Fox (1974) in a study of the effects of high magnitude floods on channel form concluded that flood effects that look impressive after a major flood are only a temporary phenomena. Although studies such as these support Wolman and Miller's (1960) hypothesis that most of the geomorphic work is accomplished by floods of moderate intensity and magnitude and not by rare catastrophic events (Patton, 1977), it should be pointed out that effectiveness of high magnitude events to some extent depends upon their distribution in time.

In addition, Wolman and Gerson (1978) have stated that the effectiveness of a destructive event depends upon the force exerted, the return period of the event, and upon the magnitude of the constructive or restorative processes which occur during the intervening intervals. Thus, the importance of events is measured in part, relative to the processes which tend to restore the surface of the landscape to the conditions existing before the new landscape were created. For instance, two high magnitude floods occurring in quick succession with little time for the channels to recover from the first event may have a greater geomorphic effect than the same floods widely separated in time.

In order to evaluate the effects of a range of flood events on channel processes, and to test Wolman and Miller's (1960) geomorphic principle that events of moderate magnitude and frequency control channel forms, the present study investigates the character and causes of channel changes in Squamish River. The climatic and physiographic setting of the river described in Chapter 2, wuold make the Squamish River prone to relatively high intensities of flooding. Chapter 5 analyses the effectiveness of floods of different magnitude and frequency in accomplishing geomorphic work of erosion in accordance with the definition for effectiveness of an event given by Wolman and Gerson (1978).

1.3 Geomorphic Change

Channel processes of change are also studied by geologists and engineers although their perspective differs from that of the geomorphologist. This difference in perspective largely relates to the differences in timescales of interest to the three disciplines; engineers look to the short term (less than 100 years), geomorphologists to an intermediate timescale, and geologists to the long term.

Moreover, the study of channel changes is compounded with deficiencies in the present knowledge on channel processes. Hooke (1977) has stated that geomorphological theory is at present inadequate to explain or predict planimetric movement because of the number of variables involved and the complexity of their interaction in the natural environment. It is, however, not only the large number of variables in channel processes that make studies in this area difficult. But also the lack of knowledge on the role small cumulative changes play in lanscape evolution compared to isolated or episodic events of great magnitude. Gage (1970) has dismissed the role catastrophic events play in landscape evolution on grounds that there is no basis for projecting the observed rate of change from isolated occurrence, no matter how dramatic. In identifying the problem Gage (1970) has stated that:

> "The crux of the problem is our inadequate knowledge of the time patterns of cumulative minor changes which, in

> accordance with the uniformitarian doctrines are judged more significant in the long run than are isolated or episodic events of great magnitude".

Thus, contemporary geomorphic changes in the short-term timescale need more detailed investigation of how they fit into the long-term evolution of landscapes if they are to be understood. This view is implicit in the aim of documenting channel changes in Squamish River in the last forty years. There are, however, others (Patton, 1977; Dury, 1980; Baker, 1977) who contend that the concept of catastrophism should continue to have a place in geomorphology.

Cumulative channel changes of Squamish River are presented and discussed in Chapters 4 and 5.

1.4 Aims, Scope and Objectives of Study

The aim of this study is to document the channel planform dynamics of Squamish River in the last forty years. It is hoped that this work will be used as a basis for future studies on the effects of frequent flooding in this river. This study is limited to the assessment of lateral cumulative changes in a short-term timescale and to the investigation of causative factors bringing about change. Extrapolation of observed changes into long-term effects of landscape evolution is not warranted by the short period of study. Future short-term channel changes in selected locations of Squamish River, however, are predicted. In order to assess and evaluate the geomorphic principle that most of geomorphic work is accomplished by flows of moderate magnitude and frequency, the general objective of this thesis is:

> To examine the character and causes of channel planform changes in a high energy fluvial environment at a short timescale of decades.

The research hypothesis states that most channel changes in Squamish River are caused by infrequent high-magnitude floods regardless of the initial channel planform.

To achieve the general objective of this study and to test the research hypothesis, three specific objectives were formulated:

(i) To map channel changes;
(ii) To characterize channel changes in different planform types;
(iii) To determine the extent to which frequency and magnitude of floods control erosion/deposition rates and channel planform of Squamish River in its braided and meandering reaches.

The above objectives are achieved through the accomplishment of several tasks. These include (i) mapping of channel changes from aerial photographs; (ii) analyses of magnitudes of change with magnitudes and frequency of floods; and (iii) review and evaluation of previous studies on channel processes, with a view to placing the findings of the present research into a broader context of available knowledge on channel changes.

The sources, procedures and instruments used in mapping channel changes are discussed in Chapter 3 with an evaluation of approaches and techniques for studying channel changes. Characteristics of channel changes on Squamish River are discussed in Chapter 4 while Chapter 5 deals with quantitative analyses of the observed changes and their causes. The findings of the research are summarized in Chapter 6.

CHAPTER 2: PHYSICAL BACKGROUND OF STUDY AREA

2.1 Introduction

The purpose of the present chapter is to present the physical setting and hydrological characteristics of the Squamish River valley that have facilitated evaluation of causes of channel changes in Squamish River discussed in Chapters 4 and 5. It provides background information on climate, hydrology and geomorphology of the study area with a brief discussion of the evolutionary history of the regional environment under the heading 'geology and geomorphology'.

2.2 Climate and Vegetation

The Squamish River valley is located within the Coast Mountains and drains into the southern Pacific Coast of British Columbia. It experiences moderate temperatures and abundant precipitation (Meteorological Branch, 1967). Influenced by the prevailing westerlies, the climatic characteristics of the Pacific Coast region are mild winters, warm summers and a small range of temperature. Squamish has a mean annual rainfall of 2100 mm with a mean daily temperature of 8.0 °C (Environment Canada, 1982a and 1982b).

Abundant precipitation in this region promotes rapid growth and dense vegetation on mountain slopes and valley floors.

Common tree species in the Squamish River valley are a mixture of conifers and decidous trees which include spruce, cedar, and cottonwoods. Willows and alders are the primary colonisers of bare channel bars. An important effect of vegetation on channel processes is the occurrence of log jams. Slaymaker (1972) noted that log jams are instrumental in bar growth and channel formation and location. Hickin (1984) has reported the important influences of vegetation on channel forms, bar and island development in the Squamish River. Effects of vegetation on channel changes in the Squamish River in the last forty years are discussed in Chapter 5.

2.3 Hydrology

Squamish River drains an area of 2330 km^2. A record of discharge measurements made at a gauging station near Brackendale for the river commenced in 1956. Squamish River has a mean annual disharge of 250 m^3 s^{-1} with a bimodal distribution of maximum discharge, the first occurring in spring months (April - June) due to snowmelt and the second mark the fall and winter months (September - December) resulting from intense rainfalls. The magnitude and frequency of floods in the Squamish River are analysed in Chapter 5.

2.4 Geology and Geomorphology

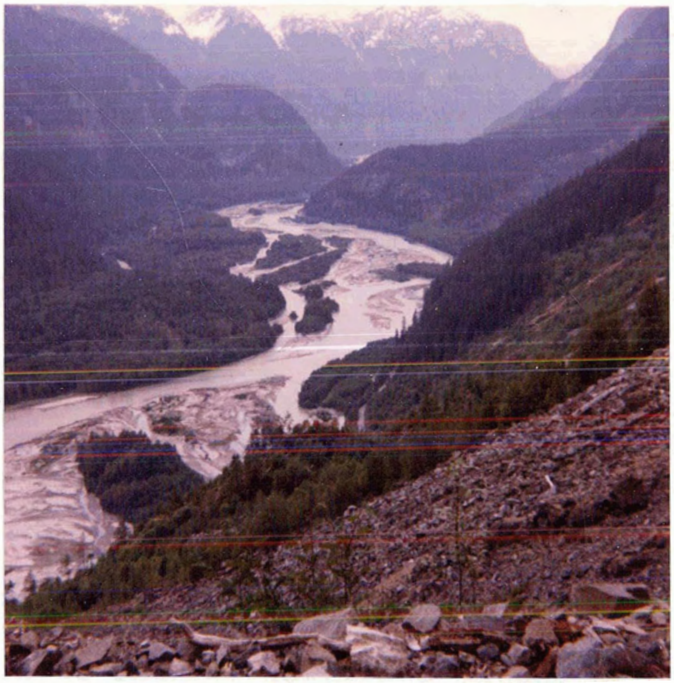
The Coast Mountain forms a predominantly high belt of rugged terrain along the northern and southern Pacific Coast of British Columbia. The mountains reflect a history that includes plutonic and tectonic uplift, subaerial denudation, glaciation and volcanism (Ryder, 1981). These geologic events have contributed to the complexity of the geology of the Coast Mountains. The mountains were formed in the Tertiary period with valleys and ridges undergoing modifications in the Pleistocene Period due to repeated events of glaciation (Ryder, 1981).

Rocks in the Squamish River valley are mainly plutonic consisting primarily of granite (quartz diorite and granodiorite) in composition with some occurrences of gneiss and schist (Roddick and Woodsworth, 1979; Woodsworth, 1977). The highest peaks (Mount Garibaldi, 2,678 m and Mount Cayley, 2,393 m) were formed during the Quaternary by intrusion of andesitic volcanoes into the region. The Squamish River valley floor which is confined by steep mountain slopes is composed of alluvial, fluvial and glacial deposits (Figure 2.1).

During the Pleistocene Epoch, the Coast Mountains suffered a number of major glacial episodes. The last glacial maximum extent of the Fraser Glaciation (the Vashon stade) occurred from 18,000 to 13,000 years B.P. in the southern Coast Mountains (Clague, 1981).

FIGURE 2.1

An Oblique View of Braided Reach Facing Upstream



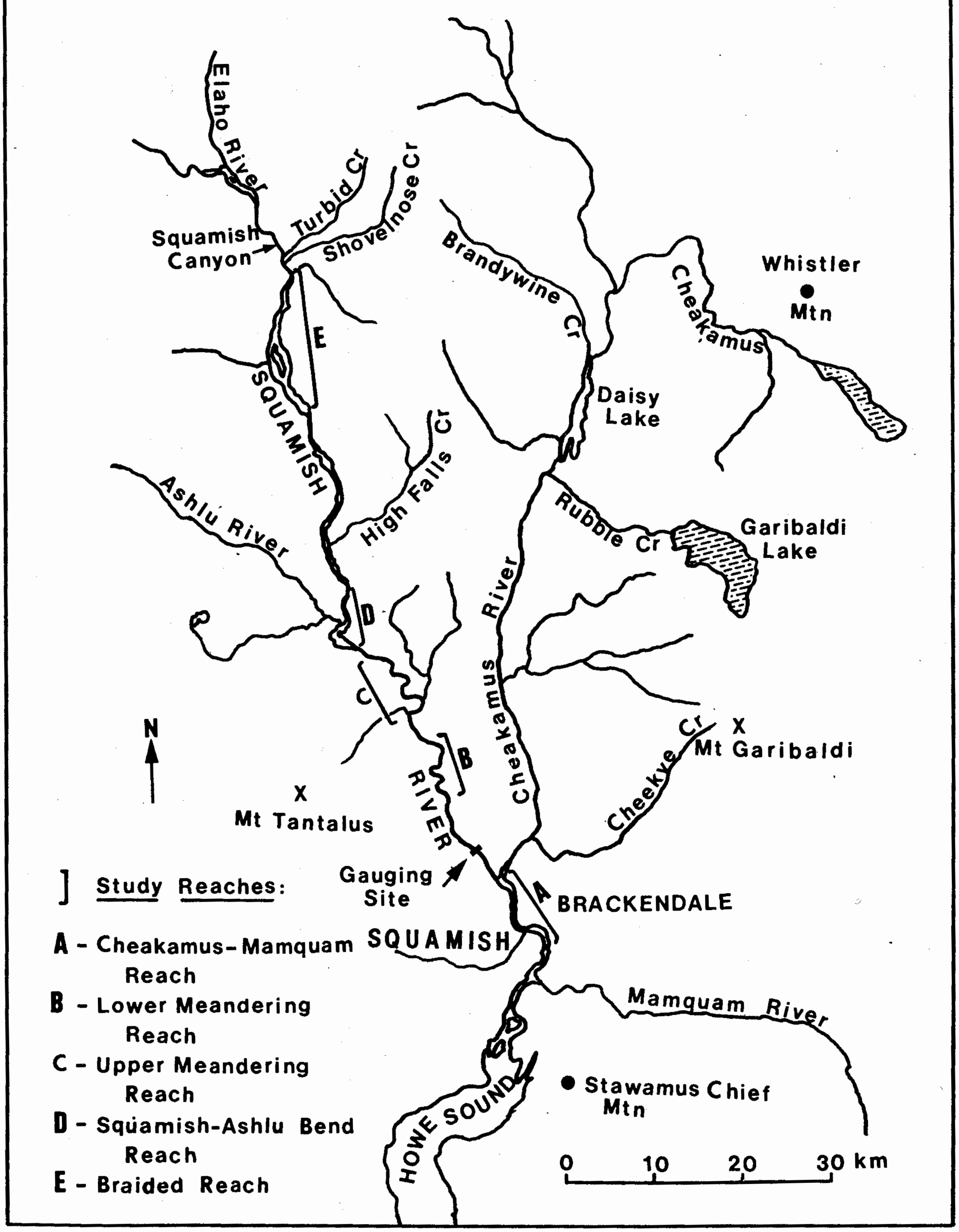
North is to the top of the photograph.

The present landscape of the Squamish River valley and most of the region evolved in the last 10,000 years (Church and Ryder 1972; Fulton, 1971) in response to the deglaciation of the region. During this period paraglacial processes have contributed to the formation of alluvial fan sediments deposited as debris flows or fluvial gravels derived from tributary valleys (Church and Ryder, 1972). Mathews (1952) and Brierley (1984) have indicated that sediment sources in Squamish drainage system are abundant. Landslides due to major slope instabilities have also been indicated to be important sources of sediments which eventually enter the Squamish fluvial system (Clague and Souther, 1982). Thus, from numerous sources the Squamish fluvial system contains massive amounts of bed-calibre materials readily available to be reworked by the river.

2.5 Study Reaches

Examination of the character and causes of channel changes by planform type in Squamish River necessitated selection of clearly defined reaches for study (Figure 2.2). Channel planform is another term for 'channel pattern' used by Leopold and Wolman (1957) to describe the plan view of a river reach as meandering, braided or straight. The term 'channel planform' is used in this thesis. Study reaches were initially selected on the basis of visual inspection of photographs where greatest amounts of

FIG. 2.2 LOCATIONAL DETAIL OF STUDY REACHES



change were observed. Later these reaches were redefined on the basis of presence of conditions and features of geomorphic importance. These are outlined in different reaches below.

2.5.1 Cheakamus-Mamquam Reach

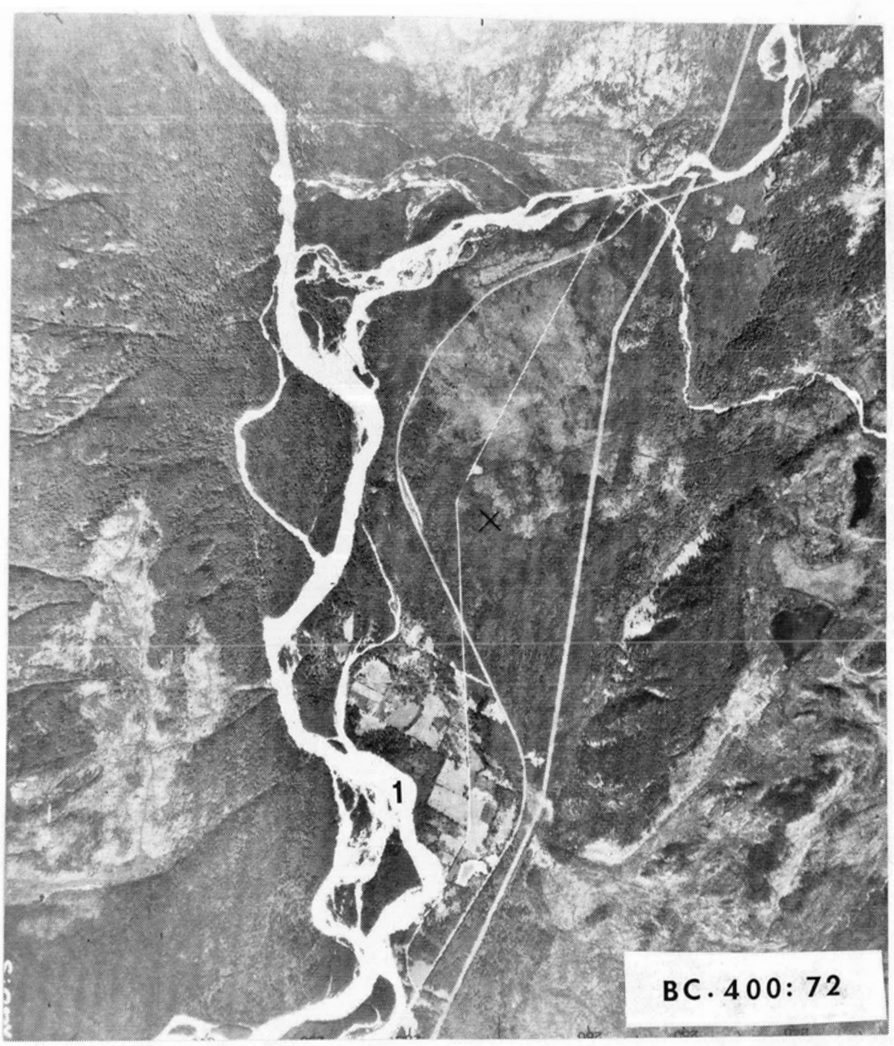
This reach is located immediately downstream of the straight reach of Squamish River (Figure 2.3) lying at about 5 m above sea level. This reach was selected for study because of its location downstream of the Cheakamus River, a tributary of Squamish River. The Cheakamus-Mamquam Reach is partly braided and is suitable for a study of the effects of gravel deposition in a confined straight channel. The reach also provides an opportunity to assess the effect of stream bank stabilization on the Squamish River to protect houses and roads from bank erosion and flooding in Brackendale area.

2.5.2 Meandering Reach

The meandering reach of the Squamish River is located between the braided reach on the upstream and the straight reach on the downstream end of the river (Figures 2.4 and 2.5). This reach was selected for study mainly to assess the character of channel changes in the confined and freely migrating meander bends. The elevation of the valley floor of the meandering reach is between about 50 and 80 m above sea level.

FIGURE 2.3

Aerial Photographs of Cheakamus-Mamquam Reach in 1947



North is to the top of photograph. Numbers represent studied bend.

FIGURE 2.4

Aerial Photograph of Lower Meandering Reach in 1947

North is to the top of photograph. Numbers represent studied bends.

FIGURE 2.5

Aerial Photograph of Upper Meandering Reach in 1947

North is to the top of photograph. Numbers represent studied bends.

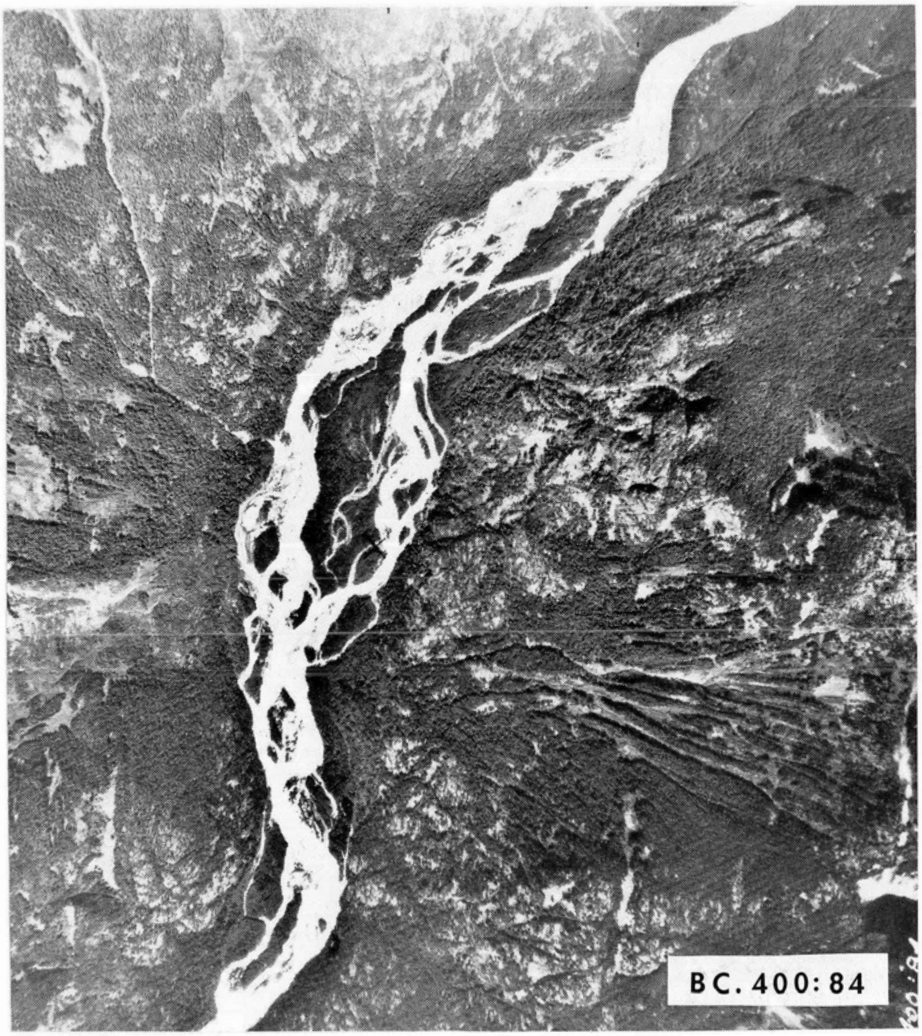
FIGURE 2.6

Aerial Photograph of Squamish-Ashlu Bend Reach in 1951

North is to the top of photograph. Numbers represent studied bends.

FIGURE 2.7

Aerial Photograph of Braided Reach in 1947



North is to the top of photograph.

2.5.3 Squamish-Ashlu Bend Reach

This reach is located in the transition zone between the braided and meandering planform types where the Squamish River joins the Ashlu River (Figure 2.6). The valley floor of the Squamish-Ashlu bend reach lies between about 80 and 120 m above sea level. This reach was selected for study because of the need to assess relative stability of bars and islands in the maintenance of the transition zone.

2.5.4 Braided Reach

The braided reach stretches downstream for about 20 km to the south from Turbid Creek at the head of Squamish River lying north of the 50 degree line of latitude. Located within the headwaters region the elevation of the valley floor of this reach is between 300 and 400 m above sea level. This reach was selected for study because of its distinctively braided planform (Figure 2.7).

CHAPTER 3: METHOD OF STUDY

A variety of methods for studying channel changes in fluvial geomophology are available. The choice of method employed to a large extent depends upon the objectives of study, and the quality and quantity of data available. The present chapter deals with sources, instrumentation, techniques and procedures followed in mapping channel changes in order to meet the objectives of the research.

3.1 Sources of Data

While many previous studies have used climatic and environmental data to assess channel changes; the present study uses mainly discharge and precipitation data published by Inland Waters Directorate (1983; 1984a; and 1984b) and Environment Canada (1982) respectively. Evidence of channel changes were obtained from B.C. Government photography for the following years: 1947, 1951, 1952, 1958, 1960, 1964, 1969, 1976, 1977, 1980 and 1982. In addition, photographs taken by the Pacific Survey Corporation in 1978 and 1980 were also used.

Moreover, small format aerial photography was obtained in the months of September and November, 1984 specifically for this research. Fortunately, the 1984 set of photographs bracket the highest recorded flood which occurred on October 8, 1984. The sampling frequency of observations of photographs used between 1947 and 1984 ranges from two months to seven years. However, this range varies from reach to reach. Old and latest topographical maps were also used but solely for the purposes of determing scales of photographs and as aids in selection of reference points used on base maps when mapping channel changes. These sources were supplemented with field observations in summer of 1984.

3.2 Evaluation of Approaches and Techniques for Studying Channel Changes

A variety of approaches for studying channel changes is available. The relevant approach adopted in this thesis is the graphical approach (Hooke, 1985) in which stream courses, determined from historical sources such as old maps and sequential photography, are superimposed to reveal changes. This approach is considered superior to others because it allows for the assessment of magnitudes and patterns of change at short timescales. A further advantage of this over other approaches is that directions of lateral movements of channels and relationships between channel form and movement can easily be established and the identification of stable river forms is made possible (Hooke, 1977).

The use of photographs in channel changes is complicated by problems of image distortion and variation in photograph scales.

These errors can be minimized, however, by use of appropriate correction methods.

Another problem relates to the frequency of sampling what essentially is a continuous process. In the final analysis, however, one is limited to what observations (in this case, aerial photography) are available. Church (1980) has stated that geomorphological processes are characterized in most places and at most times by relatively low rates of activity and by long elapsed time for cumulatively important effects to occur. The graphical approach based on sequential photography is well suited for studying slow rate channel processes.

A further difficulty with the use of photographs is the interpretation of the observed changes. Lewin (1977) observed that, although the general directions and rates of channel changes can be integrated over time between dates of photographs, these can seldom be related to the individual events which may have produced them. Lewin (1977) in justifying the use of this approach stated that:

> "However, given the timescale of pattern change, it is commonly necessary to use such sources of information whatever the problems may be. Provided these problems are recognized, results which are both useful, and for which there is no alternative, can and have been obtained."

The sections below deal with procedures, techniques and methods of measurement used in mapping and assessing channel changes on the Squamish River.

3.3 Mapping of Geomorphological Features

The use of sequential photography to assess channel changes entails comparing changes in channel location and other geomorphic features between different dates. To achieve this both active and formerly active channel systems, islands, vegetated and unvegetated bars were mapped and delineated. Mapping of channel changes was done in three stages. Firstly, a total of 310 aerial photographs with scales ranging from 1:68,000 to 1:10,000 were interpreted and all geomorphological features in the channels mapped, classified and inscribed on to an emulsion backed acetate paper using Bausch and Lomb mirror stereoscopes. In the second stage maps obtained at the end of stage one, were transferred to a scale of 1:25,000, the scale at which channel changes were mapped. The last stage involved the mapping of channel changes and the production of final isochrone maps for the five study reaches.

3.4 Mapping Channel Changes

Maps obtained at the completion of stage one were transferred to a uniform scale of 1:25,000 using a C-240-D (ST) Photo Ace Process Camera. This was achieved by marking bars of 1 km in length on all maps according to the scales of the photographs from which they were inscribed. These bars were then adjusted to the 1 km bar on a scale of 1:25,000 before the maps were photographed.

Once the maps were on a uniform scale of 1:25,000 error analysis was conducted to determine their accuracy. With the aid of topographical maps, a sample of between two and five length distances on the maps were selected and measured using a ruler and a divider. By adopting the method used by Hooke and Perry (1976) the differences between measurements on (1:25,000 maps) and the same measurements on (topographical) maps were calculated as percentages of the latter. The arithmetic means and absolute values, means of standard deviations and absolute standard deviations of all measurements on each of the maps in the Cheakamus-Mamquam Reach were calculated and tabulated. The analysis showed that the errors of measured distances on the maps compared with the same distances on topographical maps were within 5% of the topographical distances.

However the reported accuracy of the compiled maps could have been considerably altered in the last stage of mapping. The study by Hooke and Perry (1976) is the best work providing detailed description of how error analysis on historical documents for geomorphological studies can be conducted.

In the final stage of mapping channel systems, islands and vegetated and unvegetated bars were mapped at a scale of 1:25,000. Because of slight variations in scales the maps were readjusted to the correct scale by using the Bausch and Lomb Zoom Transferscope, a technique also used by Werrity and Ferguson (1980). Measurements of areas of erosion and deposition were made from final maps using a Compensating Polar Planimeter.

Average areas of channel changes were calculated by averaging between 3 and 10 planimeter measurements (depending on how close the first three measurements were) and the results tabulated for analysis. A necessary requirement for sound results using this technique is to have an accurate base map to which all other maps are adjusted.

To meet this requirement base maps for study reaches were produced from mosaics of recent photographs with some features appearing on topographical maps incorporated. Creeks on the sides of the valley floor, rock outcrops where the river abuts into bedrock, and roads were used as reference points. Corroborative evidence of channel changes were obtained by field observation in the summer and fall of 1984 in selected locations.

For two reasons, mapped changes in the Squamish River from 1947 to 1984 concerned primarily two geomorphological features, namely: bank alignment, defined by flood plain vegetation (Sigafoos, 1964) and the boundaries of densely vegetated islands. Firstly, these two geomorphic features were found most suitable for mapping short-term channel changes in Squamish River without encountering problems of defining channel bank line from photographs taken at different flood levels. Secondly, the mapping of these two features was done so as to reduce complexity of the final maps. To further reduce the complexity of the maps three or four isochrone maps of each reach were produced.

The first map in each reach shows channel changes from 1947 to 1969 while the second map shows changes from 1969 to September, 1984. The third map shows changes observed between September and November 1984 caused by the October 8 major flood event. In addition to showing changes between September and November, 1984 the third map also shows the locations and extents of other geomorphological features within bankfull channels at the end of the study period. Recorded geomorphological features include bare, thinly vegetated and densely vegetated gravel bars, secondary and main channels. The recording of channel features in three separate maps has the advantage of allowing for a clearer tracing of changes in form and movement of channels in the entire period of study. This has been achieved without obscuring the observation of salient aspects of types and patterns of channel changes on the Squamish River between 1947 and 1984 because the last date of observation in the preceding map is the initial date of the map covering the period thereafter.

In summary, this study employs a graphical approach to investigate the character of channel changes in Squamish River. Aerial photographs are the main sources of evidence of channel changes supplemented with some field observations.

Although absolute assessment of errors contained in historical documents is considered to be exceedingly difficult (Stone, 1972) the author has a high degree of confidence in the methods and techniques used for this study. At best the measurements made from the compiled maps have an accuracy of +/-25 m for length measurements and +/-1.25 x 10^3 m^2 for area measurements on the ground. On maps measurements would be correct to the nearest 1 mm and 2 mm^2 for length and area measurements respectively. These are the smallest measurements that can be made accurately with the equipments used in this study.

Major types of changes which have characterized channel changes in Squamish River in the last forty years and the locations where these were observed are discussed in Chapter 4. In the section below methods of assessing bed load sediment are discussed.

3.5 Assessment of Bed Load Sediment Movement from Channel Changes

Changes in a reach of a river channel are essentially the net result of sediment supply and the import of materials by sediment transport. Many approaches are available for estimating bed load sediment transport using measured or calculated hydraulic variables (Graf, 1971; Yang, 1973).

Since assessment of channel changes is basically the analysis of amounts of erosion and deposition in rivers, rates of sediment transport can be calculated from measurements of these processes. This can be done by making use of areas or volumes of eroded and/or deposited materials from two or three dimensional data of changing channel morphologies. This study estimates amounts of sediment moving through reaches of Squamish River by area measurements with assumptions that sediment carried by the river originate from the stream bed and stream banks and that materials are transported and deposited within the same reach. Justification for these assumptions is obtained from Wolman and Leopold (1957), Leopold (1973) and especially from Simons et al. (1979) who stated that:

> "The amount of sediment contributed by bank erosion can ... be most accurately evaluated by analysis of aerial photographs of the system over a period of several years... Most materials eroded from the banks is usually transported only a short distance down the stream before it is redeposited in the form of bars, new bankline or bed material accumulations."

Chapter 5 analyses in quantitative terms amounts of erosion and deposition and estimates of annual averages of areas of sediments moving through the studied reaches of Squamish River. Patterns and types of channel changes are discussed and analysed in qualitative terms in the next chapter.

CHAPTER 4: CHARACTERISTICS OF CHANNEL CHANGE

4.1 Introduction

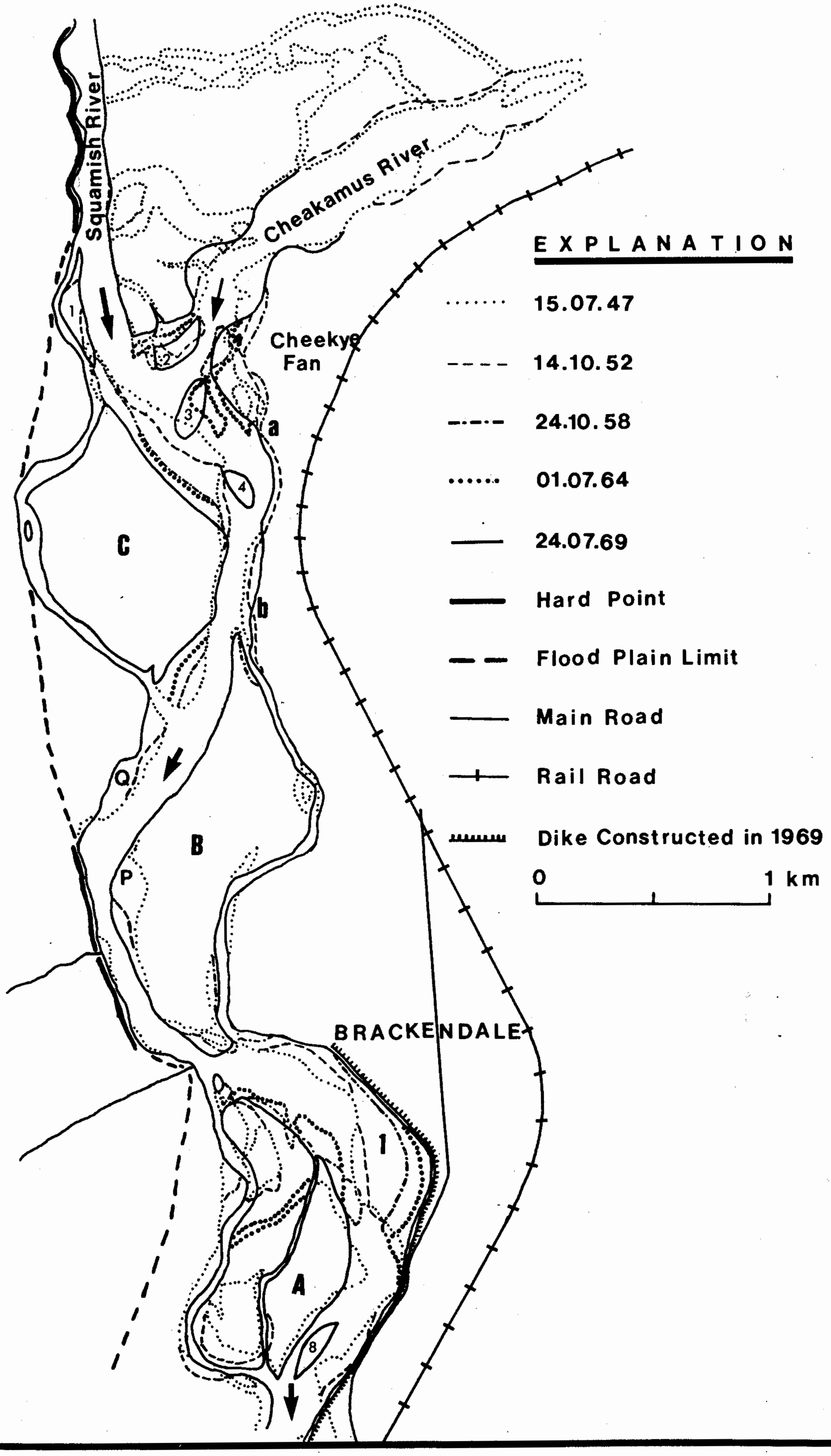
The purpose of this chapter is to present the results of the analysis of channel changes of Squamish River and to discuss their causes. The discussion of channel changes is on a reach basis which largely are differentiated on planform types.

In the timespan of about forty years Squamish River has experienced short-term changes which include formation and migration of islands, channel shifting and widening, downstream and lateral migration of river bends, flood plain construction and destruction and reactivation of old channels. Descriptions and explanations of these changes in different reaches are discussed below.

4.2 Cheakamus-Mamquam Reach

The Cheakamus-Mamquam Reach stretches from Squamish-Cheakamus confluence to downstream of Brackendale bend. In this reach the Squamish River is confined on the left bank upstream of the present Squamish-Cheakamus confluence and in places in the middle portion of the reach. Between 1947 and 1984 major channel changes in this reach have included downstream migration of the Squamish-Cheakamus confluence (Figure 4.1). This was caused by abandonment of minor upstream channels of the

FIG.4.1 CHANNEL CHANGES IN CHEAKAMUS-MAMQUAM REACH 1947-1969



Cheakamus River due to sedimentation and growth of vegetation in the channels especially during periods of low flows (Sigafoos, 1964). Downstream migration of the confluence was promoted by the restriction of Squamish River on the left bank and the subsequent downstream migration of islands formed at the mouth of Cheakamus River shown in Figures 4.1, 4.2 and 4.3.

Another major change in this reach was the growth of islands especially Brackendale Island (A) mainly by coalescing of small islands into a single large one. This occurred through the process of sediment deposition and growth of vegetation between islands and on gravel bars around the islands. In addition, sizes and shapes of islands changed over the years. There were also instances when whole islands disappeared and new ones formed that were not present in previous observation years (Coleman, 1968) especially around the Squamish-Cheakamus confluence. These changes are attributed to gradual erosion of island banks and/or destruction of islands by one or more flood events when the magnitude of erosion increased.

Major channel changes in Cheakamus-Mamquam Reach have also been characterized by downstream migration of Baynes Island (C) from 1947 to 1984 and Brackendale Island (A) from 1976 to 1984. This change is attributed largely to bank erosion at upstream ends of islands. Growth at downstream ends has been small due to removal of sediments by channels which surround the islands.

FIG.4.2 CHANNEL CHANGES IN CHEAKAMUS-MAMQUAM REACH FROM 1969 TO 1984

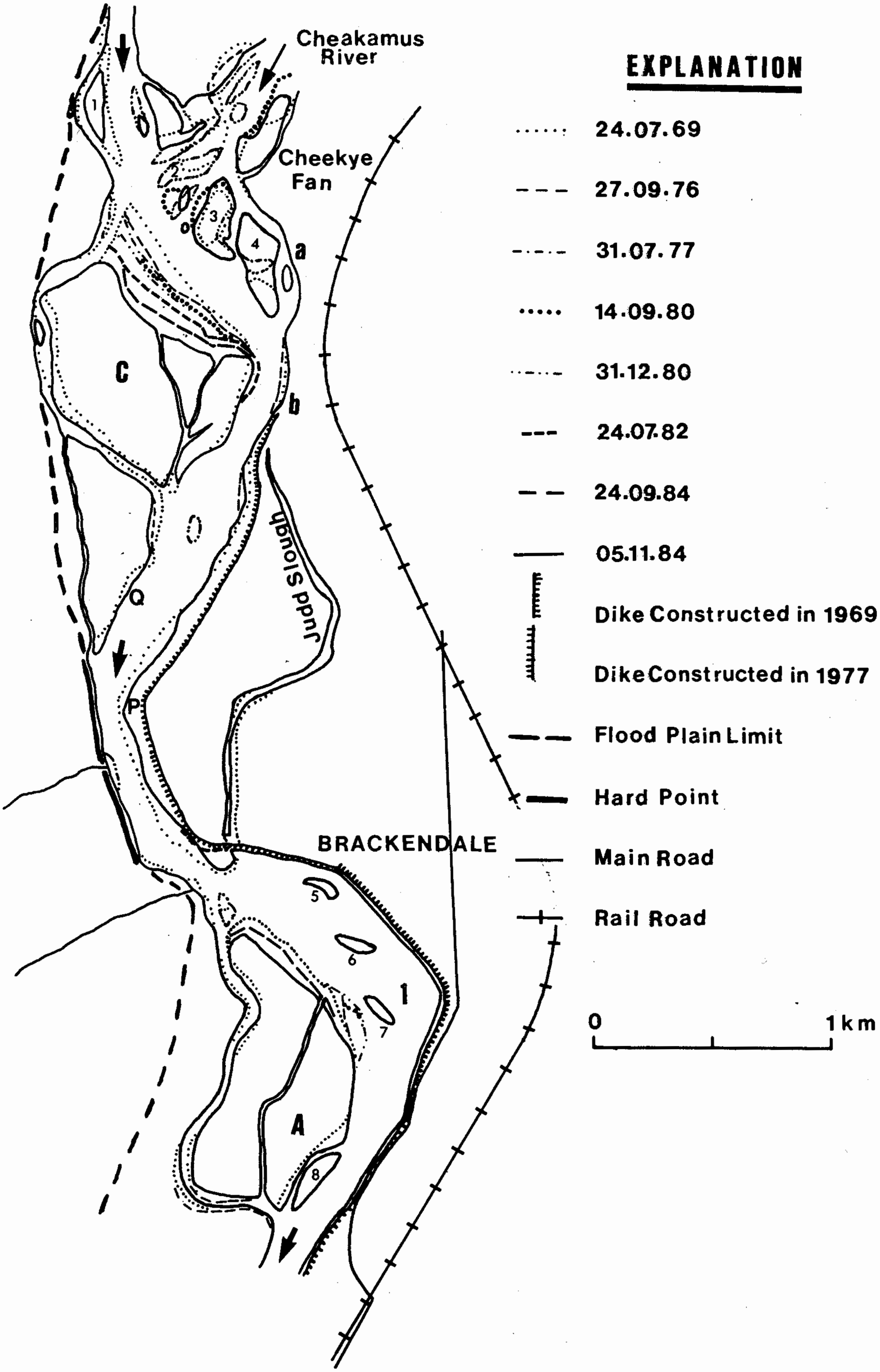
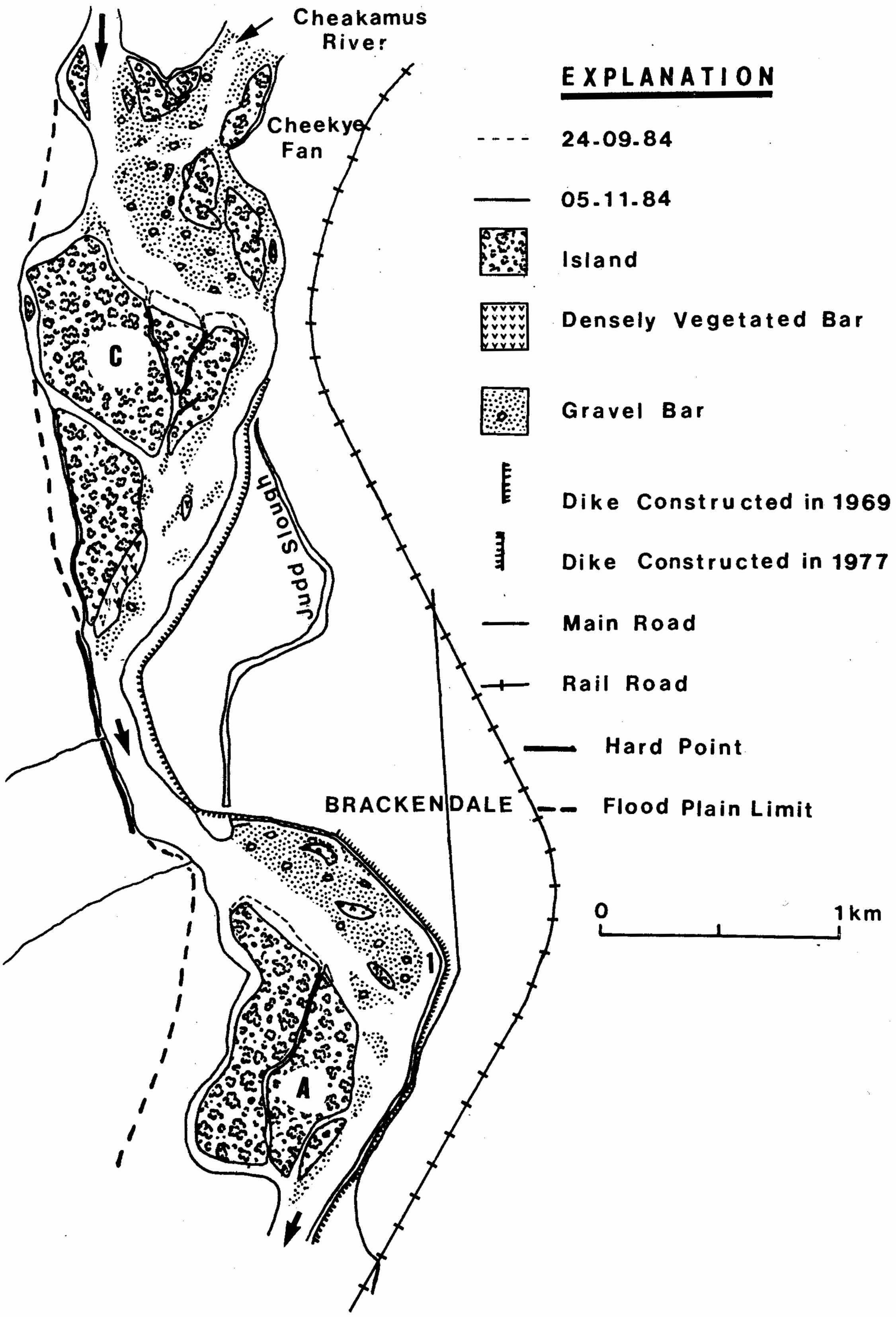


FIG.4.3 CHANNEL CHANGES IN CHEAKAMUS-MAMQUAM REACH IN 1984



Considerable lateral channel migration occurred at site (P) and (Q) and along the concave bank of Brackendale Bend (1) from 1947 to 1969 as Figures 4.1 and 4.2 show. Among other factors the migration of Brackendale bend (1) is explained in part by exceptionally high deposition of gravel sediments around Brackendale Island (A) and its subsequent development due to vegetation growth. The likely source of these sediments is the head of Baynes Island (C) which suffered tremendous bank erosion during the same period and erosion of the Cheekye Fan in the 1950's.

Whereas river equilibrium has been defined in terms of hydraulic geometry variables (Wolman, 1955; Leopold and Wolman, 1957; Leopold, Wolman and Miller, 1964) bar stability may be defined in terms of growth and establishment of vegetation converting it into a densely vegetated island within a specified period of time.

If the above definition of bar stability is accepted, then the vegetation and growth of Brackendale Island (A) may be seen as defining the period when the island was in a stable condition. Although natural river response is complex (Schumm, 1971; 1973; 1977) the lateral migration of Brackendale bend is seen as a response to the growth and stability of Brackendale Island (A) until 1976. This condition was brought about by the inability of the river to move the incoming materials through the reach. However, migration of Brackendale bend ceased after 1969 due to dike construction and by 1977 the right bank of the

Squamish River from downstream of Squamish-Cheakamus confluence was completely diked (Figures 4.1 and 4.2).

Dike construction introduced a man-made type of channel change which is blockage of minor channels. The now semi-active Judd Slough is an example of this change. As a result of diking the island marked (B) was cut from the active Squamish fluvial system between 1969 and 1977 and led to the continued erosion of Brackendale Island (A) shown in Figures 4.2 and 4.3. It was was expected that stream stabilization on one bank of Squamish River would have caused increased erosion on the unstabilised banks. This seems not to have happened perhaps because of the presence of bedrock in places on the left bank of the river. The increased channel width might have aided in the absorption of the effects of flooding events. The problem may have been compounded by the fact that bank stabilization has altered the threshold values at which channel changes can easily be identified.

Fairbridge (1980) has defined threshold in geomorphology as an upper limit to some cumulative process beyond which that particular sequence of events is terminated and a totally new sequence is introduced. Stated in this form the threshold concept (Schumm, 1973; 1980) can be used to support the inference that the erosion of the upstream end of the Brackendale Island (A) after 1977 is the consequential effect of the stimuli provided by bank stabilization. Thus, the natural threshold condition of island stability and growth was exceeded and in reverse a new process of island erosion introduced. This type of change is a manifestation of the effects of bank stabilization on channel processes and awaits further detailed investigation.

4.3 Meandering Reach

Although depth and velocity are implied in the magnitudes of floods the hydraulic factors of Squamish River are not included in the discussion of channel changes. This section deals with changes in the planimetric properties of meanders such as shape and width. For mapping purposes the meandering reach of Squamish River has been divided into the Lower and Upper Meandering Reaches discussed below.

4.3.1 Lower Meandering Reach

Channel changes in the Lower Meandering Reach of Squamish River include the cutoff of an old meander loop prior to 1947 as Figure 2.4 shows. This might have happened in the late 1930's or 1940 when there was a major flood. In the period 1947 to 1984 major channel changes in this reach have been characterized by downstream migration of meander Bends 2 and 3, largely due to erosion of the upstream ends of convex banks and downward migration of the concave bank in bend 2. Bend 3 is an example of a confined bend due to the existence of bed rock or 'hard point', term used by Brice (1964), on the concave bank. Because of confinement the convex bank of Bend 3 has experienced erosion both from the upstream and downstream banks. The downstream bank (Figures 4.4 and 4.5) constitutes an indirect attack of the river caused by the controlled alignment of the flow (Brice, 1964). This has caused narrowing of the flood plain forming the convex bank between 1980 and 1982. Two major floods of 1980 and 1981 are the most probable and sufficient causes of this change.

The realignment of the river at Bend 3 introduced another major type of channel change. This is the retreat of the flood plain at the convex bank by about 225 m. The consequence of this was the widening of the river width and straightening of Bend 3. This change resulted in the attack of the river to be directed at the upstream end of convex bank of Bend 2. Although the erosion of convex and concave banks of Bend 2 has been gradual (Figures 4.4 and 4.5), the magnitude of erosion of the convex bank between September and November, 1984 of about 75 m at the point of maximum erosion and the destruction of the flood plain by 1.7×10^4 m^2 in area (Figure 4.6) is explained by the October 8, 1984 flood of record. This change is considered a major geomorphic event in this reach due to its dramatic occurrence.

Another type of change in the Lower Meandering Reach is the formation of concave-bank benches in concave banks of Bends 2 and 3. A concave bank bench has been defined as fine grained alluvial materials deposited at the concave bank of a tightly

FIGURE 4.4 CHANNEL CHANGES IN LOWER MEANDERING REACH FROM 1947 TO 1969

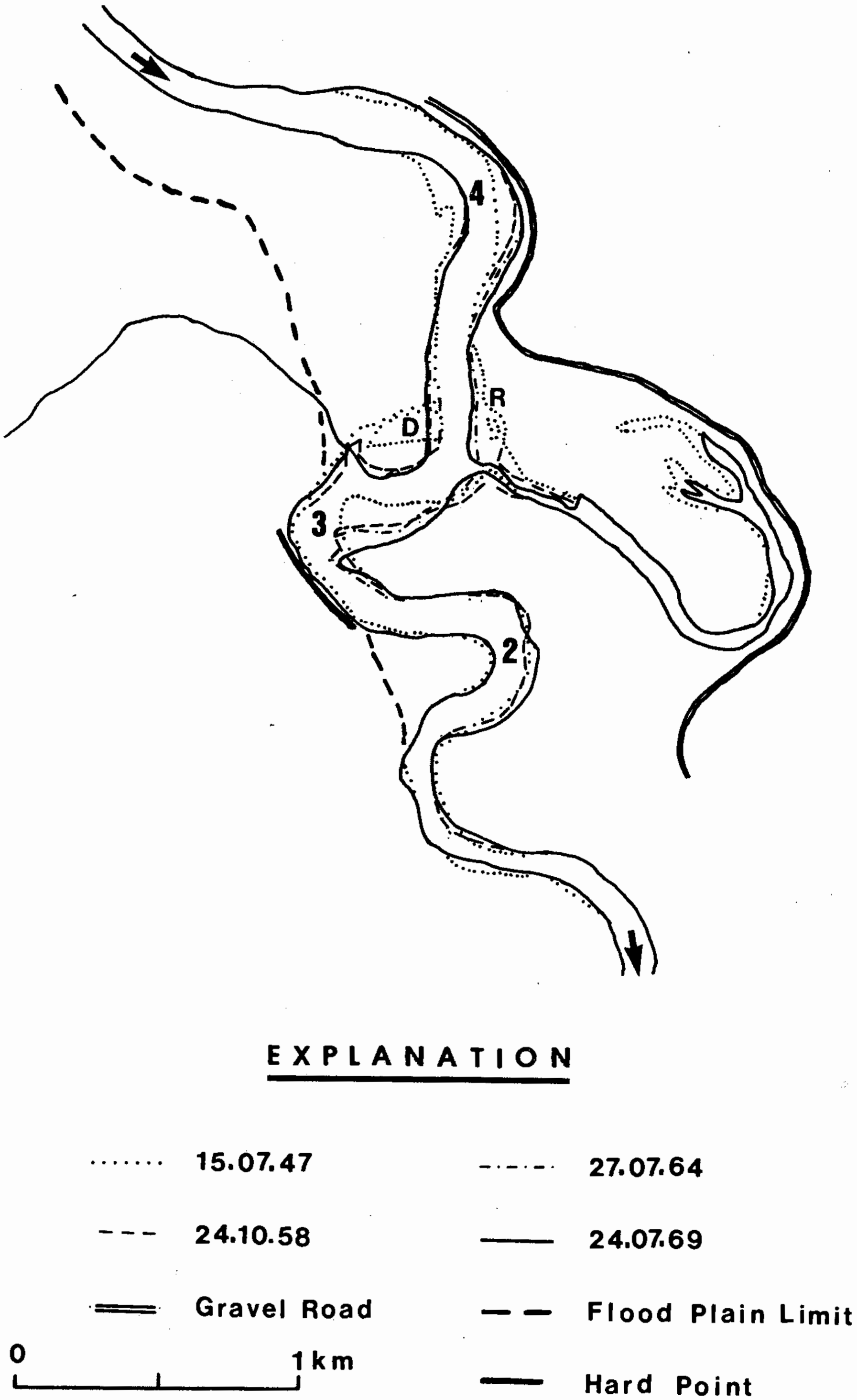


FIGURE 4.5 CHANNEL CHANGES IN LOWER MEANDERING REACH FROM 1969 TO 1984

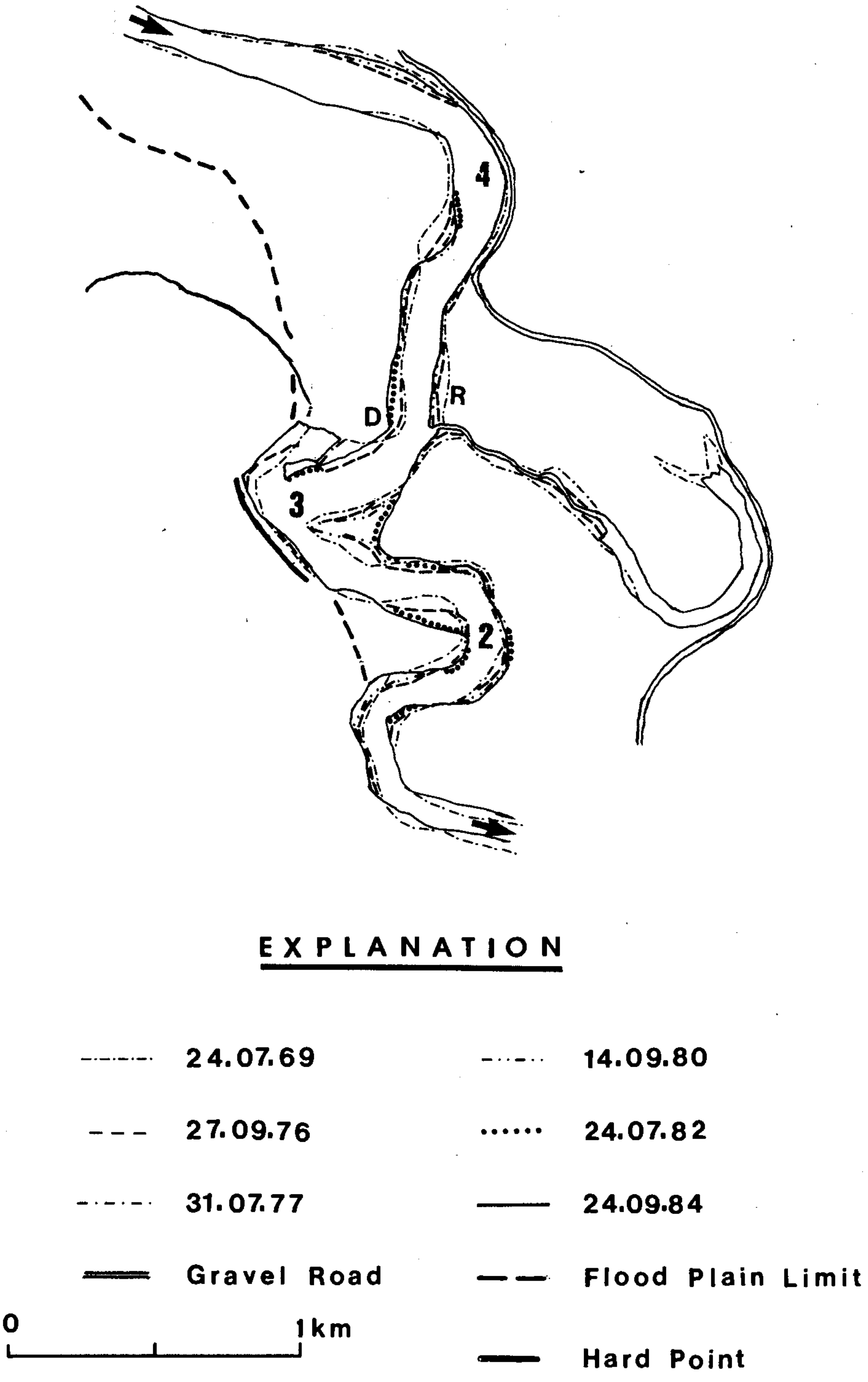
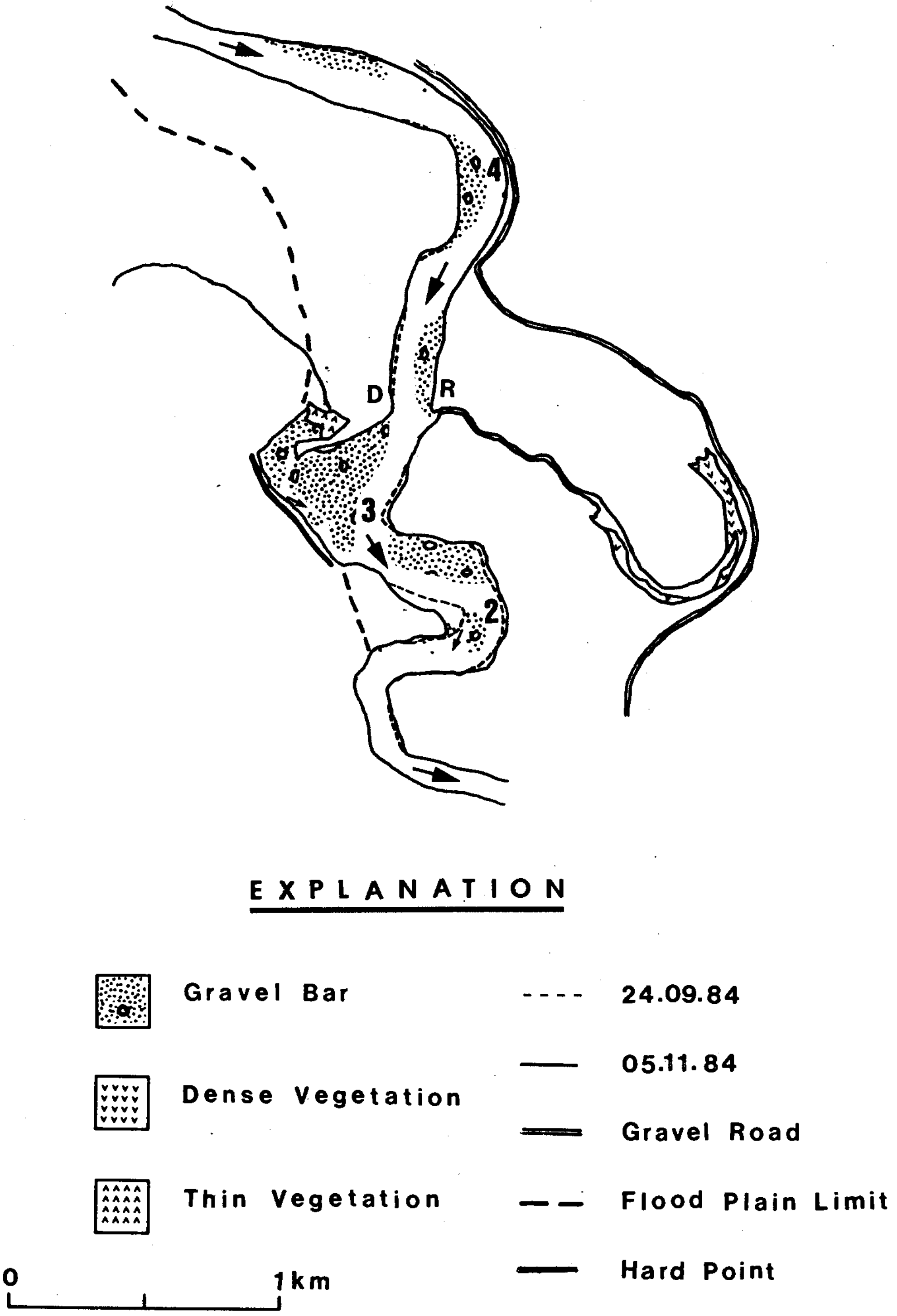


FIGURE 4.6 CHANNEL CHANGES IN LOWER MEANDERING REACH IN 1984



curved bend (Woodyer, 1975). In the studied reaches of Squamish River, Bend 2 and 3 are the only locations where this rare geomorphic feature has been observed. Although these concave benches were not identified on aerial photographs, they were observed in the field in the summer of 1984.

Hickin (1979) measured the dimensions of bank benches in Bends 2 and 3 and found the concave bench in Bend 3 to be about 400 m in length with an average width of 50 m lying horizontal at 2.5 m beneath bankfull water surface. By 1984 this bench has increased in area due to the retreat of the convex bank by bank erosion in the recent years. Hickin (1979) found the concave bench in Bend 2 to be 300 m in length with an average width of 50 m lying horizontal at about the bankfull stage level. Hickin (1979) estimated that erosion of this concave bench removed 200 m^2 of sediment.

Concave bank benches form essentially by the establishment of a separation zone nearer the concave bank with the fast flowing flow located nearer the convex bank. The establishment of a seperation zone may be achieved by the retreat of the convex bank which increases the channel width. Once these conditions have been created fine sediments from suspension advected into the separation zone by vortices and secondary circulation of helical flow are deposited (Hickin, 1979). The formation of concave bank benches has wider implications for changing river regimes. For instance, the extent of the bench may be used as an indicator of the period of time of uniform hydrologic condition. Hickin (1979) in reference to the concave bench in Bend 2, has observed that:

> "It appears that the position of the bench fore edge fluctuates by lateral erosion and deposition about some mean stream boundary.... It is probably a long term (5 years?) equilibruim feature which at any point in time may be undergoing extension by deposition or contraction by erosion... Longer term stability is dependent on the general pattern of river migration."

In the context of regimes of flow most of the deposition of sediments is likely to occur during periods of normal flows with some erosion taking place at bankfull stages. In periods of pronounced high-magnitude flows, erosion of the bench would predominate leading to its partial or complete destruction. Since the periods of both short term and long term equilibria are not known, it is not possible to say how long it would take for the feature to reform once it has been destroyed.

Lateral migration has characterized changes in Bend 4 between 1947 and 1969. This change is the result of concave bank erosion with concomitant flood plain construction at the convex bank aided by vegetation growth on the point bar (Figures 4.4 and 4.5). The training of the concave (outer) bank around 1969 to protect the nearby road stopped lateral migration of the bend. As result, in the period 1969 to 1984 there has been periodic retreat and readvance of the convex bank. The retreat of the convex bank is assumed to have occurred in periods of high flows due to erosion while readvance of the bank was achieved by point bar deposition and vegetation growth during periods of more moderate flows.

The process of convex bank retreat and readvance is explained largely by changing location of the thread of maximum velocity at bends during rising and falling flood stages. Mathews (1941) in attempting to clarify the misconception regarding the attack of shifting currents on concave banks observed that:

> "It is true that during ordinary stages and particularly falling-flood stages the thread of greatest velocity is close to the concave bank. However, during rising flood-stages the threads of maximum velocity tends to shift away from the outside of the curve towards the centre of the channel, and during a bankfull stage is usually found away from the concave bank... The thread of greatest velocity then scours across the convex bank...".

Erosion of the convex bank can occur at any bend but the confinement of the concave bank in Bend 4 tends to increase the frequency of this process.

While mapping channel changes it was observed that eroded stream banks in some locations had recovered in periods of 5 to 10 years. Rapid growth of vegetation in this environment promotes a short term recovery interval of stream channels. Sigafoos (1964) observed that once trees became established they persist for long periods of time and coincidentally preserve the location of the bank.

Flood plain construction as a major change occurred around Site (R) and around Island (D) in Figure 4.4 and 4.5. The flood plain has advanced in the channelward direction around site (R) due to vegetation growth on gravel bars on the bank where cutoff occurred. The cutoff itself has been vegetated to a large degree and most of it has been incorporated as part of the flood plain. On the bank opposite the cutoff flood plain construction has been in the downstream direction due to vegetation of the gravel bars and development of concave bank bench in Bend 3. Flood plain construction in this area has been speeded up by the growth of Island (D) and its subsequent attachment to the flood plain by channel abandonment (Schumm and Lichty, 1963).

4.3.2 Upper Meandering Reach

The meander bends marked 5, 7, and 8 in the Upper Meandering Reach in Figure 4.7 may be said to be migrating freely across the flood plain. But meander bend 6 is confined because it hugs the bedrock on the valley wall. The major channel changes in the Upper Meandering Reach include lateral and downstream migration of meander bends and island growth. Isochrone maps of channel locations in Figures 4.7 and 4.8 demonstrate that meander bends 5, 7 and 8 display developmental phases of meander migration similar to those proposed by Hickin (1977) shown in Figure 4.9. Bend 5 migrated freely from 1947 to about 1969 when the concave (outer) bank was trained by the emplacement of boulders on the bank to protect a nearby road. During the same period the convex bank migrated laterally due to deposition and vegetation stabilization of the point bar. After 1969 aerial photographs show evidence of periodic retreat and readvance of the convex bank as explained in section 4.3.1.

FIGURE 4.7 CHANNEL CHANGES IN UPPER MEANDERING REACH FROM 1947 TO 1969

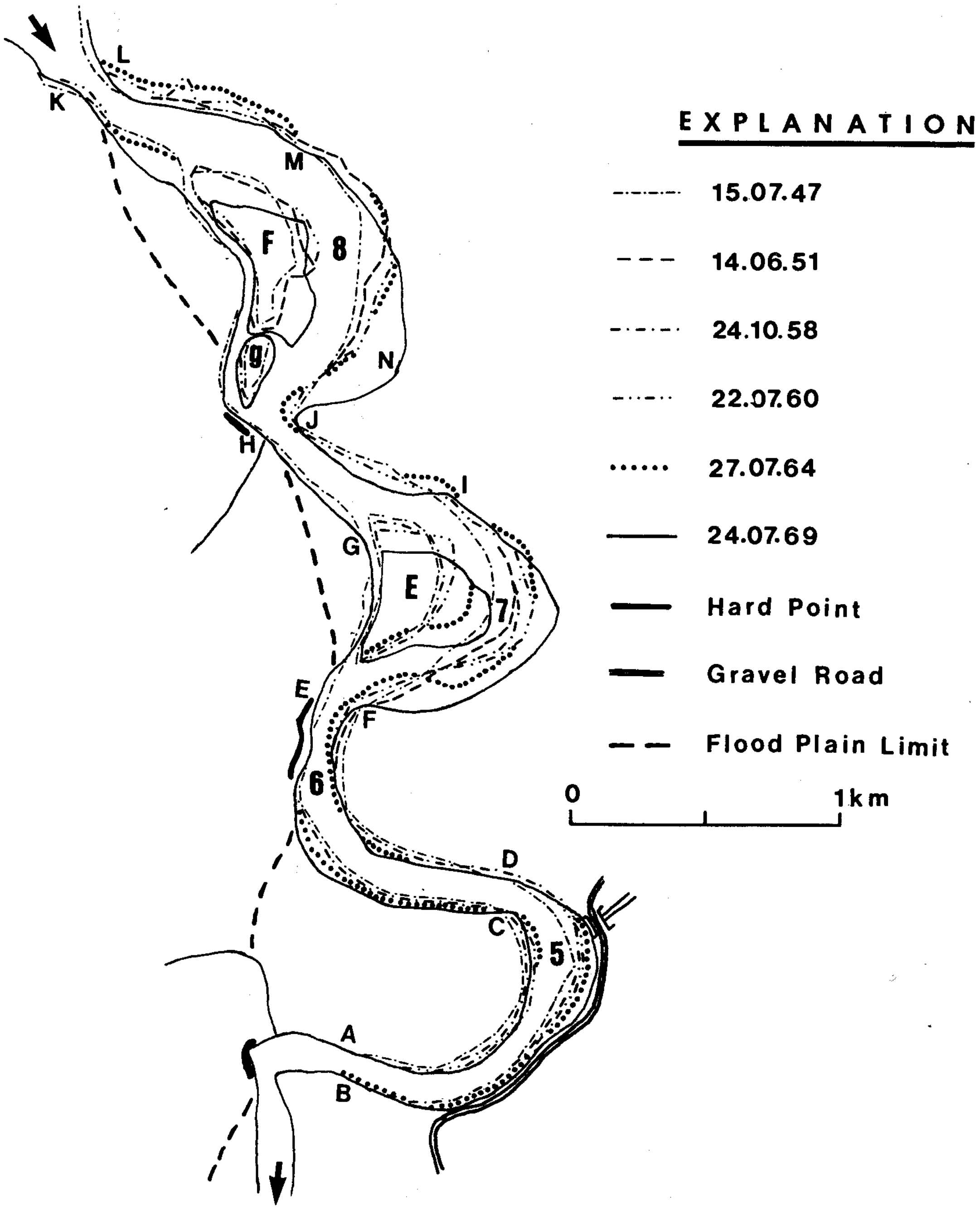


FIGURE 4.8 CHANNEL CHANGES IN UPPER MEANDERING REACH FROM 1969 TO 1984

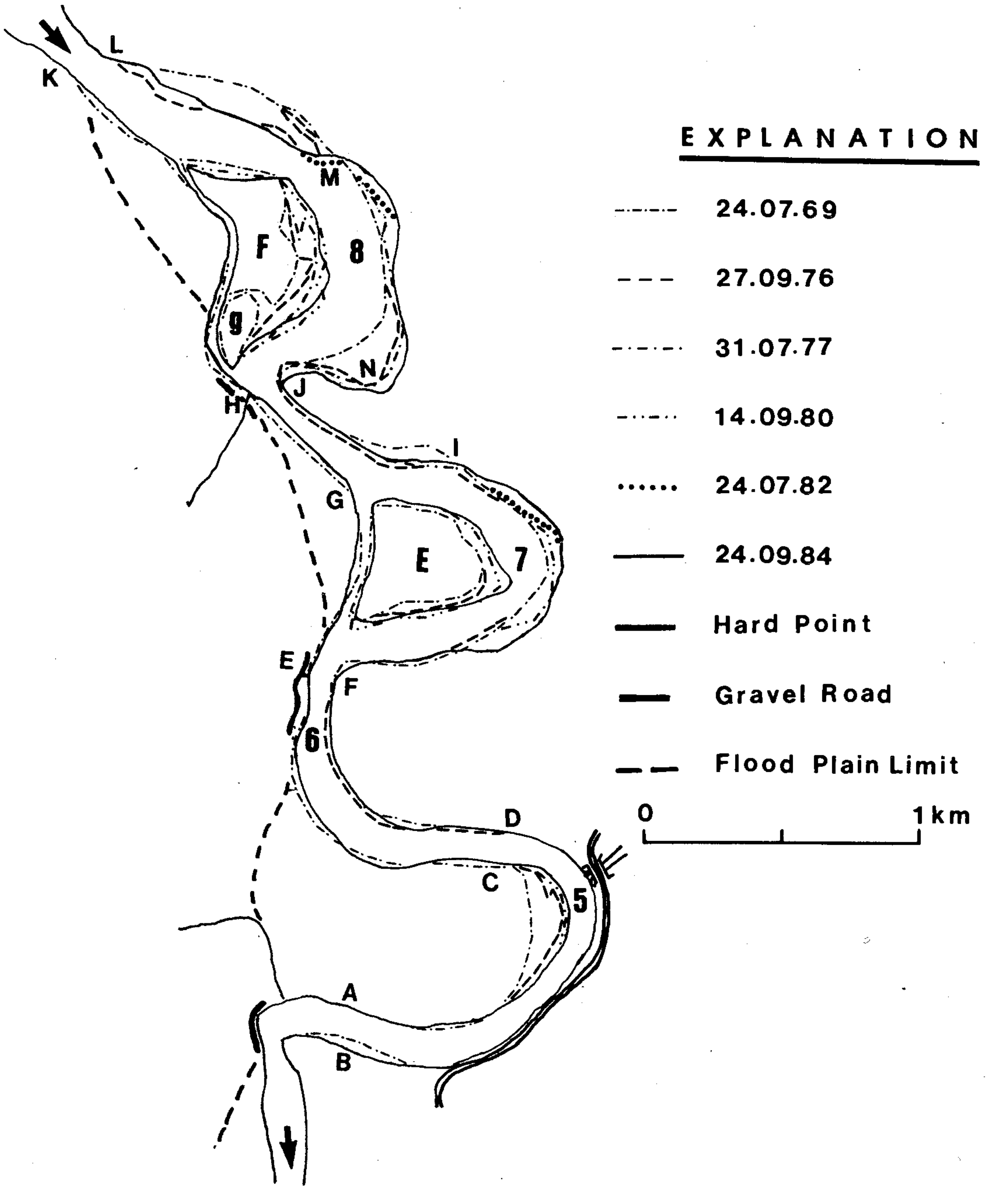
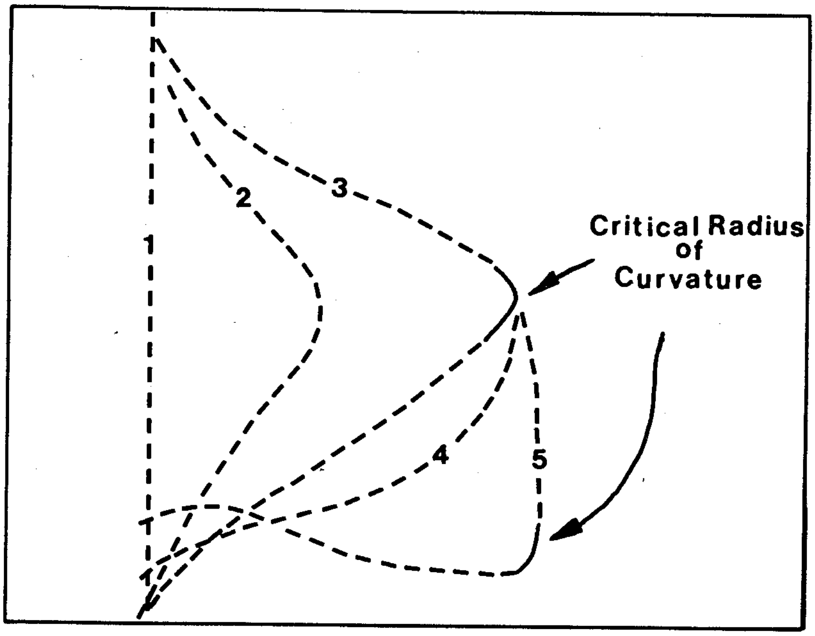


FIG.4.9 TYPICAL CHANNEL-MIGRATION PHASES IN A DEVELOPING MEANDER LOOP



Numbers represent phases of development.

Adapted from Hickin (1977; Fig.16.6; p.260).

Although the natural river processes have been interfered with in Bend 5, the bend has features of a meander bend in Phase Four of development.

In contrast, from 1947 to 1984, Bend 7 has continuously migrated lateraly mainly due to concave bank erosion and concomittant deposition on the convex bank of Island E (Figures 4.7 and 4.8). This type of migration is characteristic of a bend in Phase Two or Three of development. Unlike other bends Bend 8 has undergone two phases of development from 1947 to 1984. Between 1947 and 1964 Bend 8 was in Phase Two of meander development. In this phase the bend was freely migrating laterally at an almost constant rate. But after 1964 the pattern of development changed. The bend began migrating downstream passing through Phases Three and Four and is now in Phase Five. Bend 8 entered Phase Five after 1969 when the greatest amount of erosion was concentrated at site (N) shown in Figure 4.8. Thus, Bend 8 is now in the last stage of meander development which is characterized by downstream migration of bends.

Because Bend 8 has undergone two phases of development between 1947 and 1984 the meander forms of this bend before and after 1964 are different. Before 1964 the outer bank possessed a freely migrating semi-circular concave bank which straightened out after 1964 and became almost semi-rectangular in shape due to decreased lateral erosion on the upstream part of the bend and increased erosion at the downstream end.

Other channel changes in the Upper Meandering Reach include the growth of islands (E) and (F) mainly due to sediment deposition on the convex banks keeping pace with the erosion of concave banks in bends 7 and 8 respectively. Island (F) also grew due to the attachment of island (g) to it by sedimentation and vegetation growth. Islands (E) and (F), like the general changes in the bends, also migrated downstream due to erosion on the upstream ends and deposition on the downstream ends.

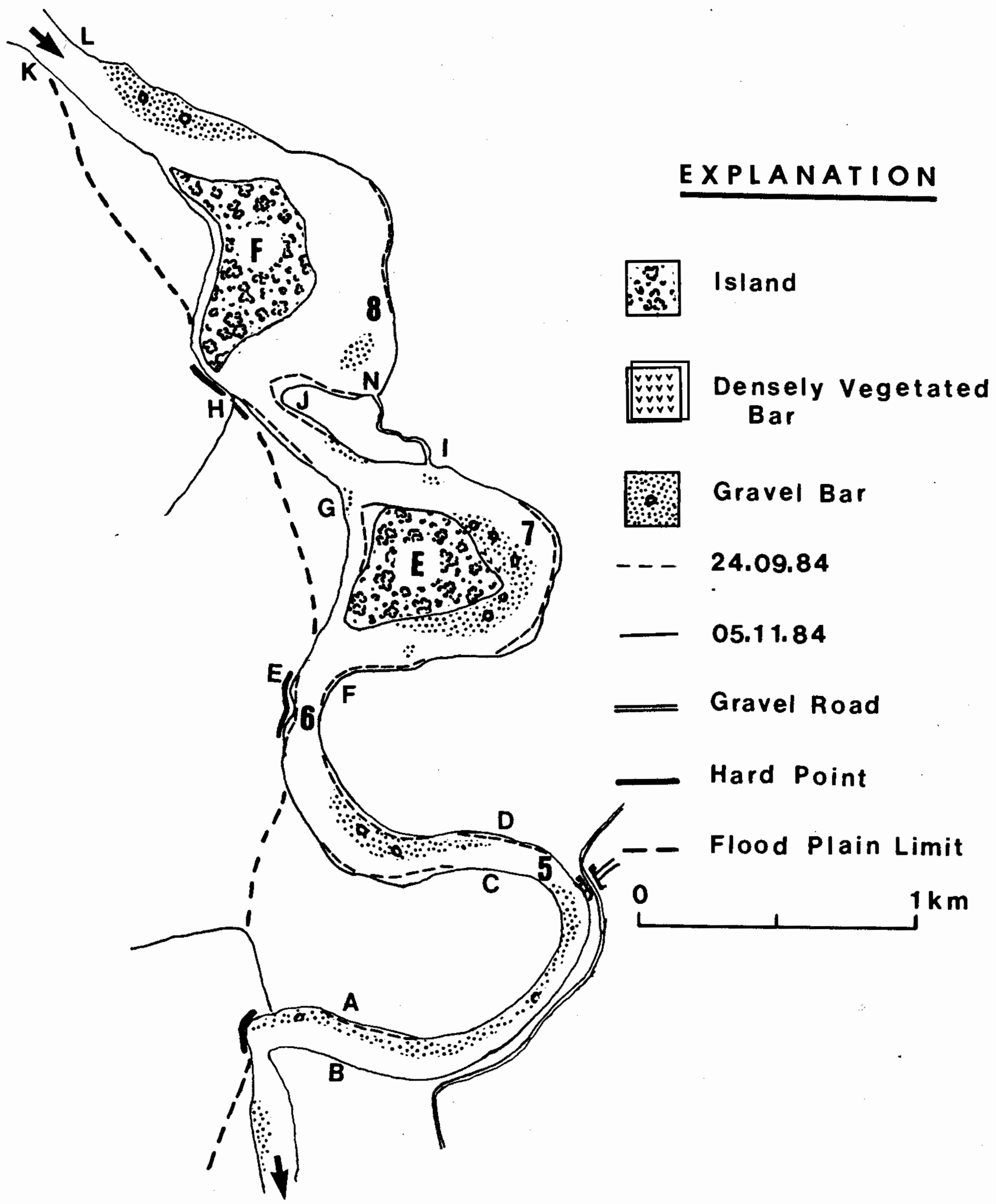
There was more erosion than deposition at site (N) perhaps due to the ease of erodibility of soils, allowing the concave bank to recede faster than the advance of convex bank of Island (E). It is possible that this process has been accentuated by the presence of bedrock at site (H) forming what Carey (1969) called 'abrupt-angle feature' of river development. In Figure 4.8 the downstream migration of point (J) and Island (F) confirm Carey's (1969) observation that:

> "...The abrupt-angle feature of river alignment migrates downstream in the same manner as the better known smoothly curving caving bend. The point bar island ...also migrates in an effort to keep up with the receding and migrating bend... However, the rate of movement for such an island is less than that of the remainder of the topographical environment."

This explains the small rate of movement of Island (F) and why the channel width at site (N) increased by more than half the 1947 width after 1964 due to increased concave bank erosion.

With a high degree of certainty predictions of future channel changes in the Upper Meandering Reach especially in meander bends 7 and 8 (Figure 4.10) are possible. In a period of

FIGURE 4.10 CHANNEL CHANGES IN UPPER MEANDERING REACH IN 1984



decades the secondary channel around Island (F) in Figure 4.10 is likely to be abandoned and the island joined to the flood plain since it is 'doomed to be left behind' (Carey, 1969) by the rapid downstream migration of the main channel. The other likely future change is the creation of an island at point (J) if and when the river takes a shorter straighter route at site (N) now occupied by an intermittent stream. This change would produce one or both of the following in Bend 7. Abandonment of the secondary channel around Island (E) causing excessive erosion of the convex bank of the island; or the shifting of the main channel into the minor channel eventually leading to cutoff of the meander loop.

4.4 Squamish-Ashlu Bend Reach

Channel changes in the Squamish-Ashlu Bend Reach have predominantly been bank erosion and island formation and destruction. Figures 4.11 and 4.12 show that the greatest amount of bank erosion occurred on the upstream bank of Island (I) with limited erosion occurring on the downstream bank. Most of the erosion occurred between 1947 and 1976 when the river bank line migrated a distance of 550 m causing erosion of 2.6×10^5 m^2 of the flood plain surface on the upstream bank. From 1947 to 1984 the downstream bank of Island (I) retreated a maximum distance of 200 m causing erosion of 1.2×10^5 m^2. The convex bank of Island (I) also experienced deposition and growth of vegetation causing bank erosion on the upstream end of the concave bank at

FIG. 4.11 CHANNEL CHANGES IN SQUAMISH-ASHLU BEND REACH FROM 1947 TO 1969

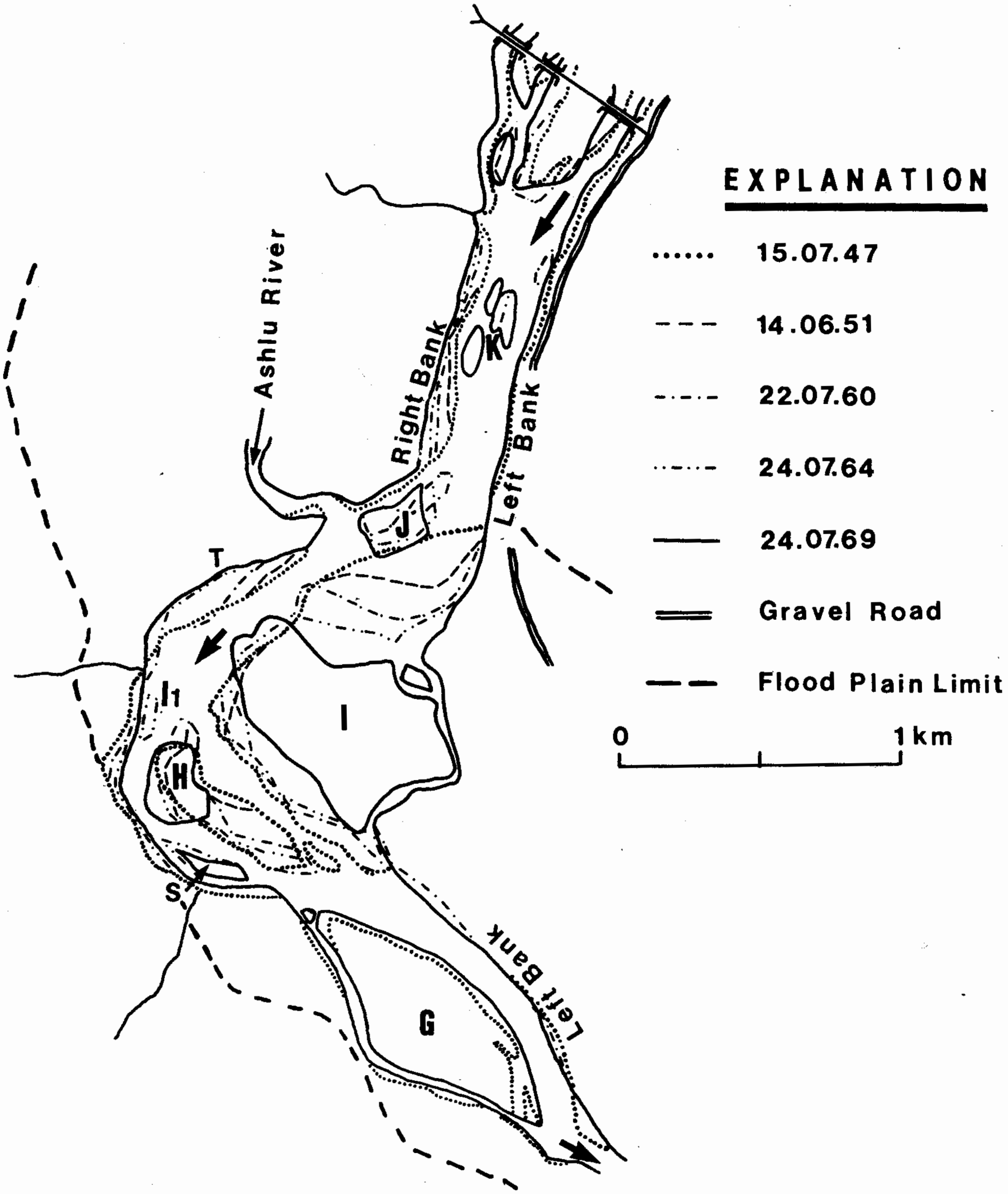
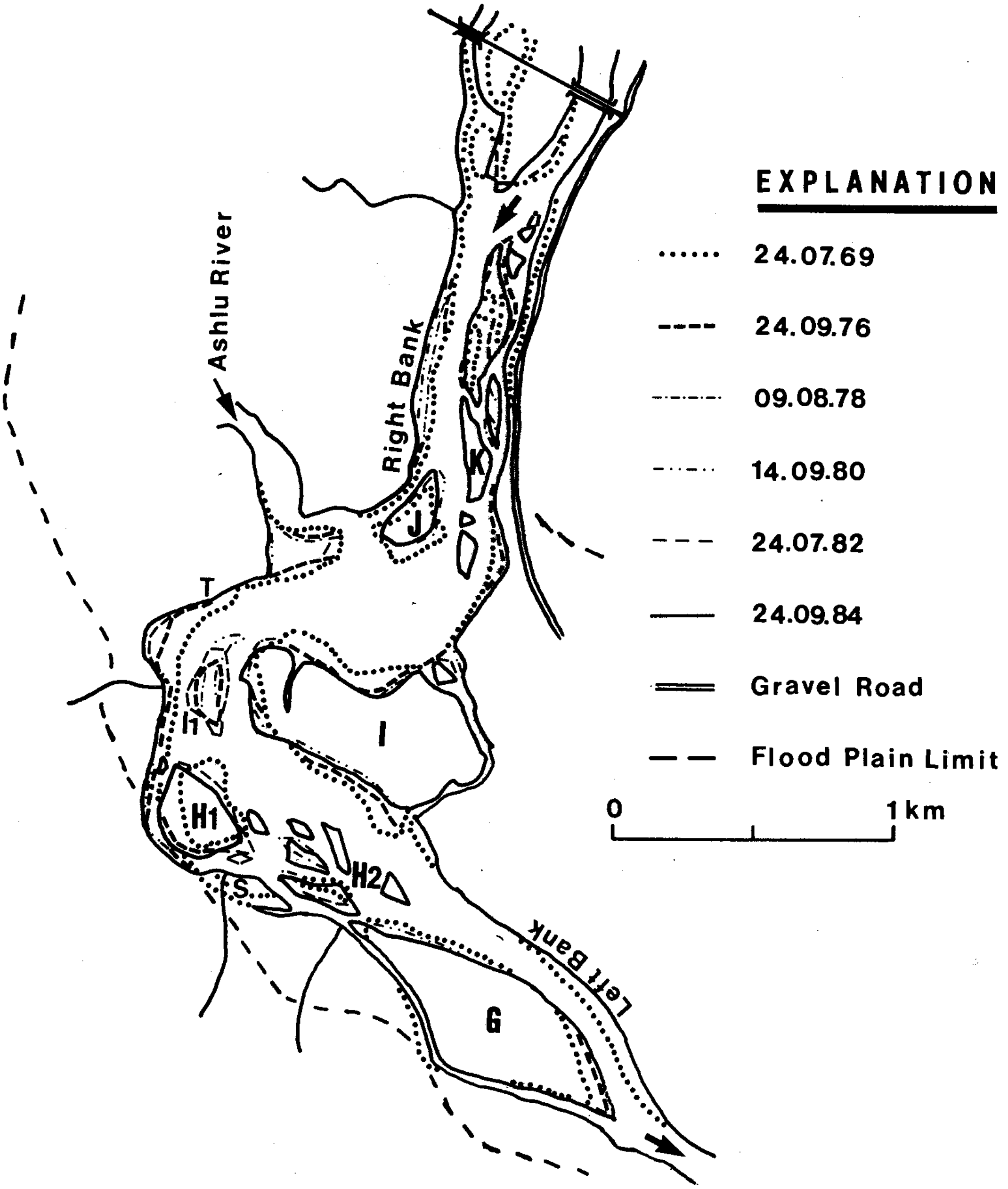


FIG. 4.12 CHANNEL CHANGES IN SQUAMISH-ASHLU BEND REACH FROM 1969 TO 1984



site (T).

The concave bank of the Squamish-Ashlu bend experienced deposition between 1947 and 1969 mainly due to alluvial fan formation and vegetation stabilization of gravel bar deposits. Alluvial fans have formed against the valley wall where sediments brought down by creeks cascading down mountain slopes have accumulated. Alluvial fans form the concave bank and have therefore contributed to the migration of the channel. But in the period after 1969 the alluvial fans have suffered erosion allowing the concave bank to migrate laterally.

Island formation and destruction by deposition and vegetation of gravel bars and erosion respectively, are other types of channel changes in this reach. These changes have been traced in Squamish-Ashlu bend reach. For instance, the downstream end of Island (H) suffered erosion from 1947 to 1969 when it was split into the two Islands (H1) and (H2) shown in Figures 4.11 and 4.12. During the same period (H1) grew in size on the concave bank keeping pace with the outward migration of the bend. Illustrative examples of island formation and growth and destruction are given by Islands (J) and (K) on the upstream side of the Squamish-Ashlu Bend.

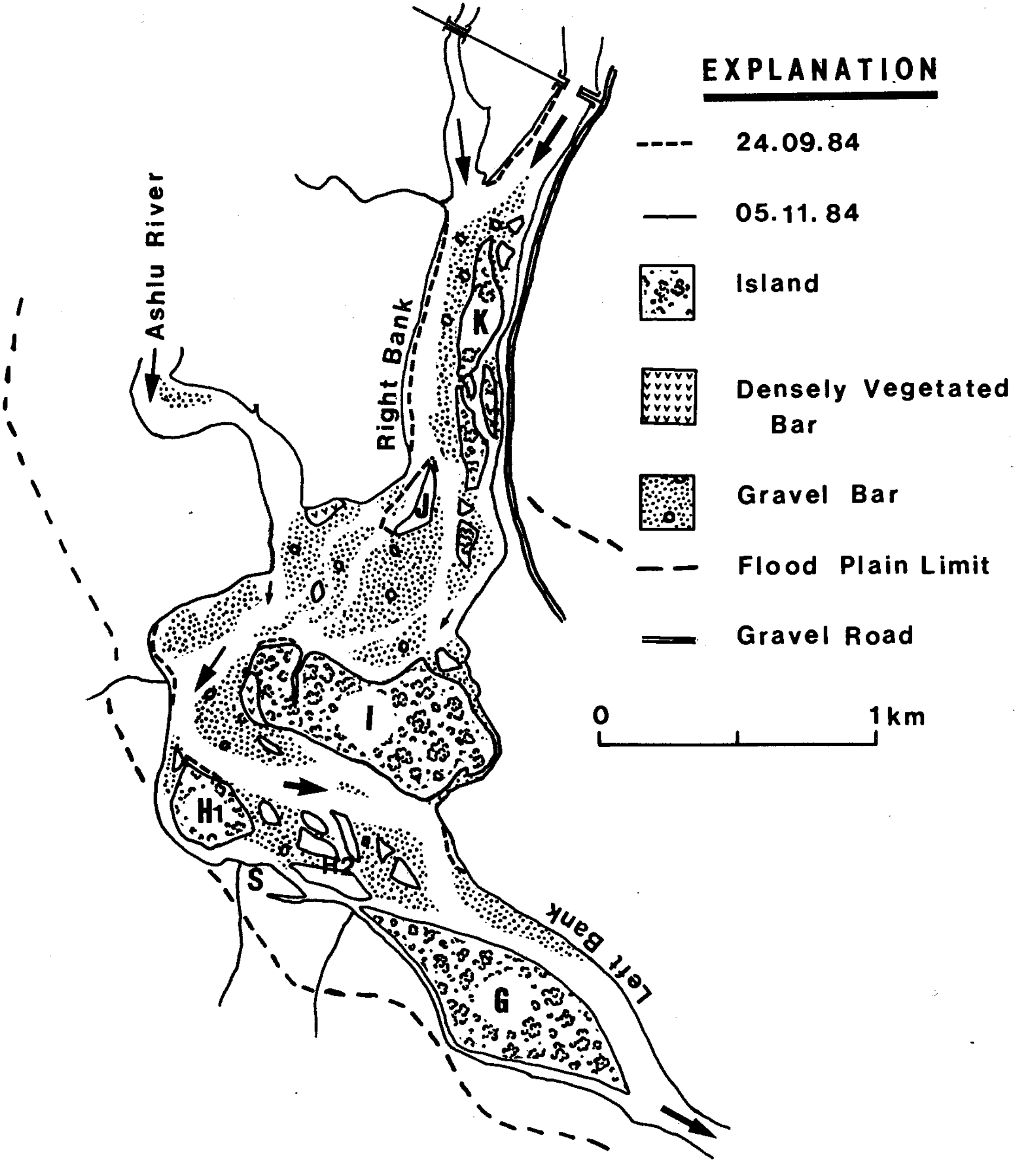
Island (J) emerged between 1951 and 1960 and by 1964 two islands had been established. The original two islands coalesced by sediment deposition and vegetation growth forming a large island as Figures 4.11 and 4.12 show. Similarly, Island (K) also emerged initially as three central gravel bars between 1960 and

1964 which became vegetated and by 1984 had grown into a large set of islands covering a total area of 7.3×10^4 m^2. The formation and growth of Islands (J) and (K) changed the single channel river in the 1940's and through the 1960's to braided. In response to the growth of Island (K) the Squamish River has adjusted itself by increasing channel width. This was achieved by lateral erosion of the right bank upstream of the Squamish-Ashlu confluence (Figures 4.12 and 4.13). The left bank instead experienced deposition and migration in the channelward direction by the processes of channel in-channel sedimentation and vegetation leading to channel recovery.

Some islands which were formed were later destroyed by erosion which ensued in subsequent years. This type of change has been traced in the formation and destruction of Island (I1) which formed around 1976 but was destroyed by 1984. Other islands, in particuler, Island (S) was attached to the flood plain. Island (S) developed as a lateral bar upstream of an alluvial fan around 1960. By 1969 the upstream end of the island was attached to the flood plain (Sundborg, 1956; Wolman and Lichty, 1963) and by 1976 the island was incorporated as part of the flood plain. The stability of Island (S) has to a large extent been promoted by the existence of a large alluvial fan immediately upstream of Island (G) in Figures 4.11 and 4.12.

Two dramatic channel changes have occurred in the Squamish-Ashlu Bend reach. The first is the downstream migration of the Squamish-Ashlu junction between 1980 and 1982 which moved

FIG. 4.13 CHANNEL CHANGES IN SQUAMISH-ASHLU BEND REACH IN 1984



by 200 m due to erosion of the downstream bank by high magnitude floods of 1980 and 1981. This change caused the Ashlu River to adopt a straighter route into Squamish River. The second major change is the erosion of 1.1 x 10^4 m^2 of Island (J) between September and November 1984. This was the work of the October 8, 1984 highest recorded flood. The high effectiveness of this flood can be judged by the knocking down of the Squamish-Ashlu bridge on the upstream end of the reach (Figure 4.13). Elsewhere, the October 8, 1984 flood caused massive erosion of islands in Cheakamus-Mamquam reach and excessive bend erosion in the lower meandering reach which have been discussed in sections 4.2 and 4.3 above. This flood also caused major changes in channel planform discussed in the braided reach below.

4.5 Braided Reach

Main types of changes observed in the Braided Reach include island formation and destruction, flood plain aggradation by deposition and destruction by bank erosion, new channel formation and reactivation of old channels by high floods. In 1947 the braided reach was characterized by numerous small islands with large vegetation-free gravel bars and anabranches. The period from 1947 to 1969 was a period of inter-braid island growth as a consequence of bar stabilization by vegetation (Carson, 1984) due to deposition both on the upstream and downstream end of islands (Coleman, 1968). The process of upstream erosion and downstream deposition resulted in the downstream migration of islands. The processes of downstream and upstream migration of islands are exemplified by Islands (L) and (M) in Figures 4.14 and 4.15 which increased in size in the 1950's and 1960's but decreased in 1970's and 1980's.

The high degree of island formation (braiding) in the braided reach is attributed to the high supply rates of bed-calibre sediments from the major landslide and debris flow of 1963 in Dusty Creek, a tributary of Turbid Creek on Mount Cayley (Clague and Souther, 1982). Sediment supply into the Squamish fluvial system is also augmented by bank erosion of alluvial fan deposits on the valley sides formed by creeks cascading down the mountain slopes. The abundant supply of bed-calibre sediments promotes channel shoaling, infilling of stream channels, and channel avulsion. Channel shoaling contributes directly to island growth and flood plain aggradation.

The processes of flood plain construction, channel abandonment and stabilization of gravel bars and alluvial fan deposits by vegetation has caused narrowing of the channel width. Reduction of channel width by these processes has been observed in the bottom part of the reach and around site (U) in Figure 4.15. This type of change is attributed to low frequency of high magnitude floods between 1969 and 1980. Although there were high magnitude floods in the years 1948, 1958, 1968 and

FIGURE 4.14 CHANNEL CHANGES IN BRAIDED REACH FROM 1947 TO 1969

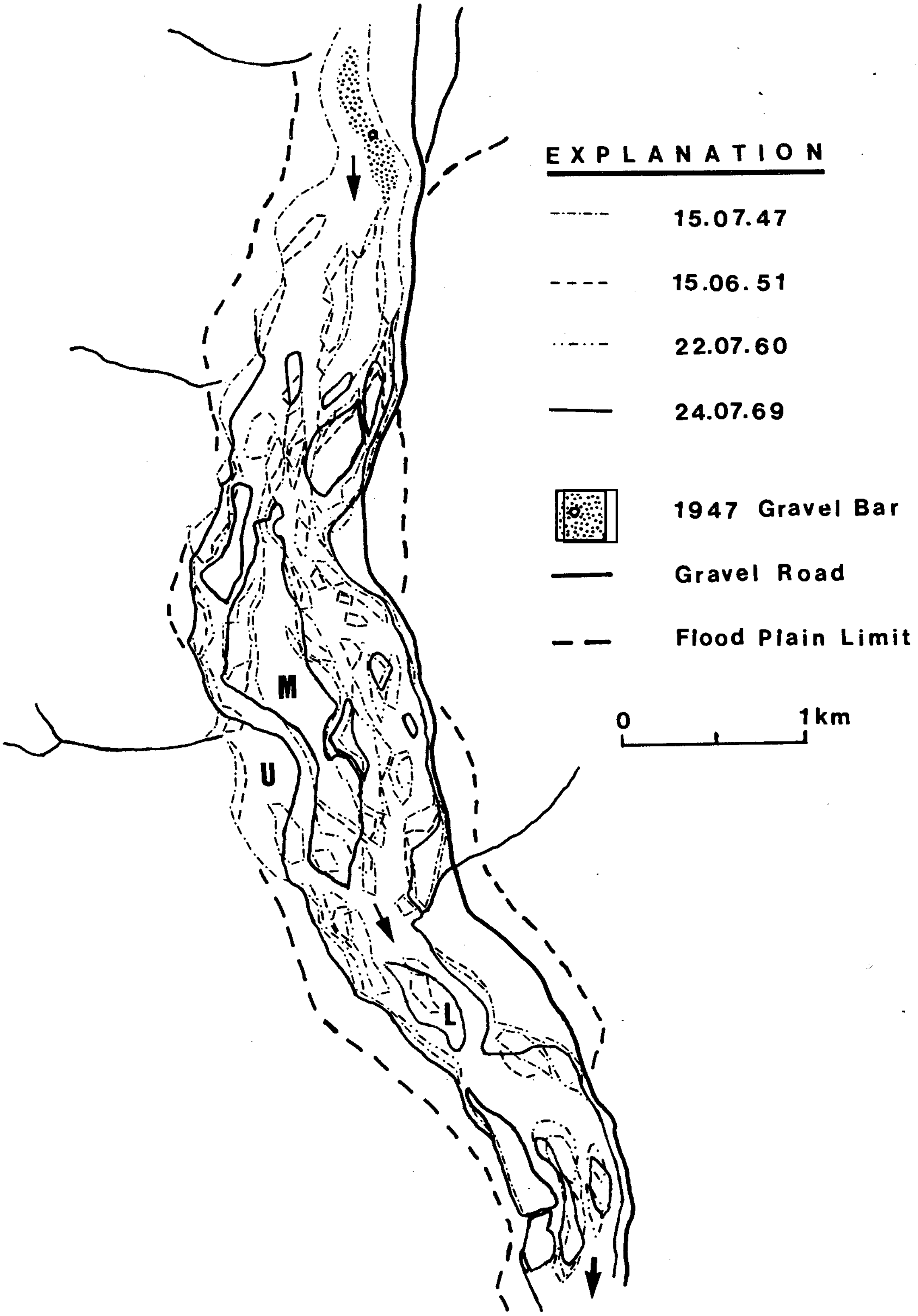
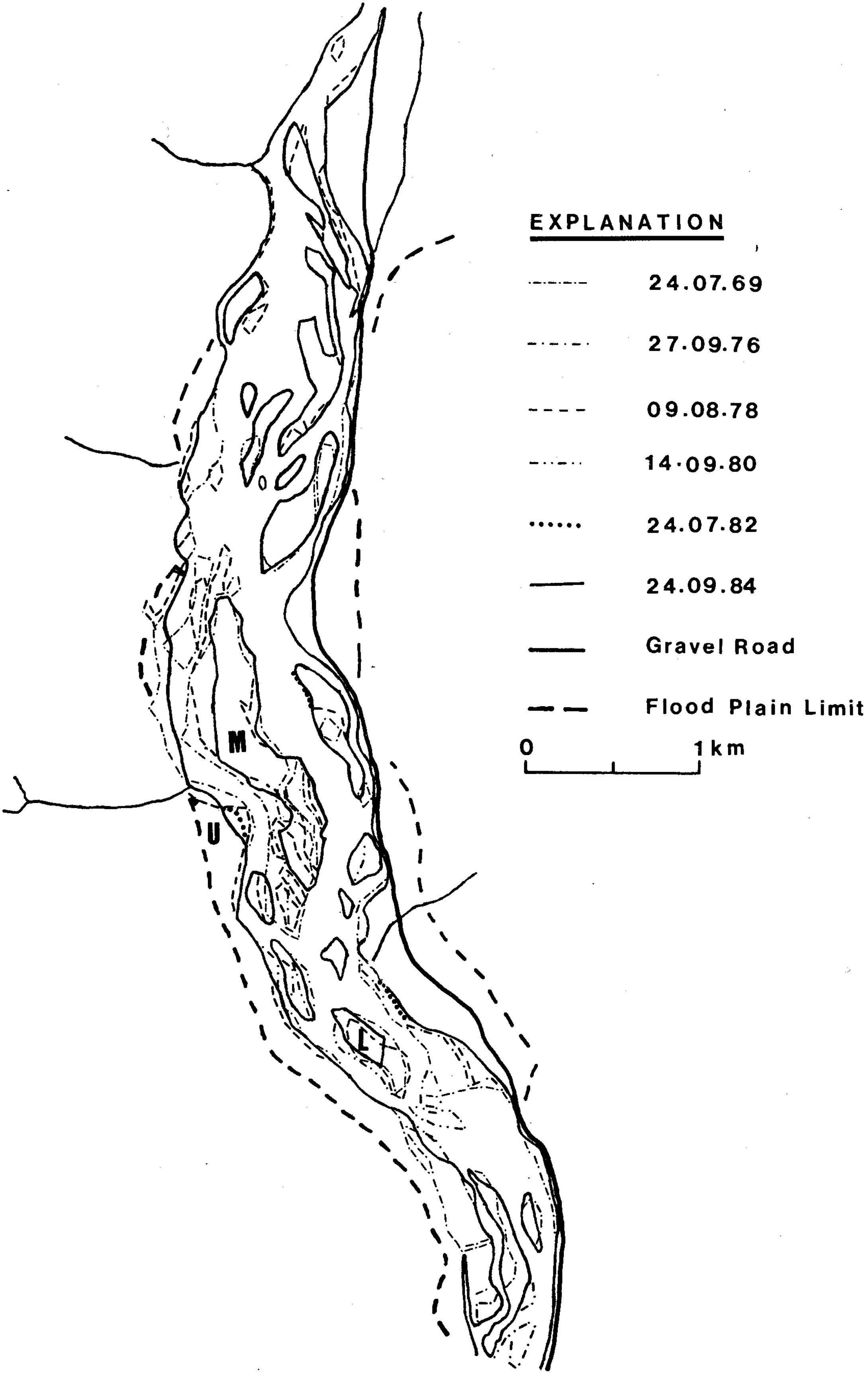


FIGURE 4.15 CHANNEL CHANGES IN BRAIDED REACH FROM 1969 TO 1984



1975 these seem not to have caused major changes perhaps due to longer observation intervals of the photographs used. That is, stream channels could have recovered from the effects of erosion in the intervening periods.

A more plausible explanation, however, is that although the recorded high floods between 1947 and 1980 were in the range of bankfull discharges at the measuring site near Brackendale, where the river is incised, these floods were much smaller in the braided reach. That is, based on the greater width and multiple channel configuration of the braided reach compared to the straight reach at the measuring site. This explains why the recorded high floods did not produce impressive geomorphic impacts in the braided reach prior to 1980.

In contrast, the period 1980 to 1984 has been characterized by island destruction mainly by reactivation of old channels and increased bank erosion. These changes are attributed to increased frequency of high magnitude floods during this period. The consequences of this has been multiplication of secondary channels and increased number of smaller islands (Figure 4.16).

Dramatic channel changes in the braided reach immediately downstream of Squamish Canyon occurred in 1984 as a result of the October 8, 1984 flood. This flood event created new islands by dissecting the flood plain and reactivating old channels (Figures 5.17a and b). In addition, the river reach changed from predominantly single channel before 1984 to two major channels

FIGURE 4.16 BRAIDED REACH IN 1984

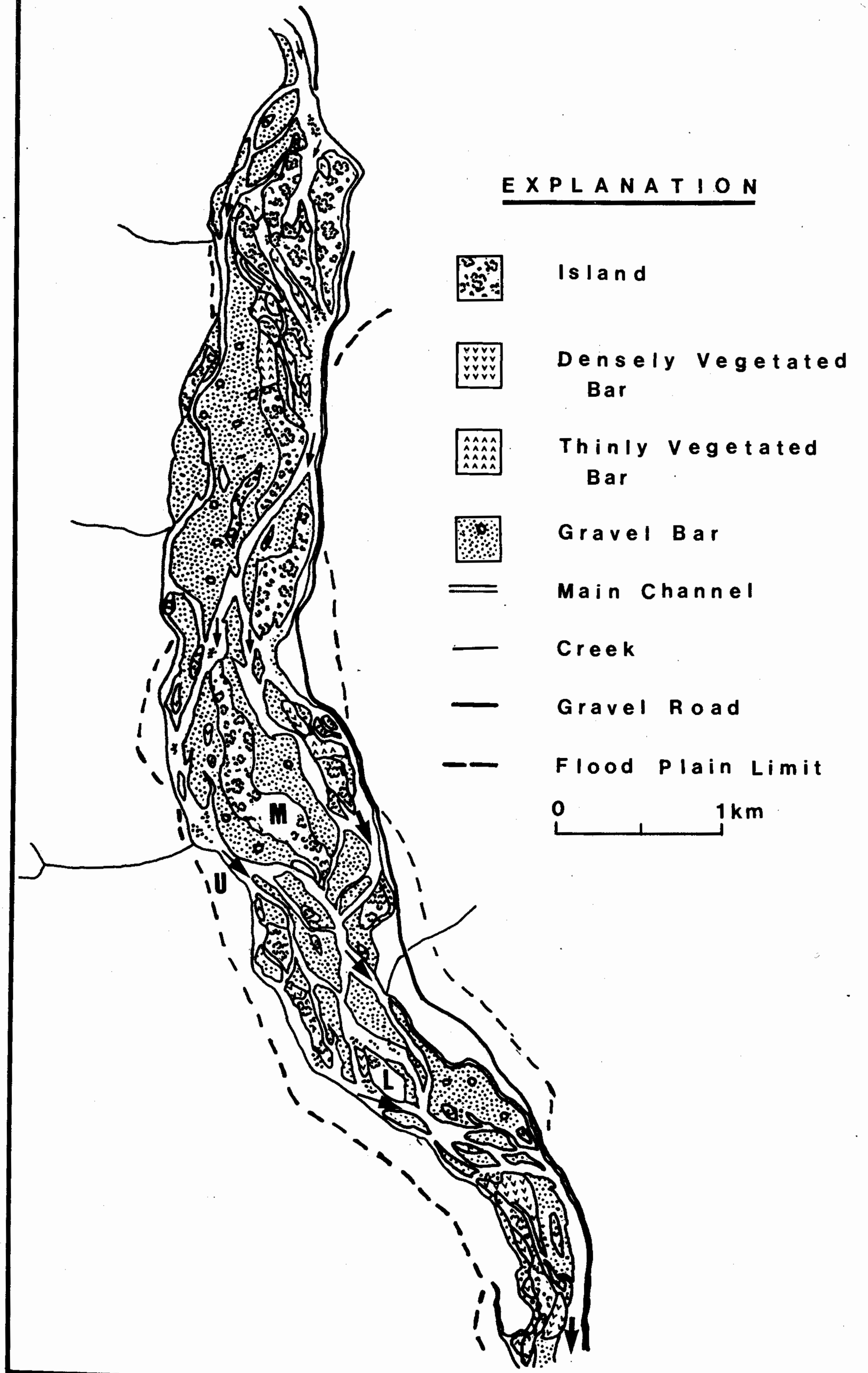
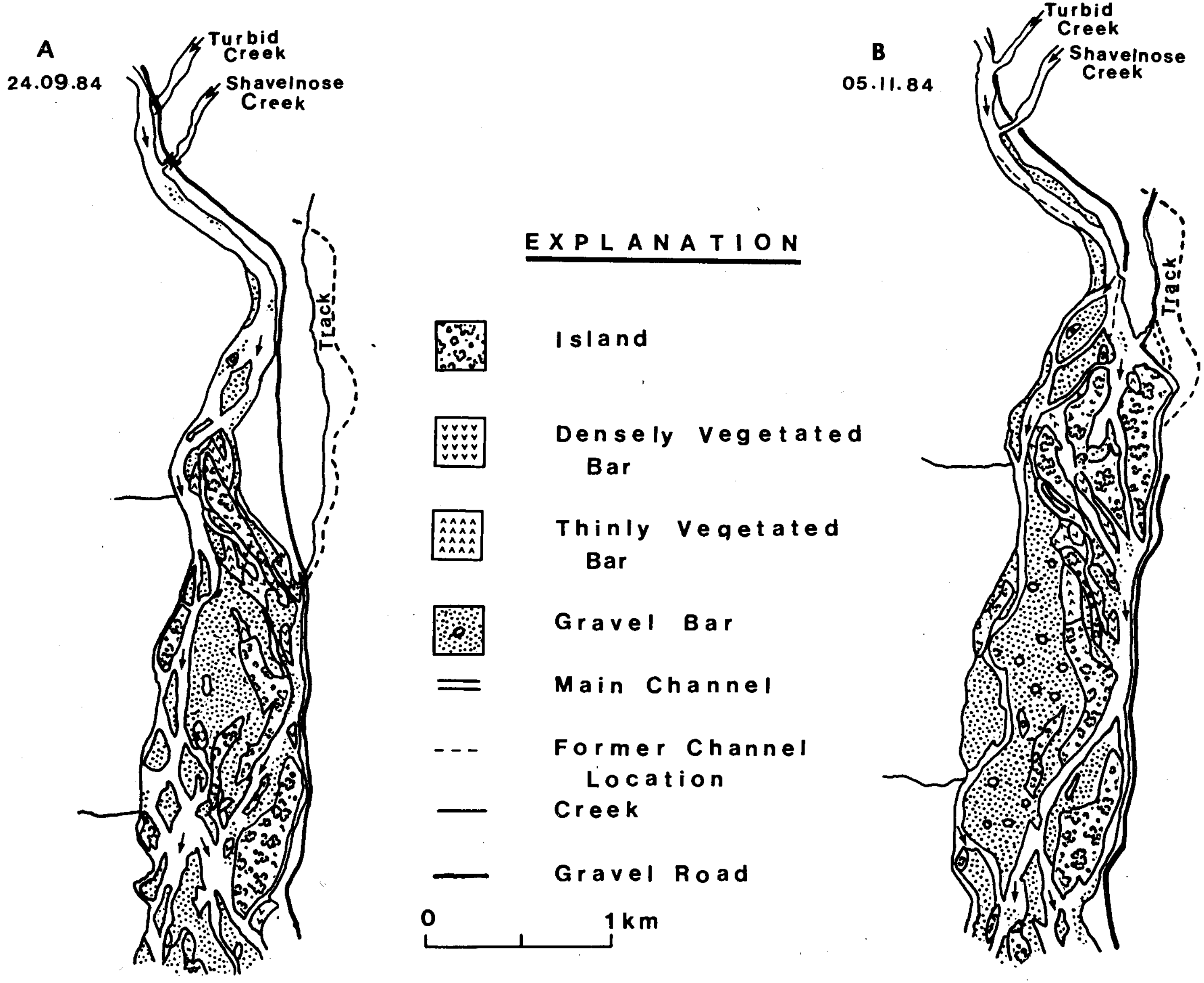


FIGURE 4.17

CHANNEL CHANGES IN BRAIDED SUBREACH IN 1984



after the flood. The channel width also increased as a result of this change. By any standard these changes constitute major adjustments in the morphology of Squamish River in this reach.

The October 8, 1984 flood destroyed about 1 km length of road and some new channels were created where the road was positioned. The reactivation of old channels has created new islands which between 1947 and 1984 were part of the flood plain. The obliteration of the pre-1984 river system and the emergence of a different system after the flood, was undoubtedly, accomplished through massive erosion and transportation of large quantities of fine and coarse sediments with variable effects downstream which cannot presently be analysed. The October 8, 1984 high flood is the only hydrological event in the last forty years which has produced impressive channel changes in the braided reach. In terms of magnitude this is the only flood in which the discharge exceeded bankfull. Instead the flood plain acted as the flood water channel scouring and reactivating old channels in the process. The above observation concurs with Carlston's (1965) observation of the effects of overbank floods that at higher flood stages the flood plain takes the role of a flood channel for the most efficient removal of flood waters.

The overbank flow of October 8, 1984 produced greatest geomorphic effects in the braided reach as far as changes in channel configuration are concerned. The extent to which these changes are a permanent feature in the landscape, however, is difficult to assess at present and should await further study.

4.6 Summary and Conclusion

The discussion of channel changes in Squamish River in the period 1947 to 1984 leads to the conclusion that the major types of changes have predominantly been excessive bank erosion and migration especially in bends, island formation and destruction, flood plain aggradation and destruction, and reactivation of old channels. Bank erosion was accompanied by widening of stream channels in the Cheakamus-Mamquam, Lower and Upper Meandering and in the Squamish-Ashlu Bend reaches. Higher bank erosion rates are attributed more to the magnitude of high floods than to their frequency in 1950's and 1960's. But in the 1970's and especially in early 1980's the higher rates of bank erosion are attributed both to the higher magnitude and higher frequency of high floods.

Island formation and growth characterise channel changes in the last forty years especially in the Brackendale Bend, Upper Meandering reach, upstream portion of Squamish-Ashlu Bend and braided reaches. Island formation and growth was predominant in most reaches with the exception of Baynes Island (C) which was continuously eroded between 1947 and the present. The continuous erosion of Baynes Island (C) is somehow unique in Squamish River because it is a direct consequence of downstream migration of the Squamish-Cheakamus confluence made possible by vegetation stabilization of bars at the mouth of Cheakamus River.

The process of island formation and growth which occurred in most reaches was dramatically reversed after 1980 due to intensified island erosion and destruction precipitated by increased frequency of high magnitude floods. High magnitude floods especially in 1980 and 1981 eroded large areas of stream banks and islands while the October 8, 1984 flood caused more erosion and reactivated old channels in the braided reach dissecting the narrow flood plain. Erosion of islands either on the upstream or downstream ends caused islands to move in the downstream or upstream direction depending on whether greatest erosion occurred on the upstream or downstream ends. A summary of major channel changes observed in Squamish River in the period of study is given in Table 4.1.

Flood plain aggradation or construction is one of the major types of changes observed in Squamish River in the last forty years. Flood plain construction occurred as a positive consequence of lateral bar stabilization by vegetation and by island attachment to the flood plain with the abandonment of channels separating such islands from the flood plain. Conversely, flood plain destruction or degradation occurred as a consequence of the migration of banklines in flood plain direction due to stream bank erosion and reactivation of old channels by high magnitude floods.

TABLE 4.1

Summary of Channel Changes in Squamish River from 1947 to 1984

Reach*	Site or Location	Type of Channel Change#
I	Bend 1	be conc- conv+ W+
	I's: (A),(B),(C)	be conv+ fpa fpd
II	Bend 2	be conc-+ conv-+ fpa fpd
	Bend 3	be conc- W+ fpa fpd
	Bend 4	be conc- conv+ fpa fpd
III	Bend 5	be conc- conv+ fpa fpd
	Bend 6	be conc- conv+ fpa fpd
	Bend 7	be conc-+ conv+ fpa fpd
	I(E)	I-+
	Bend 8	be conc- conv+ W+ fpa fpd
	I(F)	I-+
IV	Bend 9	be conc- conv-+ W+ fpa fpd
	I's: (G),(H),(I) (J),(K),(S)	I-+
V	Entire Reach	be I-+ fpa fpd patt old chann

Source: Abbreviations of types of change have been adapted from Gregory (1977; Table 1.1; p. 6-7).

*I = Cheakamus-Mamquam; II, III = Lower & Upper Meandering IV = Squamish-Ashlu Bend; V = Braided. I(A) = Island (and designation).

#be = bank erosion; conc-+ = concave bank (erosion)(deposition) conv = convex bank; W-+ = channel width (decrease)(increase); fpa/d = flood plain aggradation/degradation; old chann = reactivation of old chann.; patt = change in channel planform type.

CHAPTER 5: QUANTITATIVE ANALYSIS AND INTERPRETATION

5.1 Introduction

This chapter presents results of quantitative analyses of hydrological data, area measurements of erosion and deposition, and measurements of channel displacement for the nine photo periods. Factors causing channel changes and the implied rates of flood plain reworking are discussed for all but the braided reach. Magnitudes of channel changes are discussed in relation to magnitudes and frequencies of floods.

There are several problems concerning the measurement of channel changes from of aerial photographs. These include (i) the two dimensional nature of information obtained (Lewin, 1977); (ii) the difficulty of knowing the magnitude of change within the intervals between flood events, and (iii) the recurrence of non-linear responses and threshold conditions of river processes (Anderson and Calver, 1980); and (iv) the possible loss of information through mapping errors. These problems may cause misleading interpretations of channel changes but they remain as uncertainties. It is assumed, however, that the errors both in mapping channel changes and in measuring areas of erosion and deposition are small. The discussion of magnitudes of change is preceded by an analysis of the magnitude and frequency of floods in Squamish River.

5.2 Magnitude and Frequency of Floods

Peak discharges of monthly or annual flows, presented in this study, are referred to as floods 'whether or not they cause inundation' (Dury, 1969) of the flood plain. Recorded annual floods on Squamish River range from 700 to 2600 m^3 s^{-1}. The record of flood magnitudes from 1947 to 1984 are presented in Figure 5.1. Gumbel flood frequency analysis of the flood record in Figure 5.2 has shown that the annual bankfull discharge of the Squamish River is about 1100 m^3 s^{-1} (using the 1.5 year recurrence interval used by Leopold, Wolman and Miller (1964) and the 1.58 year recurrence interval used as a statistical definition of the most probable annual flood used by Dury (1969)). The bankfull discharge of Squamish River was also determined by the stage-discharge relationship method (Patton, 1977) by field survey of bankfull stage at gauging site near Brackendale. It was estimated to be 1600 m^3 s^{-1}.

If discharges between 1000 and 1200 m^3 s^{-1} are considered to be in the range of bankfull discharges which do not 'overtop' the banks (Richards, 1982), then discharges in excess of 1600 m^3 s^{-1} definitely do and may appropriately be considered equivalent to channelfull discharges. These high magnitude floods might be the ones which mould the form of channels in Squamish River and should be given particular importance. Lines of best fit in

FIG. 5.1 ANNUAL FLOODS ON SQUAMISH RIVER IN THE PERIOD 1956 TO 1984

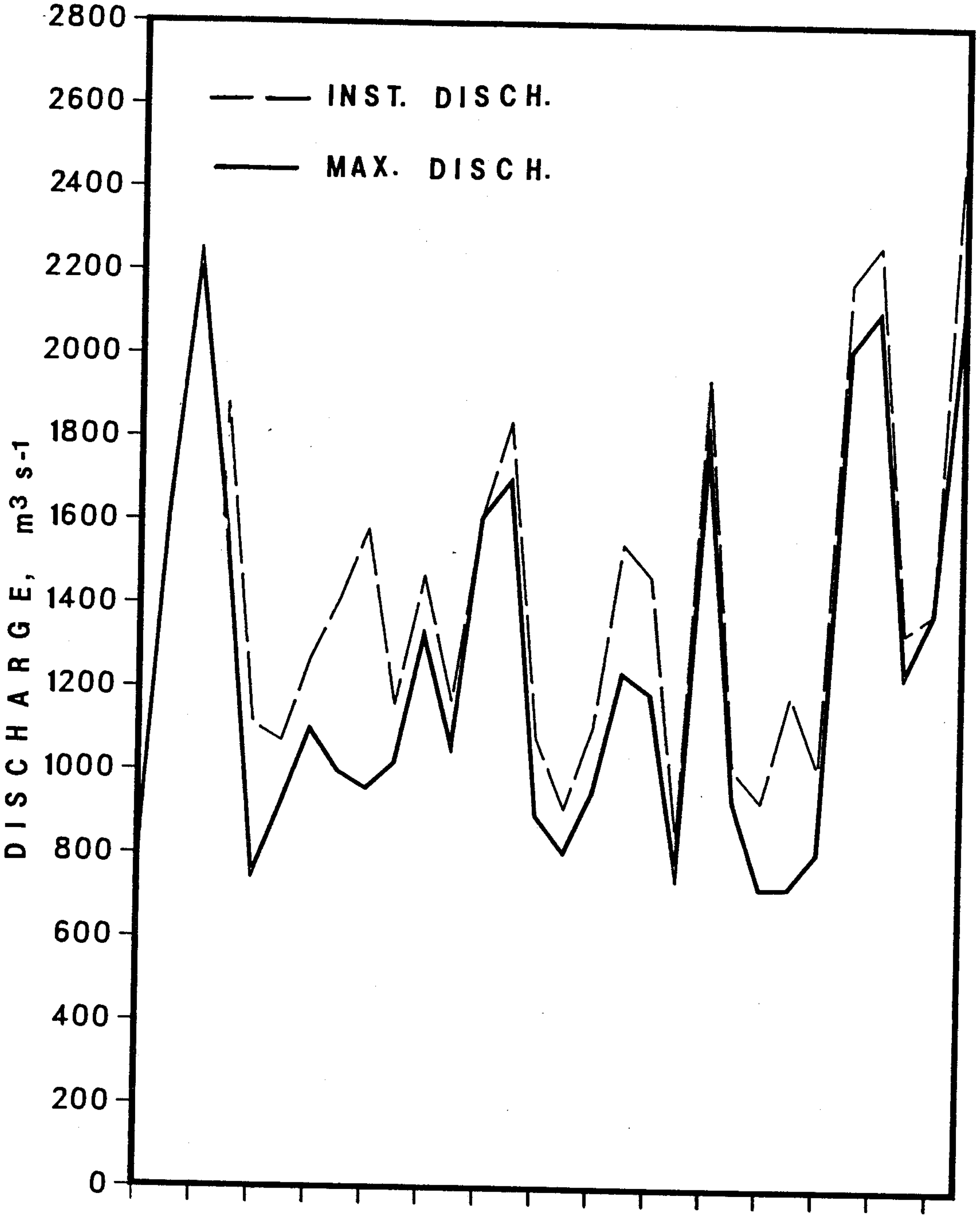


FIGURE 5.2

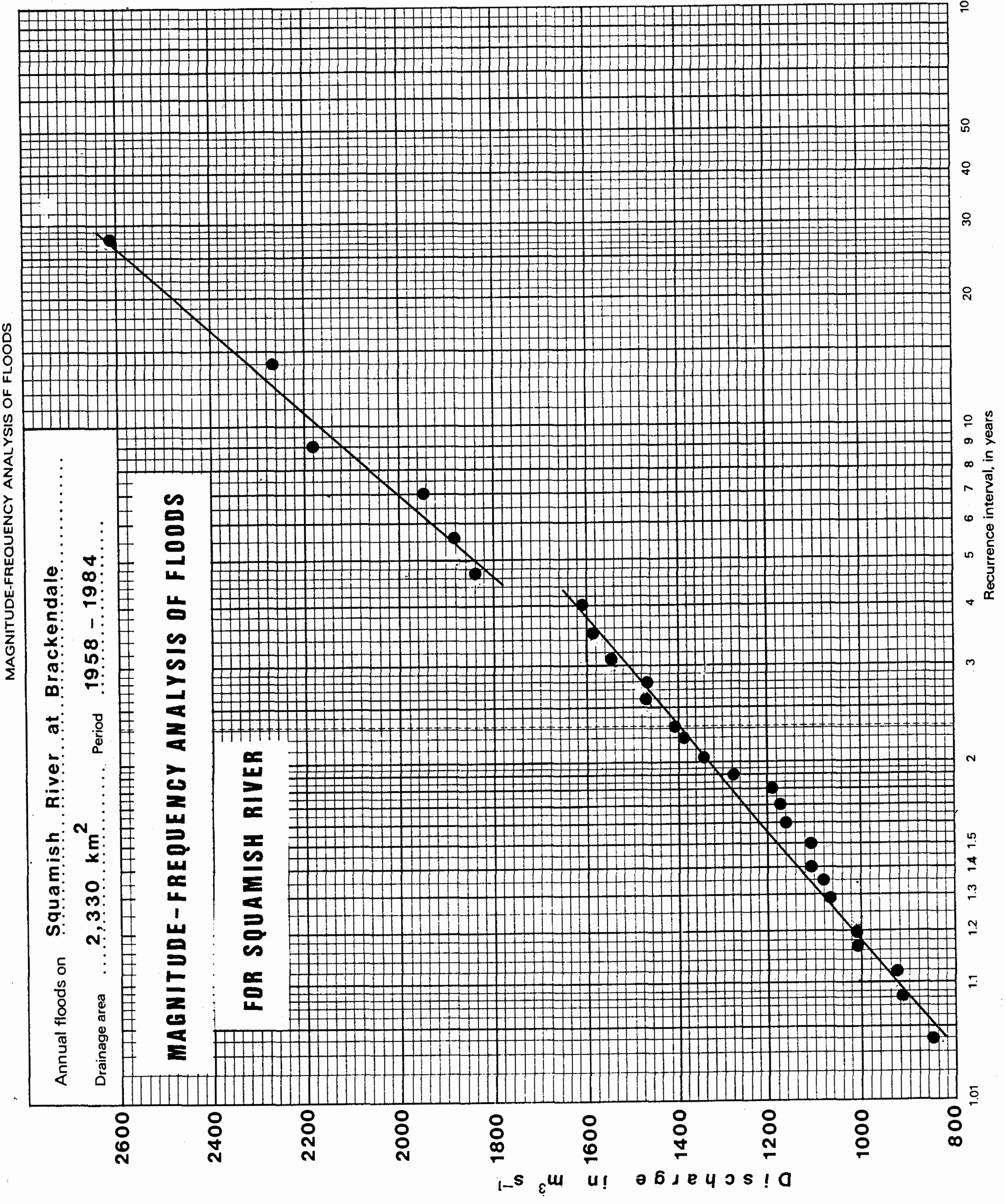

MAGNITUDE-FREQUENCY ANALYSIS OF FLOODS
Annual floods on Squamish River at Brackendale
Drainage area 2,330 km^2
Period 1958 – 1984
MAGNITUDE-FREQUENCY ANALYSIS OF FLOODS
FOR SQUAMISH RIVER
Discharge in m^3 s^{-1}
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
Recurrence interval, in years
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100

Figure 5.2 show that there are two distinct populations of floods. These are snowmelt-related floods below 1600 m^3 s^{-1} and those storm-related events above this level. Figure 5.3 shows the distribution of monthly peak fows from 1958 to 1984. It should be noted that several floods equivalent in magnitude to annual floods occur on several occasions per year. Flood frequencies by month shown in Figure 5.3 illustrate much more clearly the ranges of magnitudes and frequencies of recorded floods in Squamish River. The relationships of precipitation and temperature with discharge and their effect on the occurrence of floods is discussed in section 5.7.

In order that magnitudes of change be analysed in relation to the magnitude and frequency of floods, floods in Squamish River have been divided into three groups. Low floods ranging from 700 to 1000 m^3 s^{-1} with recurrence intervals of between 1.01 and 1.14 years; moderate floods between 1000 and 1600 m^3 s^{-1} and high floods in excess of 1600 m^3 s^{-1}. The recurrence intervals of moderate floods is between 1.56 and 3.0 years while high floods have return periods ranging from 4.3 to 30 years. Figure 5.4 shows that floods up to 1000 m^3 s^{-1} occurred between 80 and 96 percent; while moderate floods occurred between 25 and 80 percent; and high floods occurred between 4 and 25 percent of time. Magnitudes of change of erosion and deposition are analysed and discussed below in relation to magnitudes and frequencies of three groups of floods in periods of measurement under more salient types of channel change.

FIG. 5.3 RECORD OF MONTHLY PEAK FLOWS ON SQUAMISH RIVER FROM 1956 TO 1984

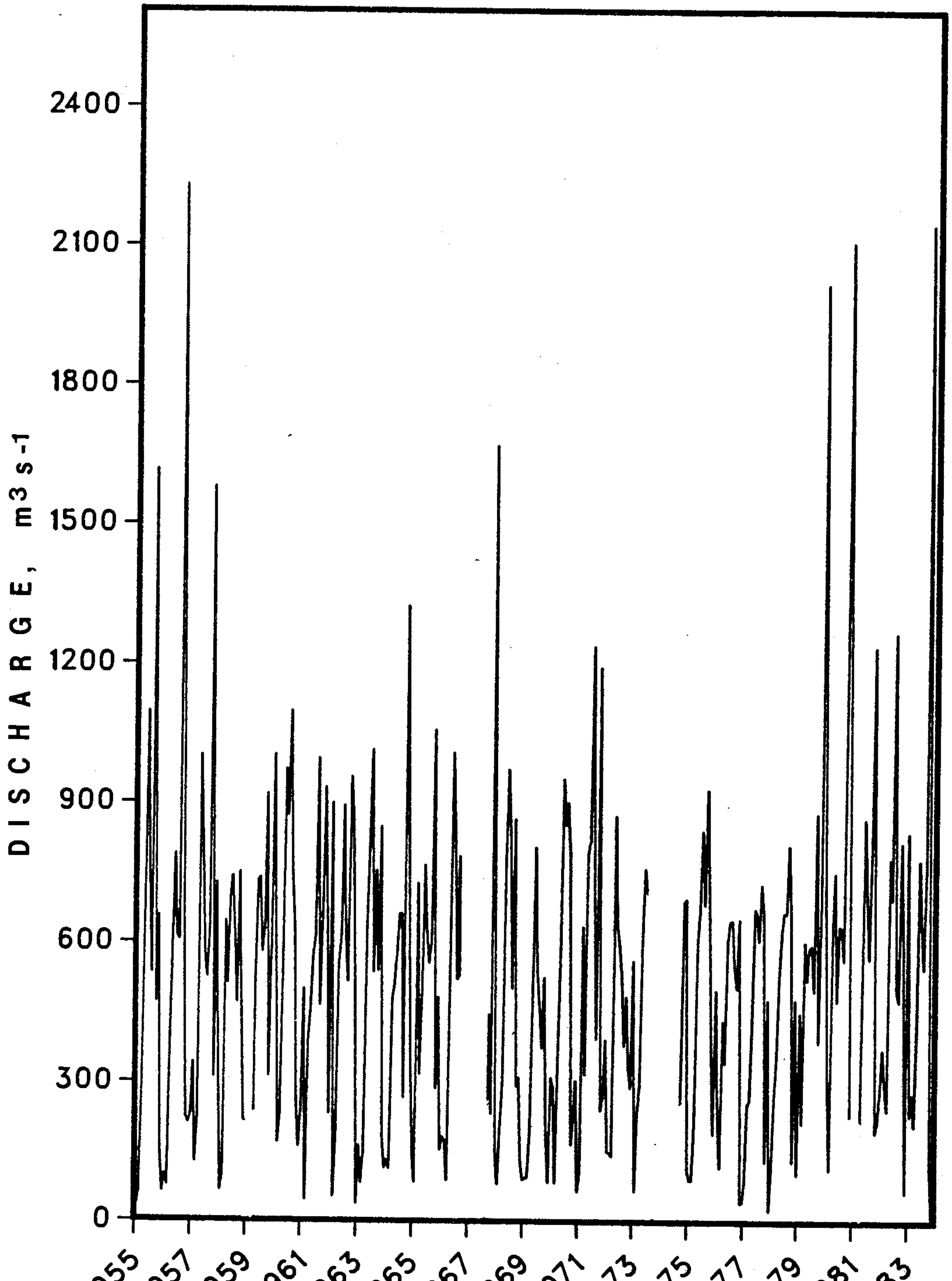
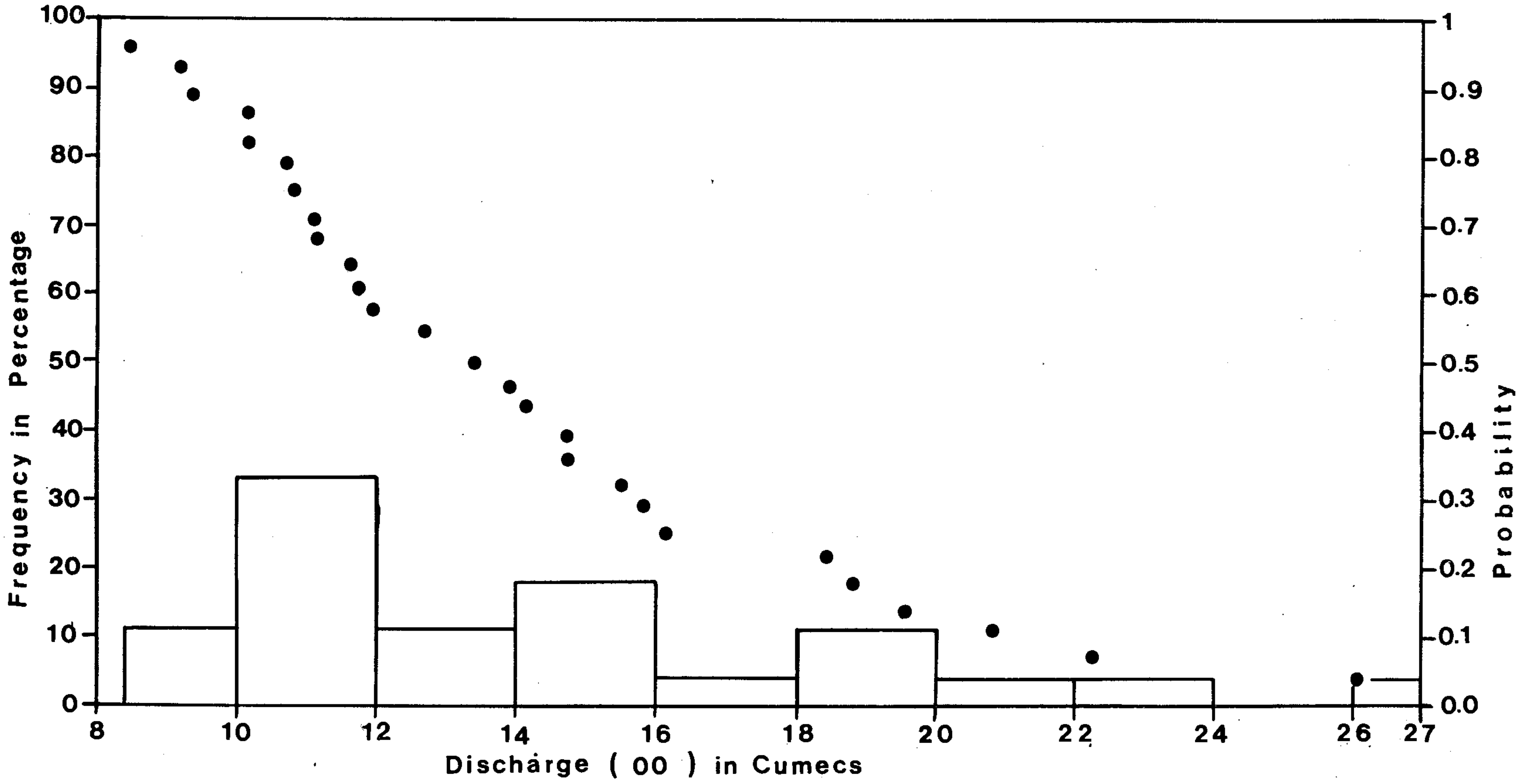


FIG. 5.4

FREQUENCY AND PROBABILITY OF FLOODS FOR SQUAMISH RIVER
FROM 1958 TO 1984



5.3 Bend Erosion

Enormous amounts of erosion and deposition between 1947 and 1984 occurred in bends of Squamish River. Zones of major erosion in bends were concave banks with concomittant deposition occurring on convex banks. Perhaps processes of erosion and deposition operated at the same rates but the measurement of erosion and deposition of vegetated islands and vegetated depositional areas in this study tends to show higher erosion rates than deposition. Rates of deposition tend to lag behind erosion because of the length of time required for vegetation growth. Higher amounts of erosion on concave banks and concomittant deposition on convex banks led to rapid development of Islands (A), (E), and (F) respectively (Figures 4.1, 4.7).

Table 5.1 shows that in Brackendale bend (1) and Brackendale Island (A) a total of 2.3 x 10^5 m^2 was eroded on the concave bank from 1947 to 1969 when the bank was diked. Deposition on Island (A) contributed to the increase in area by 1.2 x 10^5 m^2 between 1947 and 1984. These changes are the result of floods of different magnitude and frequency.

The magnitudes of erosion and deposition in Brackendale bend and island show wide variations of total and mean changes in different observation periods. The variability of geomorphic effects is attributed to local geomorphic factors. The highest areas of erosion and depostion of 9.0 x 10^4 m^2 and 1.3 x 10^5 m^2

TABLE 5.1

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Brackendale Bend from 1947 to 1984

Period	TYPE OF CHANGE Erosion ($10^3 m^2$) (Total)	 (Mean)	 Deposition ($10^3 m^2$) (Total)	 (Mean)	No. of Days 700 $\leq Q \leq$ 1000	R.I.	No. of Days 1000 $\leq Q \leq$ 1600	R.I.	No. of Days $Q \geq$ 1600	R.I.
1947 - 1952#:	45.40	9.08	39.15	7.83						
1952 - 1958*:	89.84	14.97	130.52	21.75	19	1.07	3	1.56	3	10
1958 - 1964:	76.90	12.82	8.82	1.47	34	1.14	5	3.0	0	0
1964 - 1969*:	57.52	11.50	36.75	7.35	53	1.13	4	2.5	1	4.3
1969 - 1976*:	7.35	1.05	-	-	37	1.12	5	2.7	1	6.0
1976 - 1977:	5.88	5.88	10.26	10.26	0	0	0	0	0	0
1977 - 1980:	-	-	3.75	1.25	3	1.11	2	1.67	0	0
1980 - 1980:	1.47	1.47	-	-	2	1.01	2	2.5	1	7.5
1980 - 1982:	19.11	9.56	12.20	6.10	27	1.14	3	2.0	1	15
1982 - 1984:	-	-	4.11	2.06	13	1.11	1	1.88	0	0
1984 - 1984:	16.17	16.17	-	-	1	1.01	1	1.65	2	30
Subtotal	319.64	82.50	245.56	39.07						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. # No discharge record. * Incomplete discharge record. For details refer to Appendix 5.

respectively occurred between 1952 and 1958 caused by the 10-year flood in combination with low and moderate floods of up to 1.56 years recurrence interval. Negligible amounts of erosion were observed between 1977 and 1980 and between 1980 and 1982 associated with low and moderate floods which occurred in these periods. Mean areas of erosion show that the largest eroded area of 1.6 x 10^3 m^2 occured in 1984 caused by the 30-year flood which occurred on 8th October 1984.

Similarly, in Bend 2 (Table 5.2) the 30-year flood produced the greatest geomorphic impact of 1.7 x 10^3 m^2 of eroded area both in total and mean measurements. This change is largely explained by the changed river alignment in bend 3 after 1980. The regional high flood of 1948 (Sewell, 1969) plus the 10 and 15-year floods in the periods 1947 to 1958 and 1980 to 1982 accomplished comparatively minor channel changes influenced by the alignment of the confined bend upstream.

High but variable geomorphic impact of erosion and deposition were also observed in bend 7 and 8 (Tables 5.3 and 5.4). In Bend 7 the largest total eroded area of 1.1 x 10^5 m^2 was accomplished by the 4-year flood in combination with low and moderate floods of up to 2.5 years return interval between 1964 and 1969. But the highest mean of eroded area of 3.4 x 10^4 m^2 was effected by the 30-year flood in 1984 while the highest mean of deposited area occurred between 1958 and 1960 in the period of more moderate floods of up to 1.25 years recurrence interval. This observation indicates that low and moderate flows promote

TABLE 5.2

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Bend 2 from 1947 to 1984

Period	TYPE OF CHANGE Erosion ($10^3 m^2$)		Deposition ($10^3 m^2$)		No. of Days 700 $\leq Q \leq$ 1000	R.I.	No. of Days 1000 $\leq Q \leq$ 1600	R.I.	No. of Days $Q \geq$ 1600	R.I.
	(Total)	(Mean)	(Total)	(Mean)						
1947 - 1958*:	2.94	0.27	8.23	0.75	19	1.07	3	1.56	3	10
1958 - 1964:	13.23	2.21	8.12	1.35	42	1.14	6	3.0	0	0
1964 - 1969*:	-	-	-	-	44	1.14	6	2.5	1	4.3
1969 - 1976*:	5.88	0.84	14.11	2.02	37	1.12	5	2.7	1	6.0
1976 - 1977:	-	-	-	-	0	0	0	0	0	0
1977 - 1980:	6.23	2.08	2.82	0.94	3	1.11	2	1.67	0	0
1980 - 1982:	1.25	0.63	-	-	13	1.14	3	2.3	2	15
1982 - 1984:	12.20	6.10	-	-	13	1.11	1	1.88	0	0
1984 - 1984:	17.05	17.05	-	-	1	1.01	1	1.65	2	30
Subtotal	58.78	29.18	33.28	5.06						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. * Incomplete discharge record. For details refer to Appendix 6.

TABLE 5.3

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Bend 7 from 1947 to 1984

Period	TYPE OF CHANGE Erosion (10^3 m^2)		Deposition (10^3 m^2)		No. of Days 700 ≤Q ≤1000	R.I.	No. of days 1000 ≤Q ≤1600	R.I.	No. of Days Q ≥ 1600	R.I.
	(Total)	(Mean)	(Total)	(Mean)						
1947 - 1951#:	58.99	14.75	8.23	2.06						
1951 - 1958*:	29.89	4.29	8.23	1.18	19	1.07	3	1.56	3	10
1958 - 1960:	31.31	15.66	23.41	46.82	7	1.09	2	1.25	0	0
1960 - 1964:	57.33	14.33	18.52	4.63	37	1.14	5	3.0	0	0
1964 - 1969*:	113.42	22.68	72.25	14.45	42	1.14	5	2.5	1	4.3
1969 - 1976*:	-	-	58.02	8.29	41	1.07	5	2.7	1	6.0
1976 - 1980:	20.58	5.15	-	-	3	1.11	2	1.67	0	0
1980 - 1982:	39.69	19.85	41.60	20.80	13	1.14	3	2.3	2	15
1982 - 1984:	18.38	9.19	3.38	1.69	16	1.11	1	1.88	0	0
1984 - 1984:	34.48	34.48	-	-	1	1.01	1	1.65	2	30
Subtotal	404.07	140.38	257.05	76.51						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. # No discharge record; * Incomplete discharge record. For details refer to Appendices 12 and 13.

TABLE 5.4

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Bend 8 from 1947 to 1984

Period	TYPE OF CHANGE Erosion (10^3 m²) (Total)	(Mean)	Deposition (10^3 m²) (Total)	(Mean)	No. of Days 700 ≤Q ≤1000	R.I.	No. of Days 1000 ≤Q ≤1600	R.I.	No. of Days Q ≥ 1600	R.I.
1947 - 1951#:	73.91	18.48	22.05	5.51						
1951 - 1960*:	42.48	4.72	46.76	5.20	28	1.09	6	1.56	5	10
1960 - 1964:	42.63	10.66	6.32	1.58	37	1.14	5	3.0	0	0
1964 - 1969*:	147.88	29.58	131.26	26.25	42	1.14	5	2.5	1	4.3
1969 - 1976*:	58.80	8.40	85.21	12.17	41	1.07	5	2.7	1	6.0
1976 - 1977:	8.82	8.82	-	-	0	0	0	0	0	0
1977 - 1980:	7.79	2.60	31.31	10.44	3	1.11	2	1.67	0	0
1980 - 1982:	40.49	20.25	-	-	13	1.14	3	2.3	2	15
1982 - 1984:	13.52	6.76	17.93	8.97	16	1.11	1	1.88	0	0
1984 - 1984:	24.99	24.99	-	-	1	1.01	1	1.65	2	30
Subtotal	465.27	135.26	340.84	70.12						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. # No discharge record. * Incomplete discharge record. For details refer to Appendices 14 and 15.

the establishment of vegetation on deposited areas while high floods tend to have a destructive impact on the landscape.

In Bend 8 the highest total and mean areas of erosion and deposition were caused by the 4-year flood in combination with low and moderate flood events. It is also interesting to note that flows below annual flood levels in the period 1976 and 1977 caused 8.8 x 10^3 m^2 of total and mean eroded area. This observation together with other observations above demonstrate that floods of different magnitude and frequency do produce similar and variable geomorphic impacts on the landscape influenced by local scale variability.

Channel changes in bends 5 and 6 were small compared to those in freely migrating bends 1 (until 1969), 2, 7 and 8 where larger areas of the flood.plain were eroded than deposited. This indicates that Squamish River in these subreaches experienced condiderable amounts of channel displacement. The consequence of these changes was channel widening.

By contrast Table 5.5 shows that the total amounts of erosion and deposition in bends 5 and 6 were equivalent in the period of study. Totals of amounts of erosion and deposition in bend 5 were 8.7 x 10^4 m^2 and 5.0 x 10^4 m^2 in bend 6 between 1947 and 1984 respectively. In bend 5 the mean measurements of erosion and deposition of 2.1 x 10^3 m^2 and 2.2 x 10^3 m^2 were also equivalent. These measurements show that the river in these bends was able to maintain a natural balance between bank erosion and depostion. But because these bends have not migrated

TABLE 5.5

Summary of Channel Changes in Bends 5 and 6 from 1947 to 1984

	BEND 5				BEND 6			
Period	Erosion $(10^3\ m^2)$		Deposition $(10^3\ m^2)$		Erosion $(10^3\ m^2)$		Deposition $(10^3\ m^2)$	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
1947 - 1958:	47.04	4.28	8.75	0.80	5.00	0.45	5.88	0.53
1958 - 1960:	13.67	6.84	12.50	6.25	-	-	-	-
1960 - 1964:	11.76	2.94	1.88	0.47	4.37	1.09	13.23	3.31
1964 - 1969:	10.00	2.00	5.63	1.13	10.63	2.13	3.75	0.75
1969 - 1976:	-	-	35.57	5.08	4.41	0.63	27.20	3.89
4976 - 1977:	-	-	-	-	-	-	-	-
1977 - 1980:	-	-	17.05	5.68	-	-	-	-
1980 - 1982:	-	-	-	-	-	-	-	-
1982 - 1984:	-	-	5.88	2.94	-	-	-	-
1984 - 1984:	5.00	5.00	-	-	26.07	26.07	-	-
Subtotal	87.47	21.06	87.26	22.35	50.48	30.37	50.06	8.48

(A) = total observed change; (B) = mean observed change; (-) = negligible change. For details refer to Appendices 10 and 11.

freely no attempt has been made to relate the changes to the magnitude and frequency of floods. However, the same trends of change observed in other bends such as the highest mean areas of erosion as having been caused by the 1984 flood of record, are also evident in bends 5 and 6.

The analytical discussion of magnitudes of change in relation to the magnitude and frequency of floods on Squamish River above has revealed the complex nature of channel adjustment. Also floods of higher magnitude are seen to produce proportionately higher amounts of erosion and deposition. The variable geomorphic impact of floods of different magnitude and frequency have been shown to reflect the importance of local factors in influencing the character and magnitude of channel changes. Perhaps because stream channels had not yet recovered from the effects of the 1980 and 1981 high flood events, the 30-year highest flood of 1984, generally accomplished higher erosional effects in most of the bends discussed above.

5.4 Intense Bank Erosion

Intense bank erosion (other than bend erosion) as a major type of change was observed in upstream banks of Baynes Island (C) at the Squamish-Cheakamus confluence, on convex bank of confined Bend 3 and at the upstream bank of the Squamish-Ashlu Bend or Island (I). Table 5.6 shows that between 1947 and 1952 at the upstream bank of Baynes Island an area of 4.6×10^3 m^2 was eroded and 1.2×10^4 m^2 deposited on the left bank.

TABLE 5.6

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Baynes Island from 1947 to 1984

Period	TYPE OF CHANGE Erosion (10^3 m^2) (Total)	(Mean)	Deposition (10^3 m^2) (Total)	(Mean)	No. of Days 700 $\leq$Q $\leq$1000	R.I.	No. of Days 1000 $\leq$Q $\leq$1600	R.I.	No. of Days Q $\geq$ 1600	R.I.
1947 - 1952#:	4.60	0.92	12.20	2.44						
1952 - 1958*:	17.58	2.93	-	-	19	1.07	3	1.56	3	10
1958 - 1964:	16.02	2.67	-	-	36	1.14	5	3.0	0	0
1964 - 1969*:	23.27	4.65	-	-	51	1.13	7	2.5	1	4.3
1969 - 1976*:	35.49	5.07	-	-	41	1.07	5	2.7	1	6.0
1976 - 1977:	1.76	1.76	-	-	0	0	0	0	0	0
1977 - 1980:	10.29	3.43	-	-	3	1.11	2	1.67	0	0
1980 - 1980:	12.64	12.64	-	-	2	1.01	2	2.5	1	7.5
1980 - 1982:	30.28	15.14	-	-	11	1.14	1	1.56	1	15
1982 - 1984:	28.82	14.41	-	-	16	1.11	1	1.88	0	0
1984 - 1984:	36.75	36.75	-	-	1	1.01	1	1.65	2	30
Subtotal	217.75	100.80	12.20	2.44						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. # No discharge record. * Incomplete discharge record. For details refer to Appendix 3.

Throughout the study period Baynes Island (C) has continuously been eroded with negligible amounts of deposition.

Generally high amounts of erosion were observed in the periods which recorded high floods ranging from 4 to 30 years recurrence interval. In Baynes Island the highest amount of erosion was effected by the highest flood event of 1984. In contrast channel changes in Bend 3 (Table 5.7) show that the highest amount of total and mean erosion of 3.4×10^4 m^2 and 1.7×10^4 m^2 was accomplished by the 15-year flood of 1981. But both low and moderate floods caused similar amounts of erosion and deposition in this bend. Similarly, most of the erosion and deposition in Island I (Table 5.8) were effected by low, moderate and high floods of up to 10 years return period from 1947 to 1980. The 15 and 30-year floods of 1981 and 1984 produced only minor geomorphic impact in this location.

This type of change is explained largely by the shifting of the zone of intense benk erosion from the upstream of Island (I) until 1980 to around the Squamish-Ashlu confluence on the right bank. The major change in Island (I) is the migration of the bankline further downstream which at the point of maximum movement migrated a total distance of 550 m between 1947 and 1976. This gives an average annual rate of movement of 14.9 m y^{-1}. From 1976 to 1984 the river moved by less than 25 m. Yet it is in the latter period that the highest frequency of high magnitude floods were recorded.

TABLE 5.7

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Bend 3 from 1947 to 1984

Period	TYPE OF CHANGE Erosion (10^3 m²) (Total)	(Mean)	Deposition (10^2 m²) (Total)	(Mean)	No. of Days $700 \leq Q \leq 1000$	R.I.	No. of Days $1000 \leq Q \leq 1600$	R.I.	No. of Days $Q \geq 1600$	R.I.
1947 - 1958*:	23.96	2.18	14.11	1.28	19	1.07	3	1.56	3	10
1958 - 1964:	10.73	1.79	13.90	2.32	42	1.14	6	3.0	0	0
1964 - 1969*:	26.46	5.29	-	-	44	1.14	6	2.5	1	4.3
1969 - 1976*:	12.20	1.74	41.60	5.94	37	1.12	5	2.7	1	6.0
1976 - 1977:	6.76	6.76	-	-	0	0	0	0	0	0
1977 - 1980:	7.79	2.60	-	-	3	1.11	2	1.67	0	0
1980 - 1982:	33.81	16.91	-	-	13	1.14	3	2.3	2	15
1982 - 1984:	2.21	1.11	7.21	3.61	13	1.11	1	1.88	0	0
1984 - 1984:	8.82	8.82	-	-	1	1.01	1	1.65	2	30
Subtotal	132.74	47.20	76.82	13.15						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. * Incomplete discharge record. For details refer to Appendix 7.

TABLE 5.8

Analysis Table of Magnitude of Change with Magnitude and Frequency of Floods in Upstream Bank of Island (I) in Squamish-Ashlu Bend from 1947 to 1984

Period	TYPE OF CHANGE Erosion (10^3 m^2) (Total)	(Mean)	Deposition (10^3 m^2) (Total)	(Mean)	No. of Days 700 $\leq Q \leq$ 1000	R.I.	No. of Days 1000 $\leq Q \leq$ 1600	R.I.	No. of Days $Q \geq$ 1600	R.I.
1947 - 1951#:	62.18	15.55	9.41	2.35						
1951 - 1960*:	61.30	6.81	7.64	0.85	28	1.09	6	1.56	5	10
1960 - 1964:	47.90	11.17	11.17	2.79	37	1.14	5	3.0	0	0
1964 - 1969*:	67.60	13.52	11.47	2.29	42	1.14	5	2.5	1	4.3
1969 - 1976:	25.73	3.68	7.49	1.07	41	1.07	5	2.7	1	6.0
1976 - 1978:	3.82	1.91	1.56	0.78	1	1.11	0	0	0	0
1978 - 1980:	5.51	2.76	1.56	0.78	3	1.01	2	1.67	0	0
1980 - 1982:	-	-	-	-	11	1.14	3	2.31	2	15
1982 - 1984:	2.63	1.32	-	-	16	1.11	1	1.88	0	0
1984 - 1984:	1.87	1.87	-	-	1	1.01	1	1.65	2	30
Subtotal	278.54	59.40	50.30	10.91						

Q = Maximum discharge; R.I. = Recurrence interval of highest flood in annual series; (-) = negligible change. # No discharge record. * Incomplete discharge record. For details refer to Appendix 17.

These changes quite clearly illustrate the complex nature of river responses to changing hydrological conditions that reflect non-linearity of channel changes. Changes such as these complicate predictions of future river behaviour and locations. The above analysis leads to the caution that predictions of channel changes far beyond the studied period remain speculative at best. Because river behaviour does not always follow perceived directions of processes of erosion and deposition.

5.5 Migration of Stream Junctions

Two types of migrations of stream junctions have been observed in Squamish River. The first is what may be referred to as gradual and easily traceable movement of the Squamish-Cheakamus confluence from 1947 to 1984 (Figures 4.1, 4.2 and 4.3). Appendix 1 shows that the area around the Squamish-Cheakamus confluence in the period of study had a total net deposition of flood plain construction of 9.5×10^4 m^2 in area. In section 4.2 types of channel changes in this location have been discussed. Here it will suffice to add that the formation of islands at the mouth of Cheakamus River with a net total and average areas of 8.8×10^4 m^2 and 10×10^3 m^2 (measurements of individual islands are shown in Appendix 2) had the consequence of increasing bank erosion on Baynes Island. The effect of this has been downstream migration of the island.

This type of change is a manifestation of how a confined river on one bank adjusts itself when it is choked with sediments from a tributary stream. Instead of migrating laterally away from the tributary stream it moves downstream causing erosion of the flood plain deposits in its way.

The second type of migration of stream junction is one in which the movement occurs suddenly as a result of excessive bank erosion caused by high magnitude floods. This type of change occurred in Squamish-Ashlu confluence. Appendix 22 shows that total erosion on the downstream bank of the junction between 1947 and 1980 was 1.3×10^4 m^2 in area with an average eroded area of 2.2×10^2 m^2. But between 1980 and 1982 1.8×10^4 m^2 of total area was eroded by a 15-year high flood of 1981. This flood event caused the stream junction to migrate a distance of about 325 m downstream. As a result of this change Ashlu River adopted a straighter and shorter route into the Squamish River.

5.6 Island Formation and Destruction

Island formation and destruction of larger islands has already been discussed in sections 5.3 and 5.4. For brevity, here only changes in small islands which emerged after 1947 in the Squamish-Ashlu bend reach will be discussed. Appendix 19 shows that Islands (J) and (K) emerged after 1951 and 1960 respectively. Between 1951 and 1984 Island (J) had a positive net change of 2.2×10^4 m^2 while average net change was 5.6 x

10^3 m^2. High and moderate floods after 1960 caused moderate amounts of erosion. Island (K) on the other hand experienced no erosion since its formation in the early 1960's. From 1960 to 1984 Island (K) increased in area by more than 10 times its total area of 7.4 x 10^3 m^2 in 1960 to 7.3 x 10^4 m^2 in 1984. On average the island increased in area by 1.3 x 10^4 m^3 between 1960 and 1984. This rapid growth of Island (K) is an indication that this part of the river has remained relatively stable for at least two decades.

In contrast Island (J) is located in an area of high river activity. In this section the complex nature of river adjustment has again been brought to the fore by the fact that a 15-year high flood of 1981 which caused much erosion in bend 3 and Squamish-Ashlu junction produced negligible amounts of erosion in both Islands (J) and (K). But it took a 30-year high flood of October 8, 1984 to erode total and average areas of 1.1 x 10^4 m^2 of Island (J). This amount of erosion clearly demonstrates the high effectiveness of the 1984 flood as the erosion it caused equals half the total area eroded in the period 1951 to 1982. The above analysis further underlines the common observation that floods of different magnitude and frequency produce variable amounts of geomorphic effects but also that exceptionally high floods produce higher geomorphic impact on the landscape.

Other impressive changes of island formation and destruction have been observed in Islands (G) and especially (H) which although experienced intense erosion and was split into two had an equivalent total amount of erosion and deposition of 8.7 x 10^4 m^2 and 8.7 x 10^4 from 1947 to 1984 respectively (Appendices 20a and b). But the average amounts of erosion and deposition in the same period were 1.6 x 10^2 m^2 and 2.2 x 10^2 m^2 respectively. Thus although the channel of Squamish River immediately downstream of Squamish-Ashlu bend changed considerably by the formation of multiple islands after 1960 the area occupied by the river channels has remained unchanged.

5.7 Causes of Channel Change

Throughout in Chapters 4 and 5 above the major focus of causes for channel changes has been hydrological (mainly flooding). But there are other factors which are also important and will be discussed in this section. Table 5.9 shows that from 1955 to 1984 41% of floods occurred in the month of October, 15% in June, while July, August and September recorded 7% each. This indicates that 15% of floods are partly the result of snowmelt in spring and summer months due to rising temperatures while heavy rainfalls in fall months of October and November account for 60% of the floods. No annual floods were recorded in winter months except in December which recorded 4%.

Figure 5.5 depicts the precipitation, temperature and runoff relationships quite clearly. However, it cannot be stated with great certainty that most of the floods in June or October

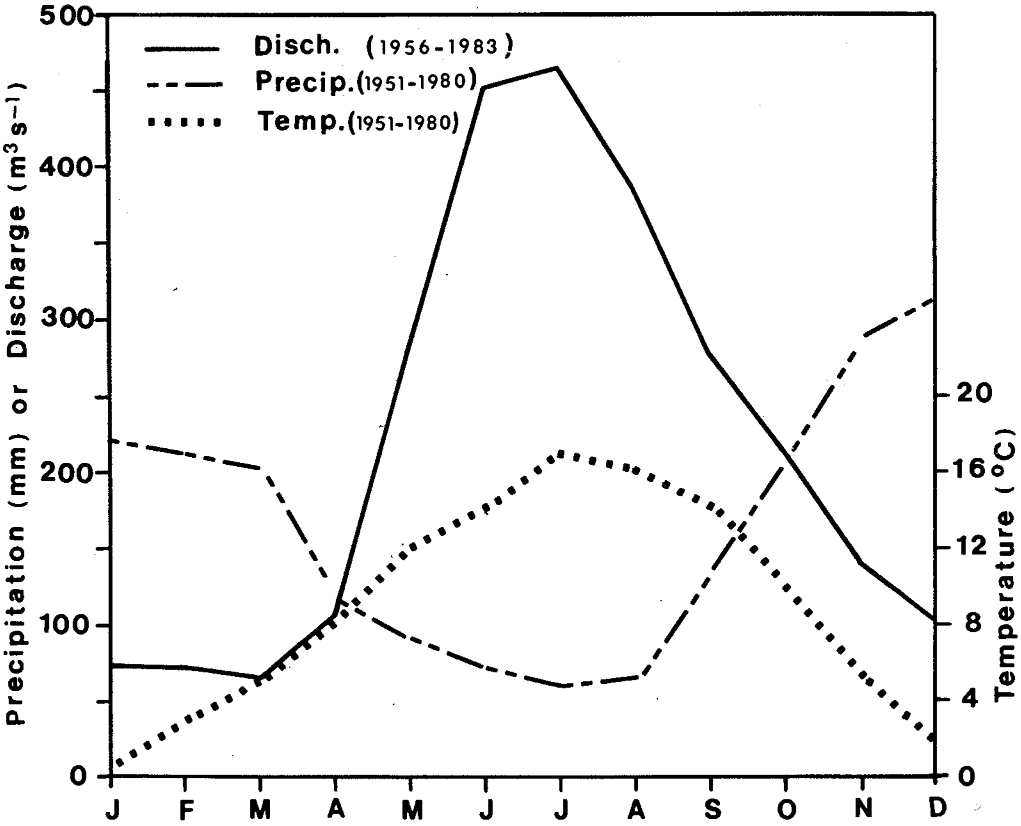
TABLE 5.9

Monthly Percentage Distribution of Floods in Squamish River

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	15	7	7	7	41	19	4

FIGURE 5.5

LONG TERM MONTHLY VARIATION OF MEAN DISCHARGE, MEAN PRECIPITATION AND MEAN TEMPERATURES



are a direct cause of precipitation because the distribution of floods also pertains to the amount of antecedent runoff. In order to be able to say how much precipitation and temperature contribute to flooding, antecedent runoff must be known. At present the amount of antecedent runoff in Squamish River valley is unknown.

The October 8, 1984 high flood was caused by heavy rainfalls which occurred a few days before this date. It is, however, not clear whether these rainfalls were the result of convectional activities or the result of the orographic effects of the Coast Mountains on the moist westerly winds. Elswhere, similar heavy rainfalls in the month of October studied by Rapp and Stromquist (1976) were found to have been caused either by cyclonic rainfalls in large areas or by convectional rainfalls in small areas. Rapp and Stromquist (1976) found the frequency of heavy rainfalls in Scandanavian Mountains to be low but that their effects on the slopes could be long-lasting due to very slow regrowth of vegetation in cold climates.

Undoubtedly, temperature and precipitation and antecedent runoff play a major role and control the hydrology of Squamish River but because of their covariance their effects on channel changes cannot be analytically discussed. In Figure 5.5 probably the points of intersection of discharge, precipitation and temperature graphs indicate the periods of low, moderate and high flood dominance on an annual basis.

Channel changes of bank erosion are dominantly the result of shearing of material or corrasion of stream banks. During periods of low flows this process may proceed at imperceptible rates and is most pronounced at high floods. Another process of bank erosion is slumping of materials from stream banks especially when the moisture content in soils is high. Examples of bank slumping were observed in summer of 1984.

Erodibility of stream banks depends among other factors on the cohesion of bank materials, type and density of vegetation and upon local geology. Cottonwoods and spruce are the common and dominant trees in Squamish River valley. Nanson (1980) and Hickin and Nanson (1984) found that in northern B.C. the roots of these trees penetrate to the level of the river bed thereby providing a strong woody mesh that reinforces alluvial banks and considerably reduce rate of bank erosion. In Squamish River the high density of cottonwoods and spruce on stream banks also tend to offer protection to the banks. However, high rates of bank erosion discussed in Chapters 4 and 5 above, plus field observations of a large number of trees with roots on them carried by the river, call into question the degree to which trees offer protection to stream banks.

From these observations it may be inferred that trees on stream banks might not offer much protection to banks in sections where river currents attack the banks below root zones. Simons et al. (1979) observed that the added surcharge weight of the vegetation may contribute to failure of banks leading to bank slumping. The collapsing of trees into the river may cause deflection of currents that further concentrate the flows in such a manner as to attack the banks thereby increasing bank erosion. Thus, the presence of vegetation in zones of direct river attack may aid in bank erosion and only offer little protection to the banks.

Observations reported by Hickin (1984) and the assessments of the nature of channel changes in Squamish River, in this study, indicate that there is considerable circumstancial evidence to suggest that vegetation on islands and flood plain in Squamish River offer greater protection to banks when they act in combination with log jams. Hickin (1984) has observed that logs commonly occur at the head of bars with a trail of sand and gravel deposited in the wake zone and that to a large extent island formation is dependent on vegetation-sediment interaction. Log jams play an important role in protecting islands and stream banks from direct river attack and help in vegetation development. Although this aspect of change has not been studied in detail in this study, log jams are believed to have played a major role in channel formation and abandonment in Squamish River which has already been reported by Hickin (1984) and elsewhere by Slaymaker (1972).

The effect of log jams in influencing channel changes in Squamish River is seen in the inability of the river to cause chute cut-offs in two locations even during periods of high floods. The first location is on the upstream bank of Island (I) at the entrance of an intermittent stream (Figure 4.13). The river could have easily caused an avulsion at high floods by flowing direct through the intermittent stream. But this did not happen; quite possibly a large log jam at this site could have averted a cutoff from taking place. In addition the realignment of the river after 1976 leading to decreased rate of channel migration and bank erosion around this location (discussed in section 5.4) may be attributed to the protection offered to the bank by flood plain vegetation reinforced by the logs trapped there.

The second location is in Bend 8 at site (N) in Figure 4.10 where the river could have easily caused a cutoff through an intermittent stream especially during the October 8, 1984 high flood. But this did not happen due to a massive log jam which was constructed there. Thus, until log jams in these two locations are dismantled channel avulsions might not take place through chute cut-off development.

Lastly, but not the least, local geology has played an important role in bringing about channel changes observed in Squamish River. Geology is responsible for the supply of sediments carried by the river leading to island formation and flood plain construction. However, the effect of geology on channel morphology is seen in the influence it exerts on changing river alignment especially in the meandering reaches where the river hugs bedrock in the valley wall. The existence of 'hard points' in the valley wall has the effect of realigning river channels and retarding lateral movement especially in bends. This gives bends a restricted development.

5.8 Sediment Transport

In preceding sections and in chapter 4 areal measurements of erosion and deposition have been discussed. In this section an approach whereby the area of materials eroded is equated to the area of materials deposited in a given reach or subreaches of a river is used. These areas of erosion and deposition are used as estimates of the quantity of sediment moving through a reach in a specified period of time. Amount of sediment transport is assessed in four reaches of Squamish River. Changes in the braided reach have not been quantitatively analysed due to the complex nature of changes in this reach. It is a fact that there are several sources of sediments and that sediments are distributed to different parts of a fluvial system. In order that the approach employed here obtains two assumptions are put forward as *a priori*; namely:

(i) Sediments carried by the river originate from the stream bed and stream banks;

(ii) Materials eroded from stream banks are transported and deposited within the same river reach.

Table 5.10 gives a summary of areal channel changes of erosion and deposition in Squamish-Ashlu Bend Reach. The total area eroded between 1947 and 1984 is 7.9 x 10^5 m^2 with 4.4 x 10^5 m^2 of deposition. On average 2.2 x 10^5 m^2 of area was eroded and 1.1 x 10^5 was deposited in the observation period. Percentage analysis of the magnitudes of change in different periods shows that large amounts of both total and average areas of erosion and deposition occurred between 1947 and 1976. The period 1976 to 1984 was generally a period of moderate channel changes. But in the periods of high magnitude floods large amounts of channel changes were observed. The 18% and 15% of mean erosion between 1982 and 1984 and between September and November 1984 illustrate this observation.

The above analysis shows that the largest amount of erosion was achieved in the 1950's and 1960's. In the 1970's and early 1980's only moderate amounts of erosion and deposition were accomplished. Integration of the net change between the quantity of sediments eroded and deposited in the period of study shows that 3.5 x 10^5 m^2 total area of sediment moved through the reach. This gives a total of 9.5 x 10^3 m^2 y^{-1}area of sediment movement in the reach per annum. Comparatively, the average total area of sediment in the Squamish-Ashlu bend reach is 1.0 x 10^3 m^2 with an annual sediment movement of 2.8 x 10^3 m^2 y^{-1}.

Similarly, Table 5.11 shows that the total areas of erosion and deposition in upper meandering were 9.7 x 10^5 m^2 and 6.5 x 10^5 m^2 respectively from 1947 to 1984. Out of these totals 33%

TABLE 5.10

Summary of Areal Channel Changes in Squamish-Ashlu Bend Reach from 1947 to 1984

Period	Erosion (10^3 m^2)				Deposition (10^3 m^2)			
	(Total)	(%)	(Mean)	(%)	(Total)	(%)	(Mean)	(%)
1947 - 1951:	99.51	13	24.88	11	13.82	3	3.46	3
1951 - 1960:	150.59	19	16.73	8	71.29	16	7.92	7
1960 - 1964:	110.43	13	27.61	13	60.68	14	15.17	14
1964 - 1969:	150.15	18	30.03	14	22.66	28	24.53	22
1969 - 1976:	111.86	14	15.98	7	70.20	16	10.03	9
1976 - 1978:	4.76	1	2.38	1	3.12	1	1.56	1
1978 - 1980:	19.89	3	9.95	5	45.88	9	22.94	20
1980 - 1982:	36.43	5	18.22	8	7.87	2	3.94	3
1982 - 1984:	77.62	10	38.81	18	47.10	11	23.55	21
1984 - 1984:	31.88	4	31.88	15	-	0	-	0
Total Change	793.12	100	216.47	100	442.62	100	113.10	100

TABLE 5.11

Summary of Areal Channel Changes in Upper Meandering Reach from 1947 to 1984

Period	Erosion (10^3 m^2)				Deposition (10^3 m^2)			
	(Total)	(%)	(Mean)	(%)	(Total)	(%)	(Mean)	(%)
1947 - 1951:	142.90	15	35.73	10	30.28	5	7.57	4
1951 - 1958:	85.31	9	12.18	3	37.78	6	5.40	3
1958 - 1960:	84.61	9	42.31	12	91.16	14	45.58	27
1960 - 1964:	116.02	12	29.01	8	39.95	6	9.99	6
1964 - 1969:	216.37	22	43.27	12	171.72	26	34.34	20
1969 - 1976:	63.21	7	9.03	3	166.31	25	23.76	14
1976 - 1977:	8.82	1	8.82	2	-	0	-	0
1977 - 1980:	28.37	3	9.46	3	89.96	14	29.99	18
1980 - 1982:	100.72	10	50.36	14	17.93	3	8.97	5
1982 - 1984:	28.96	3	14.48	4	9.26	1	4.63	3
1984 - 1984:	90.54	9	90.54	25	-	0	-	0
Total Change	965.83	100	358.67	100	654.35	100	170.23	100

of erosion and 25% of deposition occurred between 1947 and 1960. The proportion in percentage of average areas of erosion and deposition were found to be 25% of erosion and 34% of deposition. In the period 1960 to 1969 34% of erosion was effected with 32% of deposition. Between 1969 and 1980 11% of total area was eroded and 39% of the total deposited area with 8% and 32% of average area of erosion and deposition. From 1980 to 1984 32% and 18% of total eroded and deposited areas were accomplished by floods in this period. On average moderate and high floods between 1980 and 1984 eroded 22% of the flood plain area. The integrated net change of total and average areas of sediment which moved through the upper meandering reach in the period of study were 3.1×10^5 m^2 and 1.9×10^5 m^2 respectively. On an annual basis this shows that 8.4×10^3 m^2 of total area and 5.1×10^3 m^2 of average area of sediment moved in upper meandering reach of Squamish River.

Estimates of flood plain surface area transfers in lower meandering reach are shown in Table 5.12. The total area of erosion in this reach from 1947 to 1984 was 3.1×10^5 m^2 and 2.9×10^5 m^2 of deposition with 1.1×10^5 m^2 of mean erosion and 5×10^2 m^2 of mean deposition. From these 14% of total erosion and 26% of total deposition occurred between 1947 and 1958. In the period 1958 to 1969, 28% of total erosion and 22% of total deposition were effected. The corresponding average proportions were 15% of erosion and 22% of deposition.

TABLE 5.12

Summary of Areal Channel Changes in Lower Meandering Reach from 1947 to 1984

Period	Erosion (10^3 m^2)				Deposition (10^3 m^2)			
	(Total)	(%)	(Mean)	(%)	(Total)	(%)	(Mean)	(%)
1947 - 1958:	44.54	14	4.05	4	77.17	26	7.02	14
1958 - 1964:	50.42	16	8.40	8	49.80	17	8.30	17
1964 - 1969:	37.21	12	7.44	7	13.23	5	2.65	5
1969 - 1976:	38.80	13	5.54	5	122.59	42	17.51	5
1976 - 1977:	6.76	2	6.76	6	-	0	-	35
1977 - 1980:	20.34	7	6.78	6	2.82	1	0.94	0
1980 - 1982:	60.63	19	30.32	27	-	0	-	2
1982 - 1984:	24.03	8	12.02	11	27.40	9	13.70	0
1984 - 1984:	29.46	9	29.46	26	-	0	-	27
Total Change	312.19	100	110.77	100	293.01	100	50.12	100

Between 1969 and 1980, 22% of total erosion and 4% of total deposition were accomplished. The highest amount of erosion of 36% of total eroded area was caused by the floods in the period 1980 to 1984 compared to 9% of deposition in the same period. Comparatively, average measurements show that 64% of the total erosion occurred in this period. Thus in the lower meandering reach the area of erosion increased in recent years compared to what it was in the 1950's and 1960's. The difference between the total area eroded and that deposited from 1947 to 1984 is 1.9×10^4 m^2 with an average net area of erosion and deposition of 6.1×10^2 m^2. This was the quantity in area of sediment moving through the reach. On an annual basis the total amount of sediment moving through the reach was found to be 5.2×10^2 m^2 y^{-1} with an average of mean measurents of sediment movement of 1.6×10^2 m^2 y^{-1}.

The overall areal channel changes in Cheakamus-Mamquam Reach are presented in Table 5.13. The total areas of erosion and deposition from 1947 to 1984 were 7.6×10^5 m^2 and 6.6×10^5 m^2 respectively. In this reach most of the erosion and deposition also occurred between 1947 and 1976. Average areas of erosion and deposition show that a higher proportion of total erosion occurred from 1980 to 1984. The four year period from 1980 to 1984 was a period of pronounced bank erosion and low deposition as 35% and 6% of the total eroded and deposited areas were accounted for this period. The average proportions of erosion between 1982 and 1984 were 19% and 31% respectively. The

TABLE 5.13

Summary of Channel Changes in Squamish-Mamquam Reach from 1947 to 1984

Period	Erosion $(10^3\ m^2)$				Deposition $(10^3\ m^2)$			
	(Total)	(%)	(Mean)	(%)	(Total)	(%)	(Mean)	(%)
1947 - 1952:	65.82	9	13.16	4	152.91	23	30.58	18
1952 - 1958:	134.92	8	22.49	8	171.36	26	28.56	17
1958 - 1964:	93.02	12	15.50	5	72.85	11	12.14	7
1964 - 1969:	120.98	16	24.20	8	142.38	22	8.48	5
1969 - 1976:	60.96	8	8.71	3	51.56	8	7.37	4
1976 - 1977:	7.64	1	7.64	3	10.26	2	10.26	6
1977 - 1980:	10.29	1	6.43	2	13.73	2	4.58	3
1980 - 1980:	22.24	3	22.24	8	2.50	-	1.25	-
1980 - 1982:	49.39	6	24.70	9	12.20	2	48.80	29
1982 - 1984:	115.10	15	57.55	19	31.37	4	15.69	11
1984 - 1984:	87.93	11	87.93	31	-	0	-	0
Total Change	768.29	100	287.55	100	661.14	100	167.71	100

integration of net change between total area of erosion and deposition gives 1.1 x 10^5 m^2 with an average net change of 1.2 x 10^3 m^2 area of sediment moving through the reach. The annual rate of sediment movement is 2.9 x 10^3 m^2 y^{-1} by area. The average of the mean area of sediment is 3.2 x 10^2 m^2 y^{-1}.

The section on sediment transport is concluded by saying that the discussion of areas of change in periods of about 10 years has shown that highest amounts of change especially erosion occurred in 1950's and 1960's. The 1970's decade was a period of low channel erosion. The four-year period of the early 1980's was particularly a period of pronounced erosion. In studied reaches total annual rates of sediment movement by area have been found to be 9.5 x 10^3 m^2 y^{-1} in Squamish-Ashlu Bend reach; 8.4 x 10^3 m^2 y^{-1} and 5.2 x 10^2 m^2 y^{-1} in Upper and Lower Meandering reaches; and 2.9 x 10^3 m^2 y^{-1} in Cheakamus-Mamquam reach. Corresponding averages of the mean annual rates are 2.8 x 10^3 m^2 y^{-1}, 5.1 x 10^3 m^2 y^{-1}, 1.6 x 10^2 m^2 y^{-1} and 3.2 x 10^2 m^2 y^{-1} in the Squamish-Ashlu bend reach, Upper and Lower meandering reaches and the Cheakamus-Mamquam reach respectively.

5.9 Comparison of Rates of Channel Movement with Published Rates

In Chapter 4 and in the preceding sections of this chapter, the discussions on patterns and magnitudes of change have revealed that there have been periods of stability and instability in different sites and locations of Squamish River.

In the period of study changes in bends have exhibited progressive bank erosion with the consequence of meander migration. Most of the erosion in bends occurred on the concave (outer) banks with the exception of confined bends where most erosion occurred on the convex (inner) banks. In order to compare published rates of channel movement rates in Squamish River meander bends were calculated from measurements on unconfined bends.

Table 5.14 provides a list of rates of bank erosion data from readily available sources. It is based on an inventory assembled by Hooke (1980) with and additional data by Hickin and Nanson (1984) and Nanson and Hickin (1984). Rates of movement in five meander bends (bends 2, 4, 5, 7 and 8) in meandering reach of Squamish River have been found to fit well in the general distribution of world wide ranges of observations. The reach mean rate of movement is 5.9 m y^{-1} while rates in individual bends range from 2.4 to 11.5 m y^{-1} (Figure 5.6). The observed rates in increasing order are 2.4 m y^{-1}, 2.7 m y^{-1}, 4.1 m y^{-1}, 8.8 m y^{-1} and 11.5 m y^{-1} in bends 4, 2, 5, 7 and 8 respectively. The variations in rates is explained by a host of factors discussed in section 5.7 and perhaps is a reflection of the importance of local factors on channel changes.

Although the comparison of published results is complicated by the use of both mean and maximum rates, Figure 5.6 shows that the relationship between rates of erosion and drainage area is a general increase of rates with increasing drainage size.

TABLE 5.14

Published Rates of Bank Erosion

River and Location	Drainage area, km	Width, m	Mean discharge, $m^3 s^{-1}$	Rate of movement, $m y^{-1}$	Period of measurement	Method	Source
Ohio River, Kentucky				0.357	1807-1958	Maps	Allexander & Nunnaly (1972)
R. Endrick, Scotland	97.66	25	6.94	0.5	1896-1957	Maps, mean	Bluck (1971)
White River., Indiana	6042		66.2	0.67	1937-1968	Maps, mean	Brice (1973)
R. Mississippi				23	1722-1971	Maps & hist. data max.	Brunsden & Kessel (1973)
R. Mississippi				23	1881-1963	Maps	Carey (1969)
R. Brahmaputra	9349900	6000-13000	1898	6-273 15-792	1952-1963 1944-1952	Maps Maps	Coleman (1968)
R. Pembina, Alta, Cda		64	19.2	3.35 0.3	1910-1956	Maps Bedrock channel	Crickmay (1957)
Little Missouri R., Dakota		91.5	16	1.7-7.0	100 + yrs	Cottonwood trees	Everrit (1968)
Des Moines R., Iowa				6.6	1880-1970	Maps	Handy (1972)
R. Beatton, B.C. Cda	16000	48	225	0.48	250 yrs	Trees & deposits	Hickin & Nanson (1975)

Little Smoky R. Alt, Cda		39	44	0.53	1950-1975		Hickin & Nanson (1984)
Milk R. Alta, Cda		47	78	1.68	1945-1978	Aerial	—
Belly R. Alta, Cda		42	101	1.18	1951-1978		—
Lesser Slave R., Alta, Cda		42	101	0.86	1950-1970	photos,	—
Beaver R., Alta, Cda		49	244	1.4	1952-1977		—
Waterton R., Alta, Cda		72	247	3.93	1951-1978	mean	—
Eagle R. (Upper), B.C., Cda		49	272	1.34	1952-1977		—
Eagle R. (Lower), B.C., Cda		48	272	0.71	1951-1977	for	—
Swan R., Alta, Cda		41	272	1.52	1952-1978		—
Shuswap R. (Upper), B.C., Cda		63	306	1.73	1951-1975	reach	—
Fontana R., B.C., Cda		63	365	2.20	1950-1979		—
Pembina R., Alta, Cda		79	369	2.60	1949-1974	max.	—
Mushowa R., B.C., Cda		49	377	2.65	1948-1971		—
Oldman R., Alta, Cda		95	383	7.26	1950-1979		—
Notikiwan R., Alta, Cda		54	388	1.21	1950-1970		—
Shuswap R. (Lower), B.C., Cda		92	454	1.89	1951-1976		—
Clearwater R., Alta, Cda		135	198	1.51	1951-1972		—
Chinchaga R., Alta, Cda		91	766	1.03	1950-1978		—
Prophet R., B.C., Cda		141	830	2.34	1952-1979		—
Sikanni Chief R., B.C., Cda		127	1259	2.92	1950-1979		—
Fort Nelson R., B.C., Cda		281	3972	4.44	1952-1979		—
West Prairie R., Alta, Cda		30	102	0.86	200 yrs	Tree dating	—
Crawfordaburn R., N. Ireland	3	2-3		0-0.5	1966-1968	Erosion pins	Hill (1973)
Clady R., N. Ireland	4	2-2.5		0-0.064	1966-1968	Erosion pins	Hill (1973)
R. Exe, Devon, U.K.	620	26-33	140	0.88	1842-1974	Maps, mean	Hooke (1980)
R. Creedy, Devon, U.K.	235	16	55	0.07	"	" "	—
R. Culm, Devon, U.K.	270	13-17	7-18	0.31	"	" "	—
R. Axe, Devon, U.K.	288	16-35	80	0.25	"	" "	—
R. Yarty, Devon, U.K.	51	8.5	2.5	0.24	"	" "	—
R. Kolby, Devon, U.K.	74			0.08	"	" "	—
R. Hookmoor, Devon, U.K.	9.6	4.2	6	0.08	"	" "	—

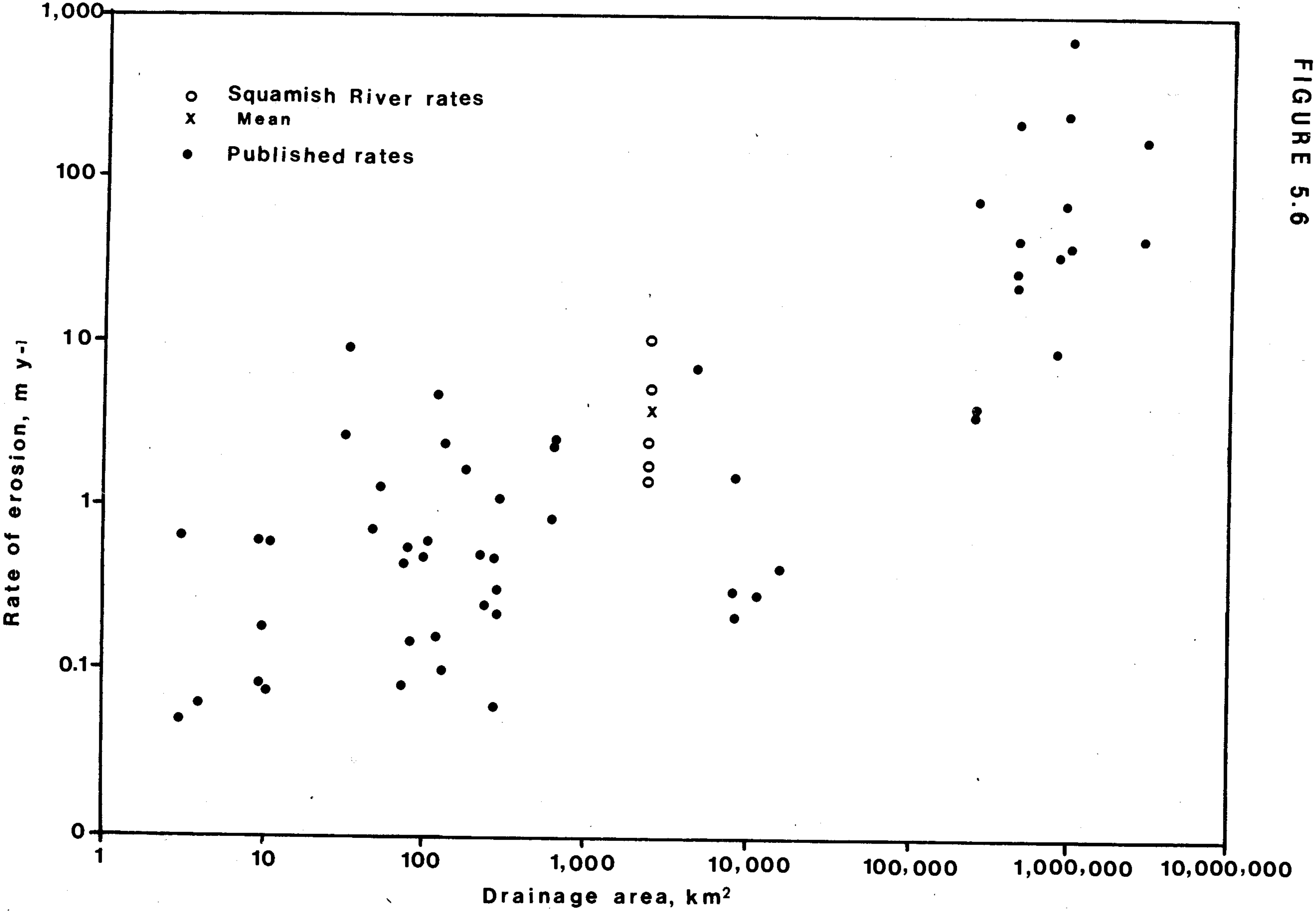
R. Cound, Shropshire	100	17	4	0.64	1972-1974	Pegs, mean	Hughes (1977)
R. Mississippi				14.9-40.5	1963-1970	Field measurement	Kesel et al. (1974)
Wisloka R., Poland			22.5	8-11	1970-1972	" "	Klimek (1974)
Dunajec R., Poland		30-120	40	0.4-1.0		Maps	Klimek & Trafas (1972)
R. Bollin-Dean, Cheshire	120	3-12		0.01-0.09	1967-1969	Erosion pins	Knighton (1973)
R. Mississippi		1200	16800	0.61-305		Maps	Kolb (1963)
				100		Maps, max.	Kondtrat'yev & Popov (1967)
Russian Rivers				10-15	1897-1958	Maps	Kondtrat'yev (1968)
				2.25-3.1		Maps	—
R. Ob, USSR			1434	0.15	1897-1958	Maps	Kulemina (1973)
R. Hernad, Czechoslovakia	5400	50-60	10-30	5-10	1937-1972	Maps, mean	Laczay (1977)
R. Rheidol, Wales	179			1.75	1951-1971	Maps, max.	Lewin (1972)
R. Tyfi, Wales	633			2.65	1905-1971	Maps	
R. Bollin, Cheshire	114	13	39	0.16	1872-1935	Maps	Mosley (1975)
					1935-1973	Maps	—
Jadzcze R., Poland	11-74		0.2	Equation	1970-1971	Field measurement	Niemrowski (1972)
Jamme R., Poland	9-14						
Chemung R., Pennsylvania				3.05	1938-1955	Air photos, one bend, mean	Nelson (1966)

Lower Missouri R.			1120-1400 over	1/3 floodplain reworked	1879-1954	Maps	Ruhe (1975)
R. Klaralven, Sweden	5420-11820	120	650	1.6	1850-1950	Resurvey	
				0.23	1800-1850	Maps, max.	Spangler & Handy
R. Torrens, S. Australia	78	5-10		0.32	1850-1950	ratio	(1973)
				0.58	1960-1963	Erosion pins	Twidale (1964)

Source: Hickin (1985).

FIGURE 5.6

RELATIONSHIP BETWEEN EROSION RATES AND DRAINAGE AREA



Source: Hooke (1980; Fig. 2; p. 150).

Squamish River rates fit well with other measurements and maintain this general relationship. This means that the measurements of rates of erosion and perhaps also the magnitudes of changes reported in this study would not be very different from similar observations in other areas.

5.10 Predicting Channel Change

Mosley and Zimpfer (1976) have discussed and shown that each of several types of explanations employed in geomorphology (based e.g., on cause-and-effect analysis, morphometric analysis, systems analysis or functional analysis) of a given phenomenon has limitations and drawbacks; and is only appropriate in certain circumstances. But also it is the case that each study employing any one of the approaches adds to our knowledge of the phenomenon. Thus, there is no 'best' explanation because each deals with a different aspect of a landform.

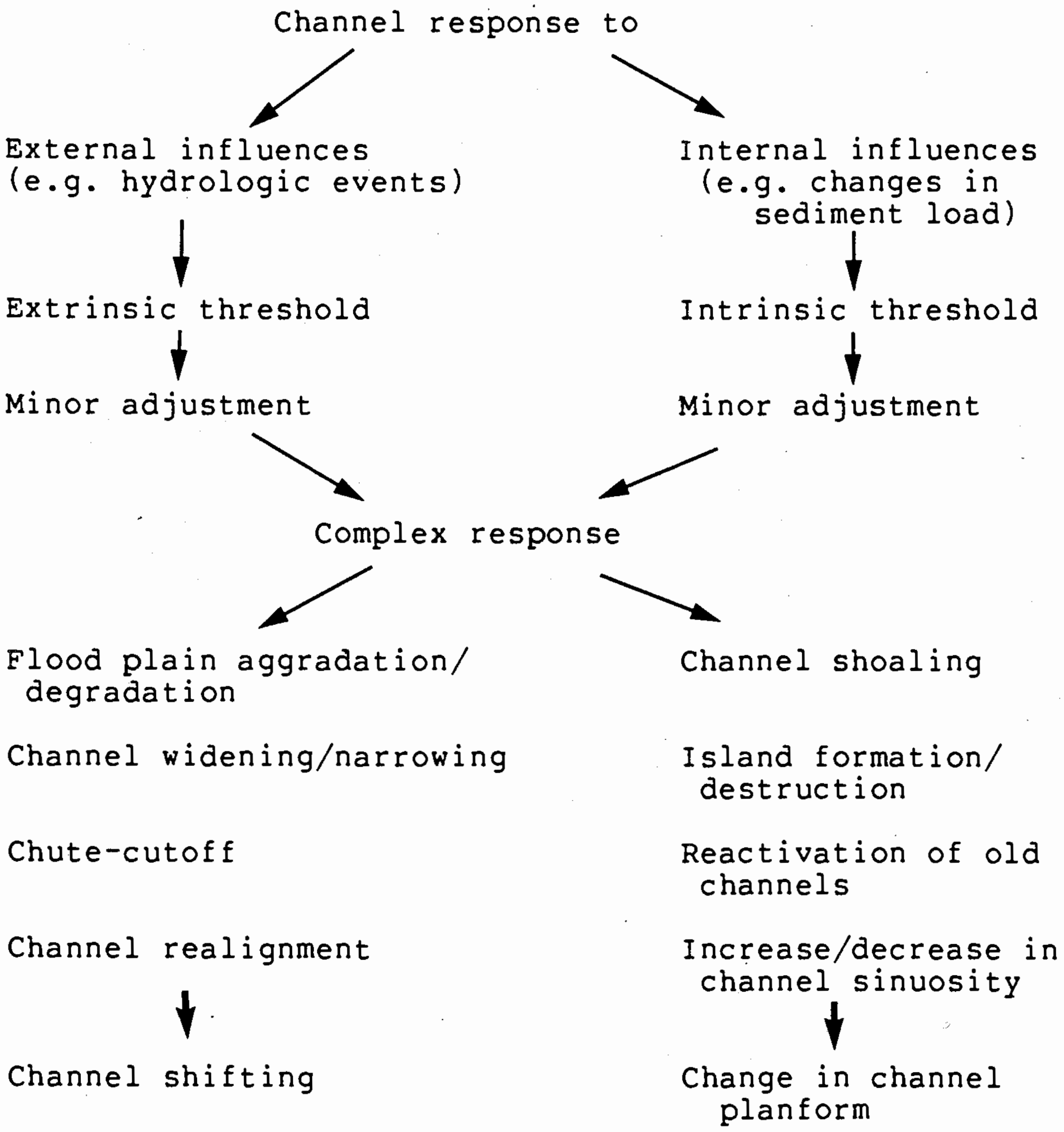
The problem of explanation is faced by many writers. Hickin (1985) has stated that given the complexity of the factors in lateral migration rate of river bends it is not possible to derive a general method for successfully predicting the rate of river bend migration. The difficulty of deriving general models to explain geomorphic phenomena is complicated by the great morphologic variability that occur within fluvial systems (Schumm, 1977).

However, in the absence of hydrologic and morphologic uniformity within a fluvial system the concepts of geomorphic threshold and complex response (Schumm, 1973) provide a basis for predictive geomorphology (Schumm, 1977). Schumm (1977) has offered a cascading system of explanation to explicate the understanding of the total fluvial system. Insights gained from the types of channel changes in Squamish River within a short period of time lead to the extension of Schumm's (1977) types of landform response to change into an idealized explanatory model of types of channel changes (Figure 5.7). Figure 5.7 shows the types of channel changes that a channel may experience once under extrinsic or internal influences leading to the exceedance of extrinsic or intrinsic thresholds. In a timescale of decades extrinsic and internal influences may be in the form of hydrologic events and changes in sediment load respectively. Such influences may lead to the exceedance of geomorphic thresholds thereby bringing about a series of minor channel adjustments. It is through complex response that channels adjust themselves in search of a new equilibrium.

Using examples of types of channel changes observed on Squamish River, it is conceived that short-term terminal results of minor adjustments might be either channel shifting (irrespective of planform type) or change in channel planform type. If, in the process of complex response, dominant types of change are flood plain aggradation/degradation, channel widening or narrowing, chute-cutoff or channel realignment; the river

FIGURE 5.7

An Idealized Explanatory Model of Types of Channel Change*



* Model is an extension of Schumm's (1977; Fig. 9.1; p. 323) types of landform response to change.

reach would experience channel shifting in the period of such adjustment. On the other hand, if dominant types of change comprise channel shoaling, island formation or destruction, reactivation of old channels, increase or decrease in channel sinuosity; the river or subreach would experience change in planform type in the period of such adjustment. There is no specific order of channel adjustment and no final stage of channel changes is conceived since channels are in constant adjustment with changing hydrologic and morphologic conditions.

It is not expected that the model proposed here will apply to rivers in different regions but would probably find examples on other high energy fluvial systems in humid regions. But types of channel changes might be different depending on geologic, geomorphologic and hydrologic characteristics of given fluvial systems. The model is only valid for Squamish River and has been presented as an alternative predictive model of channel change in a short period of time. Because as Schumm (1977) put it:

> "Using the approach of Mosley and Zimpfer (1976) no single explanation is wholly adequate to explain landforms, and the historic, equilibrium and probabilistic approaches all have validity and each presents partial explanation of complex natural systems."

CHAPTER 6: SUMMARY, CONCLUSIONS AND IMPLICATIONS OF STUDY

6.1 Summary

Five major types of channel changes were observed in Squamish River between 1947 and 1984. The common occurring change is bank erosion especially in meandering reaches where bends migrated between 88 and 425 m at annual average rates of between 2.4 and 11.5 m y^{-1}. Other than in meandering reaches, erosion and migration was observed in Brackendale bend where the bend migrated a distance of 325 m at an annual rate of 14.8 m y^{-1} between 1947 and 1969. Bend migration was achieved by erosion of concave banks with concomitant deposition on convex banks with the consequence of flood plain conctruction. Flows in the ranges of low, moderate and high floods caused similar amounts of erosion in different places and at different times.

Another type of bank erosion which has been classified as intense bank erosion was observed at the head of Baynes Island (C) and on upstream bank of Squamish-Ashlu Bend or Island (I). Baynes Island during the period of study has experienced continuous erosion at an excessive rate. The bankline on this island migrated downstream a total distance of 450 m at an annual average rate of 12.2 m y^{-1}. Similarly, upstream of Squamish-Ashlu bend experienced enormous erosion and the bankline migrated downstream a distance of 550 m between 1947 and 1976. The annual average rate of movement of this change is

14.9 m y^{-1}. Bank erosion in Squamish-Ashlu bend has since considerably declined. Intense bank erosion was the work of all ranges of floods but high magnitude floods in early 1980's produced comparatively higher amounts of erosion in Baynes Island.

Excessive bank erosion especially in bends caused widening of stream channels. Notable examples of channel widening are in Bends 8, 3, and 2 in Upper and Lower Meandering reaches. In Bend 8 excessive bank erosion during 'normal' years between 1964 and 1969 led to the river increasing its width by at least more than half the 1947 channel width. During periods of higher intensities of high floods Squamish River increased its width by 200 m between 1980 and 1982 in Bend 3 and by 75 m between September and November, 1984 in Bend 2. These two examples of dramatic changes were caused by high magnitude floods of 15 and 30 years recurrence intervals which occurred in 1981 and 1984 respectively.

The third type of channel changes is the formation and destruction of islands. Island formation and development was observed in Braided, Squamish-Ashlu Bend, and Squamish-Mamquam reaches. The development of islands in these reaches is seen as a measure of relative stability experienced by the river in sites and locations where islands were established. Conversely, island development in meandering reaches occurred as a natural response of concave bank erosion and deposition on convex banks of islands acting as point bars. Island formation and the subsequent attachment of some islands to the flood plain by abandonment of minor channels contributed to flood plain construction in studied reaches. In the meandering reaches point bars, at points of maximum movement migrated total distances ranging from 100 to 325 m in thirty-seven year period. These observations are comparable to the outward migration of concave banks.

The last type of channel change observed only in the braided reach is the reactivation of old channels between September and November, 1984 caused by the 30-year high flood which occurred on October 8, 1984. This flood event almost obliterated old stream planform by the dissection of the flood plain leading to the creation of more than one major channel in the subreach which was previously a single main channel system. Reactivation of old channels and subsequent creation of new islands and new channels in the Braided Reach, among other measures is seen as indicative of the high effectiveness of the 1984 high flood.

In the aspect of assessment of sediment movement from measurements of areas of erosion and deposition in Squamish River, this study has shown that the quantity of sediment moving through the system decreases in the downstream direction. The highest annual average quantity of 9.5×10^3 m^2 y^{-1} area of sediment was recorded in Squamish-Ashlu Bend Reach; while in the Upper and Lower Meandering reaches the estimates of 8.4×10^3 m^2 y^{-1} and 5.2×10^2 m^2 y^{-1} respectively were obtained. The

Squamish-Mamquam Reach was found to carry an estimated area of 2.9×10^3 m^2 of sediment per year. However, average rates of flood plain surface transfer between observation periods are comparatively lower than these measurements. But both estimates reflect the important sources of sediments in the headwaters region and the Cheekye Fan in the vicinity of the Squamish-Cheakamus confluence.

6.2 Conclusions and Implications

In conclusion it can be said that this study has demonstrated the complexity of river adjustments to a range of flow conditions in a high energy fluvial system. Low floods of recurrence intervals of between 1.01 and 1.14 years with moderate floods in the range of 1.56 and 3.0 years recurrence intervals produced geomorphic effects similar to those of high floods of recurrence intervals between 4.3 and 30 years in different places and at different times. However, higher intensities of high magnitude floods have caused dramatic channel changes which might have long term effects on the morphology of the Squamish River.

The effectiveness of high floods has been found to be limited by local factors such as existence of bedrock (hard point) in valley walls and log jam construction around bars and islands. Log jams have played an important role in channel formation and abandonment and especially in averting possible chute channel cutoffs from occurring.

Most of the objectives of the study have been achieved. However, the cause-and-effect approach used in explaining the magnitudes of change with the magnitude and frequency of floods was adequate only in explaining the effects of a combination of floods of different magnitude and frequency in Squamish River. Because of the length of observation periods it has not been possible to determine the magnitude of the effects of any given flood event in relation to its magnitude and frequency. This means that the objective of determining the extent to which frequency and magnitude of floods control erosion/deposition rates and channel planform on Squamish River has only partially been achieved.

This study might have raised more questions than it has been able to answer. It is suggested that studies in this area be concerned with volumetric assessment of sediments moving through reaches of Squamish River. From wider methodological implications of this study the improvement of the methods used in assessing channel changes in this research should brighten the gloomy picture painted by Lewin (1977) who concluded that:

> "...no general model - perhaps linking patterns and rates of change to channel shape, discharges of water and sediment, and bank materials - is yet possible, and it often remains very difficult to compare or even reconcile results from different research projects one with another. The purposes, methods, and measures used are diverse and diffuse to a confusing extent."

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APPENDICES

APPENDIX 1

Area Measurements of Channel Changes Around Squamish-Cheakamus Confluence from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3 m^2) (Total)	 (Mean)	 Deposition (10^3 m^2) (Total)	 (Mean)
15.07.47 - 14.10.52:	ub	7.50	1.50	11.87	2.37
14.10.52 - 24.10.58:	ub	16.25	2.71	-	
24.10.58 - 01.07.64:	ub	-	-	3.75	0.63
01.07.64 - 24.07.69:	ub	17.50	3.50	6.88	1.38
24.07.69 - 27.09.76:	ub	5.00	0.71	3.75	0.63
27.09.76 - 14.09.80/82:	ub	-	-	10.00	2.50
24.07.82 - 24.09.84:	ub	-	-	-	-
24.09.84 - 05.11.84:	ub	19.38	19.38	-	-
15.07.47 - 14.10.52:	db(a-b)	-	-	55.00	11.00
14.10.52 - 24.10.58:	db	11.25	1.88	39.37	6.56
24.10.58 - 01.07.64:	db	-	-	30.00	5.00
01.07.64 - 24.07.69:	db	14.37	2.05	25.62	3.66
Subtotal		91.25	31.73	186.24	33.73

ub = upstream bank; db = downstream bank; (-) = negligible change

APPENDIX 2

Area Measurements of Islands Around Squamish-Cheakamus Confluence from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion $(10^3\ m^2)$ (Total)	(Mean)	Deposition $(10^3\ m^2)$ (Total)	(Mean)
24.07.69:	I(1)			25.00	
24.07.69 - 24.09.84:	(1)	8.13	0.54	-	-
24.07.69:	I(2)	-	-	20.63	
24.07.69 - 27.09.76/80:	(2)	9.37	0.85	7.81	0.71
14.09.80 - 24.09.84:	(2)	3.44	0.86	-	-
24.09.84 - 05.11.84:	(2) wiped out	15.63	15.63	-	-
24.07.69:	I(3)			18.75	
24.07.69 - 27.09.76/80:	(3)	3.75	1.40	15.00	1.36
14.09.80 - 24.07.82:	(3)	8.13	4.07	-	-
24.07.82 - 24.09.84:	(3)	-	-	7.50	3.75
24.07.69 - 27.09.76:	I bt(2)&(3)	-	-	6.25	
27.09.76 - 31.12.80/82:	"	-	-	2.50	0.42
24.07.82 - 24.09.84:	"	5.62	2.81	-	-
24.07.69 - 24.09.84:	Other I's	-	-	2.81	0.19
24.07.69:	I(4)	-	-	8.75	-
24.07.69 - 27.09.76/80:	(4)	-	-	18.75	1.70
14.09.80 - 24.07.82/84:	(4)	-	-	8.13	2.03
Subtotal		54.07	26.16	141.88	10.16

I(1) = Island (and designation); bt = between; (-) = negligible change.

APPENDIX 3

Area Measurements of Channel Changes in Baynes Island (C)from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3m^2) (Total)	 Erosion (10^3m^2) (Mean)	 Deposition (10^3m^2) (Total)	 Deposition (10^3m^2) (Mean)
15.07.47 - 14.10.52:	ub rb	4.60	0.92	12.20	2.44
14.10.52 - 24.10.58:	ub	5.38	0.90	-	-
14.10.52 - 24.10.58:	db	12.20	2.03	1.47	0.25
24.10.58 - 01.07.64:	ub	3.38	0.56	-	-
24.10.58 - 01.07.64:	db	12.64	2.11	-	-
01.07.64 - 24.07.69:	ub	5.19	1.04	-	-
01.07.64 - 24.07.69:	db	18.08	3.62	-	-
24.07.69 - 27.09.76:	ub	35.49	5.07	-	-
27.09.76 - 31.07.77:	ub	1.76	1.76	-	-
31.07.77 - 14.09.80:	ub	10.29	3.43	-	-
14.09.80 - 31.12.80:	ub	12.64	12.64	-	-
31.12.80 - 24.07.82:	ub	30.28	15.14	-	-
24.07.82 - 24.09.84:	ub	28.82	14.41	-	-
24.09.84 - 05.11.84:	ub	36.75	36.75	-	-
Subtotal		217.50	100.38	13.67	2.69

ub = upstream bank; db = downstream bank; rb = right bank;
(-) = negligible change.

APPENDIX 4

Area Measurements of Channel Changes Between Baynes Island (C) and Brackendale Bend (1) from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion $(10^3\ m^2)$ (Total)	(Mean)	Deposition $(10^3\ m^2)$ (Total)	(Mean)
15.07.47 - 14.10.52:	Site (P): rb	8.32	1.66	-	-
15.07.47 - 14.10.52:	I(B): lb	-	-	34.69	6.94
14.10.52 - 01.07.64:	I(B): lb db	-	-	30.28	2.52
14.10.52 - 24.07.69:	Site (P): rb	8.32	1.66	-	-
24.07.69 - 27.09.76:	Site (P)	-	-	-	-
27.09.76 - 24.09.84:	Site (P): rb	-	-	8.82	1.66
24.07.69 - 05.11.84:	I(B):	69.09	4.61	-	-
Subtotal		85.73	7.93	81.14	11.12

I(B) = Island (and designation); lb = left bank; rb = right bank; db = downstream bank; (-) = negligible change.

APPENDIX 5

Area Measurements of Channel Changes in Brackendale Bend (1) and Island (A)from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion ($10^3 m^2$)		Deposition ($10^3 m^2$)	
		(Total)	(Mean)	(Total)	(Mean)
14.10.52 - 24.10.58:	conc	89.84	14.97	-	-
24.10.58 - 01.07.64:	conc	59.26	9.88	-	-
01.07.64 - 24.07.69:	conc	30.90	6.18	-	-
15.07.47 - 14.10.52:	I(A)	-	-	39.15	7.83
14.10.52 - 24.10.58:	bt I's	-	-	130.52	21.75
24.10.58 - 01.07.64:	conv	17.64	2.94	8.82	1.47
01.07.64 - 24.07.69:	conv	26.62	5.32	36.75	7.35
24.07.69 - 27.09.76:	up conv	7.35	1.05	-	-
27.09.76 - 31.07.77:	conv	5.88	5.88	-	-
31.07.77 - 14.09.80:	conv	-	-	-	-
14.09.80 - 31.12.80:	conv	1.47	1.47	-	-
31.12.80 - 24.07.82/84:	up conv	19.11	4.78	-	-
24.09.84 - 05.11.84:	up conv	16.17	16.17	-	-
24.07.69 - 24.09.84:	I's (5)	-	-	6.32	0.42
24.07.69 - 24.09.84:	(6)	-	-	5.88	0.39
24.07.69 - 24.09.84:	(7)	-	-	3.75	0.25
24.07.69 - 24.09.84:	(8)	-	-	14.37	0.96
Subtotal		319.64	68.64	245.56	40.42

I's = Islands; I(A)/(5) = Island (and designation)
conc = concave bank; conv = convex bank; up = upstream bank;
(-) = negligible change.

APPENDIX 6

Area Measurements of Channel Changes in Bend 2 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3m^2) (Total)	 (Mean)	 Deposition (10^3m^2) (Total)	 (Mean)
15.07.47 - 24.10.58:	conc conv	2.94	0.27	8.23	0.75
24.10.58 - 27.07.64:	conc conv	3.23	2.21	8.12	1.35
27.07.64 - 24.07.69:	conc conv	-	-	-	-
24.07.69 - 27.09.76:	conc conv	5.88	0.84	14.11	2.02
27.09.76 - 14.09.80:	conc conv	6.32	1.58	2.82	0.71
14.09.80 - 24.07.82:	conc conv	1.25	0.63	-	-
24.07.82 - 24.09.84:	conc conv	10.29	5.15	6.56	3.28
24.09.84 - 05.11.84:	conc	12.20	12.20	-	-
24.09.84 - 05.09.84:	conv	17.05	17.05	-	-
Subtotal		69.16	39.93	39.84	0.11

conc = concave bank; conv = convex bank; (-) = negligible change.

APPENDIX 7

Area Measurements of Channel Changes in Bend 3 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion $(10^3 m^2)$		Deposition $(10^3 m^2)$	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 24.10.58:	conv ub db	23.96	2.18	14.11	1.28
24.10.58 - 27.07.64:	conv ub db	10.73	1.79	13.90	2.32
27.07.64 - 24.07.69:	conv ub db	26.46	5.29	-	-
24.07.69 - 27.09.76:	conc conv ub db	12.20	1.74	41.60	5.94
27.09.76 - 31.07.77:	conv ub db	6.76	6.76	-	-
31.07.77 - 14.09.80:	conc ub	7.79	2.60	-	-
14.09.80 - 24.07.82:	conv	33.81	16.91	-	-
24.07.82 - 24.09.84:	conv db	2.21	1.11	7.21	3.61
24.09.84 - 05.11.84:	conc db	8.82	8.82	-	-
Subtotal		132.74	47.20	76.82	13.15

conv = convex bank; conc = concave bank; ub = upstream bank; db = downstream bank; (-) = negligible change.

APPENDIX 8

Area Measurements of Channel Changes in Bend 4 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion ($10^3 m^2$) (Total)	(Mean)	Deposition ($10^3 m^2$) (Total)	(Mean)
15.07.47 - 24.10.58:	conc conv	17.64	1.60	21.61	1.96
24.10.58 - 27.07.64:	conv	14.70	2.45	-	-
27.07.64 - 24.07.69:	conc conv	5.88	1.18	8.82	1.76
24.07.69 - 27.09.76:	conc conv	15.43	2.20	18.52	2.65
27.09.76/77 - 14.09.80:	conv db	6.32	1.58	-	-
14.09.80 - 24.07.82:	conc	22.05	11.03	-	-
24.07.82 - 24.09.84:	conv	5.87	2.94	-	-
24.09.84 - 05.11.84:	conv	2.18	2.18	-	-
Subtotal		90.07	25.16	52.09	6.37

conc = concave bank; conv = convex bank; db = downstream bank; (-) = negligible change.

APPENDIX 9

Area Measurements of Channel Changes Around Sites (D) and (R) on Cutoff Bank from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3m^2) (Total)	(Mean)	Deposition (10^3m^2) (Total)	(Mean)
15.07.47 - 24.10.58:	Site (G)	-	-	33.22	3.02
24.19.58 - 27.07.64:	(G)	11.76	1.96	14.11	2.35
	(V)	-	-	13.76	2.29
27.07.64 - 24.07.69:	Site (G)	4.85	0.97	-	-
	(V)	-	-	4.41	0.88
24.07.69 - 27.09.76:	Site (G)	-	-	41.60	5.94
	(V)	5.29	0.76	6.76	0.97
27.09.76 - 14.09.80:	Site (G/V)	-	-	-	-
14.09.80 - 24.07.82:	Site (V)	3.52	1.76	-	-
24.07.82 - 24.09.84:	Site (G)	-	-	11.17	5.59
	(V)	3.75	1.88	5.88	2.94
24.09.84 - 05.11.84:	Site (V)	1.41	1.41	-	-
Subtotal		30.58	8.74	130.82	23.98

(-) = negligible change.

APPENDIX 10

Area Measurements of Channel Changes in Bend 5 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion ($10^3 m^2$)		Deposition ($10^3 m^2$)	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 24.10.58:	conc conv	47.04	4.28	8.75	8.75
24.10.58 - 22.07.60:	conc conv	13.67	6.84	12.50	6.25
22.07.60 - 27.07.64:	conc conv	11.76	2.94	1.88	0.47
27.07.64 - 24.07.69:	conc conv	10.00	2.00	5.63	1.13
24.07.69 - 27.09.76:	conc conv	-	-	35.57	5.08
27.09.76 - 14.09.80:	conv	-	-	17.05	4.26
14.09.80 - 24.09.84:	conv	-	-	5.88	1.47
24.09.84 - 05.11.84:	conv	5.00	5.00	-	-
Subtotal		77.47	21.06	87.26	27.41

conc = concave bank; conv = convex bank; (-) = negligible change.

APPENDIX 11

Area Measurements of Channel Changes in Bend 6 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10³m²) (Total)	 Erosion (10³m²) (Mean)	 Deposition (10³m²) (Total)	 Deposition (10³m²) (Mean)
15.07.47 - 14.10.58:	conc conv	5.00	0.45	5.88	1.18
14.10.58 - 22.07.60/64:	conc conv	4.37	0.73	13.23	2.21
27.07.64 - 24.07.69:	conc conv	10.63	2.13	3.75	0.75
24.07.69 - 27.09.76/84:	conc conv	4.41	0.29	27.20	1.81
24.09.84 - 05.11.84:	conc conv	26.07	26.07	-	-
Subtotal		50.48	29.67	50.06	5.95

conc = concave bank; conv = convex bank; (-) = negligible change.

APPENDIX 12

Area Measurements of Channel Changes in Bend 7 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion $(10^3 m^2)$ (Total)	(Mean)	Deposition $(10^3 m^2)$ (Total)	(Mean)
15.07.47 - 24.10.58/60:	b(J-I)	3.38	0.26	14.92	1.15
15.07.47 - 27.07.64:	b(G-H)	14.26	0.84	-	-
22.07.60/64 - 24.07.69:	b(J-I)	9.70	1.08	25.43	2.83
27.07.64 - 24.07.69:	b(G-H)	6.26	1.25	-	-
24.07.69 - 27.09.76:	b(J-I)	-	-	33.81	4.84
27.09.76/80 - 24.09.84:	b(G-H)	-	-	3.38	0.65
24.09.84 - 05.11.84:	b(J-I)	3.75	3.75	-	-
15.07.47 - 15.06.51:	conc(I-F)	58.99	14.75	8.23	2.06
15.06.51 - 24.10.58:	conc	22.10	3.16	-	-
24.10.58 - 22.07.60:	conc	20.58	10.29	23.08	11.54
22.07.60 - 27.07.64:	conc	36.31	9.08	-	-
27.07.64 - 24.07.69:	conc	79.82	15.96	6.24	1.25
24.07.69 - 27.09.76:	conc	-	-	5.88	0.84
27.09.76 - 14.09.80:	conc	20.58	5.15	-	-
14.09.80 - 24.07.82:	conc	39.69	19.85	-	-
24.07.82 - 24.09.84:	conc	13.97	6.99	-	-
24.09.84 - 05.11.84:	conc	18.82	18.82	-	-
Subtotal		348.21	111.23	120.97	25.16

b(J-I) = stream bank between designated points;
conc = concave bank; (-) = negligible change.

APPENDIX 13

Area measurements of Channel Changes in Island (E) in Bend 7 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion $(10^3 m^2)$ (Total)	 Erosion $(10^3 m^2)$ (Mean)	 Deposition $(10^3 m^2)$ (Total)	 Deposition $(10^3 m^2)$ (Mean)
15.07.47 - 24.10.58:	up conc conv	7.79	0.71	8.23	0.75
24.10.58 - 22.07.60:	up conv	7.35	3.68	8.82	4.41
22.07.60 - 27.07.64:	up conv	6.76	1.69	18.52	4.63
27.07.64 - 24.07.69:	up conv	17.64	3.53	40.57	8.11
24.07.69 - 27.09.76:	up db	-	-	18.33	2.62
27.09.76 - 14.09.80/82:	conv	-	-	41.60	6.93
14.09.80 - 24.07.82/84:	db	4.41	1.10	-	-
24.09.84 - 05.11.84:	min chann	11.91	11.91	-	-
Subtotal		55.86	22.62	136.08	27.45

up = upstream bank; db = downstream bank; conc = concave bank; min chann = minor channel; (-) = negligible change.

APPENDIX 14

Area Measurements of Channel Changes in Bend 8 from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3m^2)		Deposition (10^3m^2)	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 22.07.60:	u conc(L-M)	7.35	0.57	-	-
15.07.47 - 22.07.60:	Site (K)	6.32	0.49	11.17	0.86
15.06.51 - 22.07.60:	u conc	16.17	1.80	-	-
22.07.60 - 27.07.64:	u conc	29.40	7.35	-	-
27.07.64 - 24.07.69:	u conc	-	-	57.77	11.55
27.07.64 - 24.07.69:	Site (K)	31.75	6.35	-	-
24.07.69 - 27.09.76:	u conc	-	-	52.92	7.56
15.07.47 - 15.06.51:	d conc(M-J)	61.59	15.40	-	-
15.06.51 - 22.07.60:	d conc	12.64	1.40	8.23	0.91
22.07.60 - 27.07.64:	d conc	13.23	3.31	6.32	1.58
27.07.64 - 24.07.69:	d conc	82.32	16.46	32.33	3.29
24.07.69 - 27.09.76:	d conc	51.10	7.30	7.79	1.11
27.09.76 - 31.07.77:	d conc	8.82	8.82	-	-
31.07.77 - 14.09.80:	d conc	7.79	2.60	-	-
14.09.80 - 24.07.82:	d conc	40.49	20.25	-	-
24.07.82 - 24.09.84:	d conc	10.58	5.29	-	-
24.09.84 - 05.11.84:	d conc	24.99	24.99	-	-
Subtotal		408.50	117.53	176.53	26.86

u/d conc(L-M) = upstream/downstream concave bank between designated points; (-) = negligible change.

APPENDIX 15

Area Measurements of Channel Changes in Island (F) in Bend 8 from 1947 to 1984

		TYPE OF CHANNEL CHANGE			
Period	Site or Location	Erosion ($10^3 m^2$)		Deposition ($10^3 m^2$)	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 14.06.51:	ub conv	12.32	3.08	22.05	5.51
14.06.51 - 22.07.60:	db conv	-	-	27.36	3.04
22.07.60 - 24.07.69:	ub conv	33.81	3.76	41.16	4.57
24.07.69 - 27.09.76*:	ub conv	7.70	1.10	24.50	3.50
27.09.76/77 - 14.09.80:	db	-	-	31.31	7.83
14.09.80 - 24.07.82/84:	ub conv	2.94	0.74	17.93	4.48
Subtotal		56.77	8.68	164.31	28.93

ub = upstream bank; db = downstream bank; conv = convex bank; (-) = negligible change. * Island (g) attached to Island (F) between 1969 and 1976.

APPENDIX 16

Area Measurements in Concave Bank of Squamish-Ashlu Bend from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion (10^3 m^2)		Deposition (10^3 m^2)	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 14.06.51:	conc Site (T)	6.17	1.54	-	-
14.06.51 - 22.07.60:	conc Site (T)	11.03	1.23	9.85	1.09
22.07.60 - 27.07.64:	conc Site (T&S)	23.52	5.88	15.27	3.82
27.07.64 - 24.07.69:	conc (T) I(S)	14.56	2.91	4.99	3.00
24.07.69 - 27.09.76*:	conc (T) I(S)	25.00	3.57	3.25	0.47
27.09.76 - 14.09.80:	conc	8.13	2.03	-	-
14.09.80 - 24.07.82:	conc	2.50	1.25	-	-
24.07.82 - 24.09.84:	conc	3.75	1.88	-	-
24.09.84 - 05.11.84:	conc	3.13	3.13	-	-
Subtotal		97.79	23.42	43.36	8.38

*Island (S) attached to floodplain between 1969 and 1976; (-) = negligible change; conc = concave bank; I(S) = Island and designation.

APPENDIX 17

Area Measurements of Channel Changes in Island (I) in Squamish-Ashlu Bend from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion $(10^3\ m^2)$		Deposition $(10^3\ m^2)$	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 14.06.51:	ub conv	62.18	15.41	9.41	2.35
14.06.51 - 22.07.60:	ub conv	61.30	6.81	7.64	0.85
22.07.60 - 27.07.64:	ub conv	47.90	11.98	11.17	2.79
27.07.64 - 24.09.69:	ub conv	67.60	13.52	11.47	2.29
24.09.69 - 27.09.76:	ub conv	25.73	3.68	7.49	1.07
27.09.76 - 09.08.78:	ub conv	3.82	1.91	1.56	0.78
09.08.78 - 14.09.80:	ub conv	5.51	2.76	1.56	0.78
14.09.80/82 - 24.09.84:	conv	2.63	0.66	-	-
24.09.84 - 05.11.84:	conv	1.87	1.87	-	-
Subtotal		278.54	58.74	50.30	10.91
14.06.51 - 22.07.60:	db	33.02	3.67	-	-
22.07.60 - 27.07.64:	db	14.73	3.68	1.87	0.47
27.07.64 - 24.07.69:	db	43.66	8.73	-	-
24.07.69 - 27.09.76:	db	15.87	2.27	-	-
27.09.76 - 24.07.82/84:	db	12.05	1.51	-	-
Subtotal		119.33	19.86	1.87	0.47

ub = uspstream bank; db = downstream bank; (-) = negligible change.

APPENDIX 18

Area Measurements of Channel Changes in Island (I1) in Squamish-Ashlu Bend from 1969 to 1984

Perid	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3 m^2) (Total)	(Mean)	Deposition (10^3 m^2) (Total)	(Mean)
24.07.69 - 27.09.76:		-	-	8.12	1.16
27.09.76 - 09.08.78:	db	-	-	1.56	0.78
09.08.78 - 14.09.80:	conc	-	-	7.50	3.75
14.09.80 - 24.07.82:	ub	-	-	2.81	1.41
24.07.82 - 24.09.84:	wiped out	19.99	10.00	-	-
Subtotal		19.99	10.00	19.99	7.10

ub = upstream bank; db = downstream bank; (-) = negligible change.

APPENDIX 19

Area Measurements of Channel Changes in Islands Upstream of Squamish-Ashlu Bend from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion (10^3 m^2)		Deposition (10^3 m^2)	
		(Total)	(Mean)	(Total)	(Mean)
15.06.51 - 22.07.60:	I(J)	-	-	18.74	2.08
22.07.60 - 27.07.64:	I(J)	4.99	1.25	23.15	5.79
27.07.64 - 24.07.69:	I(J)	4.85	0.97	8.09	1.62
24.07.69 - 27.09.76/78:	I(J)	8.75	0.97	2.81	0.31
09.08.78 - 14.09.80:	I(J)	3.75	1.88	0.94	0.47
14.09.80 - 24.07.82/84:	I(J)	-	-	1.87	0.47
24.09.84 - 05.11.84:	I(J)	11.25	-	-	-
Subtotal		33.59	11.25	55.60	10.74
22.07.60 - 27.07.64:	I(K)	-	-	7.35	0.82
27.07.64 - 24.07.69:	I(K)	-	-	14.11	2.82
24.07.69 - 27.09.76:	I(K)	-	-	17.50	2.50
27.09.76 - 09.08.78/80:	I(K)	-	-	5.62	1.41
14.09.80 - 24.07.82/84:	I(K)	-	-	28.12	7.03
Subtotal		-	-	72.70	12.58

(-) = negligible change; I(J) = Island and designation.

APPENDIX 20A

Area Measurements of Channel Changes in Islands Downstream of Squamish-Ashlu Bend from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion (10^3 m^2)		Deposition (10^3 m^2)	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 14.06.51:	I(H) db ub	16.17	4.04	4.41	1.10
14.06.51 - 22.07.60:	db ub	29.51	3.28	7.79	0.87
22.07.60 - 27.07.64:	split 1 & 2	10.62	2.66	1.87	0.47
27.07.64 - 24.07.69:	I(H1)	-	-	15.50	3.10
24.07.69 - 27.09.76:	I(H1)	14.70	2.10	-	-
27.09.76 - 14.09.80:	I(H1)	-	-	18.80	4.70
14.09.80 - 14.09.84:	I(H1)	12.05	3.01	-	-
24.09.84 - 05.11.84:	I(H1)	2.50	0.63	-	-
24.07.69 - 27.09.76:	I(H2)	-	-	11.03	1.58
09.08.78 - 14.09.80:	I(H2)	-	-	11.46	5.73
14.09.80 - 24.09.84:	I(H2)	1.41	0.35	16.17	4.04
Subtotal		86.95	16.07	87.03	21.59

db = downstream bank; ub = upstream bank; (-) = negligible change; I(H) = island and designation.

APPENDIX 20B

Area Measurements of Channel Changes in Islands Downstream of Squamish-Ashlu Bend from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3 m^2) (Total)	(Mean)	Deposition (10^3 m^2) (Total)	(Mean)
15.07.47 - 24.07.69:	I(G)	-	-	47.77	3.67
24.07.69 - 27.09.76:	I(G)	-	-	11.25	1.61
27.09.76 - 24.07.82:	I(G)	1.93	0.32	1.87	0.31
24.07.82 - 24.09.84:	I(G)	4.37	2.19	-	-
24.07.69 - 24.07.82:	lb opp I(G)	11.87	0.91	-	-
24.07.82 - 24.09.84:	"	5.88	2.94	-	-
24.09.84 - 05.11.84:	"	1.25	1.25	-	-
Subtotal		25.30	7.61	60.89	5.59

I(G) = island and designation; (-) negligible change;
lb opp = right bank opposite.

APPENDIX 21

Area Measurements of Channel Changes in Left and Right Banks Around Squamish-Ashlu Confluence from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE			
		Erosion $(10^3\ m^2)$		Deposition $(10^3\ m^2)$	
		(Total)	(Mean)	(Total)	(Mean)
15.07.47 - 14.06.51:	rb up junc	14.99	3.75	-	-
14.06.51 - 22.07.60:	rb	15.73	1.75	2.94	0.33
22.07.60 - 27.07.64:	rb	8.67	2.17	-	-
27.07.64 - 24.07.69:	rb	16.98	3.40	-	-
24.07.69 - 27.09.76:	rb	8.75	1.25	-	-
27.09.76 - 09.08.78/80:	rb	2.81	0.70	-	-
14.09.80/82 - 24.09.84:	rb	16.25	4.06	-	-
24.09.84 - 05.11.84:	rb	11.88	11.88	-	-
Subtotal		96.06	28.96	2.94	0.33
15.07.47 - 22.07.60:	lb up I(I)	-	-	24.33	1.87
22.07.60 - 24.07.69:	lb	-	-	5.63	0.63
24.07.69 - 27.09.76:	lb	3.75	0.54	8.75	1.25
27.09.76 - 24.09.84:	lb	1.87	0.23	0.94	0.12
Subtotal		5.62	0.77	39.65	3.87

lb = left bank; rb = right bank; up = upstream; junc = junction; (-) = negligible change; I(I) = island and designation.

APPENDIX 22

Area Measurements of Channel Changes Downstream of Squamish-Ashlu Junction from 1947 to 1984

Period	Site or Location	TYPE OF CHANNEL CHANGE Erosion (10^3 m^2) (Total)	 Erosion (10^3 m^2) (Mean)	 Deposition (10^3 m^2) (Total)	 Deposition (10^3 m^2) (Mean)
15.07.47 - 15.06.51/69:	db junc	2.50	0.11	5.10	0.23
24.07.69 - 27.09.76:	db	7.50	1.07	-	-
27.09.76 - 09.08.78:	db	0.94	0.47	-	-
09.08.78 - 14.09.80:	db	2.50	1.25	-	-
14.09.80 - 24.09.84:	db	17.50	4.38	3.19	0.80
Subtotal		30.94	7.28	8.29	1.03

db = downstream bank; junc = junction; (-) = negligible change.

APPENDIX 23

Photographs Used in the Thesis

Year	Agency	Photo Classif. No.	Photo No.
1947	B.C.	400:	70-79; 82-85
1951	B.C.	1227:	14-19
	B.C.	1228:	78, 81; 91-93
1952	B.C.	1634:	46-50
1958	B.C.	5005:	54-56; 63; 67-73
1960	B.C.	5012:	242-248
1964	B.C.	5099:	118-122
1969	B.C.	5316:	43-47
	B.C.	5341:	244-248
	B.C.	5342:	29-34; 54-56; 72-75
1976	B.C.	5758:	1-9; 16-18; 33-39; 63-65; 72-76
1977	B.C.	77058:	180-187; 195-210
1978	Pacific Surv. Corp.		11524, 115438-97
1980	Pacific Surv. Corp.		237091-95; 237087-89
1980	B.C.	81001:	13-16; 28-31
1982	B.C.	82010: 82012: 82013:	34-37; 156-158 222-223; 234-235 169-170