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ISBN 0-315-56314-1

HYDROLOGICAL REGIMES OF NIVAL AND GLACIERIZED MOUNTAIN BASINS, YOHO NATIONAL PARK, BRITISH COLUMBIA

by

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Thesis presented to
the School of Graduate Studies and Research
in partial fulfillment of the requirements for
the degree of
Master of Arts in Geography

University of Ottawa

ABSTRACT

This study focuses on the medium (1977-1984) and short (inter-seasonal and intra-seasonal) time frames hydrological regimes of Kicking Horse River at Cathedral Mountain (51°25′N, 116°25′W), Twin Falls Creek (51°32′N, 116°30′W) and Amiskwi River (51°23′N, 116°50′W), Yoho National Park, British Columbia.

Seasonal hydrographs (late May-early June to late August-early September) of runoff from a nival and two partly-glacierized streams from eight years (1977 to 1984) of observation are compared.

Annual distribution of runoff estimates indicate the major proportion of streamflow occurs from May to September in the mountainous study area; 79.5% at Amiskwi River (0% glacierized), 90.5% at Kicking Horse River (26.4% glacierized) and 95% at Twin Falls Creek (59.3% glacierized). Coefficient of variation (C_v) of streamflow for simultaneous time periods indicate the nival stream of Amiskwi, to be the most variable in terms of streamflow fluctuation at 61.5% for the eight year set. Significantly lower C_v figures are obtained in streams with a glacial component, 44.7% at the Kicking Horse and 46.6% at Twin Falls Creek. The discrepancy in C_v is accounted for by the glacial component to total runoff which commences once snowmelt has terminated. Its contribution has the effect of regulating streamflow while maintaining high discharge levels throughout summer.

Intra-seasonal distribution comparisons of runoff on a monthly basis between nival and glacierized basins reveal trends which are highly variable with regard to quantity and timing of peak flows. The ice-melt component to total runoff cause flow to peak later in the ablation season with increasing glacier proportions in the basin. Monthly C_v figures point to a decrease in streamflow fluctuation as the contribution originating from the glacial component to total runoff increases. The hydrograph of the nival basin begins its gradual decline to low flow as the snow recedes to upper basin elevations. Amiskwi's dependance on precipitation and groundwater movement as main components to total runoff makes it highly variable during summer. Accordingly, an increase in monthly C_v is observed.

Seasonal hydrographs were also examined against certain hydrometeorological elements with the intent of comparing streamflow between years of contrasting meteorological conditions.

Kicking Horse River was the least affected in terms of quantity and variability between years of extreme hydrometeorological conditions. Amiskwi River was the most variable due to the nature of the components making up total discharge in late summer.

RESUME

Cette étude se penche sur le régime hydrologique à moyen (1977-1984) et à court terme (saisonnier) des rivières Kicking Horse au niveau du Mont Cathedral (51°25'N, 116°25'O), Amiskwi (51°23'N, 116°50'O) et du ruisseau Twin Falls (51°32'N, 116°30'O), situés dans le parc national de Yoho en Colombie Britannique.

Les courbes de débit saisonnier (fin mai-début juin à la fin août-début septembre) entre des cours d'eau alimentés par la fonte de neige et de glace sur une période de huit ans (1977 à 1984) sont comparées.

Les débits estimés ayant trait à la répartition annuelle indiquent que la grande proportion des eaux s'écoule entre les mois de mai et septembre dans cette région montagneuse: 79.5% à Amiskwi (0% couverture glacielle), 90.5% pour la rivière Kicking Horse (26.4% couverture glacielle) et 95% dans le ruisseau Twin Falls (59.3% couverture glacielle). L'écoulement des eaux en provenance d'un bassin nival (Amiskwi) s'avère très variable. Son coefficient de variation (C_v) étant 61.5% pour huits années d'observation. Les coefficients calculés pour la rivière Kicking Horse et Twin Falls sont de 44.7% et 46.6% respectivement. Un apport provenant de l'écoulement des eaux de fonte de glace a pour

effet de soutenir le haut niveau et minimiser les écarts saisonniers de débit.

Au niveau mensuel, la comparaison des courbes de débit entre les bassins avec et sans glacier fait ressortir des différences significatives au niveau du régime d'écoulement. L'écoulement des eaux de fonte de glace a pour effet de retarder le débit saisonnier maximum à une date de plus en plus repoussée en été. La courbe d'écoulement du bassin nival décroît rapidement suite à la fonte graduelle du manteau neigeux. Les C_v mensuels indiquent une diminution des fluctuations des débits avec l'augmentation de l'apport des eaux de fonte glaciaire à l'écoulement total. La forte dépendance de la rivière Amiskwi des précipitations, des fluctuations de la nappe phréatique et du mouvement des eaux souterraines en été ne peuvent soutenir les hauts débits de saison de fonte de glace. Par conséquent, les fluctuations d'écoulement tendent à décroître au niveau d'étiage suite aux crues du printemps.

Les courbes d'écoulement ont été comparées avec certains éléments météorologiques afin d'examiner les fluctuations des débits entre des années qui offrent des contrastes météorologiques marqués. On constate que l'écoulement des rivières ayant un apport d'eau de fonte de glace change peu alors que l'écoulement de la rivière Amiskwi est fortement influencé étant donné la nature des sources d'alimentation qui régissent l'écoulement total de cette rivière.

ACKNOWLEDGEMENTS

I wish to thank Dr. P.G. Johnson for his tremendous support and supervision through this stage of the Master's Program. The opportunities he provided me insofar as gaining valuable field research experience in several projects are greatly appreciated.

Hydrological data was provided by Environment Canada. The logistical support and advice provided by John Power, National Hydrology Research Institute, Environment Canada is greatly acknowledged. Recognition is directed to all members who, at one time or another, were involved with collection of field data and especially to Dr. P.G. Johnson, Dr. G.J. Young, Dr. K. Hewitt and Dr. D.N. Collins for their inspiration and dedication in the area of glacial hydrology research.

Financial support was provided by Natural Sciences and Engineering Research Council operating grant A7486 and Environment Canada contracts awarded to Dr. P.G. Johnson.

Special thanks to all those who provided moral support and relentless encouragement throughout the preparation of this thesis.

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CHAPTER 1

INTRODUCTION

In the mountainous region of the Southern Canadian Rockies, a considerable proportion of annual discharge is derived from snow and ice melt. Groundwater is the main contributor to streamflow in the winter while during summer (May-October), runoff is made-up of meltwater (snow and ice). The release of this enormous water reserve is limited to a short period of time. It has important resource management implications. This self regulated source of runoff peaks at a time when agricultural demand for water is at its highest.

Many of the small communities located in the remote mountain ranges of British Columbia rely on diesel generated electricity as their prime source of power. Cost per kWh is extremely high. Hydro transmission lines running through these areas are prone to frequent failures in view of the instability of the terrain with snow avalanches, mudflows and flashfloods. In the region of Grande Dixence, Switzerland, a complex network of reservoirs was designed to collect glacial meltwaters which are used to generate hydro power (Lang, 1985). Harnessing of this source of generating power demonstates the feasibility as the system produces 700,000 kW. A better understanding of the hydrological regimes could assist in identifying and assessing the degree of influence which the components of discharge have in their contribution to total seasonal and annual runoff. The study concentrates on subcatchment areas of the Kicking Horse River system where analysis of discharge data on a seasonal basis could assist in the development of a discharge forecasting model. The results could also be utilized in the operational planning stage of future hydro-electric projects in the Kicking Horse basin.

Annual glacier-runoff is characterized by significant seasonal changes. These discharge variations are driven by climatic changes which control the amount and rate of water production and the timing of the release of the runoff from snow and ice melt. Energy input is the major control on meltwater production. Variations in energy receipt produce fluctuations in melt of snow and ice.

Energy reception by a specific area within a basin is modified by topography. Differential snow accumulation patterns and melt rates may occur as a result of slope angle, slope exposure and altitudinal variations. Shading provided by vegetation cover is another physiographic factor which modifies energy reception by the snowpack.

Orographic effects and thermal convection currents are likely to create temperature and precipitation regimes which differ within and between basins (microclimates), modifying both water storage (solid precipitation) and melt rates.

The influence of climatic and topographic factors compounded by snow and ice melt and the resulting hydrological response to these factors can be better understood when discharge data from neighbouring glacierized and non-glacierized watersheds are compared. This dissertation attempts a comparison between three basins with a range of 0% to 60% glacier cover.

The author participated in the collection of hydrological and mass balance data in 1983 and 1984. These measurements were carried out as part of the Peyto Glacier mass balance program financed by Environment Canada.

1.1 Objectives and Hypotheses

1.1.1 Objectives

The aim of this study is to describe and compare summer (May to September) and short-term summer flow regimes of three watersheds.

The initial objective was to compare seasonal runoff regimes (May-September) of nival and glacierized streams for the 1977-1984 period. In view of significant gaps in discharge data due to measurement problems, only a select number of years were retained for comparitive purposes. This study will focus upon medium and short-term seasonal variations in streamflow where simultaneous measurement records are available for at least two catchments.

The objectives of the thesis are:

1. To describe and compare runoff regimes of glacierized and non-glacierized basins. Hydrograph analysis of simultaneous daily mean discharge measurements collected from one nival and two glacierized basins will reveal similar and/or contrasting regimes between ablation seasons and during a single melt season. The role of physiographic contrasts on the hydrograph will also be considered.

2. To assess season to season, monthly and 14-day period variability of mean discharge with temperature and total precipitation. The purpose is to examine the impact of variations of climate-runoff relationships on a seasonal basis and trace the evolution of these

relationships throughout the ablation season. It is intended to show how these relationships differ between a nival and glacierized basins.

1.1.2 Hypotheses

1a) Maximum seasonal streamflow variations will occur in the nival basin.

As the basin's glacier cover increases to 25%, seasonal discharge variability will decrease due in part to the compensating effect of snow and ice melt during seasons of low precipitation. As glacierization increases from 25% to 60%, variability in streamflow is expected to increase. The ascending snowline results in greater ice exposure and consequently, increased meltwater production.

1b) Maximum daily peak discharge will occur later in the ablation season with increased basin glacier cover.

2a) On a season to season basis, lag time between meteorological conditions and streamflow responses will vary with snowpack depth.

In the early melt season, in years of light accumulation, lag time response will be reduced and lag time will increase in years of heavy accumulation.

2b) Within a single melt season, variability in air temperature and precipitation should have a similar impact on runoff in all basins. Significant differences are expected in streamflow response to climate variables once the snow reserve has depleted.

1.2 Field Area

1.2.1 Location

Amiskwi, Twin Falls and Kicking Horse above Cathedral Mountain are the hydrological basins under investigation (51° 30′N, 116° 35′W) (Figure 1.1). They are located in the Canadian Rockies Southern British Columbia, in the northeast of Yoho National Park, west of the Continental Divide. Yoho Valley is situated 3 km east of Field, B.C. while Amiskwi Valley is located 10 km west of Field. Confluence of Twin Falls and Yoho Rivers occurs at approximately 1600 m.a.s.l. in the upper reaches of the Yoho Valley. The Yoho River is the major component of the Kicking Horse upstream of Cathedral. The Amiskwi is tributary to the Kicking Horse

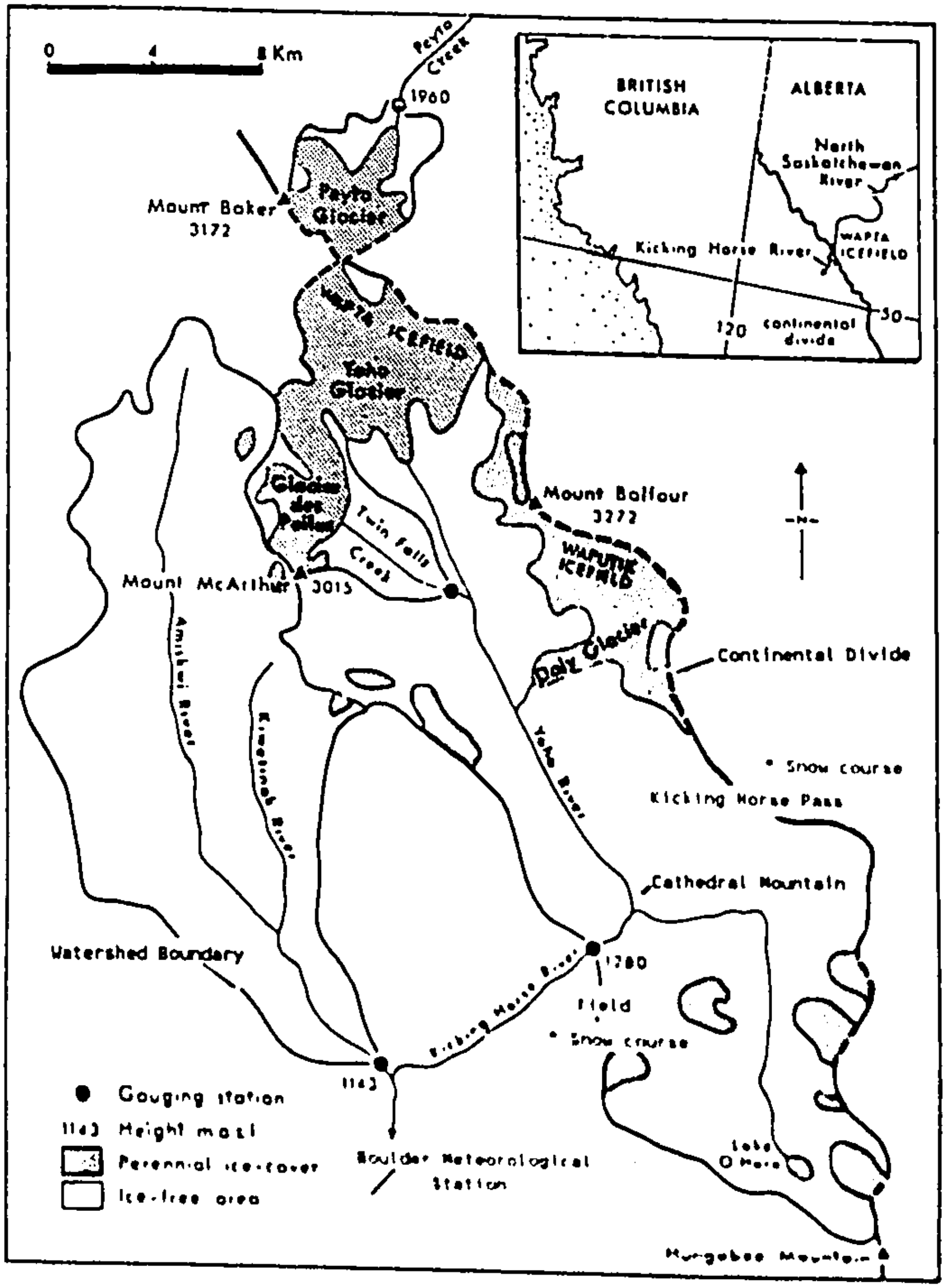

Figure 1.1 Location map of the catchments of Twin Falls Creek, Amiskwi River and Kicking Horse River, Rocky Mountains, British Columbia. Source: modified from Collins and Young (1981).

below Field which then flows west into the Columbia River at Golden, British Columbia. The three basins are adjacent and parallel, running in a northwesterly south easterly direction.

The main runoff component at Amiskwi originates from snowmelt in May and June. It is an ice-free catchment with an extensive vegetation cover. At Twin Falls Creek and Kicking Horse River, runoff contributions from snowmelt is supplemented in July to October by an ice-melt component.

The proximity of the catchment areas and the distribution of hydrometric monitoring stations in the study area provide an excellent opportunity for comparing the hydrological regimes.

1.2.2 Climate

The Continental Divide has a tremendous influence in determining the climate of the Yoho and Twin Falls Valleys. Topography and climate are the main factors responsible for the presence of perennial ice cover in the area. Moisture laden air travelling eastward from the Pacific over the Divide causes significant amounts of precipitation on the western side where the Yoho and Twin Falls Valleys are located (Indian and Northern Affairs and Parks Canada, 1976). In sharp contrast is the neighbouring Amiskwi basin where the lack of any extensive glaciated coverage suggests the existence of very distinct microclimates within the study area.

This demonstrates the influence of the Divide on local climate. The result is extreme local variability in temperature and precipitation regimes. On a regional scale, Janz and Storr (1977) examined temperature regimes between the Banff and Boulder Warden's stations for 1974. The results of their regional climate analysis reveal the following:

1. Extreme day to day temperature fluctuations occur from November to March. Daily temperature range in summer is less.

   They conclude that mean daily temperature better describes summer temperature regimes since the daily range is less. The use of daily mean temperature as a descriptor of winter regime could lead to erroneous results since temperature ranges are greater.

2. Both stations display similar day to day fluctuations therefore the same climatic controls are operating east

and west of the Divide.

On a regional scale, temperature is highly variable. Monthly temperatures at Golden, Boulder and Lake Louise meteorological stations are presented in Table 1.1.

The impact of the Divide on precipitation regimes is best demonstrated when data from several meteorological stations in a transect are compared. The results indicate increasing precipitation with gain in altitude. Snow cover data near Field (51° 23′N, 116° 31′W; 1280 m.a.s.l.) and at Kicking Horse Pass (51° 26′N, 116° 21′W; 1650 m.a.s.l.) follow a similar trend.

Meteorological data collected at the Boulder meteorological station (51° 23′N, 116° 32′W) located at 1219 m.a.s.l. will be retained for analytical purposes. Being the closest to the study area, it will provide site specific daily temperatures, total daily precipitation and total daily sunshine hours.

Table 1.1 Summary of selected meteorological data for Golden and Boulder, British Columbia and Lake Louise, Alberta (1951-1980).

	Temperature (°c)			Mean Precipitation (mm)			Mean Snowfall (mm)			Temperature Variability (C_v)			Precipitation Variability (C_v)		
	Gold.	Boul.	L.L.	Gold	Boul	L.L.	Gold.	Boul.	L.L.	Gold.	Boul.	L.L.	Gold.	Boul.	L.L.
Jan.	-11.0	-10.9	-15.2	68.0	51.9	78.6	64.3	48.3	78.2	.35	.26	.24	.45	.46	.65
Feb	-5.1	-5.6	-10.0	34.6	27.3	52.5	29.9	26.0	51.5	.59	.26	.24	.58	.56	.65
Mar	-0.5	-2.0	-6.7	18.0	21.8	43.3	11.7	21.9	41.5	—	.9	.31	.69	.91	.58
Apr	5.7	3.3	-0.3	24.2	26.1	41.0	6.5	91.8	33.7	.23	.29	6.0	.79	.73	.71
May	11.3	8.5	5.7	33.6	52.0	46.9	8.1	1.7	12.7	.11	.13	.21	.54	.69	.53
Jun	15.0	12.4	9.6	41.5	73.6	57.5	0.0	0.1	0.2	.09	.10	.14	.51	.41	.41
Jul	17.9	15.1	13.2	32.9	55.0	53.8	0.3	0.0	0.1	.06	.08	.08	.49	.44	.44
Aug	16.5	14.3	11.8	30.2	45.2	51.8	0.1	0.0	0.0	.18	.10	.13	.59	.73	.47
Sept	11.3	9.6	7.1	37.3	45.0	46.5	0.6	2.4	4.8	.10	.19	.25	.56	.47	.46
Oct.	5.2	3.8	1.5	32.6	43.3	46.9	3.1	7.0	30.6	.19	.32	1.1	.55	.48	.60
Nov.	-2.7	-4.3	-7.7	46.6	50.9	60.8	30.2	50.0	66.0	.96	.31	.32	.59	.57	.53
Dec	-8.3	-9.1	-12.9	68.1	64.8	97.9	62.5	73.1	97.0	.41	.35	.23	.51	.34	.43

Gold = Golden
Boul = Boulder
L.L. = Lake Louise

1.2.3 Vegetation

Treeline elevation ranges from 1750 to 2100 m.a.s.l.. The study area encompasses two biogeoclimatic zones, the sub-Alpine Englemann Spruce (Picea engelmanni) and Fir (Abies lasiocarpa) and the Alpine zone (Yoho Valley Interpretive Management Unit Plan, 1976).

Glacial termini advance and recession, heavy meltwater sediment deposition and erosion has hindered the growth of vegetation in the immediate glacierized areas. Below timberline, frequent disturbances (rockslides, snow avalanches, etc.) often limit growth to shrubs. The absence of recent glacial activity is probably responsible for the extensive vegetation cover in Amiskwi Valley. It has led to increased slope stability and reduction of the occurrence of disturbances.

Two wetland areas have been reported by a water resources study of Yoho National Park (Reynolds, 1977) in the sections of Upper and Lower Amiskwi Valley. The report also states that the basin's vegetation cover has been significantly disturbed by commercial timber harvesting and destroyed by fire on several occasions.

1.2.4 Geology

The structure of the southern Rockies is the result of several superimposed periods of tectonic activity some of which may have occurred in the Lower Paleozoic and are possibly contemporaneous with sedimentation (Cook, 1975; Harrison, 1969; Kodybka, 1981). The structure of the study area is dominated by broad open concentric folds and a series of north and northwest trending normal faults downthrown to the west.

A major fault, the Stephen-Cathedral to the west of Upper Yoho Valley, runs the full length of the basin directly under the valley floor. Minor faulting and extensive folding on Mount Kerr, President Range, Amiskwi Peak and Van Horne Range have been documented by Sproules (1975).

Stratigraphic rock units in the area are of the Middle and Upper Cambrian age.

The bedrock in Upper Amiskwi Valley (1630 m.a.s.l. or more) belongs to the Middle Cambrian Pika and Eldon Formations. Both formations are made up of limestone and dolomite. Amiskwi River then travels along the contact area between the Mistaya Formation (Upper Cambrian: limestone). Bedrock units in middle and lower Amiskwi Valley (below 1630 m.a.s.l.) are of the Upper and Middle Chancellor Formations (Middle Cambrian; slate and limestone).

The Sullivan Formation (Upper Cambrian; Shale, interbedded limestone and silt) is the predominent stratigraphic unit in Twin Falls Valley. Upper Yoho River flows in the contact area between the Sullivan Formation to the east and the Eldon, Pika and Waterfowl (Middle Cambrian; dolomite, some shale) Formations to the west. Yoho River then continues its course over the Sullivan Formation in the mid-valley area (1630-1477 m.a.s.l.), subsequently flowing over the Eldon Formation in the Lower Valley area.

The drainage network of the study area is controlled by the structure and is the direct result of the thrust planes forming the mountains. Regular fault and thrust planes, aligned in a northwest southeast direction, have produced near linear valleys (Reynolds, 1977).

1.2.5 Geomorphology

The U-shape of Upper Yoho Valley is characteristic of recent glacial activity. The extensive vegetation cover in Amiskwi Valley is typical of a landscape with little or no recent glaciation.

Geomorphic units differentiated by mode of deposition have been mapped by Sproules (1975). Genetic categories of surface deposits appear related to altitude above valley floor. Above treeline, the landscape is geomorphically dynamic. Bedrock is exposed in higher elevations, along ridges, cliffs and peaks, and occasionally at lower elevations, in gorges. Directly below, colluvial talus slopes made-up of debris originating from outcrops above are deposited by gravity or by snow avalanches. The material varies in size from boulders, angular rock fragments to finer debris. It is generally loose and porous. Slope gradients are high, ranging from 35 to 40 degrees (Sproules, 1975).

In areas of active glaciation, numerous glacial landforms are present. Fresh glacial features are widespread throughout the Upper Yoho and Twin Falls Valleys. Isolated glacial landforms have been identified by Sproules (1975) above the headwaters of Amiskwi River and along the Otter Creek, in the western extremity of the study area, some support vegetation. The most frequently encountered features are moraine ridges, hummocky moraines and ground moraines. Glacio-fluvial features above treeline are generally restricted to areas where glaciation is still active. An Alpine flood plain at the head waters of Waves Creek has been documented by Sproules (1975). Debris also ranges from silt to boulders. Other glacio-fluvial features are found at the terminus and margins of Daly Glacier.

The immediate area below timberline is also frequently disturbed by avalanches, rock slides, etc. The slopewash process is one of creeping of debris in response to gravity, enhanced by running water (Sproules, 1975). The slopewash talus is made up of unconsolidated materials and is covered with soil. It contains finer debris than those found in talus slopes although boulders and rock fragments are often present.

In the valley troughs, Yoho has few glacio-fluvial deposition areas and features, in contrast with Amiskwi. In view of active glaciation and steep slope gradients at Yoho, it is suspected that most of the glacio-fluvial land forms have been washed away.

Extensive Kame fields and terraces along the east and west banks of Amiskwi River are present (Sproules, 1975). Two lacustrine plains have been identified, one in Upper Amiskwi and the other in the lower basin. Amiskwi River has eroded the latter approximately 100 meters in depth. Thirty meters of the surface material is reported to be lacustrine clay. The remaining is gravel material, likely of glacio-fluvial origin (Sproules, 1975).

Sproules (1975) reports the presence of a large alluvial fan near the campground area situated across from Takakkaw Falls. Part of the hiking trail between the campground and Twin Falls Creek is on another lacustrine plain. Both the fan and terrace near Twin Falls Creek are well drained as the landforms contain large amounts of gravel. Drainage ditches on each side of the trail have been dug, in the lacustrine plain area. All are located above the river's flood plain area.

CHAPTER 2

METHODS AND TECHNIQUES

The approach to the problem is based on the comparison of hydrological regimes and the correlation of discharge to climatic parameters and the physical characteristics of the basins. The methodology is simply to compare hydrographs between sites and to analyse the relationships between climate parameters and discharge. Primarily, this involves the application of correlation and regression analysis to data acquired using standard hydrological and meteorological techniques.

2.1 Data Collection

2.1.1 Streamflow Measurements

Continuous levels were obtained with Leopold and Stevens A-71 float type stage recorders. Periodic time checks and stage height observations were inscribed on the level chart by the station attendant. Level was read to the 10th of a foot or the nearest centimeter off a vertical staff gauge located on or near the stilling well.

Discharge was measured manually using standard current meter methods (Church and Kellerhals, 1970). Depth soundings and current velocity measurements were performed from bridges. Interval length between vertical soundings was devised so that twenty or more observations per cross-section were obtained. This enhanced the accuracy of average instantaneous streamflow measurement of the stream. The wider Kicking Horse and Amiskwi Rivers required readings at one meter intervals and at Twin Falls readings were taken at half meter intervals. Stream bed profiles were drawn in the field.

At the isolated hydrometric station of Twin Falls, portable stream gauging equipment was used. This consisted of a graduated hand held rod with a Price current meter. For the larger streams, a heavy winch type reel supporting a 50lb weight and Price current meter was used. It was fastened to the bridge railing. The weight was insufficient during extreme high flow periods. The current caused the meter to drag, yielding somewhat inaccurate velocities and vertical section lengths. Velocity measurements were somewhat distorted by the constant shifting of the current meter from the desired position. Velocity measurement adjustments were performed in the calculation for Kicking Horse River because the bridge is not at right angle to streamflow.

The Price current meter was lowered to the streambed, depth of the section was recorded then raised 6/10 of the total depth from the surface. Cup revolutions were converted into velocity units from a calibration table for the current meter. The meters required regular recalibration under controlled conditions as bed load movement often damaged the cups.

Streamflow area was estimated from the bed configuration graph. Velocities for individual vertical segments were calculated and then multiplied by the area. The summation of these data gave total streamflow. Instantaneous discharge results were plotted against stage height and a curve was fitted through the scatter of points.

2.1.2 Stage-Discharge Curves

The scatter of points located above and below the rating curves illustrated in this section (Figures 2.1 to 2.3) are considered adequate to good given the conditions in which the measurements were performed. The erosional forces of turbulent proglacial streams in mountainous areas cause significant streambed shifts at gauging sites. Adjustments to the rating curves following these shifts were carried out. Consequently, stream gauging sessions had to be carried out periodically in order to redefine the relationship between stage height and discharge (Bruce and Clark, 1980).

As a result of a bridge washout in 1979 at Twin Falls Creek and the subsequent bridge relocation to another area, discharge from 1977 to 1984 was calculated using two rating curves. A significant shift in the relationship resulted from the change in location. Amiskwi and Kicking Horse rating curves were constructed from observations recorded from 1977 to 1984.

All curves are non-linear, reflecting riverbed and embankment morphology (Figures 2.1, 2.2 and 2.3). Curve fitting was done by eye. It is subject to large errors, but is practical and expedient (Chow, V.T., 1964). Graphical examination of the scatter of plotted data points suggested that a second (quadratic) or third (cubic) order polynomial curve would appear to provide an appropriate fit.

Comparison of the analytically derived quadratic and cubic curves against the graphically fitted rating curves indicate no major variations. Discrepencies did however show up in low and high flow extremes. The use of the quadratic or cubic regression lines was rejected and the graphic fit retained on the basis that physical considerations could be

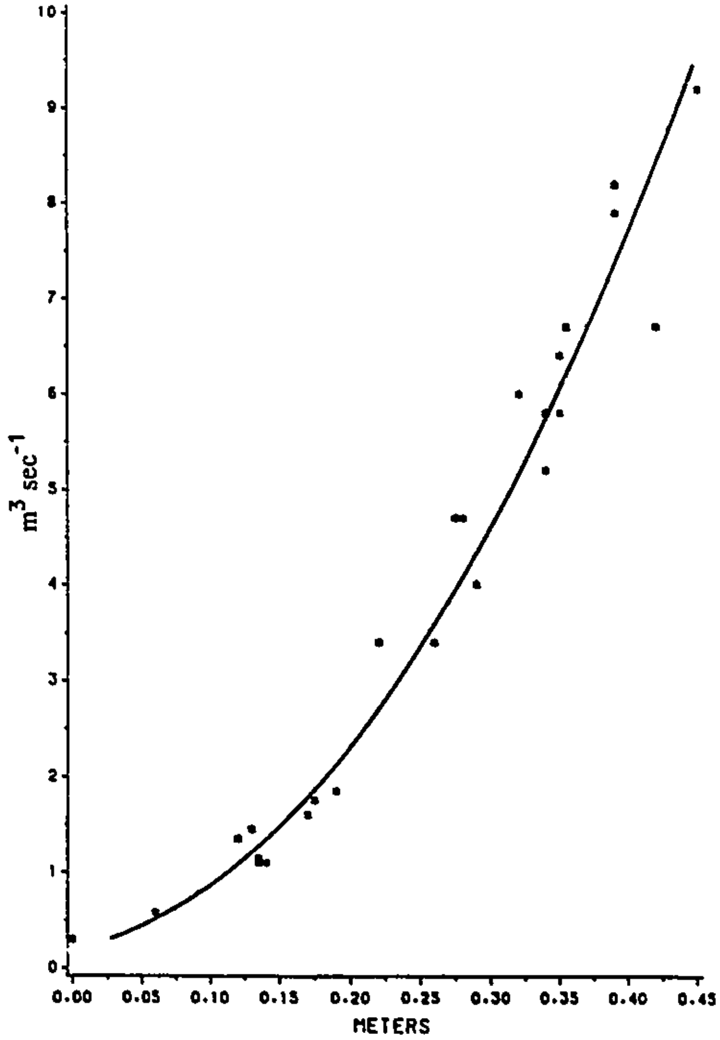

Figure 2.1 Stage-discharge rating curve: Twin Falls Creek. Source: Unpublished data N.H.R.I.

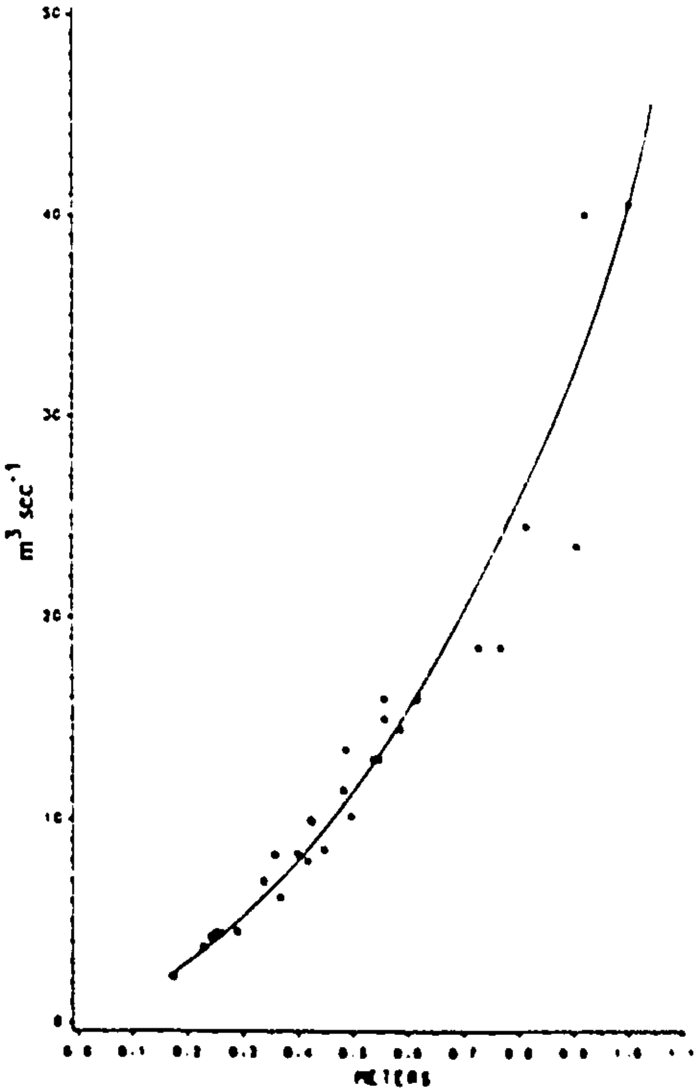

Figure 2.2 Stage-discharge rating curve: Amiskwi River. Source: Unpublished data N.H.R.I.

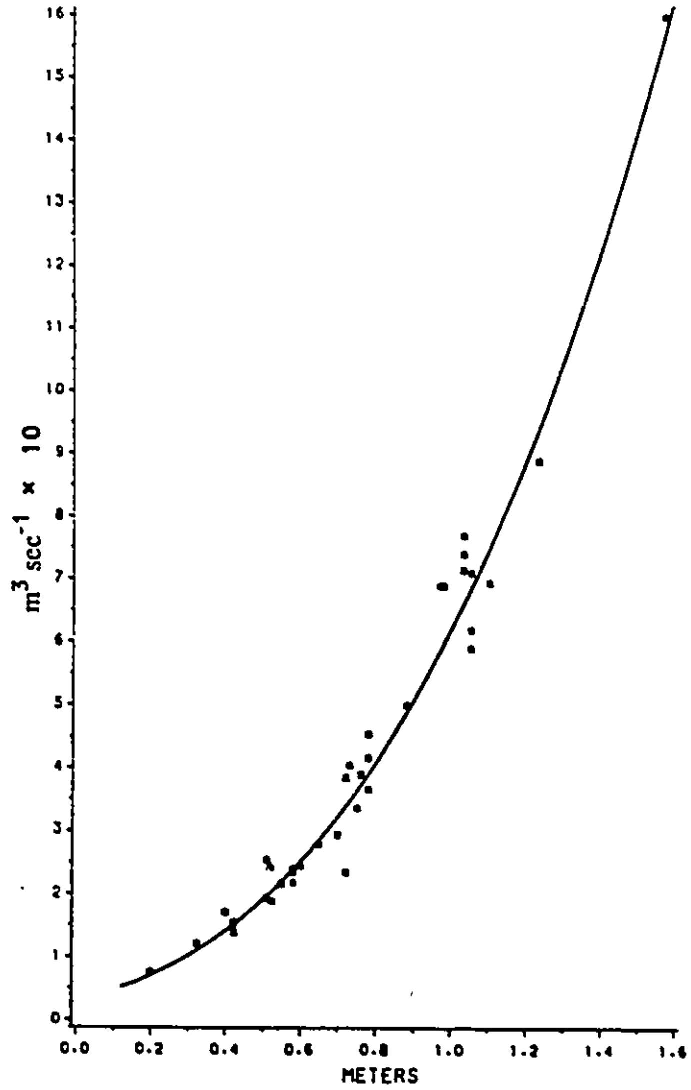

Figure 2.3 Stage-discharge rating curve: Kicking Horse River. Source: Unpublished data N.H.R.I.

incorporated into the graphic fitting procedure. Furthermore, the graphic fit allowed for the proper weight to be given to extreme values. The least squares method gives much more weight to extreme values than to the points near the line of relation since this method is designed to produce a curve about which the sum of squares of the deviations to the points from the curve is a minimum (Bruce and Clark, 1980). Because of a small sample size, confidence limits were not plotted. A stage-discharge relationship table was established from these curves.

All of the above field and curve fitting techniques, and data collection methods are standard Water Survey procedures.

2.1.3 Computation of Continuous Discharge

Continuous discharge data was generated using Water Survey computing facilities. Level charts documented with reference points (stage height, time and date) were digitized on the Gradicon (Graphic to Digital Converter) hardware system. The values of the stage-discharge tables obtained from the rating curves were entered into the computer. A trial run of the data into the Stream program was initiated, producing an output listing of continuous level heights and discharge. Generated discharge values for given stage levels were compared with those on the rating curves for accuracy and consistancy. An option card in the Stream program provided the possibility of generating discharge data on different time scales.

2.1.4 Generated Discharge Records

Daily mean discharge was computed using six hourly values recorded at 0400, 0800, 1200, 1600, 2000 and 2400 hours. Experience has shown that four to six discharge readings per day will generally yield an accurate mean daily discharge figure while retaining diurnal variation characteristics of glacial streams (Ostrem and Stanley, 1966).

Significant gaps in data continuity are due to mechanical failure of the clock on the stage recorder, freezing of the float, or silting and damage to the stilling well following major flood events. Low flow conditions made the recorders inoperative as the float bottomed out. No attempt was made to generate missing data.

2.1.5 Meteorological Data

Temperature, precipitation and sunshine data used in this study were collected at the nearby Boulder Meteorological Station. Having been in operation in excess of 15 years, the records are believed reliable. There are few gaps in data continuity and the location of the station is considered representative of the temperature and precipitation regimes of the study area.

2.1.6 Snow Course Data

Snow course data measurements collected at Kicking Horse Pass and at a snow course site outside Field were examined to underline intra-seasonal accumulation and depletion patterns occurring at different elevation ranges. They are used to examine the extreme variability of snow accumulation in winter and persistence in spring. The amount of snow accumulation in winter and subsequent melt and runoff in spring should be reflected on the hydrograph.

2.2 Data Analysis

2.2.1 Coefficient of Variation Analysis

Since the study focuses on comparison of variability in discharge between several hydrological basins and meteorology, the coefficient of variation (C_v), has been used in this study. It provides the means for comparing the relative variation of hydrometeorological elements over space and time. C_v is a dimensionless dispersion parameter applied to hydrological problems and has been used extensively (for example Collins (1986), Fountain and Tangborn (1985), Henshaw (1933), Zhenniang (1982) and Zuming (1982)). It is appropriate for interbasin comparison of runoff and also for demonstrating climate-runoff links.

In view of its widespread application, the results of this coefficient of variation analysis can be compared with those obtained by other researchers.

Since the field programme is restricted to the summer months, mean monthly discharge figures from nearby hydrometric sites, obtained in Historical Streamflow Summary, British Columbia, were used in the calculation of annual discharge variability figures.

Mean daily discharge, temperature and total daily precipitation figures were used to calculate monthly and bi-monthly (fourteen day intervals) values. The intent is to examine and describe trends in short-term variability. Collins (1986) and others have demonstrated that fluxes in temperature C_v are reflected in discharge C_v.

2.2.2 Simple and Multiple Linear Correlation Coefficient Analysis

One of the main thrusts behind this study is to establish a relationship between the discharge hydrograph and meteorological variables in order to account for hydrological trends. Plots of daily streamflow, superimposed by daily precipitation totals and mean daily temperature, were generated to graphically demonstrate these relationships.

Simple linear correlation analysis was used to measure and compare the relative strength of climate-runoff relationships.

Daily runoff data were lagged 1 to 3 days against climate variables. A stepwise multiple linear regression performed on the new data set is used as an exploratory technique to gain insight into the relationship between climate elements and lagged runoff values. This is achieved by comparing partial correlation coefficients of the model.

CHAPTER 3

LITERATURE REVIEW

3.1 Background Research

Detailed study of snow and ice hydrology is relatively new. The general Assembly of the International Association of Scientific Hydrology (I.A.S.H.), now the International Association of Hydrological Sciences (I.A.H.S.), held in Helsinki in 1960, emphasized the need for glaciological research on a global scale. Implementation of the International Hydrological Decade (I.H.D.) program in 1965 provided thrust for further glaciological studies. Since then, the literature concerning glaciological investigations has expanded rapidly. Although general concepts have been developped, there is an urgent need to continue to verify these ideas through case studies. The thesis is perceived as a case study.

An investigation in the area of glaciological controls on hydrological regimes is of particular interest since this factor is a moderator of both seasonal runoff and timing of peak discharge. Temporal variations of streamflow are critical to both runoff simulation and prediction. The results derived from discharge variation studies may benefit water resource related projects and optimise water resource uses.

3.1.1 Components of Runoff

Nival Basin

In a nival basin, two periods of contrasting hydrological response have been identified by Collins and Young (1981) on the basis of hydrochemical analysis. The authors have broken down total discharge (Q_t) into individual components, where $Q_t = Q_s + Q_g + Q_p$.

In the early melt season, meltwater originating from snowpack depletion (Q_s) has been identified as the main component of discharge while summer runoff comes mainly from liquid precipitation (Q_p) and groundwater (Q_g). The transition of regime is characterised by a significant decrease in average daily discharge.

Partly Glacierized Basins

The runoff from a glacierized basin can be considered as arising from two sub-catchments, the glacier and the ice-free areas (Collins, 1986). Total discharge is calculated with the equation: $Q_t = Q_i + Q_s + Q_p + Q_g$, where the glacial component of discharge (Q_i) includes icemelt, firnmelt and snowmelt from the ice covered areas (Collins and Young, 1981).

In spring, increasing discharge is a result of snowmelt from the ice-free areas (Q_s) and to a lesser extent of snowmelt from ice-covered surfaces (Q_i) in the lower reaches of the glacier. During mid-summer, as the contributions from Q_s diminishes, an increasing proportion of total runoff originates from Q_i. The transient snowline gradually exposes an increasing amount of ice area as it migrates to higher elevations. Above firnline, water stored within the firn aquafer and snowpack located in higher elevations is released later in summer.

Although there is a general trend which repeats itself from year to year, significant intra-season variations do occur.

3.1.2 Snowmelt Hydrology

Surface Runoff

Fluctuations in runoff originating from snowmelt have been described by Collins and Young (1981), Dunne and Black (1971) and Sarantitis (1985). Streamflow variations of this type are of low amplitude and the cycle varies in length from the onset to the end of the snowmelt ablation period.

In the early part of the snowmelt season the maximum flows are out of phase with fluctuations in meteorological conditions. Stenborg (1970) has examined the reasons for the lag response time between the melting of snow and runoff. The snowpack acts as a temporary storage reservoir delaying runoff until later in the season by retaining water through capillary attraction. Percolation of meltwaters within the snowpack may be temporarily interrupted by ice layers which are formed at the upper surface of the pack by freezing rain and buried by subsequent snowfalls (Colbeck, 1980). Impermeable layers of high density grains may develop by refreezing of percolating melwaters. These layers may disintegrate within hours following the introduction of large amounts of melt waters in the snowpack.

Although the upper layer of the snowpack may experience a positive energy balance, the lower layers of the snowpack require additional energy to remove the winter cold wave. Subsequent refreezing of the percolating melt water releases energy which is used to bring the lower layers of the snowpack to isothermal conditions (0°C).

Once attained, it is estimated that for deep mountain snowpack water in transit could be up to 6% of the snowpack water equivalent once inflow and outflow are in equilibrium (U.S. Army Corps of Engineers, 1960). An increase in grain size which augments permeability in the saturated zone of the snowpack and its gradual reduction in depth result in reduced vertical meltwater travel times.

Despite the greater distances water travels in the basal layer of the snowpack, time spent in horizontal saturated flow conditions at the base of the pack is often less than time spent in vertical unsaturated flow (Colbeck, 1980).

3.1.3 Glacial Hydrology

Meier (1973) points out that a glacier is made up of three types of materials, snow, firn and ice. Using Shumski's (1964) classification of glaciological zones, Golubev (1971) examined hydraulic properties between areas and found that each had a distinct hydrological regime with variations in time and space. With respect to streamflow control, much of the base flow during high discharge ablation period is provided by the release of water stored within the internal plumbing of the glacier and the firn aquifer. The superimposed diurnal streamflow fluctuations originate from the immediate runoff response to surface ablation on the tongue (Golubev, 1971, 1973).

Melt-waters may be routed to the portal area through several pathways. Channelling may be supraglacial, englacial or subglacial but usually a combination of the three. Although limited knowledge has been gathered on the drainage system of a glacier it is known to vary both in time and space (Elliston, 1969; Gobulev, 1969, 1973; Meier, 1973; Paterson, 1981; Stenborg, 1969; Vivian and Zumstein, 1969).

Since the snowmelt process has previously been discussed it will not be repeated in this section. The flow of water in the snowpack overlying ice is not much different from that of snowpack over soil and rock (Meier, 1973).

The amount and regimes of surface and subsurface flow in the accumulation and ablation areas may be modified in several ways:

1) Vertical movement of meltwater from the accumulation area through the unsaturated porous medium firn zone is allowed to collect laterally over the underlying ice,

thus creating a firn aquafer during the ablation period (Golubev, 1973; Oerter and al., 1981; Stenborg, 1970). Experiments carried out in the Oetztal Alps by Oerter and al. (1981) revealed a water bearing firn layer in the accumulation area at a depth of 20m below the surface. Water level measurements in boreholes indicated strong annual variations.

2) As meltwaters are released from the snowpack over firn and ice, time is required to rejuvenate the seepage network and opening of supraglacial channels. Once established, runoff may travel down the supraglacial stream system directly to the snout and into the proglacial river in a very short period of time.

3) The convex topography and the oblique tensile crevasses found on the tongue area of many glaciers, may redirect meltstreams towards the margin (Stenborg, 1969). However, some of the runoff may in fact never reach the margin. The supraglacial path may connect with vertical conduits, mills or moulins, which may route surface meltwater englacially as deep as the glacier bed. Meltwater could subsequently continue subglacially towards the terminal area. Subglacial water flow has been observed to carve a path upwards into the ice (R-channel) or down into the bedrock

(N-channel) (Meier, 1973; Stenborg, 1969; Vivian and Zumstein, 1969).

4) Percolation of meltwater through glacier ice is possible along a complex three-dimensional network of tiny prisms along three-grain intersections (Meier, 1973). Nye and Frank (1973) have calculated that as much as 1 cubic meter of water per meter square can travel through a typical glacier in one year (Meier, 1973).

Streamflow could be interrupted at any stage along its path. Internal flow passages are often modified during the summer by the collapse of decaying ice, debris accumulation in marginal areas and internal glacier flow. Ice deformation may close conduits and open others. The reduction of water availability in winter is associated with a decrease in heat generated by high discharge volumes and by lower meltwater temperatures both of which had contributed to enlarging the englacial and subglacial drainage systems during the previous summer. The overlying pressure of ice may, by plastic deformation, fill dry englacial and basal cavities or retain pockets of water delaying its release.

3.1.4 Discharge Variability

There are a number of factors which modify streamflow and produce temporal variability of discharge on different time scales.

The salient features of glacial influence on basin runoff can be revealed by comparing discharge data from glacierized and non-glacierized basins (Meier and Tangborn, 1961). The critical assumption in this comparison is that precipitation characteristics of glacierized and non-glacierized basins are similar in areas where meteorological stations are scarce (Fountain and Tangborn, 1985).

In spring, increasing discharge is caused by snowmelt in the lower basin area, but runoff is lower than predicted from quantities of snow melted because of the storage in the snowpack and glacier (Stenborg, 1970). This stored water is released later in summer, adding to high discharge resulting from ablation of the increasing surface area of ice exposed as the transient snowline rises (Collins and Young, 1979).

In the interseasonal (year to year) and intraseasonal (within the single melt season) time frames, discharge from both glacierized and non-glacierized catchments is highly variable both in the quantity and timing of peak flows

(Johnson and David, 1987).

While the presence of a glacier is seen to have a regulatory influence on total runoff and the progression of events is similar from one year to another, the timing of events is markedly different resulting in hydrographs of quite different shapes (Young, 1982). With regard to the glacierized contribution to runoff, significant variations in discharge occur as a result of differences in the extent of basin glacier cover.

Interseasonal Variability

Interseasonaly, during the snow melt period, much of the runoff is provided by the snowpack which has accumulated over the winter months. Climate inputs and depth of snowpack regulate the timing sequence and pattern of runoff. These are reflected in the hydrographs from nival and glacierized basins. Hence, yearly variations of snow on ground persistence in terms of water equivalent and interseason temporal variations in energy availability lead to variations in runoff peak and patterns during the early part of the ablation season.

Once the seasonal snow cover has melted, the differences in hydrological regimes between nival and glacierized basins are clearly illustrated when their respective hydrographs are compared. Components of total discharge originate from different sources. The nival stream relies heavily on precipitation and groundwater inputs and average daily discharge drops dramatically while high rates of runoff in ice covered basin will persist and be sustained later in the season.

The contribution of the snow and ice melt components to streamflow will fluctuate according to climate conditions, for example between years of extensive overcast and rainy periods and years which are warm and dry. However, regardless of the prevailing seasonal meteorological conditions, streamflow in the glacierized basin will be less variable. Collins (1986), Fountain and Tangborn (1985), Krimmel and Tangborn (1974), Meier and Tangborn (1961) and Stenborg (1970) all observed the compensating effects on streamflow of the icemelt component in warm and dry summers which result in a reduction of annual fluctuation of runoff.

Fountain and Tangborn (1985), Henshaw (1933), Tangborn and Rasmussen (1976), Zhenniang (1982), Zuming (1982) have all observed lower annual variation of runoff in glacierized basins compared to nival basins.

Intraseasonal Variability

Young (1982) and others have observed higher than usual runoff rates in the early ablation season following a heavy snow accumulation winter. Contribution to total runoff from the ice melt component was delayed. The greater snowfall retards the exposure of ice to radiation as the snow blanket has a high reflectivity which is maintained for a greater length of time. Also, drifting and avalanching is usually greater in those conditions thus contributing to added depth of the snow covered surfaces lying below ridges and peaks.

Fountain and Tangborn (1985) and Meir and Tangborn (1961) found variations in runoff delay to be related to the proportion of ice cover over a basin. A longer delay in the summer maximum runoff occurs with increasingly glacierized basins.

Within a single melt season (May to September), variations in discharge have been observed to be minimal in basins where glacier coverage is 30-35% (Fountain and Tangborn, 1985; Krimmel and Tangborn, 1974). Runoff variations were shown to:

1) decrease as the percentage of ice cover increases from 0% to 35%; and,

2) increase as the percentage of glacierized area increased from 35% to 100% (based on the algorithm coefficient of variation of runoff versus an arbitrary glacier cover, Fountain and Tangborn, 1985).

Diurnal Variability

Daily discharge peaks are believed to be the direct result of surface melt (Golubev, 1973) and are usually superimposed on a high background flow. With snowpack depletion, runoff originating from glacial ice surfaces is fast and fluctuations are more pronounced following diurnal flux in energy availability (Young, 1985). Daily streamflow of proglacial rivers may vary by as much as 50% over a 24-hour period with minimum discharge occuring in early morning and maximum during late afternoon or early evening.

3.2 Basin Characteristics: Effects on Snow Distribution, Melt and Runoff

Winter snowpack accumulation and energy receipt are spatially variable in mountainous areas. Some of the physical factors which cause this variability and have significant impact on snowmelt runoff are discussed in this section.

3.2.1 Topography, Aspect and Wind Effects

Topography plays a major role in that:

1) snow accumulation varies with altitude;
2) snow is distributed unevenly by wind erosion, transportation and deposition(Cooley and Robertson, 1985); and,
3) energy receipt is seasonally variable with time of year and basin aspect. Within a basin, differential energy reception occurs as a result of slope angle and exposure to direct solar radiation (Young, 1985).

Results from experiments conducted by Kotlyakov (1971) on glaciers of the Polar Urals, Caucasus and Pamir-Alai in the Soviet Union indicate that drifting may increase snow accumulation by as much as 15% on valley glaciers and up to 50% in cirque areas and slope glaciers.

Avalanching has also been identified as a major component to valley glacier nourishment by Hewitt (1985) in the Karakorams of Northern Pakistan and Kotlyakov (1971).

Both topography and wind will have an impact on winter precipitation distribution, accumulation on ground, snowmelt rate and time lag between meltwater production and subsequent runoff.

3.2.2 Altitude

Martinec (1965, 1970) and others have studied the effects of altitude on snowmelt runoff regimes and have concluded that runoff from basins located in higher elevations tends to start later in the season and is stretched over a longer period of time. A temperature lapse rate within the basin is largely responsible for retarding snowmelt in high elevation areas.

3.2.3 Vegetation Cover

Vegetation cover also serves as a regulator of snow distribution (Herrmann, 1971) and melt with its shading effects. Experiments conducted in California's Central Sierra Mountains by Anderson (1956, 1965) on melt rate variability between open and vegetated areas indicate that 50% shade provided by the forest canopy is 75% as effective as full shade (100%). Shade retarded snowmelt extending the ablation season well beyond snowpack depletion in the open areas. A vegetation canopy modifies the amount of beam and diffuse radiation reaching a surface (Marks and Marks, 1980). The canopy will absorb a greater amount of the incident beam solar radiation with increasing canopy density and modify energy exchange of the boundary layer between the ambient air and the snow surface (Dewalle and Meiman, 1971; Marks and Marks, 1980; Price and Dunne, 1976).

Interception of snow in forested areas varies considerably with canopy density. On the average, interception may range from 10% (Anderson, 1968; Rowe and Hendrix, 1951) to 25% of the seasonal snowfall (Bruce and Clark, 1980). Much of the intercepted snow may be redistributed by wind effects and to a lesser extent, absorbed by the atmosphere through sublimation during the winter and early spring and evaporation in mid to late spring as the snow reaches its melting point. Additional snow meltwaters are lost to runoff to tree, shrub and plant usage. Water in transit to the stream channels is impeded by vegetation and kept in detention storage (Bruce and Clark, 1980).

3.2.4 Soil types and Moisture

The rate and volume of spring snowmelt runoff depends not only on the amount of water in the snowpack and snowmelt intensity, but also on the initial distribution of moisture and temperature within the soil profile, the depth and nature of freezing, and variations in infiltration (Alexeev and al., 1971).

The prime factors which affect surface hydraulic conductivity during the snowmelt period are surface slope, soil type, and initial soil moisture conditions before freeze-up. Finer soils generally have a higher moisture retention limit than coarser materials. Harlan (1973) has demonstrated that sand profiles show an immediate response to warming at the surface while loam and clay profiles' response to temperature variations is delayed in time. Consequently, soils with a higher moisture content will remain frozen for a greater length of time, reducing infiltration and snowmelt runoff losses to subsurface runoff.

Once the soil is frost free, infiltration conductivity may increase depending on moisture saturation at the surface. High intensity rainfall events may exceed infiltration capacity of the soil resulting in overland flow. Some of the percolating waters may never reemerge as surface runoff since they will be utilized to recharge the groundwater table or remain trapped within depressions of the underlying bedrock topography.

Subsurface or interflow occurs when the infiltrating waters reaches a less permeable soil layer at shallow depth (Bruce and Clark, 1980). Direction of flow is lateral until it reemerges as surface flow once it reaches the stream.

Groundwater or the baseflow contributions to total streamflow occurs when the water table intersects the stream channel. There may be a lag ranging from months to years between a rainfall event and its resulting contribution to the base flow of a stream (Bruce and Clark, 1980).

Frost conditions largely determine the response of runoff to melt, because of the marked difference of surface and sub-surface runoff (Dunne and Black, 1971), and may considerably modify the hydrograph of an ice-free areas of a basin.

CHAPTER 4

DATA ANALYSIS

4.1 Basin Hydrology

A large proportion of snow and ice-melt waters originate from several highly glacierized sub-catchments located in the Yoho Valley. Glacier snouts are located at approximately 2300 m.a.s.l. Above this elevation, nearly 45% of the terrain is estimated to be glacierized (90 km^2).

There is rapid snowline rise to the 2300 m.a.s.l. level above which different rates of melt occur over the glacierized and unglacierized components of the basin. Snowline movement tends to be rapid over unglacierized surfaces. Melt rates and patterns over glacierized surfaces are comparatively slow and uniform. A snowpack overlying ice will persist much later in the season.

4.1.1 Annual Distribution of Runoff

Historical records indicate a large proportion of annual runoff occurs between May and September. Winter flow records from a downstream gauging station near Field

(51°25′06" N, 116°28′24" W) were extrapolated to the Kicking Horse River at Cathedral Mountain gauging site (Table 4.1).

Although the winter flow estimates were drawn from a short data set, they are deemed reasonable since long term winter runoff records observed farther downstream at Golden indicate that winter runoff contributes only a very small fraction of volume of water when compared to total annual runoff. From these, it is estimated that approximately 90.5% of the total annual runoff occurs from May to September (Table 4.2a). Johnson and Power (1985) have estimated 95% of annual flow at Peyto Creek occurs during those months. This figure is considered representative of the seasonal flow regime found at Twin Falls Creek. Twin Falls and Peyto are watersheds of similar size (27 km^2 and 23 km^2), glacierized elevation range (2330-2984 m.a.s.l and 2090-3172 m.a.s.l.) and proportions of glacierized basin area (59.3% and 58.3%). In 1979, late winter flow at Peyto Creek was estimated to be less than 0.1 m^3sec^{-1} (Collins and Young, 1981).

Eleven years of streamflow data from Blaeberry River below Ensign Creek gauging site were utilized to estimate the winter flow of Amiskwi River. Most of total annual runoff of Amiskwi River also occurs from May through September (Table 4.2a). The main runoff component during that period is snow

Table 4.1 Annual distribution of runoff.

	Amiskwi River		Kicking Horse River		Twin Falls Creek	
January	0.5	1.0%	1.5	0.8%	---	0.4%
February	0.4	0.8%	1.3	0.7%	---	0.4%
March	0.4	0.8%	1.2	0.7%	---	0.4%
April	4.0	8.0%	2.0	1.1%	---	0.4%
May	10.0	20.0%	8.2	4.6%	---	0.7%
June	13.8	27.5%	35.8	19.9%	---	16.4%
July	10.0	20.0%	49.8	27.7%	---	30.0%
August	5.8	12.0%	50.2	27.9%	---	35.6%
September	2.0	4.0%	18.7	10.4%	---	12.3%
October	1.6	3.2%	5.8	3.2%	---	2.0%
November	1.0	2.0%	3.0	1.7%	---	1.0%
December	0.6	1.2%	2.3	1.3%	---	0.4%

Amiskwi River winter flow estimates (May to April) from Blaeberry Creek below Ensign Creek (Historical Streamflow Summary, British Columbia).

Kicking Horse River winter flow estimates (May to April) from Kicking Horse River near Field (Historical Streamflow Summary, British Columbia).

Twin Falls Creek winter flow estimates (May to April) from Johnson and Power (1985).

Table 4.2a Summer (May-September) and winter October-April) distribution of runoff.

	Summer	Winter
Amiskwi	79.5%	20.5%
Kicking Horse	90.5%	9.5%
Twin Falls	95.0%	5.0%

Table 4.2b Monthly cumulative percentages of discharge.

	Amiskwi	Kicking Horse	Twin Falls
January	1.0%	0.8%	0.4%
February	1.8%	1.5%	0.8%
March	2.6%	2.2%	1.2%
April	10.6%	3.3%	1.6%
May	30.6%	7.9%	2.3%
June	58.4%	27.8%	18.7%
July	78.1%	55.7%	48.7%
August	90.1%	83.4%	84.3%
September	94.1%	93.8%	96.6%
October	97.2%	97.0%	98.6%
November	99.3%	98.7%	99.6%
December	100.5%	100.0%	100.0%

melt and 67.5% of total annual runoff occurs in May, June, and July. Discharge records indicate that April runoff varies considerably from year to year. A mean daily discharge range of 0.6 m^3sec^{-1} to 28.8 m^3sec^{-1} has been observed. The discharge extremes are consistent with those recorded at the Blaeberry River site for similar periods.

A greater proportion of annual discharge occurs in spring in a nival basin compared with a glacierized basin where the regulating effect of the ice-melt component extends the high streamflow regime until fall (Table 4.2b).

4.1.2 General Spring and Summer Runoff Trends

Despite significant breaks in continuity of hydrological records, sufficient information is available for interbasin comparison of discharge and trend analysis. Figures 4.1, 4.2, 4.3 and 4.4 show overlayed discharge curves of Twin Falls Creek, Kicking Horse River at Cathedral Mountain and Amiskwi River from 1977 to 1984. An eight day running mean of discharge was generated in order to suppress short term fluctuations. The hydrographs of snow and ice covered basins reveal similar and distinctive features of runoff regimes depending on the time of year.

Figures 4.1 to 4.4 Daily discharge plots for Amiskwi and Kicking Horse Rivers and Twin Falls Creek from 1977 to 1984. The unpublished data were provided by the National Hydrology Research Institute, Inland Waters Directorate, Environment Canada.

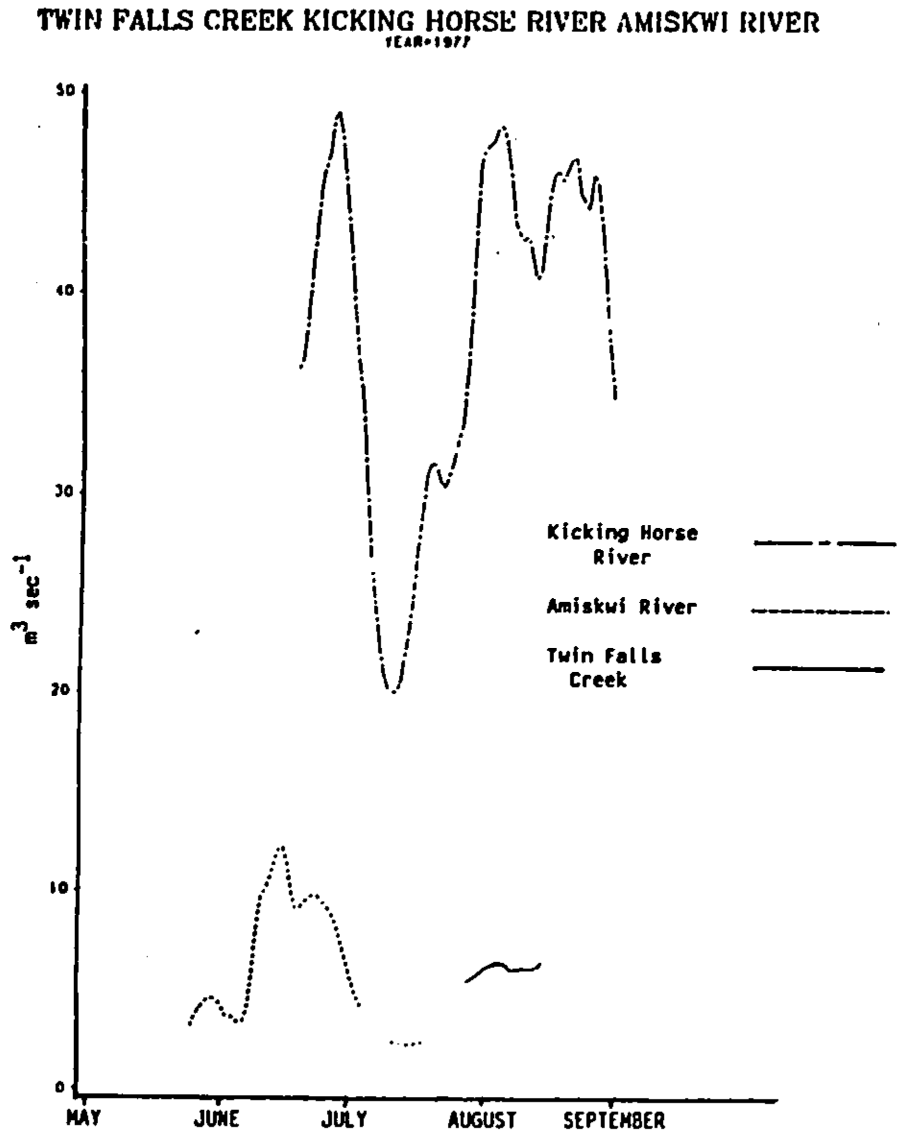

Figure 4.1a

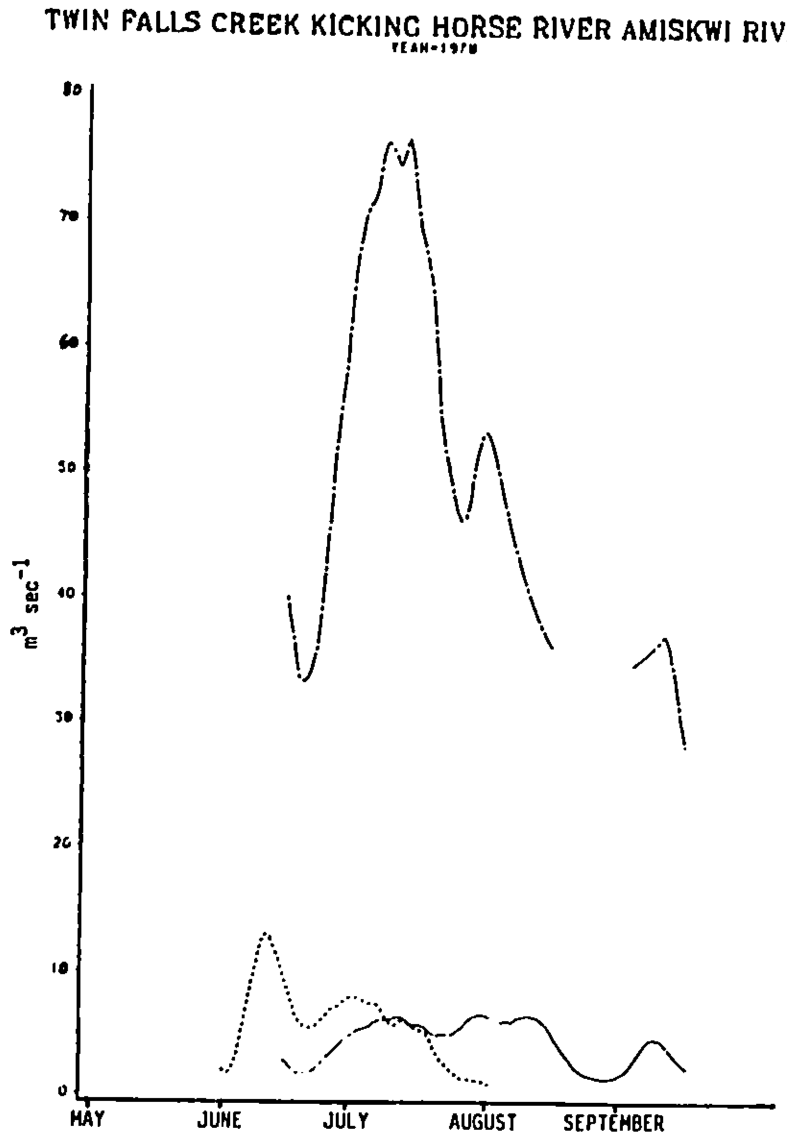

Figure 4.1b

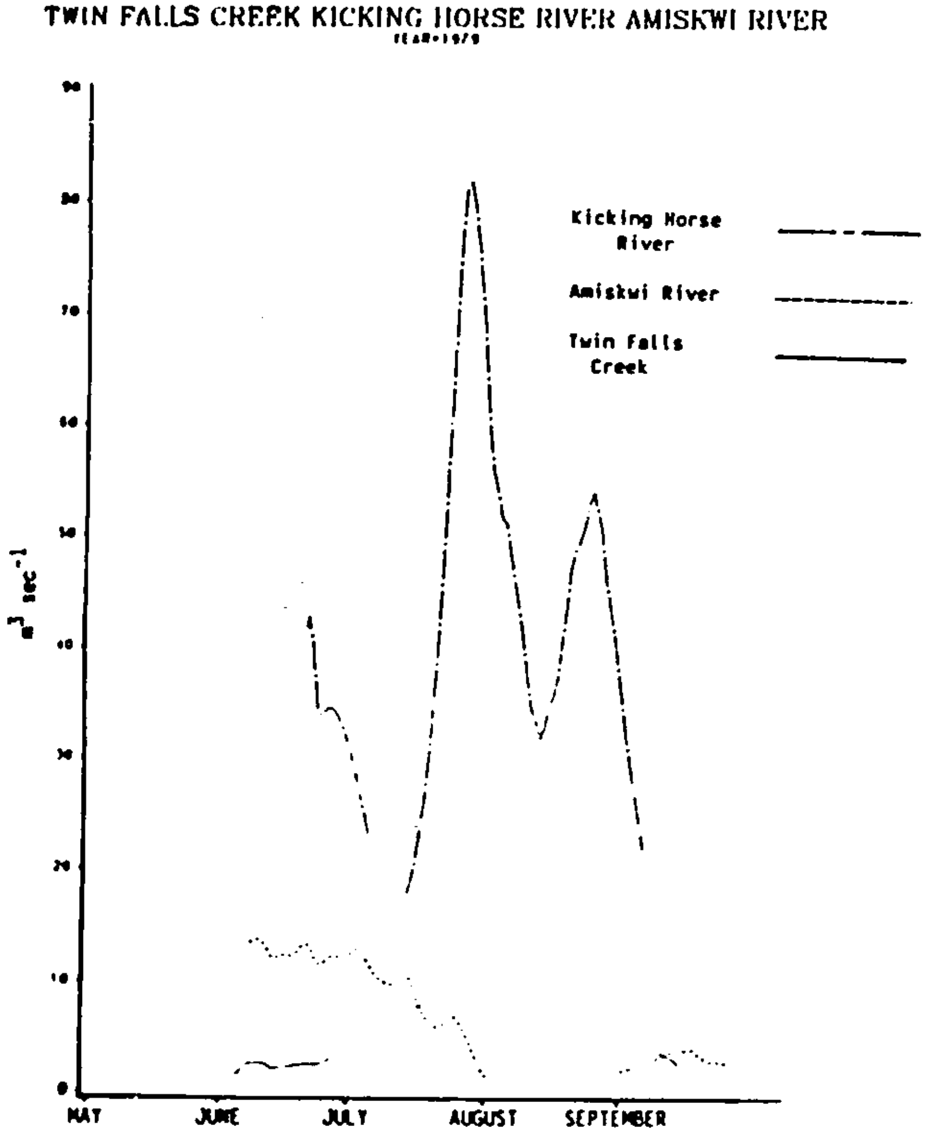

Figure 4.2a

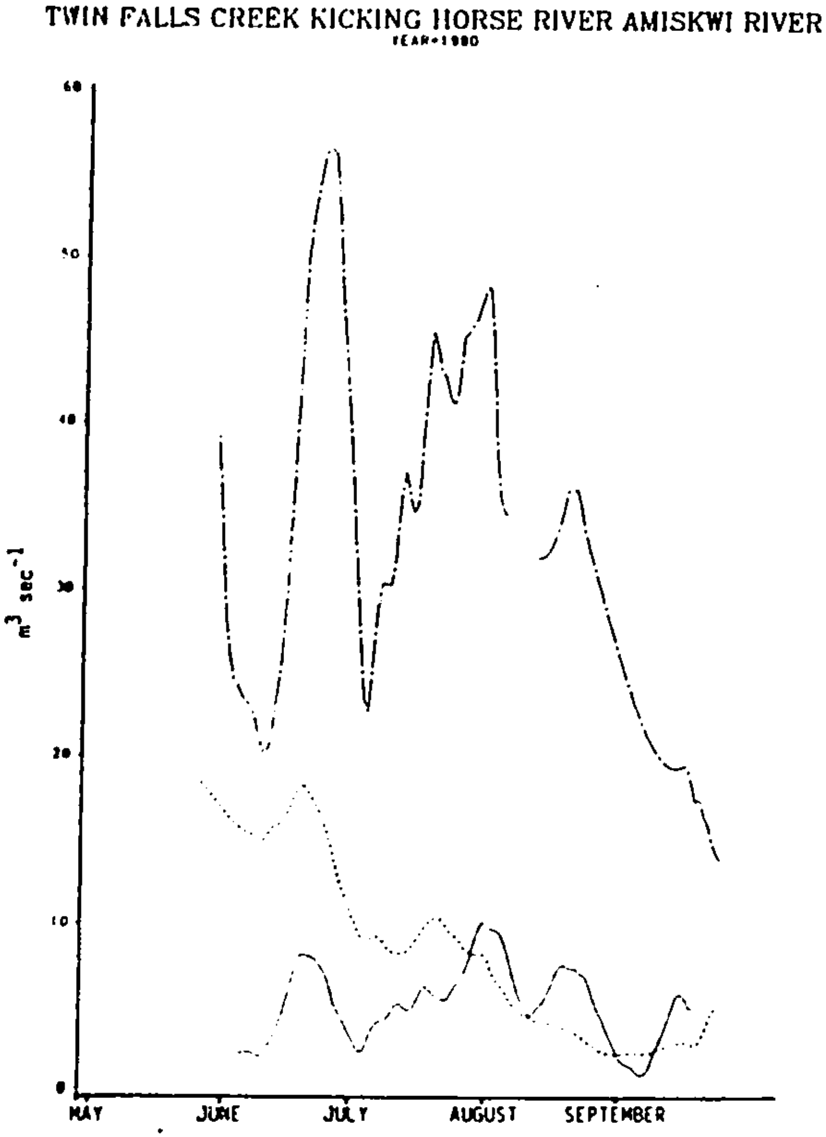

Figure 4.2b

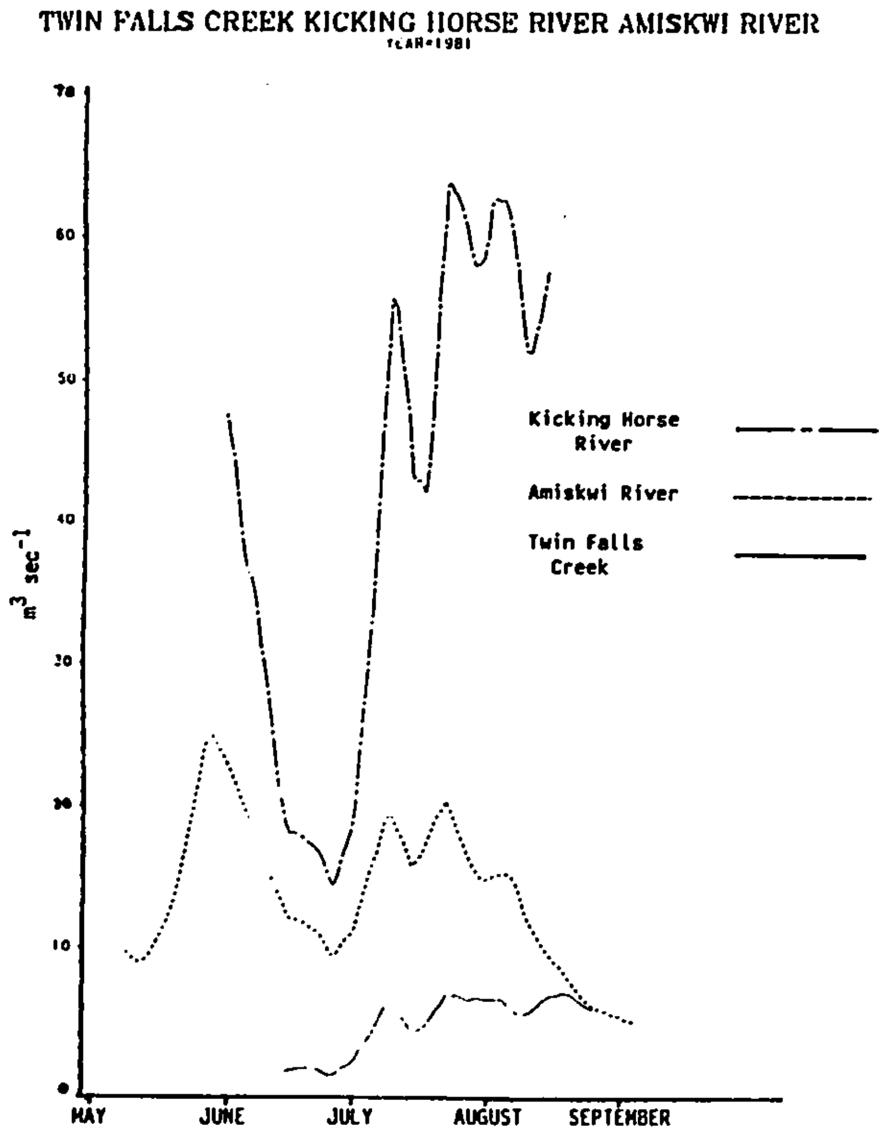

Figure 4.3a

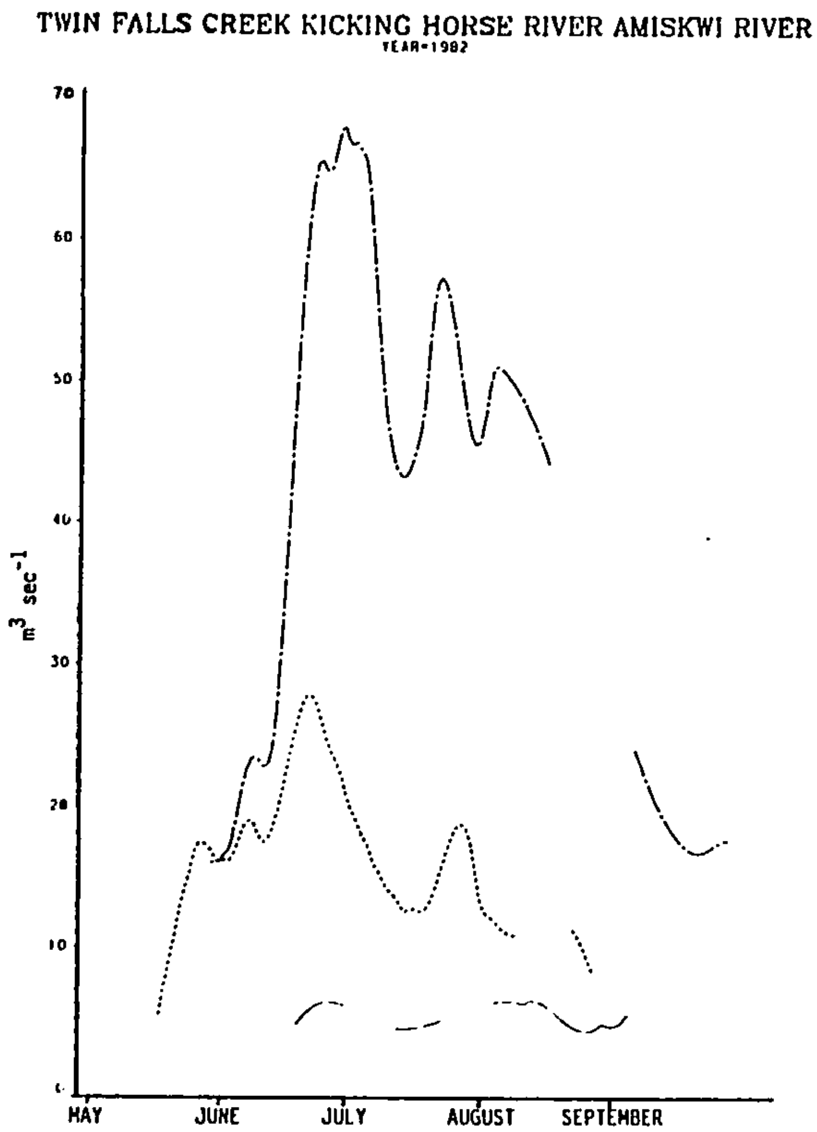

Figure 4.3b

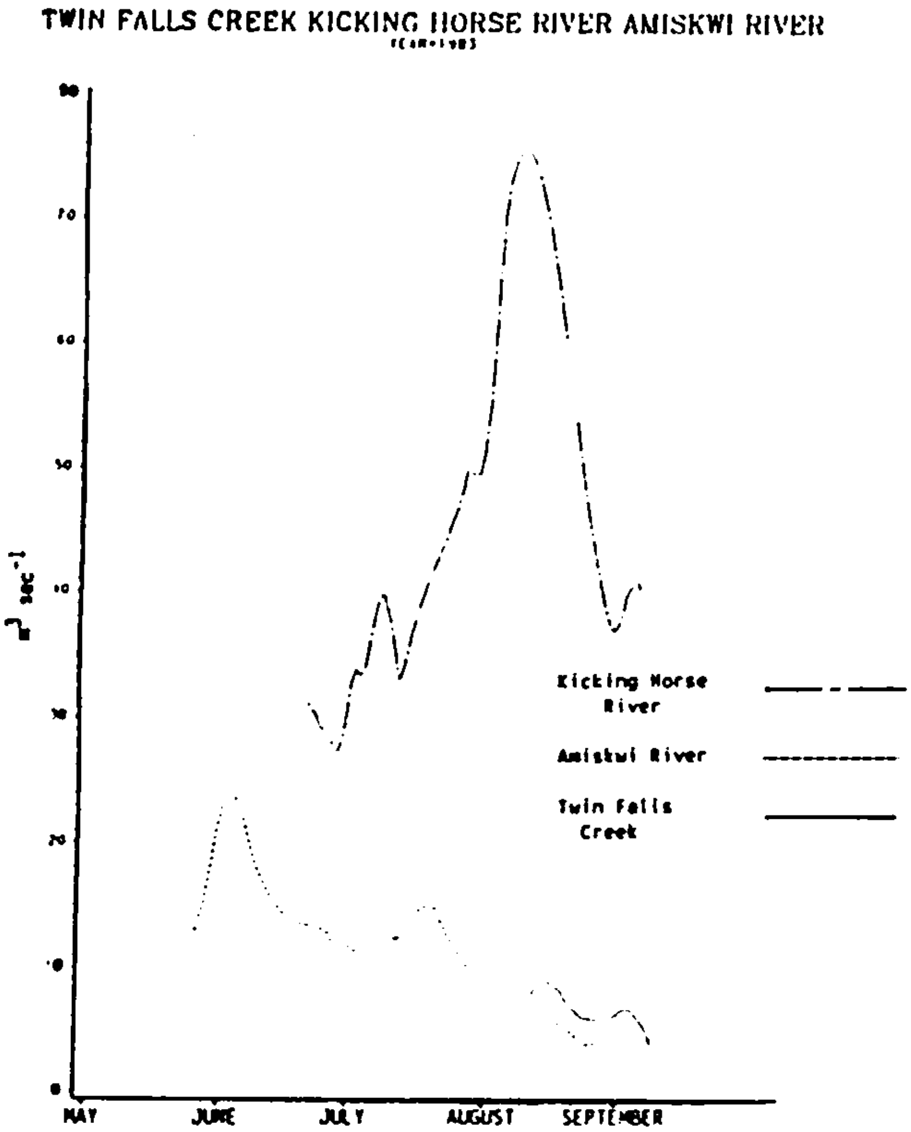

Figure 4.4a

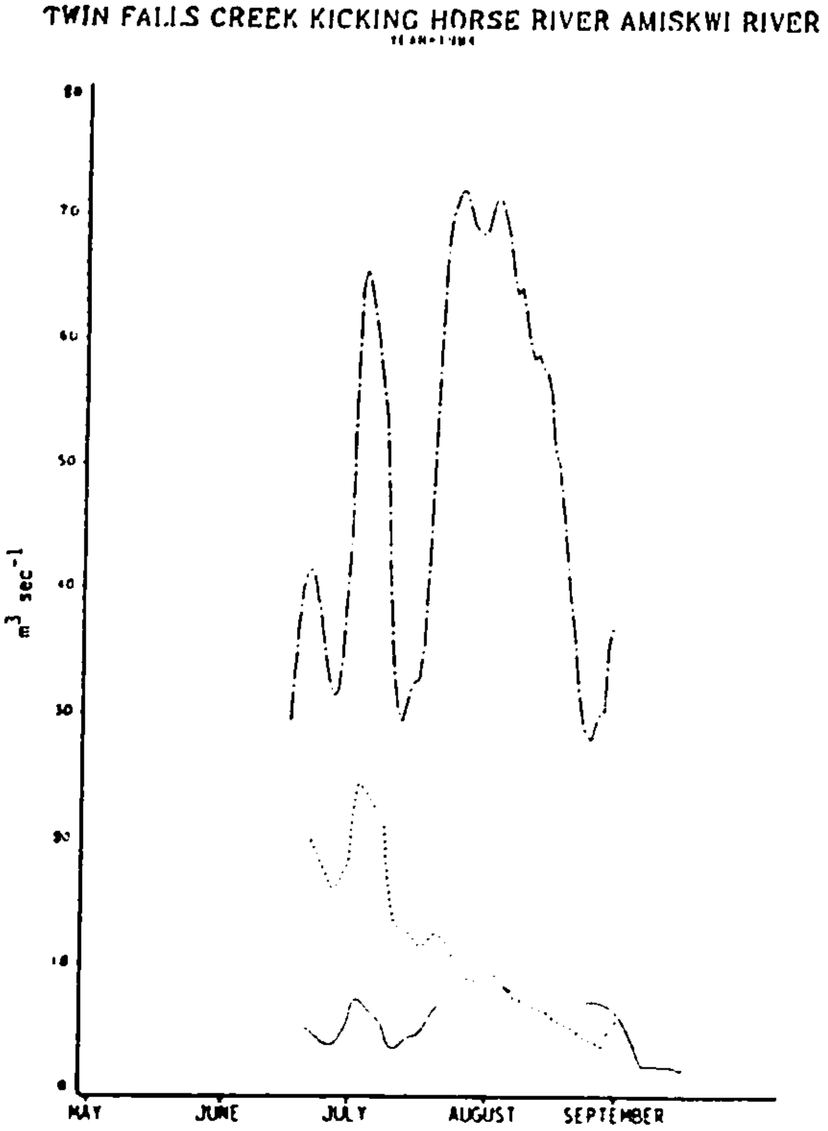

Figure 4.4b

In the early stages of the snow-melt season, from May to mid-June, discharge trends extending over several days and weeks are in phase in all basins. From late-June to mid-July, the snowmelt component to total runoff subsides due to the migration of the snow line to higher elevations causing a substantial decrease in discharge at Amiskwi. Peaks in runoff reflect heavy precipitation events and/or high temperature periods causing snow melt at higher elevations. Streamflow at Amiskwi River is reduced to seasonal low flow by the end of July to mid-August when depletion of the seasonal snow cover is complete. Hydrochemical analyses carried out on Amiskwi River (Collins and Young, 1981) revealed that by late summer the principal components of runoff originated from precipitation and groundwater.

The partially glacierized basins, Twin Falls and Kicking Horse, have a spring streamflow pattern similar to that observed at Amiskwi. As the snowline migrates up-glacier, more and more area of ice becomes exposed to solar radiation. Over time, flow generated from the glacial runoff component increases. The hydrographs from glacierized streams show a sustained and continued seasonally high flow into late August. Albedo is reduced because of the lower reflectivity of ice and glacial melt-water production is further enhanced.

Snow cover depletion and subsequent exposure of glacierized surfaces in the catchments of Kicking Horse River and Twin Falls Creek produce two distinct runoff regimes. The discharge hydrographs of proglacial streams follow a predictable pattern from one year to the next. However, the timing of the transition phase from a snow-melt to an ice-melt regime varies significantly between years due to variability of energy input and snow on ground conditions at the onset of ablation.

4.1.3 Description of Spring and Summer Runoff Trends for Selected Years

Daily discharge of Amiskwi and Kicking Horse Rivers, mean daily temperature and daily total precipitation figures from Boulder were plotted and are shown on pages 61 to 68 (Figures 4.5 through 4.12). The intent is to describe short term flow fluctuations. Fourteen-day values were used to summarize mean daily observations in an attempt to simplify hydrometeorological analysis (Table 4.3). The reduction of the data set also allowed for antecedent climate conditions to be taken into account while filtering out short term fluctuations due to local and random processes such as thunderstorms (Letréguilly, 1988). Calculation of fourteen day mean temperature, runoff and total precipitation figures

Figures 4.5 to 4.12 Daily mean discharge hydrographs of Amiskwi and Kicking Horse Rivers and daily mean temperature and total precipitation from the Boulder weather station from 1977 to 1984. The unpublished discharge data were provided by the National Hydrology Research Institute, Inland Waters Directorate, Environment Canada.

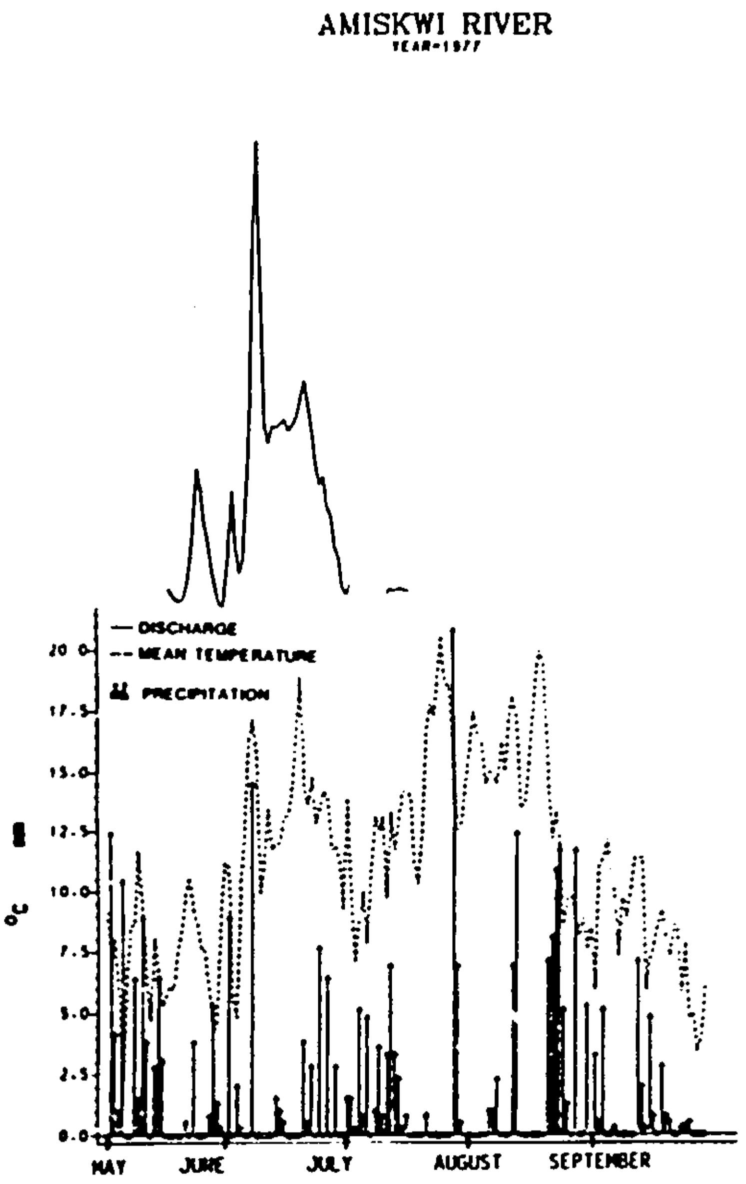

Figure 4.5a

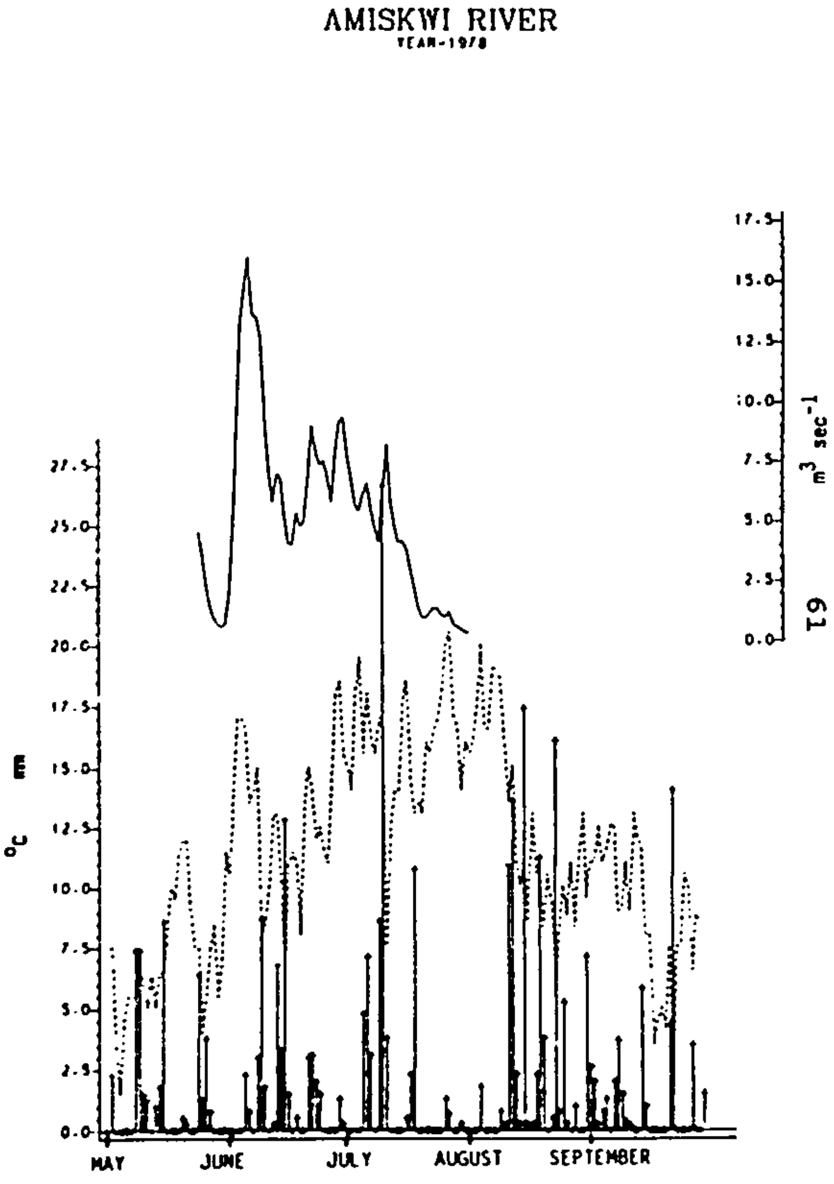

Figure 4.5b

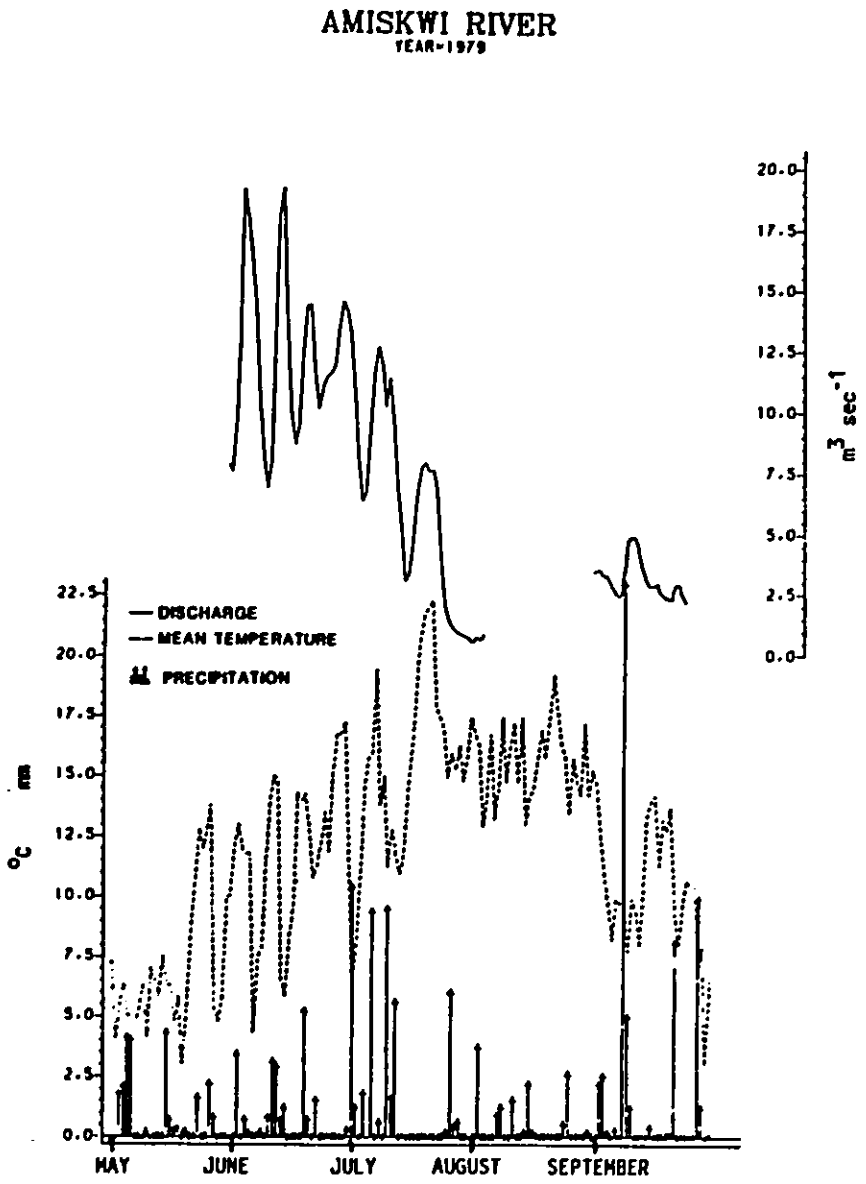

Figure 4.6a

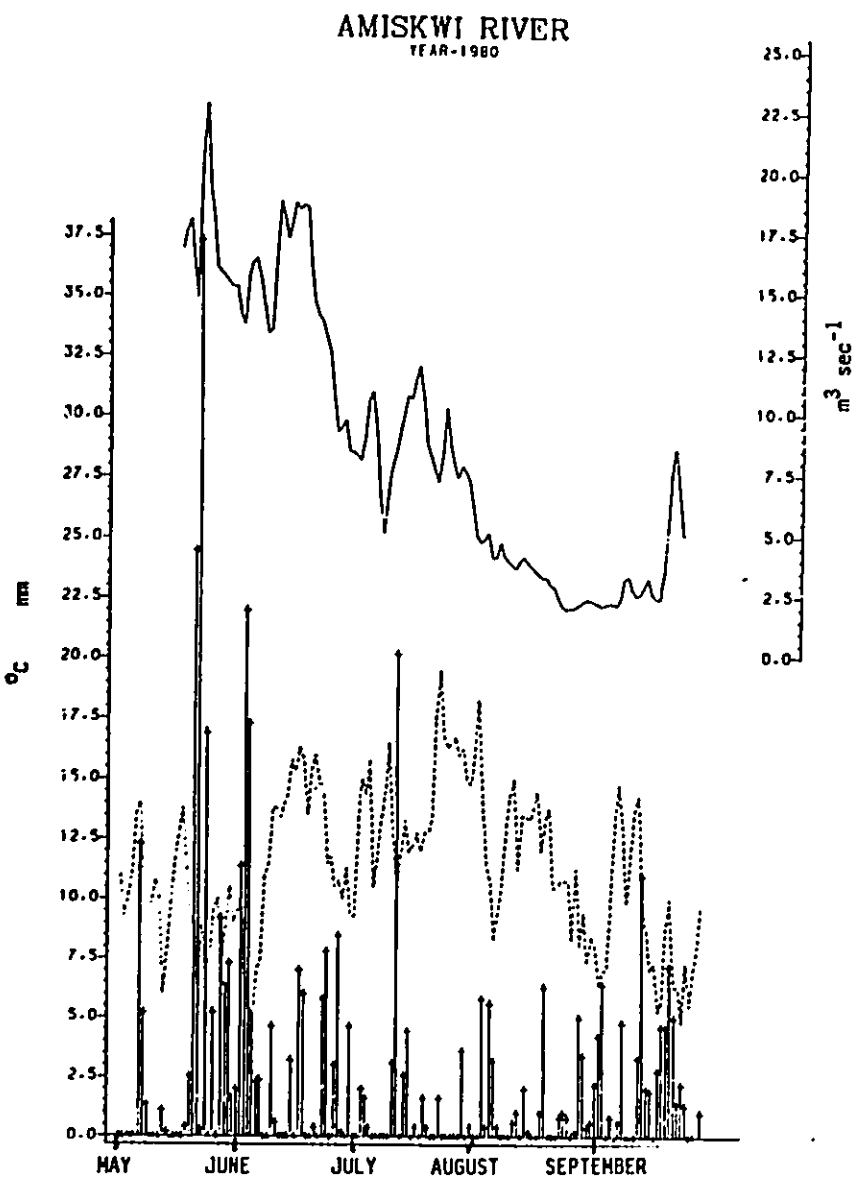

Figure 4.6b

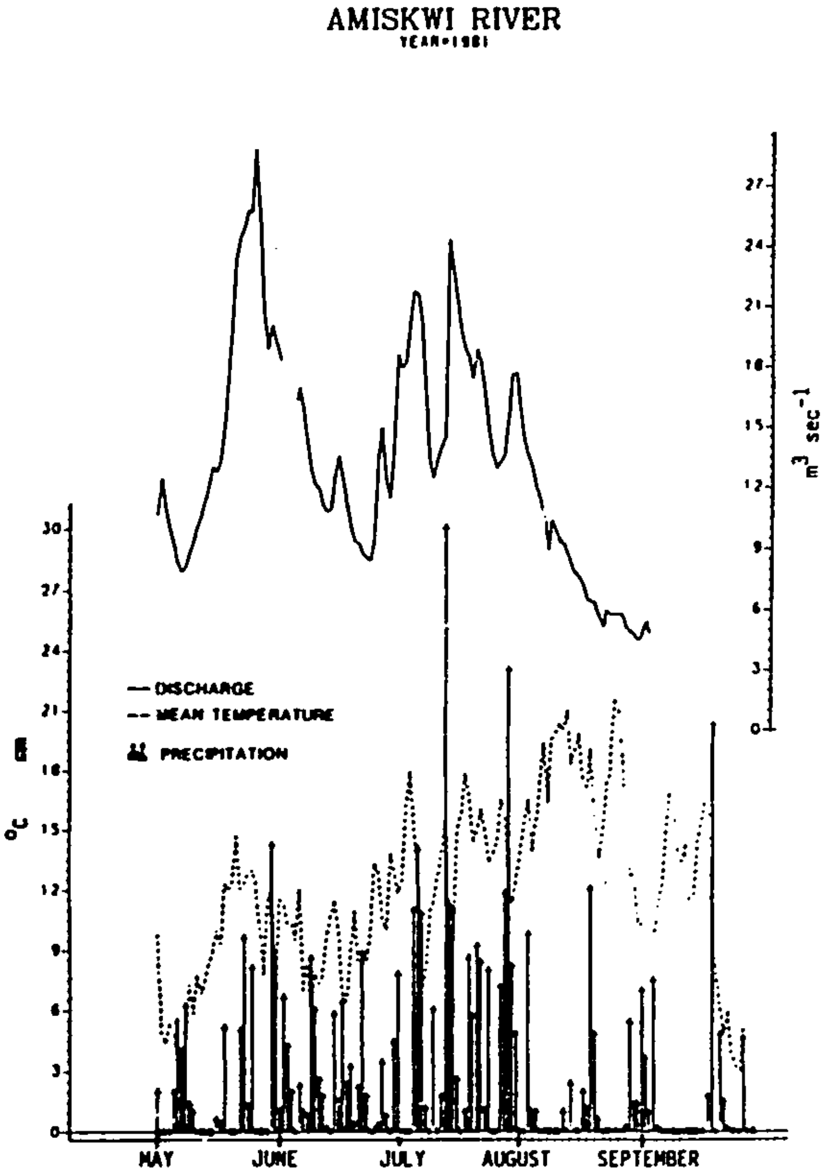

Figure 4.7a

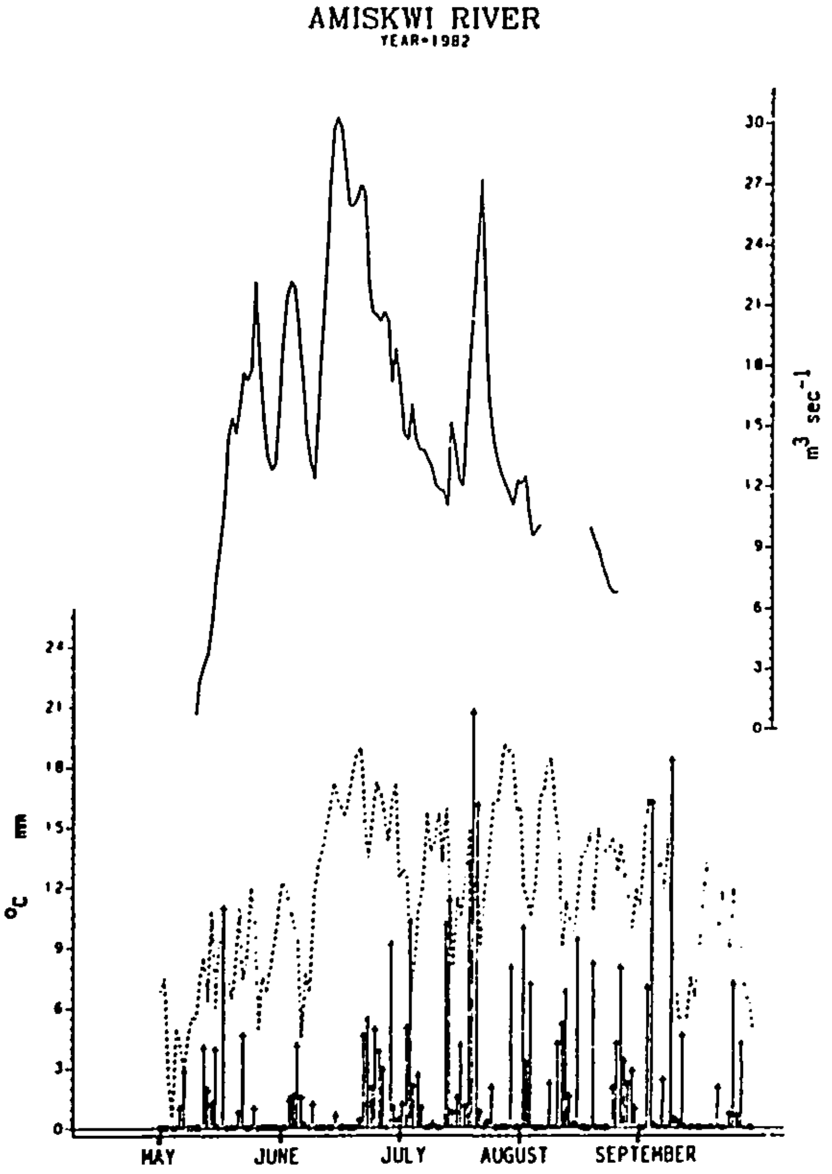

Figure 4.7b

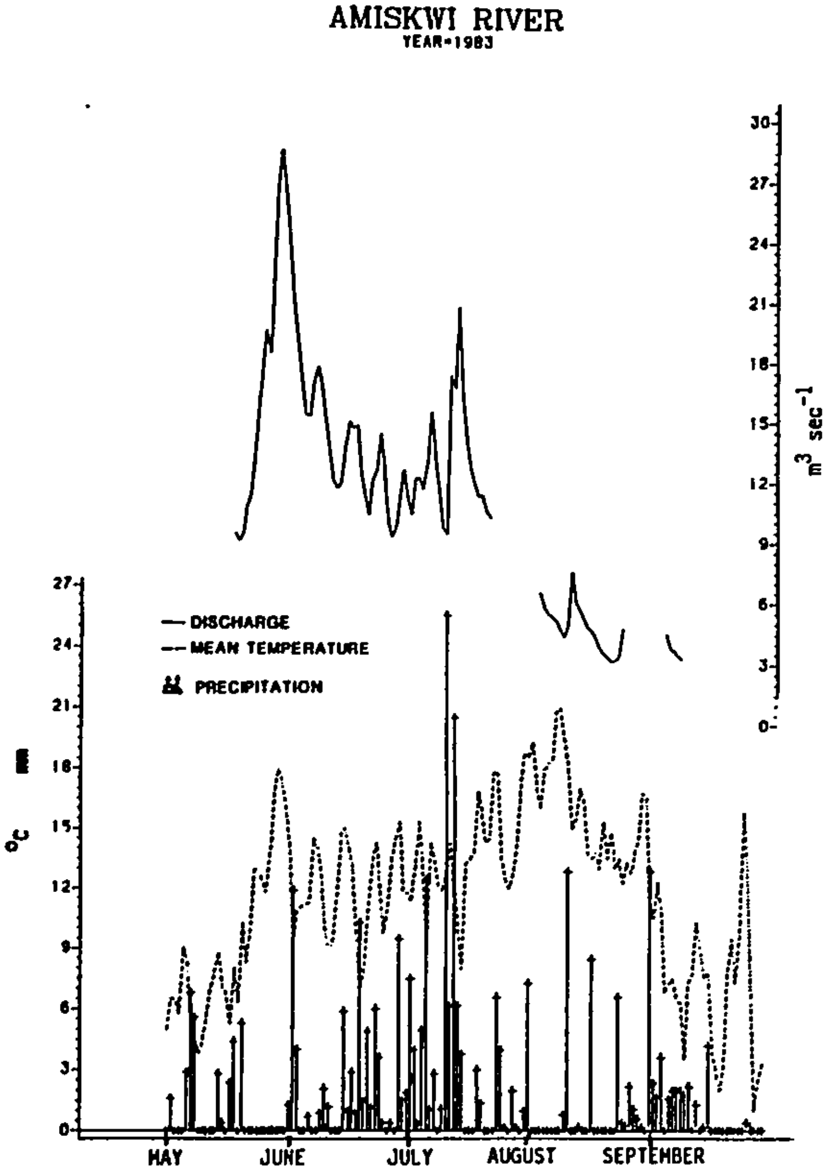

Figure 4.8a

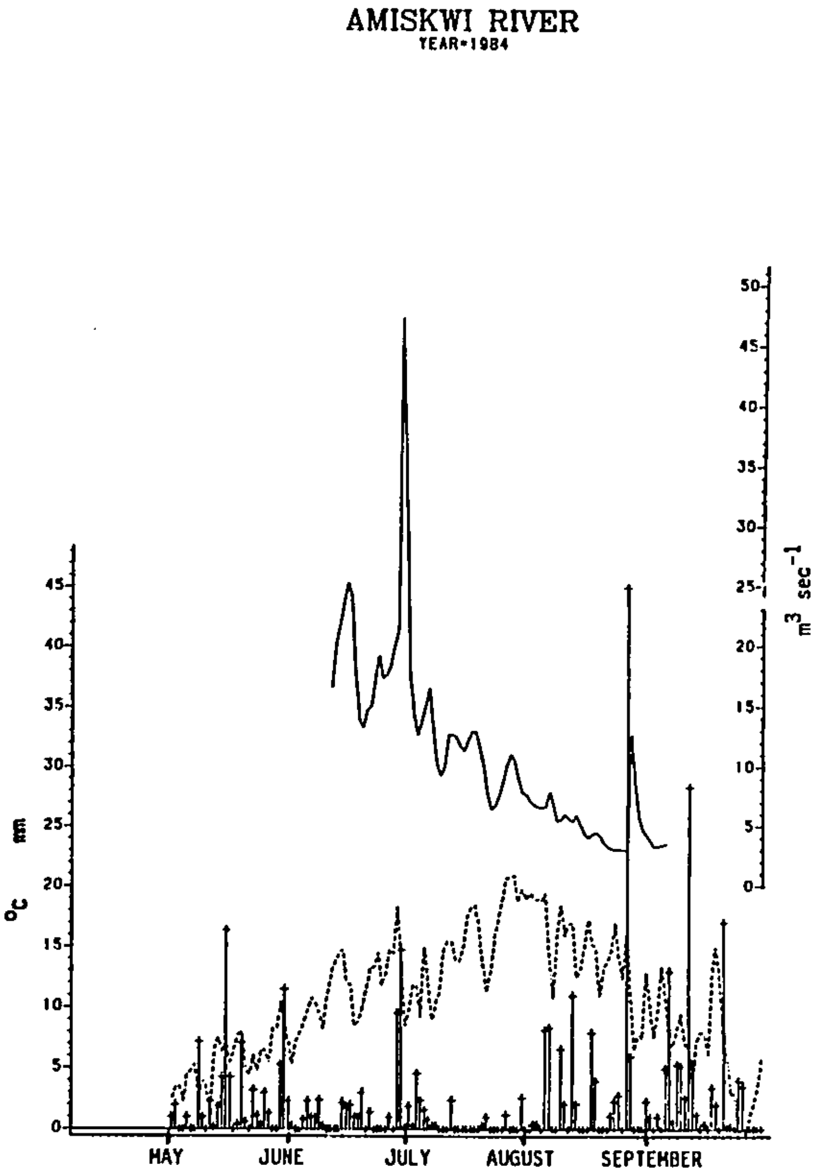

Figure 4.8b

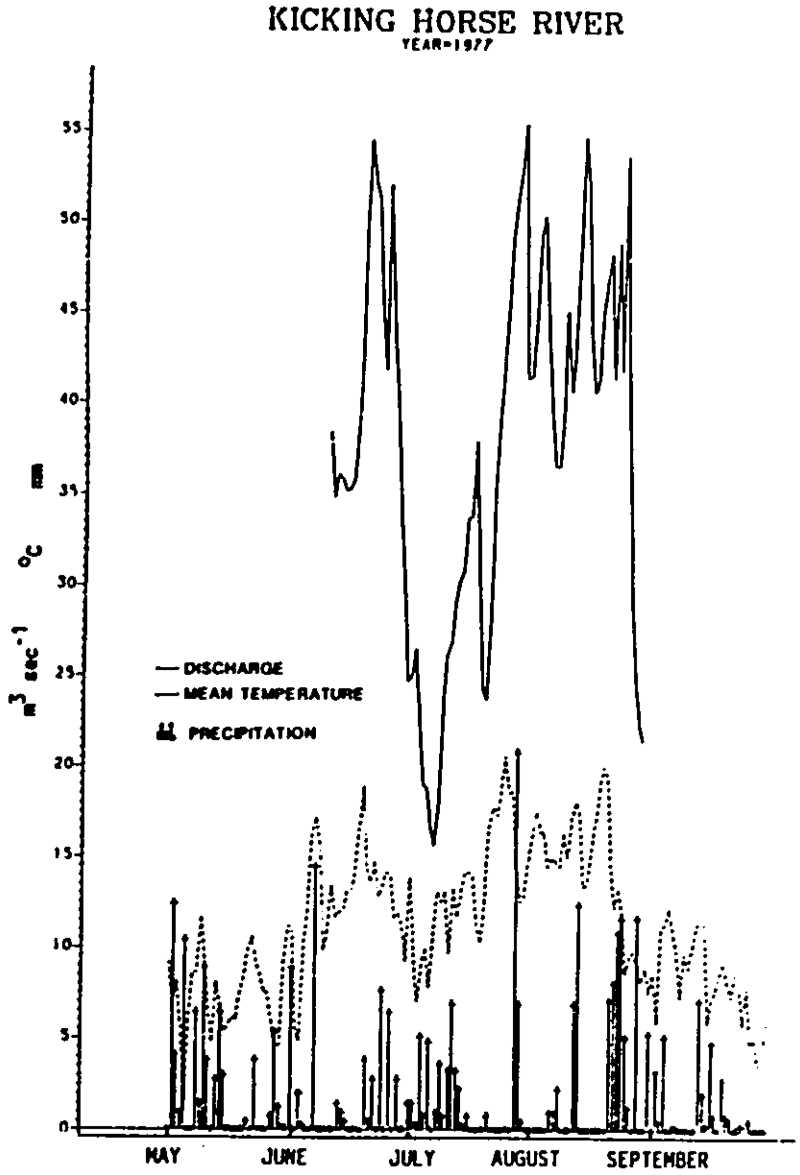

Figure 4.9a

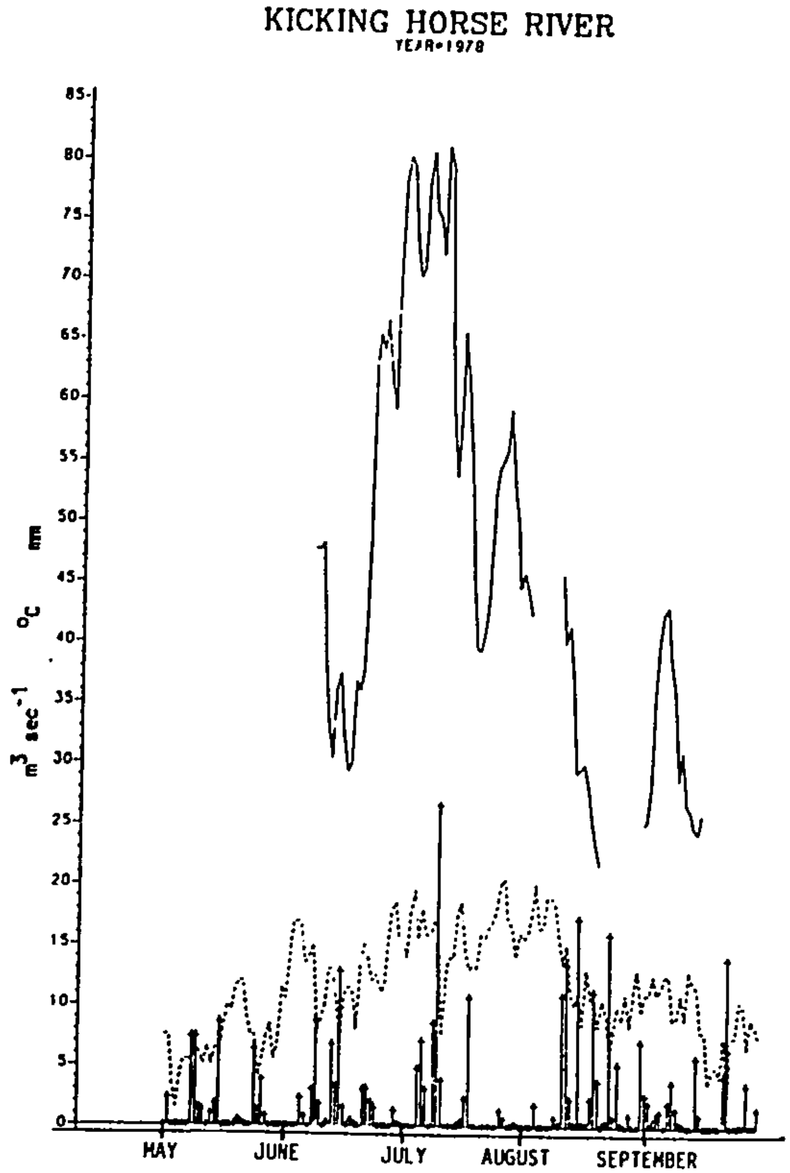

Figure 4.9b

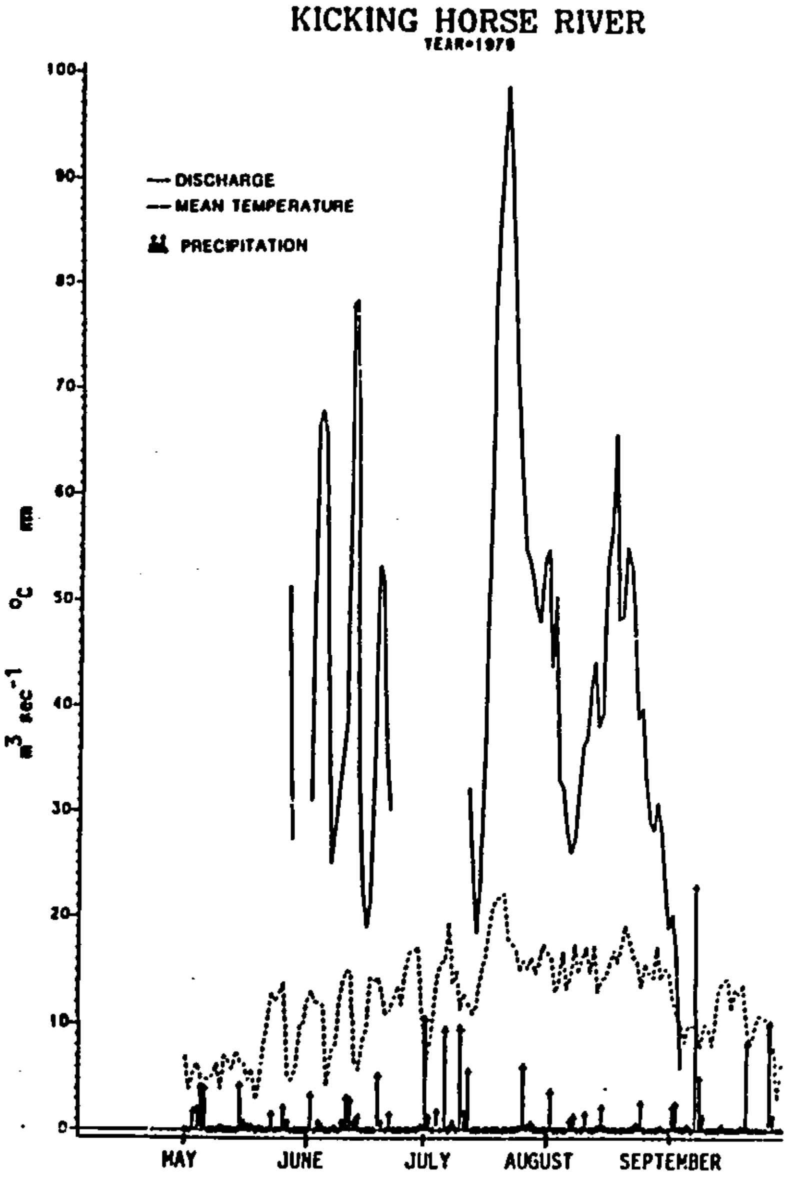

Figure 4.10a

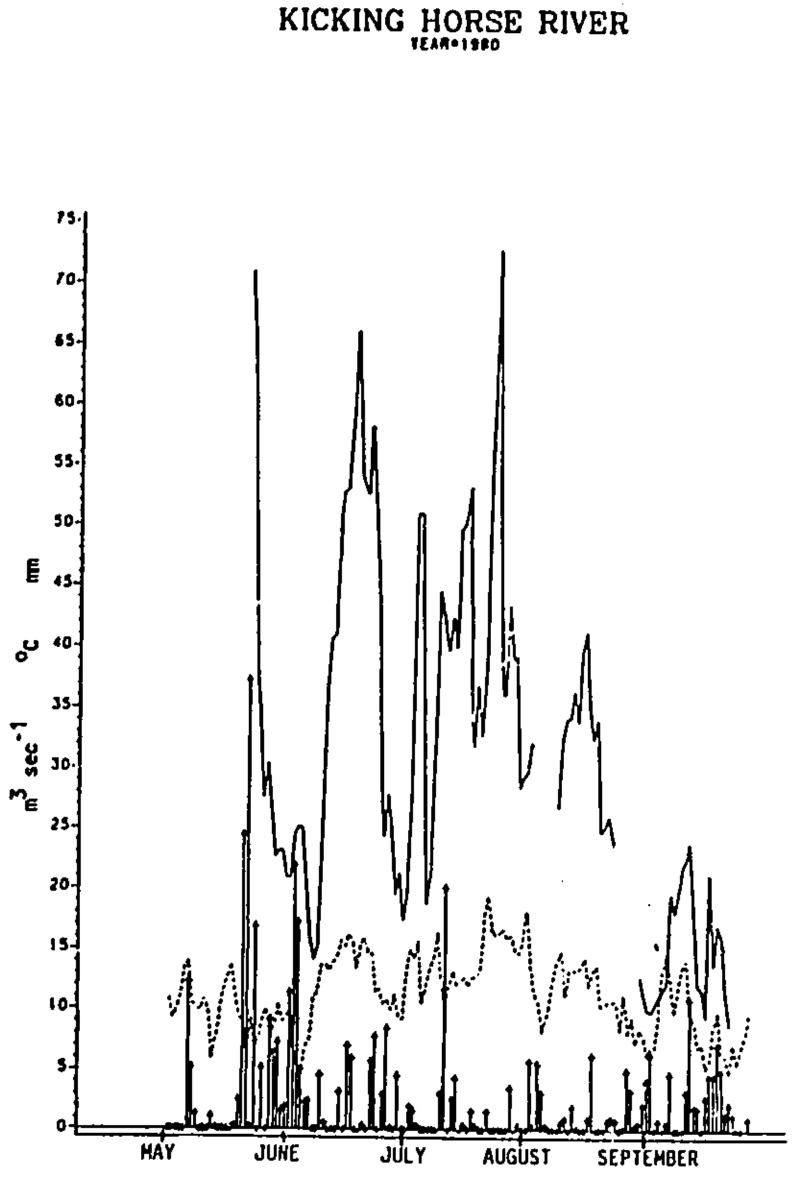

Figure 4.10b

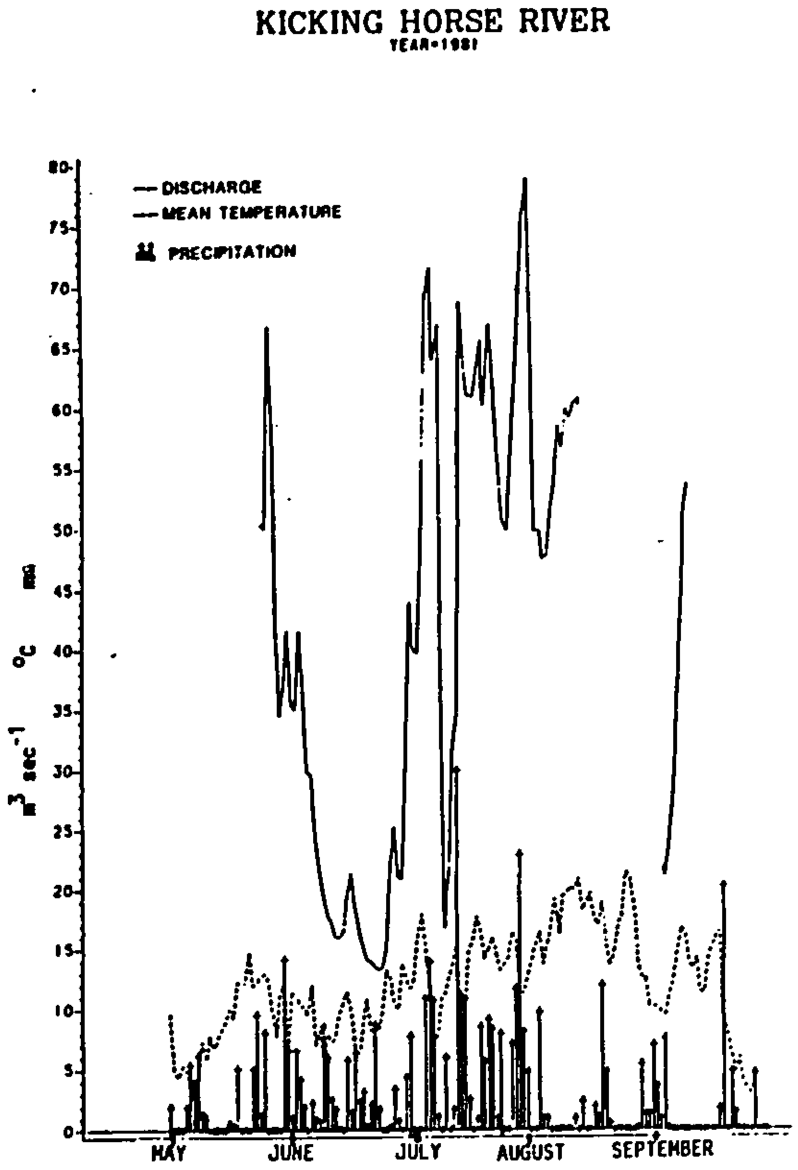

Figure 4.11a

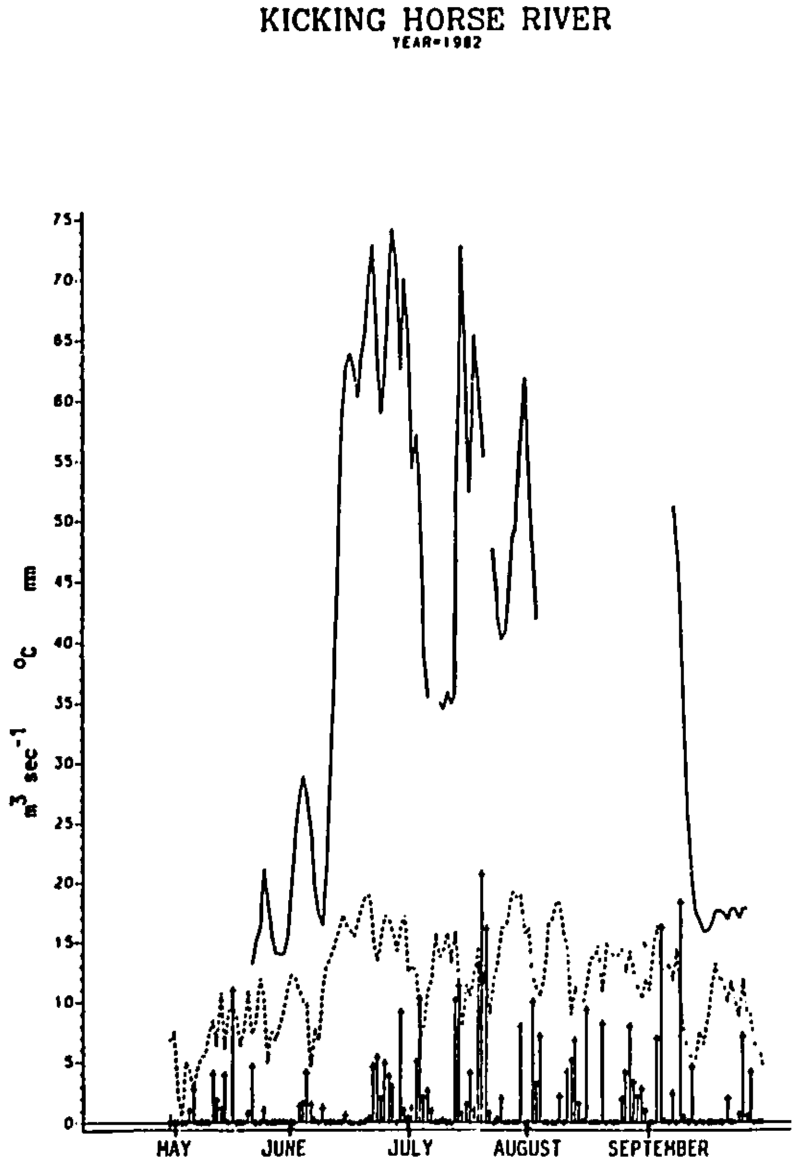

Figure 4.11b

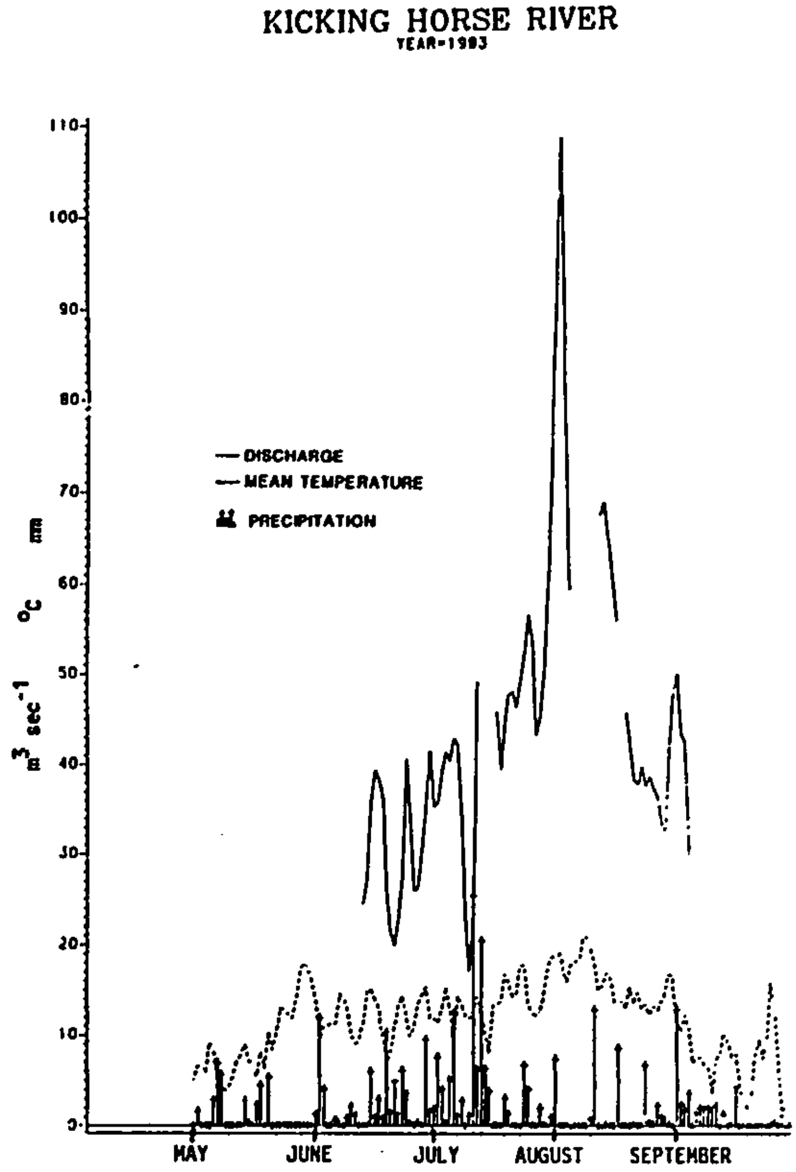

Figure 4.12a

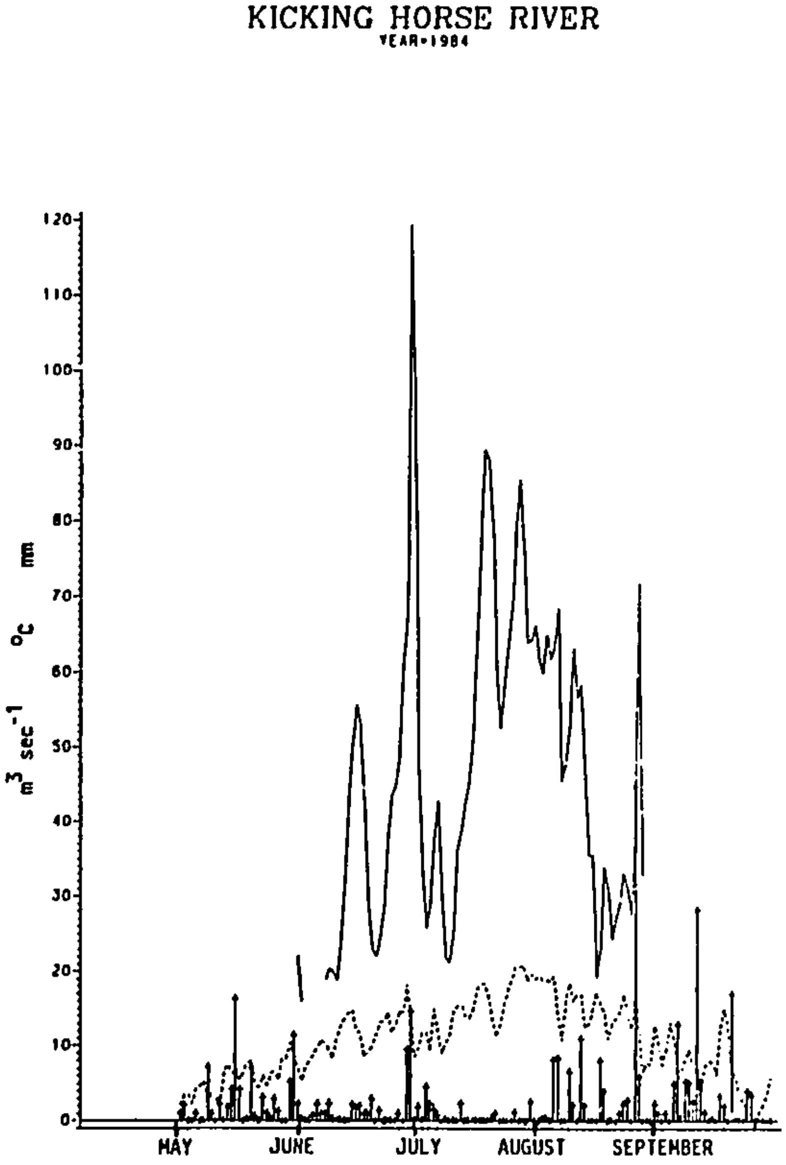

Figure 4.12b

Table 4.3 Fourteen day mean discharge at Amiskwi and Kicking Horse Rivers and mean temperature and precipitation totals at Boulder meteorological station and coefficient of variation of runoff and temperature.

	Amiskwi River		Kicking Horse River		Boulder Meteorological Station			Amiskwi River		Kicking Horse River		Boulder Meteorological Station		
	1979							1980						
Interval	Q	Q_{cv}	Q	Q_{cv}	T°	T°_{cv}	P	Q	Q_{cv}	Q	Q_{cv}	T°	T°_{cv}	P
05/01-05/14	-	-	-	-	5.7	19.7	12.2	-	-	-	-	10.3	19.4	20.1
05/15-05/28	-	-	-	-	8.0	45.6	10.4	-	-	-	-	9.6	22.7	102.7
05/29-06/11	11.0	36.0	48.8	37.0	10.5	29.5	8.4	15.6	10.5	23.5	31.1	9.6	31.3	76.5
06/12-06/25	12.6	24.6	41.0	50.0	11.4	25.6	12.2	15.4	20.4	50.0	21.9	14.3	12.8	33.2
06/26-07/09	11.1	23.7	-	-	14.2	25.7	23.7	8.5	18.7	29.5	40.2	12.9	19.4	17.3
07/10-07/23	6.7	35.1	59.3	52.0	16.4	26.1	16.7	9.6	16.4	44.8	25.7	13.6	10.6	34.3
07/24-08/06	1.1	38.9	49.1	23.0	15.6	9.0	10.9	6.2	26.3	37.3	22.4	14.3	21.4	19.4
08/07-08/20	-	-	42.6	26.5	15.8	9.3	6.2	3.7	11.6	33.9	13.5	13.0	10.6	11.1
08/21-09/03	-	-	33.3	37.5	15.2	14.1	8.0	2.3	5.8	-	-	8.9	19.3	25.0
09/04-09/17	3.4	26.6	-	-	10.5	20.0	30.1	2.8	14.4	17.6	20.1	10.4	31.1	31.0
	1981							1982						
05/01-05/14	10.0	14.3	-	-	6.0	31.0	22.0	-	-	-	-	5.6	47.5	10.9
05/15-05/28	20.0	26.5	-	-	11.4	16.0	30.1	14.9	26.3	-	-	8.3	24.4	21.3
05/29-06/11	15.4	10.0	30.1	20.3	9.4	22.9	56.0	16.9	22.6	21.5	26.0	10.0	25.6	10.0
06/12-06/25	10.4	15.1	15.9	15.1	9.4	20.5	34.6	25.0	12.6	60.9	14.3	16.6	9.1	17.9
06/26-07/09	17.7	21.2	43.0	43.5	12.3	24.3	53.7	16.2	17.2	57.2	24.0	13.3	23.6	39.5
07/10-07/23	17.9	9.9	52.9	34.2	13.9	22.4	96.5	14.7	34.9	50.4	29.0	12.3	19.9	80.3
07/24-08/06	14.2	13.2	57.4	10.3	14.5	12.4	74.0	12.3	13.7	40.3	15.1	15.4	19.5	30.7
08/07-08/20	8.2	10.7	-	-	10.7	8.8	23.4	-	-	-	-			
08/21-09/03	5.0	10.0	-	-	14.6	27.9	20.6	-	-	-	-	-	-	-
09/04-09/17	-	-	-	-	13.6	16.4	7.7	-	-	-	-	-	-	-

Q = Discharge (m^3sec^{-1})
Q_{cv} = Discharge variability
P = Precipitation (mm)
T° = Temperature (°c)
T°_{cv} = Temperature variability

began on May 1 of each year.

Amiskwi:

1979: Two discharge peaks of similar magnitudes (19.2 m^3sec^{-1}) occurred June 3 and June 13 (Figure 4.6a). Both maxima are associated with consecutive days when temperatures range between 10°C and 15°C prior to the peaks. The trough between peaks is in response to cooler temperatures from June 6 to June 8. From June 26 to July 9, temperatures rose by 2.8°C to 14.2°C while the precipitation total was up from 12.2mm to 23.7mm over the previous 14-day interval (Table 4.3). The major peak following July 4 is accounted for by a rise in average daily temperatures (Table 4.3). The surge in streamflow was sustained for several days as a result of 9.5mm of precipitation falling on July 10. Contribution originating from snowmelt caused the hydrograph to rise to 7.9 m^3sec^{-1} on July 18 and July 19 as temperatures ranged from 20.8°C to 22.3°C from July 18 to July 21.

1980: The maximum discharge peak in 1980 coincided with significant amounts of precipitation on previous days. From May 15 to May 28, 102.7mm of precipitation fell at the Boulder weather station (Table 4.3). Intensity, duration and frequency recurrence intervals compiled by A.E.S.

indicate that the 61.8mm of rain which fell on May 20 and 21 had a 25-year return period (Figure 4.6b). Between June 12 and June 25, temperatures climbed 4.7°C to 14.3°C over the previous two-week interval and average daily precipitation was down to 33.2mm from 76.5mm. Warmer weather caused streamflow to rise for several days due to snowmelt at higher elevations. The seasonal recession limb established itself in the subsequent intervals because of reduced temperatures and precipitation in the latter part of the summer. Despite the high magnitude low frequency precipitation events during the snowmelt period in 1980, the hydrograph fell sharply with increasing summer temperatures.

1981: Maximum daily discharge for the season reached 28.8 m^3sec^{-1} on May 26 under favorable climate conditions. Temperatures rose to 13°C and a total of 24mm of precipitation had fallen in the 4 days prior to the maximum. From May 29 to June 25, runoff decreased substantially with falling temperatures despite a 56.0mm precipitation period from May 29 to June 11 (Figure 4.7a). Streamflow rose to 24.4 m^3sec^{-1} on July 14 in response to rising temperatures and a 30mm precipitation event. The July 29 peak reflects 43.1mm of precipitation which fell between July 28 and July 30. From August 1st to the end of the snowmelt season, runoff declined as the frequency of days with precipitation and the magnitude of the events were reduced, this in spite of high temperatures from August 7 to 20 (Table 4.3).

1982: Maximum discharge of 25.8 m^3sec^{-1} occurred when the mean 14-day temperature was 16.6°C from June 12 to June 25 (Table 4.3). A major discharge rise to 27.2 m^3sec^{-1} on July 22 occurred in response to 50.2mm of precipitation which fell 3 days prior to the peak (Figure 4.7b). The hydrograph resumed its recession following the precipitation event, declining to baseflow.

Kicking Horse:

1979: A warm early spring had caused snowmelt in the lower portion of the basin before the 1979 field monitoring season began. The early snowmelt period is characterized by sequences of high and low flow periods, in phase with temperature fluctuations (Figure 4.10a). Average daily streamflow ranged from 41.8 m^3sec^{-1} to 59.3 m3sec-1 from May 29 to July 23 (Table 4.3). In the latter part of the season, from July 24 to August 20, variability in temperature was substantially reduced. Maximum discharge occurred following several days of clear and warm weather as temperatures rose into the low 20°C range from July 15 to July 20 (Figure 4.10a).

1980: The monitoring period began on a recession limb despite 102.7mm of precipitation which fell May 15 to May 28 (Table 4.3). From May 29 to June 11, discharge was only 23.5 m^3sec^{-1} due to cool weather. From June 12 to June 25, a sharp increase in streamflow to 50.0 m^3sec^{-1} was recorded as temperatures climbed to an average 14.3°C. From June 26 to July 9, streamflow declined to 29.5 m^3sec^{-1} as temperatures fell to 12.9°C, a 1.4°C drop over the previous 14-day set. A subsequent rise in discharge to 44.8 m^3sec^{-1} then followed from July 10 to July 23 after which discharge gradually declined with cooler autumn weather (Figure 4.10b).

1981: From mid-May to mid-June, the hydrograph displays a significant decline in streamflow following a wave of fine weather (Figure 4.11a). Falling discharge occurred despite an appreciable amount of precipitation, 56mm from May 29 to June 11, some of which likely fell in the form of snow. Average temperatures from May 29 to June 11 and June 12 to June 25 fell to 9.4°C. It is followed by a sharp increase in discharge where its fluctuations closely follow fluxes in temperature from June 26 and July 9. Pulses in discharge superimposed over high background flow are accounted by 171.3mm of precipitation which fell from July 10 and August 6. Streamflow remained high under favorable melting conditions.

1982: Maximum average discharge for a 14-day period occurred from June 12 to June 25 as 60.9 m^3sec^{-1} was flowing under very warm conditions (Table 4.3). A gradual decrease in streamflow is noted as discharge dropped from 57.2 m^3sec^{-1} recorded from June 26 and July 9 to 48.3 m^3sec^{-1} observed from July 24 to August 6. From June 26 to August 6 a total of 150.5mm precipitation had fallen (Figure 4.11b). Precipitation input in the catchment did not compensate for the reduction of ice-melt water production and runoff.

Twin Falls:

Hydrometeorological data for Twin Falls Creek is plotted on Figures 4.13 to 4.16 (pages 76 to 79) and selected years are summarized in fourteen-day values in Table 4.4.

Despite contrasting hydrometeorological conditions between the four-year set, maximum absolute two-week average streamflow figures remain similar from one summer to the next. Instantaneous seasonal discharge peaks occur between mid to late August, two to four weeks later than summer maximums recorded downstream on Kicking Horse at Cathedral. Generally, discharge variability (C_v) drops with increasing discharge.

Figures 4.13 to 4.16	Daily mean discharge hydrographs of Twin Falls Creek and daily mean temperature and total precipitation from the Boulder weather station from 1977 to 1984. The unpublished discharge data were provided by the National Hydrology Research Institute, Inland Waters Directorate, Environment Canada.

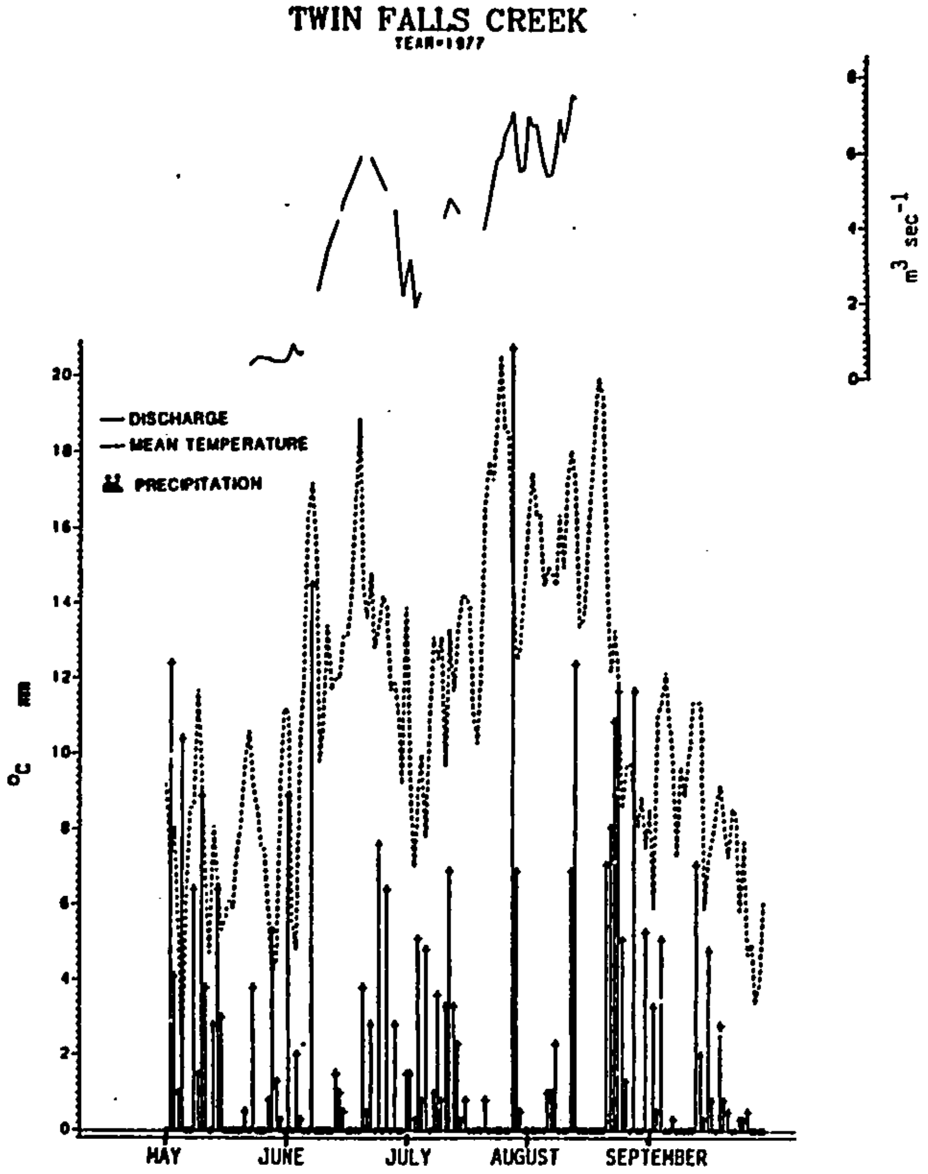

Figure 4.13a

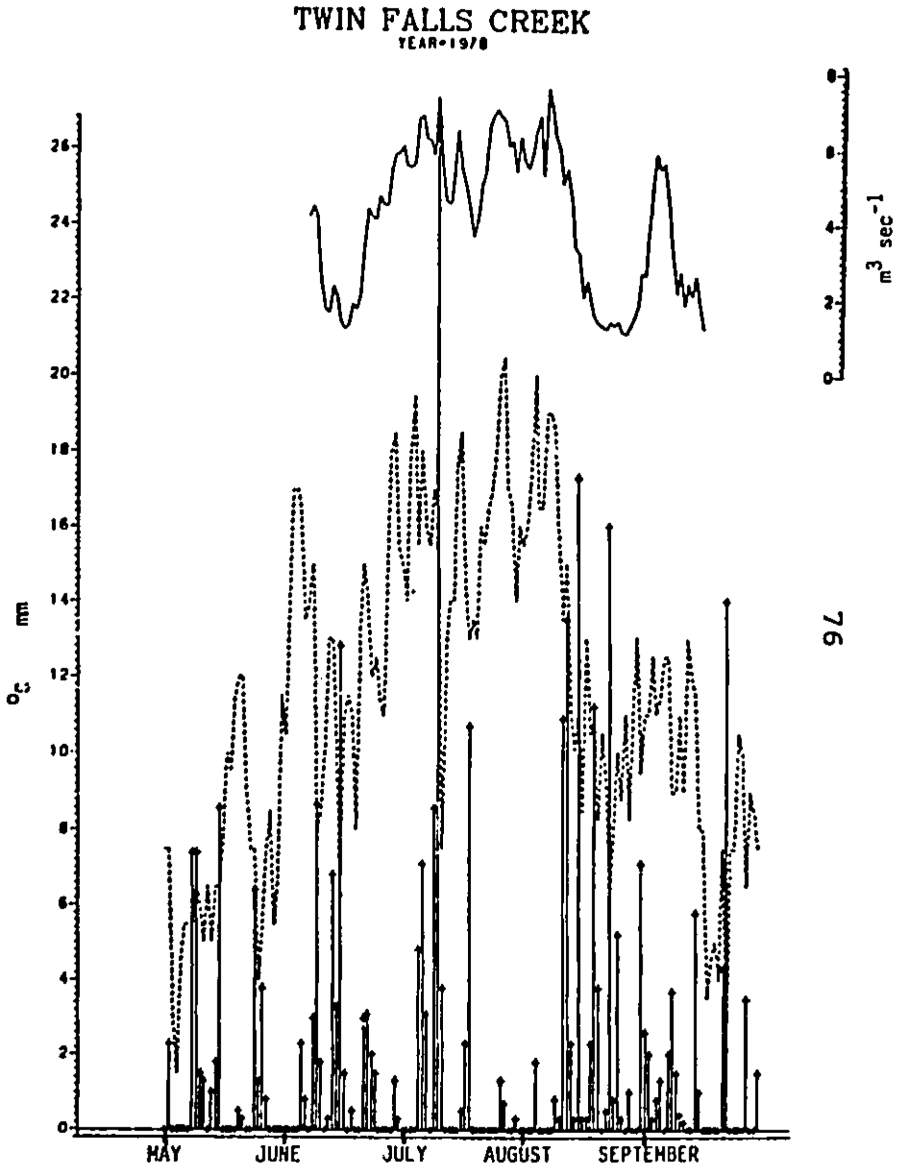

Figure 4.13b

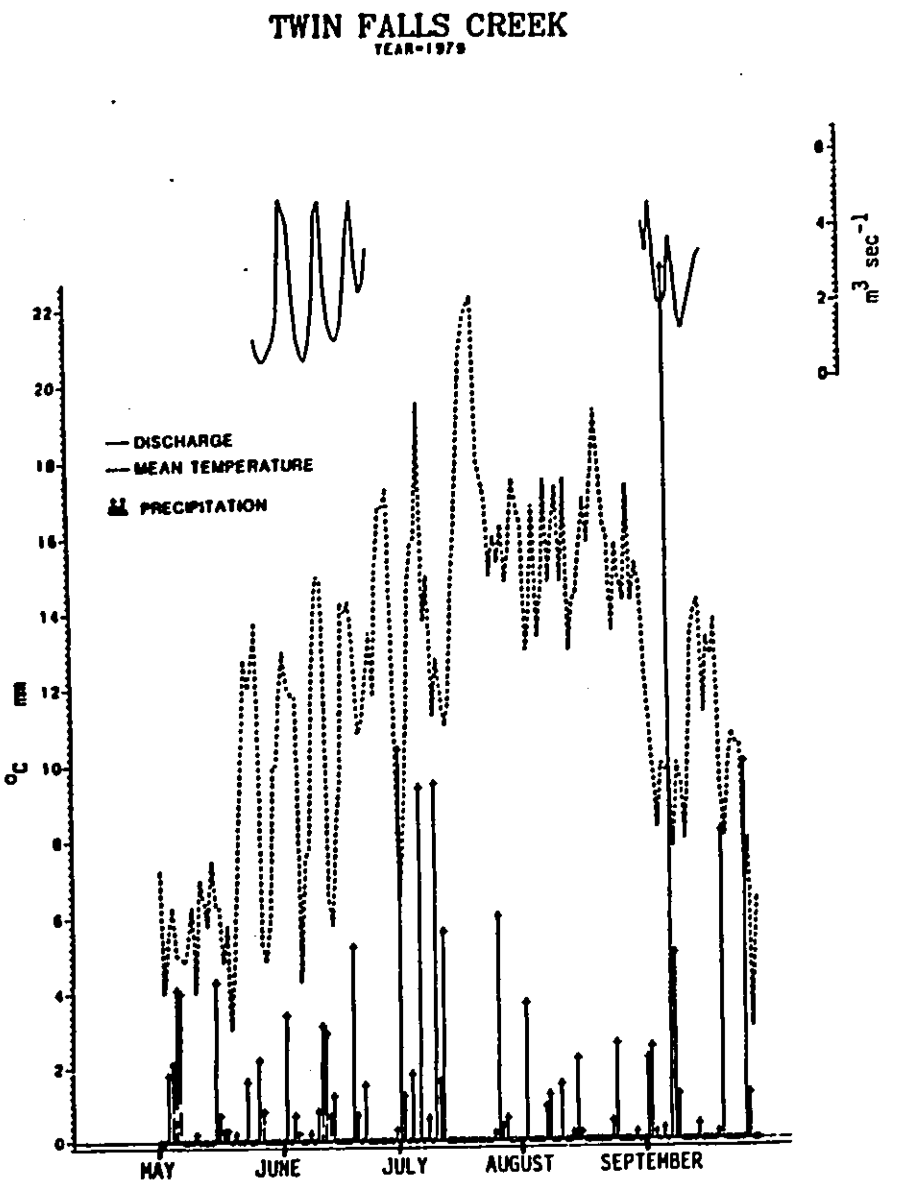

Figure 4.14a

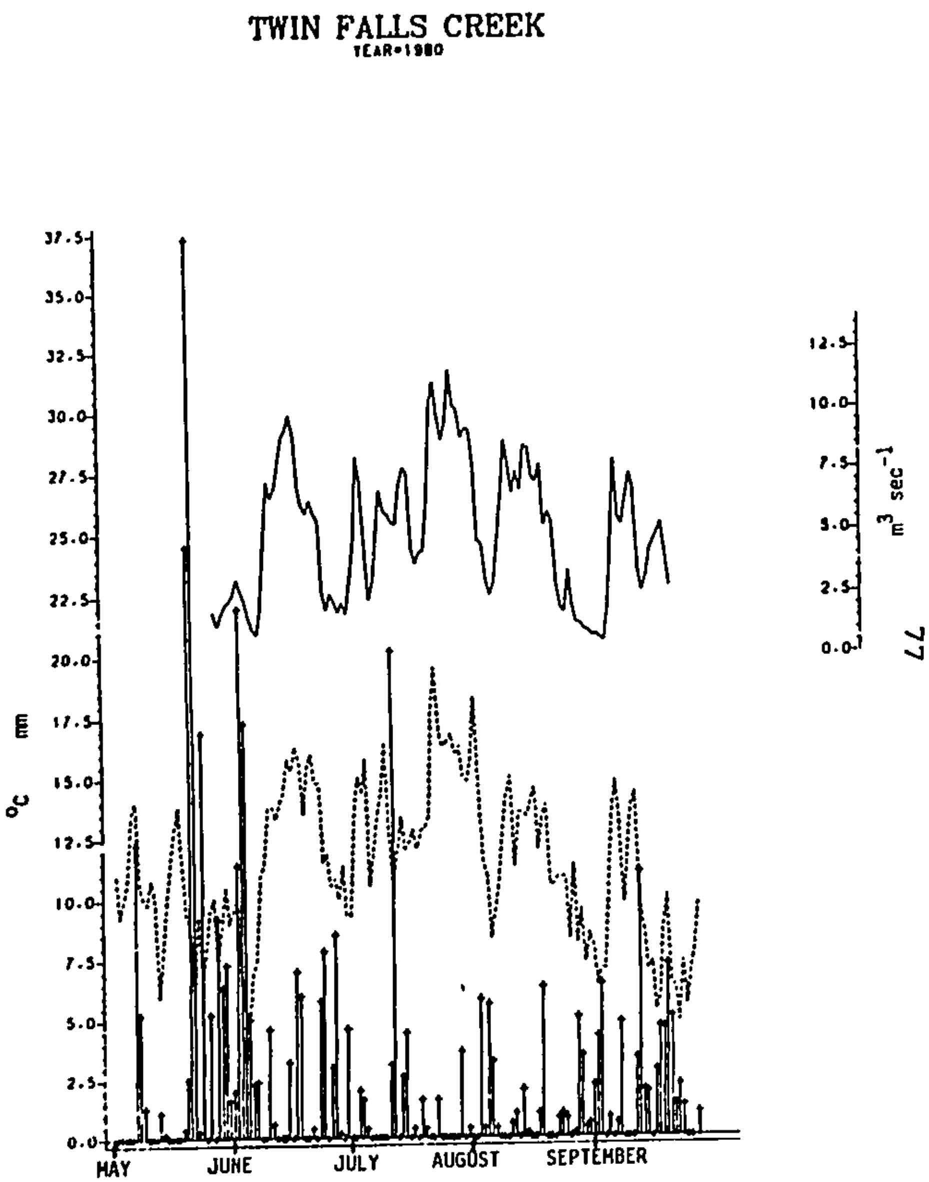

Figure 4.14b

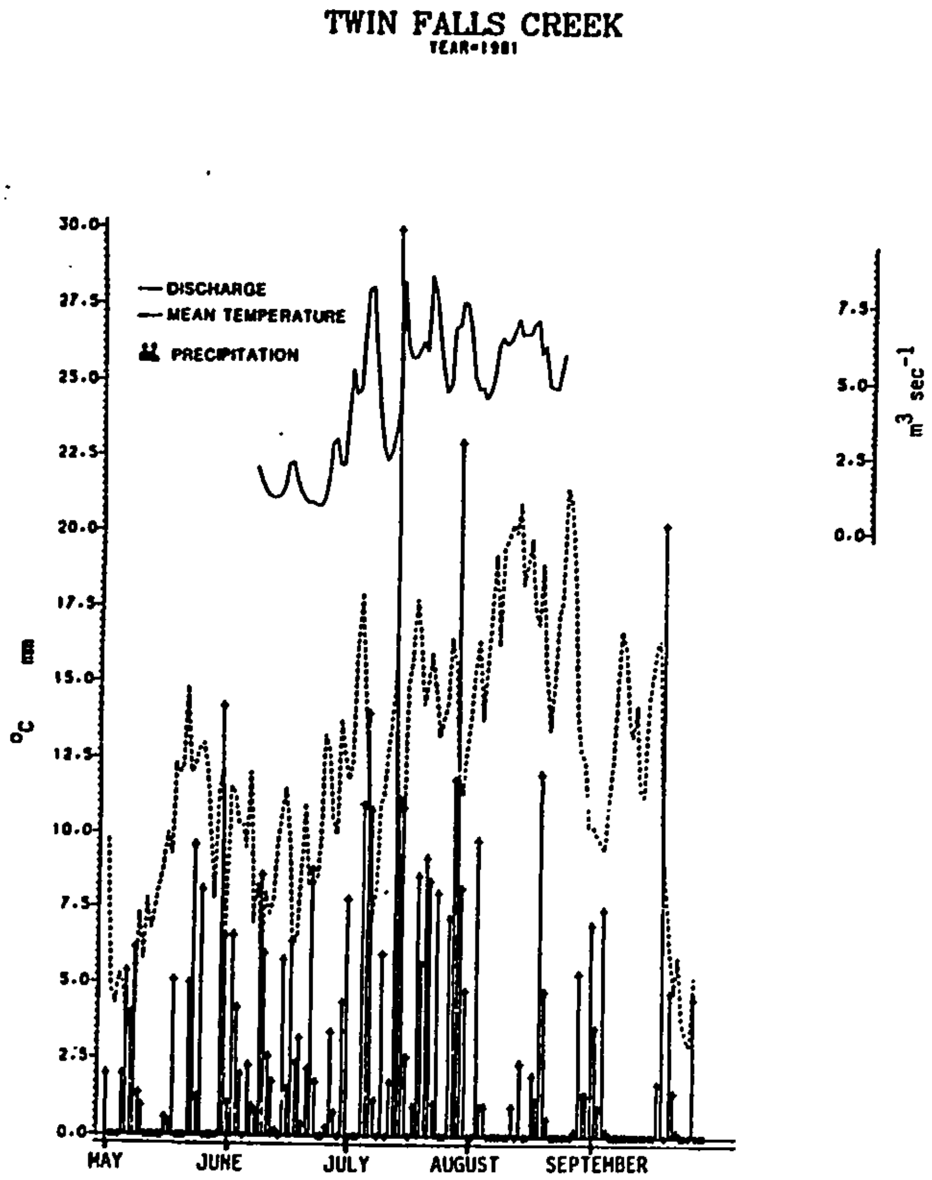

Figure 4.15a

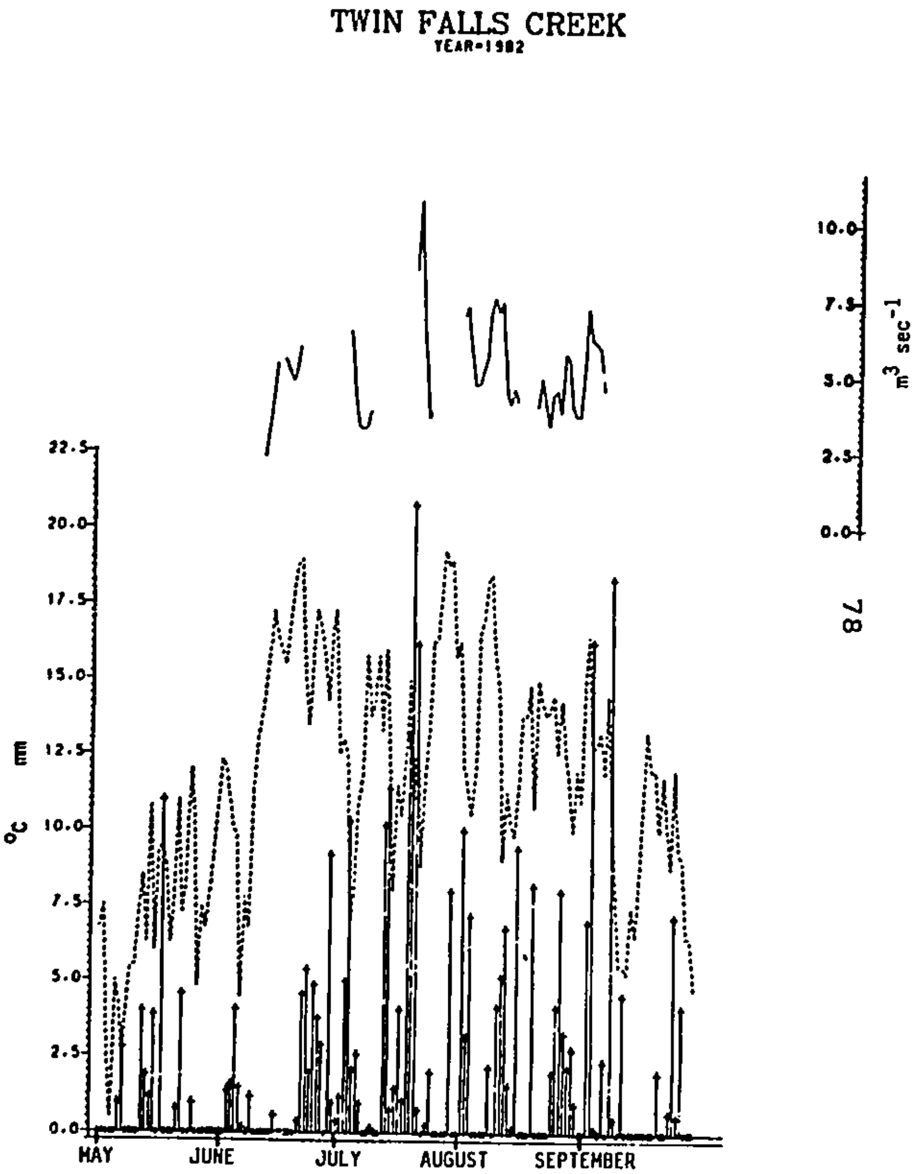

Figure 4.15b

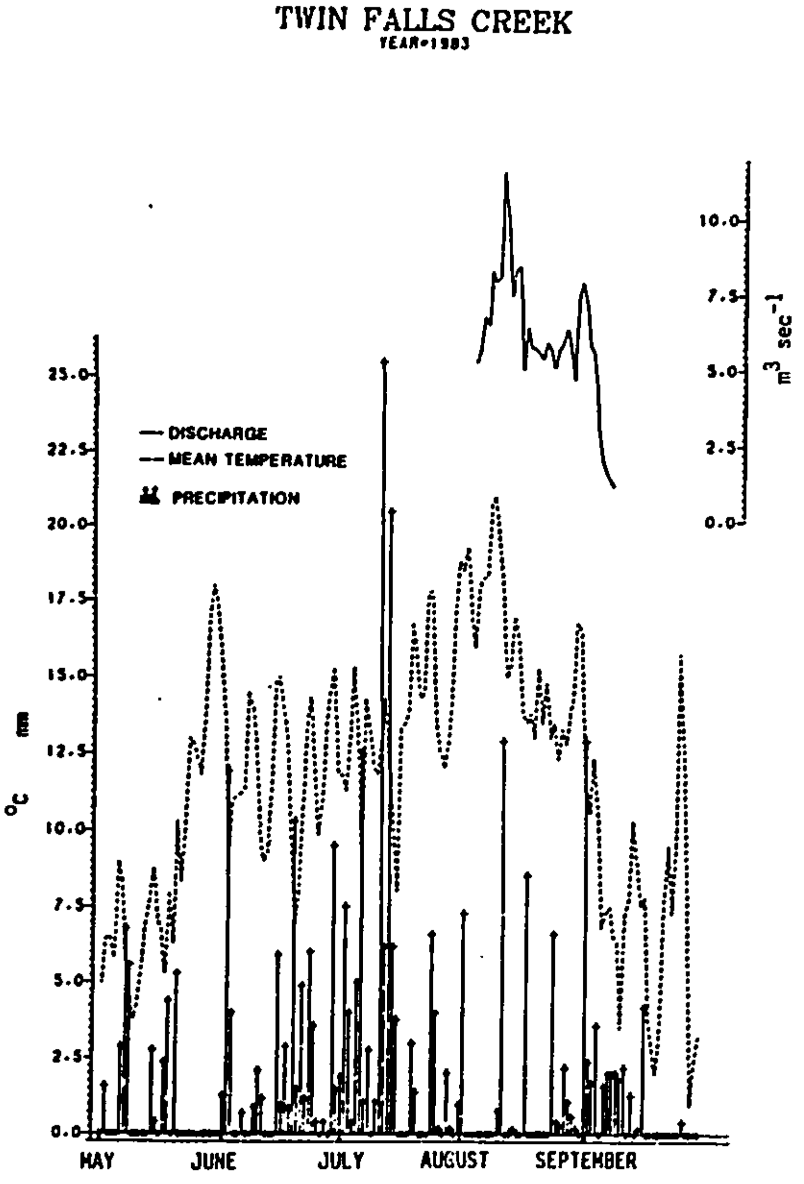

Figure 4.16a

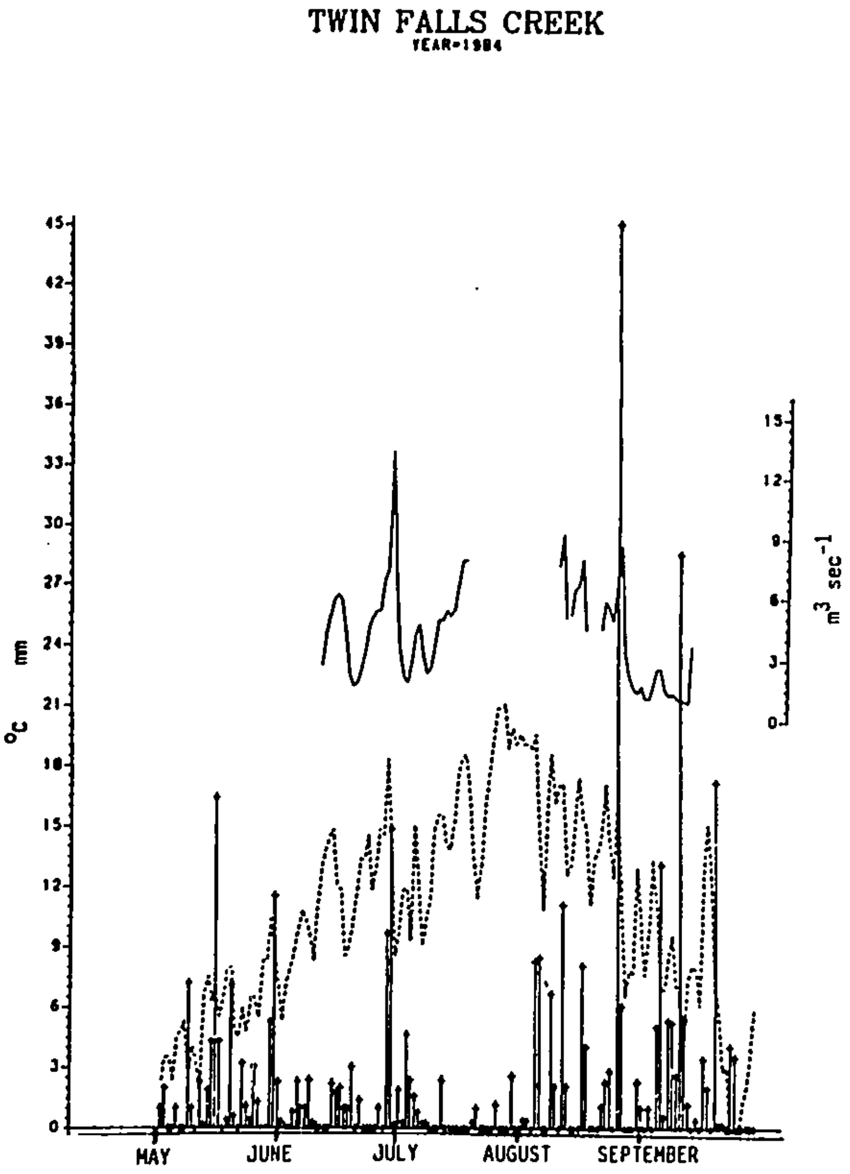

Figure 4.16b

Table 4.4 Fourteen day mean discharge at Twin Falls Creek and mean temperature and precipitation totals at Boulder meteorological station and coefficient of variation of runoff and temperature.

Interval	1978					1980					1981					1984				
	Q	Q_{cv}	T°	T_{cv}	P	Q	Q_{cv}	T°	T_{cv}	P	Q	Q_{cv}	T°	T_{cv}	P	Q	Q_{cv}	T°	T_{cv}	P
05/01-05/14	-	-	5.4	29.4	22.7	-	-	10.2	19.4	20.1	-	-	6.0	31.8	22.0	-	-	6.2	40.9	20.9
05/15-05/28	-	-	8.7	27.9	21.7	-	-	9.6	22.7	102.7	-	-	11.4	16.0	30.1	-	-	6.6	20.5	37.0
05/29-06/11	-	-	12.0	31.9	16.6	2.9	64.7	9.6	31.3	76.5	-	-	9.4	23.0	56.0	-	-	9.3	21.1	27.2
06/12-06/25	2.6	40.1	11.6	19.5	34.0	6.7	35.1	14.3	12.7	33.2	1.4	35.3	9.0	20.5	34.6	4.4	35.5	12.3	16.4	12.4
06/26-07/09	5.9	11.9	16.1	13.0	25.2	3.9	54.0	12.6	19.4	17.3	4.6	43.0	12.3	24.3	53.7	5.1	62.0	12.2	23.1	37.0
07/10-07/23	5.2	19.6	16.5	18.7	63.9	6.3	35.3	13.6	10.6	34.3	5.7	34.0	13.9	22.4	96.5	6.0	23.3	15.2	13.6	3.7
07/24-08/06	6.2	9.7	17.2	10.8	4.1	7.0	37.2	14.3	21.4	19.4	5.7	19.9	14.5	12.4	5.3	-	-	19.0	9.2	21.2
08/07-08/20	4.2	51.5	13.2	20.7	63.3	6.0	23.7	13.0	10.6	11.1	6.5	8.4	10.7	8.8	23.4	6.0	24.4	14.8	16.1	33.0
08/21-09/03	2.0	59.2	10.0	10.5	35.0	2.2	77.6	8.0	19.3	25.0	-	-	14.6		20.6	3.6	66.1	11.5	30.1	61.5
09/04-09/17	3.2	49.6	9.7	29.4	16.7	4.6	48.3	10.4	31.1	31.8	-	-	13.6		7.7	1.7	47.5	8.1	31.9	70.5
09/18-09/30	-	-	-	-	-	-	-	7.6	23.8	22.7	-	-	-		-	-	-	4.4	109.9	27.0

Q = Discharge (m^3sec^{-1})
Q_{CV} = Discharge variability
P = Precipitation (mm)
T° = Temperature (°c)
$T°_{CV}$ = Temperature variability

Discharge peaks and throughs displayed on the hydrographs approximate the daily temperature curves (Figures 4.13 to 4.16). Lag time response of streamflow to various climatic conditions is short due to the size and shape of the catchment. Precipitation rarely compensates for reductions in snow and icemelt brought about by overcast conditions. Runoff is subdued following snowfall as albedo in the basin is increased. Given these conditions, meltwater routed englacially and subglacially to the snout accounts for most of the runoff. An increase in discharge as a result of rainfall was observed on July 13, 1981 (Figure 4.15a) and August 26 in 1984 (Figure 4.16b). The crest in streamflow occurred one or two days following the rainfall events.

Temporal variation of snowline movement up valley results in peak discharge occurrence later in the sub-catchment areas because of their higher elevation ranges. A supply of snow and ice is therefore available for late season melt. Late season glacial meltwater production is responsible for the low streamflow variability figures obtained down valley at the Kicking Horse near Cathedral monitoring site.

4.2 Climate-Runoff Relationships

To complement graphic analysis of hydrographs, correlation analysis was performed to measure the relative strength of the association between climate-runoff variables.

4.2.1 Simple Linear Correlation

A simple linear correlation matrix of temperature, precipitation and sunshine hours was generated on a monthly basis for the eight year set. The intent is to measure intercorrelation between climate variables. Most coefficients presented in Table 4.5 are significant at the 95% level.

No association was found between temperature and precipitation values. The coefficients, all slightly negative, ranged between -0.02 to -0.23, with the highest figure observed in the month of July. Only the coefficients for May and September were not significant at the 95% level.

Correlation coefficients between temperature and sunshine hours were relatively stronger. They ranged from +0.36 to +0.6. The lowest correlations occurred between seasons, in May and September. The results indicate a silightly fair positive association. Both variables are surrogate measures

Table 4.5 Simple linear correlation coefficients between climate variables.

MAY

	Mean Temperature	Total Precipitation	Sunshine Hours
Mean Temperature	1.00	-0.02	0.47
Total Precipitation		1.00	-0.33
Sunshine Hours			1.00

JUNE

	Mean Temperature	Total Precipitation	Sunshine Hours
Mean Temperature	1.00	-0.13	0.52
Total Precipitation		1.00	-0.35
Sunshine Hours			1.00

JULY

	Mean Temperature	Total Precipitation	Sunshine Hours
Mean Temperature	1.00	-0.23	0.56
Total Precipitation		1.00	-0.43
Sunshine Hours			1.00

AUGUST

	Mean Temperature	Total Precipitation	Sunshine Hours
Mean Temperature	1.00	-0.13	0.60
Total Precipitation		1.00	-0.38
Sunshine Hours			1.00

SEPTEMBER

	Mean Temperature	Total Precipitation	Sunshine Hours
Mean Temperature	1.00	-0.02	0.36
Total Precipitation		1.00	-0.36
Sunshine Hours			1.00

of radiation which supply heat for snow and ice melt.

The correlation coefficients between precipitation and sunshine show the expected inverse relationship. The figures vary between -0.33 and -0.43.

The results of the correlation analysis between climate variables are inconclusive due to the limited number of observations used in their calculation.

4.2.2 Multiple Linear Correlation

A stepwise multiple linear regression performed on the data is used as an exploratory technique to gain insight into the relationships between individual climate elements (independant variables) and runoff (dependant variables). This was achieved by comparing squared partial correlation coefficients which indicate the amount of streamflow variation explained by individual meteorological observations once the linear effects of other independant variables have been accounted for. It varies from 0 to 1. Since intent of this analysis is for exploratory purposes, coefficient of determination of the regression models are not discussed.

The meteorological variables were moved forward 0 to 3 days with respect to runoff data, which in effect lagged discharge observations. It permitted the analysis of lag time response of runoff to climate conditions. The stepwise procedure was most useful in that many variables were evaluated and only the ones that accounted for most of the discharge variability were kept. Off-setting the runoff variable by up to three days generated an additionnal nine variables. The results are shown in Table 4.6.

Squared partial correlation coefficients for the complete dataset (1977-1984) show temperature moved by one day (T_1) is strongly associated with runoff in basins with a glacial component. T_3 and P_1 emerged as the second and third best variables in importance. Similar climate elements emerged as the three most significant for Twin Falls and Kicking Horse proglacial streams. Although weak climate-runoff coefficients were obtained for Amiskwi River, the results underline the basin's dependance on liquid precipitation in summer and the important contribution of precipitation to total summer discharge in the absence of a perennial ice-covered basin (Table 4.6).

Monthly T_3, T_1 and T_0-runoff coefficients obtained for the glacierized basins accounted for most of the variation in discharge. P_2 and P_1-runoff coefficients, although

Table 4.6 Squared partial correlation coefficients between climate and runoff.

1977-1984

Twin Falls Creek	Kicking Horse River	Amiskwi River
T_1 0.57 T_3 0.04 P_1 0.03 (496)	T_1 0.45 P_1 0.06 T_3 0.04 (623)	P_1 0.05 S_1 0.02 P_2 0.01 (671)

MONTHLY

	May	June	July	August	September
Twin Falls Creek	P_2 0.50 T_1 0.12 P_3 0.08 (19)	T_1 0.60 T_3 0.07 P_1 0.02 (140)	T_1 0.32 P_1 0.07 T_0 0.07 (128)	T_1 0.60 T_0 0.05 T_3 0.01 (137)	T_1 0.40 T_0 0.07 ------- (68)
Kicking Horse River	P_1 0.32 T_3 0.30 T_1 0.18 (30)	T_1 0.57 T_3 0.08 P_1 0.02 (185)	T_2 0.35 P_2 0.09 T_1 0.05 (214)	T_1 0.43 T_0 0.10 P_1 0.05 (126)	T_1 0.37 T_0 0.05 S_1 0.03 (64)
Amiskwi River	T_2 0.54 T_1 0.06 P_2 0.06 (100)	T_2 0.20 P_1 0.03 T_1 0.02 (209)	P_1 0.19 P_2 0.07 T_3 0.05 (202)	P_1 0.11 T_0 0.11 P_2 0.08 (106)	P_1 0.16 P_2 0.07 T_3 0.04 (50)

YEARLY

	1979	1980	1981	1982
Kicking Horse River	T_1 0.36 S_3 0.03 ------- (83)	T_1 0.38 P_1 0.19 P_0 0.03 (107)	T_3 0.54 P_2 0.13 T_1 0.08 (88)	T_2 0.63 P_3 0.05 T_1 0.04 (75)
Amiskwi River	T_3 0.08 S_3 0.08 ------- (80)	P_1 0.14 P_2 0.08 T_0 0.06 (124)	P_1 0.10 P_0 0.03 P_3 0.03 (117)	T_3 0.17 ------- ------- (73)

T_0, P_0 and S_0 = Temperature, precipitation and sunshine hours moved forward by 0 days.
T_1, P_1 and S_1 = Temperature, precipitation and sunshine hours moved forward by 1 day.
T_2, P_2 and S_2 = Temperature, precipitation and sunshine hours moved forward by 2 days.
T_3, P_3 and S_3 = Temperature, precipitation and sunshine hours moved forward by 3 days.

significant in early season, are gradually phased-out over the course of the summer. This probably reflects the transition from the snow-melt and liquid precipitation streamflow regime to the ice-melt dominated regime. Temperature-runoff coefficients show a decrease in lag time response with the progression of summer as the snowpack overlying the ice melts and supra-glacial and englacial channels and conduits become well established.

Discharge variability accounted for by T_2, T_1 ranges from fair to good during May and June at Amiskwi during the snow-melt period. With the depletion of the snowpack and falling contributions of meltwaters to total runoff, P_1 and P_2-runoff coefficients are singled-out as two of the three best explanatory climate variables for discharge variation in July, August and September. Streamflow variability accounted for by temperature is reduced considerably and the importance of precipitation elevated in late summer.

The results indicate that a significant amount of discharge variation could be accounted for by lagging meteorological variables if a statistical forecasting model of runoff were to be constructed. The results also indicate that several prediction models would be required to accurately reflect shifts in hydrological regimes of mountainous watersheds. Other variables including basin characteristics would have to be incorporated into the model for prediction purposes, especially for Amiskwi where the explained variance of the regression model was generally poor.

4.3 Other Hydrometeorological Considerations

4.3.1 Precipitation

Early spring rainfall is not necessarily reflected on the hydrograph. The appearance of precipitation as surface runoff is gradual and usually lags several days following rain on snow events. The major controls affecting travel time are snowpack depth, melt-water capillary retention limit of the snowpack and time required for surface runoff to channel its way to the stage level monitoring sites. In higher elevations, precipitation may fall as snow during a simultaneous event, increasing surface albedo and retarding melt for several days.

Some high magnitude precipitation events have resulted in major peaks during mid- to late season low flow periods at Amiskwi. Events of July 19 to July 20, 1982 (Figure 4.7b) and August 26, 1984 (Figure 4.8b) caused discharge to rise sharply. Low frequency, high magnitude rainfall events result in overland and surface flow when infiltration capacity of the soil is exceded. Extended periods of precipitation, such as the one observed from mid-June to mid-July in 1983 at Amiskwi (Figure 4.8a), manages to maintain mid-summer discharge at high levels. Following the spring snowmelt period, discharge begins to drop sharply. As the number of consecutive days with rainfall increases, discharge recession is modified and runoff levels varies from 9 m^3sec^{-1} to 15 m^3sec^{-1}. From mid-July to the end of the observation period, discharge decreases sharply as a wave of warmer and drier weather follows. In late summer, Amiskwi River discharge response to low magnitude precipitation events is dampenned by interception of rainfall by vegetation and infiltration in the soil. The rising and falling segments of the hydrograph are gentle and the discharge peaks are flat during a dry summer. This trend is illustrated by a 1979 storm which occurred on September 8, the driest summer of the eight-year set (Figure 4.6a).

In the glacierized basins, summer precipitation of 30mm or less rarely compensates in terms of water volume for the reduction in glacial melt-water production during overcast conditions. Discharge tends to decline as energy reception is reduced by cloud cover as observed on July 28, 1977 (Figures 4.9a and 4.13a) and July 10, 1978 (Figures 4.9b and 4.13b). In late summer, the low frequency high magnitude event which occurred on August 26 of 1984 resulted in a sharp increase in discharge of both glacierized streams (Figures 4.12b and 4.16b) and the non- glacierized stream (Figure 4.8b).

4.3.2 Winter Snow Accumulation

Snow cover data collected within the study area near the Field townsite and in Kicking Horse Pass near Wapta Lake are given in Table 4.7. Water equivalents of seasonal snowfall accumulation for the selected stations vary considerably from year to year. The data indicate that most of the snow has ablated by late May to mid-June at the Kicking Horse snow course and by early to mid-May at Field. The accumulated snowpack and its rate of depletion, described in terms of water equivalent, is considered a good indicator of potential spring runoff.

In spite of the inaccuracies associated with extrapolating point measurement such as snow course data to a surrounding area particularly in mountainous terrain, the comparison of water equivalent figures reveal the following:

1- Historically, April 1 snow on ground observations indicate snowpack depth at Kicking Horse Pass is nearly

Table 4.7 Snow cover data.

	FIELD 51°,23' ; 116°,31' 1,280m.a.s.l.			KICKING HORSE PASS 51°,26';116°,21' 1,650m.a.s.l.		
	Date	Depth (cm)	Water Equivalent (mm)	Date	Depth (cm)	Water Equivalent (mm)
1977	01/31	48	134	01/31	83	239
	03/01	53	142	03/01	94	287
	04/29	0	0	04/29	69	257
				05/13	36	137
				05/30	5	13
				06/15	0	0
1978	01/30	63	173	01/30	85	253
	02/28	66	187	02/28	92	272
	03/31	30	81	03/31	87	262
	04/28	0	0	04/28	71	247
				05/12	49	228
				05/31	4	15
1979	01/30	50	93	01/30	75	169
	02/28	73	170	02/28	120	270
	03/30	50	154	03/29	110	323
	04/27	13	30	04/27	102	290
				05/13	76	240
				05/31	24	70
1980	01/31	66	146	01/30	100	280
	02/28	61	162	02/28	107	322
	03/31	64	211	03/31	117	387
	04/30	0	0	04/30	60	237
				05/15	7	28
				06/01	0	0
1981	02/04	56	141	02/04	97	284
	03/27	53	163	03/27	107	337
	04/27	13	46	04/27	105	367
				05/15	69	269
				05/28	8	27
1982	01/29	76	154	01/29	102	237
	02/25	76	210	02/25	129	324
	03/30	74	198	03/30	130	390
	04/29	41	133	04/29	113	415
				05/13	97	392
				05/28	47	174
1983	01/27	64	117	01/27	100	204
	02/24	56	146	02/24	90	271
	03/31	42	124	03/31	100	290
	04/29	0	0	04/29	66	251
				05/12	48	187
				05/27	4	13
1984	02/04	40	91	01/03	60	105
				02/04	89	196
				03/30	88	284
				04/27	65	216
				05/14	57	223
				05/28	47	174

SOURCE: ATMOSPHERIC AND ENVIRONMENT SERVICE, ENVIRONMENT CANADA.

twice that observed at the snow course located near Field.

2- Topography is the main control on snow quantity. There is a 370 m. elevation difference between the snow course sites. The Kicking Horse Pass snow sampling site lies between the Waputik and Bow Ranges which form part of the Divide. This acts as a local barrier disrupting movement of air masses. Air flow is forced over the ridges, cooling at an adiabatic lapse rate. The decrease in pressure and air temperature causes moisture of the uplifting air mass to condense resulting in orographic precipitation and significantly high snow accumulation over the winter months in the upper reaches of the Divide area.

3- Water equivalent totals peak later in the season at higher altitudes because of temperature lapse rates. Snow on ground conditions persist by as much as a month later at Kicking Horse Pass where temperatures are significantly cooler than those found in the valley bottom. Mean monthly temperatures are 2°C to 4°C lower in the Divide area than those observed at Boulder. 1981 mean monthly temperature records are below the freezing mark from January through April. Temperatures at Boulder were below freezing in January and February only.

4- Accumulation, melt rates and patterns and temporal variation in melt-water production between sampling sites vary significantly from year to year and within a single snowmelt season. Precipitation storage characteristics differ as a result of lower temperatures and reception of greater amounts of precipitation observed at the Kicking Horse Pass.

4.4 Comparitive Analysis of the Effects of Contrasting Hydrometeorological Conditions on Runoff

Discharge data from Amiskwi River and Kicking Horse River are retained for analysis because of a good discharge series for simultaneous time periods. Table 4.8 shows the ranking order of snow persistence in spring, mean temperature, temperature variability and total summer precipitation from May to September. The hydrological seasons of 1980 and 1982 are singled out to highlight the contrasting effects on runoff of snow on ground persistence in spring. The 1979 and 1981 hydrographs are examined to compare the impact of a dry summer with that of a cool and wet one on streamflow variability.

4.4.1 Snow on Ground Persistence (1980 and 1982)

In 1982, water equivalent of the snowpack peaked two months later at Kicking Horse Pass than at Field and snowpack persisted into June at Kicking Horse Pass. In 1980, most of the snow at Kicking Horse Pass had disappeared by late-May (Table 4.7).

Amiskwi:

Amiskwi hydrographs of 1980 and 1982 display different 1980 recession segment displays a relatively gentle decreasing trend which probably had started well before the seasonal recession limbs (Figures 4.6b and 4.7b). After June 16, 1982, a sharp decline in runoff is observed. The installation of the stage recording equipment on May 16.

In 1980, the maximum seasonal daily peak discharge of 22.8 m^3sec^{-1} recorded on May 22, occurred 23 days earlier than the 30.2 m^3sec^{-1} observed on June 15 in 1982. In late summer of 1982, streamflow had fallen to 7.0 m^3sec^{-1} on August 24 considerably higher than the 2.18 m^3sec^{-1} recorded for the same date in 1980. Seasonal average discharge from May 16 to August 1 was 12.0 m^3sec^{-1} in 1980 and 17.4 m^3sec^{-1} in 1982. Discharge was less variable in 1982 with a calculated C_v of 30.8% while the coefficient of variation

Table 4.8 Snow persistence, mean temperature, temperature variability and total precipitation ranked by year (May-September).

	Temperature (°c)	Temperature Variability (C_v)	Total Precipitation (mm)
1977	11.8	30.2	284.8
1978	11.8	30.5	284.8
1979	12.3	29.8	139.0
1980	11.6	18.3	371.4
1981	12.3	28.6	349.9
1982	11.7	28.7	321.3
1983	12.1	27.8	300.2
1984	11.3	39.6	326.8

RANK

	Snow Persistence	Temperature	Temperature Variability	Total Precipitation
1977	5	4	6	6
1978	4	5	7	6
1979	2	2	5	7
1980	6	7	1	1
1981	3	1	3	2
1982	1	6	4	4
1983	5	3	2	5
1984	1	8	8	3

1- Snow persistence; most persistent spring.
1- Temperature; warmest summer.
1- Temperature variability; least variable summer.
1- Precipitation total; highest precipitation summer.

figure for 1980 was significantly higher at 39.5%.

Discharge was at an unusually high level throughout the 1982 hydrological season. Late summer streamflow was quite high compared to other years. In 1980, the onset of ablation was earlier so that there was low snow on the ground at the start of the monitoring season. Low flow would have probably occurred much earlier in the season had it not been for the wet period at the beginning of the streamflow observation period. Despite heavy precipitation events early in the snowmelt period of 1980, snowpack persistence in spring of 1982 is responsible for a higher instantaneous peak discharge and its occurrence later in summer. It is difficult to accurately isolate and quantify the volumes of water originating from snowmelt and precipitation inputs from total summer runoff between years of significant contrast with the method of analysis used in this study. However, snow stored in the basin during winter of 1981-1982 is partly responsible for the reduction in seasonal discharge variability (C_v) in 1982. T_3 emerged as a significant variable that year (Table 4.6).

Kicking Horse:

In 1980, a maximum daily streamflow reading of 73.4 m^3sec^{-1} was observed on July 23 (Figure 4.10b). The seasonal low flow on record was 8.9 m^3sec^{-1} on September 22. Maximum instantaneous discharge was attained June 27, 1982 as contributions originating from the snowmelt component peaked in spring. As autumn approached, reduced temperatures and fresh snowfalls at higher elevations in the basin increased albedo over glacierized surfaces and melt-water production was reduced.

Average daily discharge from June 21 to August 3 and September 8 to September 23 inclusive were computed for the 1980 and 1982 field seasons. Results indicate discharge to be slightly lower in 1980 at 33.2 m^3sec^{-1} with a C_v of 46.6% while runoff in 1982 was slightly higher at 39.9 m^3sec^{-1} with a streamflow variability figure of 49.6%.

The proportion of ice-melt water to total summer runoff was substantially less in 1982 than other years because of snow persistence into early summer which retarded ice-melt. Annual mass balance measurements conducted on Peyto Glacier indicate substantial water equivalent losses; -105 cm in 1980 compared to -56 cm in 1982 (Letréguilly, 1988). Despite the differing snow on ground conditions, streamflow variability was not affected to the same extent as it was in the nival stream. Squared partial correlation coefficients calculated for Amiskwi River indicate temperature accounted for more runoff variability in 1982 than in 1980

(Table 4.6).

4.4.2 Comparison Between Dry and Wet Summers

1979 was the driest and one of the warmest summers of the eight-year set of meteorological data. Only 139mm of precipitation fell in 1979 while the 1981 total observed reached 349.6mm. 1981 ranked 2 as the wettest of the eight-year set (Table 4.8).

Amiskwi:

Recession on the 1979 hydrograph begins on June 13. The 1981 hydrograph displays two major recessions with regard to discharge. A first recession beginning on May 26 ending on June 24 is followed by a second major surge in discharge caused by heavy precipitation input to the basin leading to a second recession starting on July 8. Discharge had fallen to 4.5 m^3sec^{-1} by September 3.

Maximum instantaneous discharge was achieved on June 13 with a recorded discharge of 19.25 m^3sec^{-1} in 1979 while 26.8 m^3sec^{-1} on May 26 was the peak observed in 1981. Seasonal average streamflow for the period between May 30 and August 3 was 8.9 m^3sec^{-1} in 1979 and 14.7 m^3sec^{-1} in 1981. Late season streamflow on July 31 of 0.65 m^3sec^{-1}, was the lowest of the 1979 season. 17.7 m^3sec^{-1} was recorded at the same date in 1981. The 1981 seasonal low was observed on August 31 when streamflow was 4.1 m^3sec^{-1}.

Kicking Horse:

The maximum instantaneous discharge on record was achieved on July 21 in 1979 as discharge rose to 98.7 m^3sec^{-1} as temperatures climbed above 20°C. The 1981 maximum was observed at 79.2 m^3sec^{-1} on July 31. Minimum flows for both years coincided with unfavorable hydrometeorological melting conditions. Seasonaly high temperatures in September of 1981 resulted in sustained streamflow in the 50 m^3sec^{-1} range at Kicking Horse River.

Seasonal average streamflow for the period between June 2 and June 22 and July 12 and August 13 was 47.3 m^3sec^{-1} in 1979 and 43.4 m^3sec^{-1} in 1981. Discharge coefficient of variation was 47.3% in 1979 and 52.3% in 1981.

It is interesting to note the emergence of S_3 as an important meteotrological variable against Kicking Horse and Amiskwi discharge in 1979 (Table 4.6). It probably reflects the dry summer conditions that year where precipitation total was the lowest of the eight year set. T_3 against Amiskwi discharge might reflect high altitude snowpack melt which would slowly make its way to the basin outlet.

The wet year is reflected in the results of squared partial correlation coefficients observed for 1981 at Amiskwi when precipitation variables accounted for most of the streamflow variability. Despite considerable variance in hydrometeorological conditions between years, runoff at Kicking Horse River constantly showed a relatively strong association with temperature. The absence of a perennial ice cover in the Amiskwi watershed is underlined by the variation of significant meteorological variables from year to year.

4.5 Coefficient of Variation Analysis

The variability of runoff is best described by comparing the coefficients of variation (C_v). As a dimentionless parameter, it has been useful in studies of regional hydrologic regimes and interbasin runoff variability. Collins (1986) and others have demonstrated temperature variability is reflected in discharge C_v (Table 4.3).

Logistical considerations restricted the field programme to the ablation season. Streamflow variability is described only for the ablation periods, a time during which the greater proportion of annual runoff occurs.

Table 4.9 Summer to summer discharge variability.

Years	Amiskwi River		Kicking Horse River	
	Q	C_v	Q	C_v
1979-1982	12.4	37.8%	42.9	16.3%
1977-1984	10.4	41.0%	43.9	16.8%

	Kicking Horse River		Twin Falls Creek	
	Q	C_v	Q	C_v
1979-1982	41.6	17.8%	4.5	25.2%
1977-1984	42.9	12.5%	4.9	20.5%

	Amiskwi River		Kicking Horse River		Twin Falls Creek	
	Q	C_v	Q	C_v	Q	C_v
1979-1982	14.0	35.8%	41.8	19.8%	4.6	22.7
1977-1984	10.9	50.0%	44.0	17.4%	4.9	20.1

Q = Discharge ($m^3 sec^{-1}$)
C_v = Discharge variability

4.5.1 Interseasonal Hydrometeorological Variability

Discharge variability between summers were calculated from fourteen-day mean values. The intent is to compare the impact of differing hydrometeorological conditions on streamflow variability (Table 4.9).

Streamflow variability results indicate Kicking Horse River to be the least variable between years of extreme hydrometeorological conditions from 1979 to 1982. It also registered the lowest C_v figure for the eight-year set. Amiskwi River was the most variable in terms of discharge largely due to its dependance on winter snowpack melt in spring and rain in summer as its principal sources of runoff. Both elements were earlier shown to vary considerably from year to year. The highly glacierized catchment of Twin Falls recorded C_vs of 22.7% from 1979 to 1982 and 20.1% from 1977 to 1984.

Although the discharge C_v for Amiskwi River appears high, Zuming (1982) has observed variability of unglacierized streams in Northwest China to be as high as 40%. Zuming (1982), Rasmussen and Tangborn (1976) in the North Cascades, Washington, Tollan (1972) in Norway and Collins (1986) have recorded similar coefficients of variations in glacier-fed streams. The streamflow variability figures obtained in the study area are similar to those generated by Fountain and Tangborn (1985) in the North Cascades. When plotted against the basins glacierized fraction, a similar trend in C_v is observed; a higher C_v for snow-fed streams and a discharge variability minimum for 30% glacier-fed basins.

4.5.2 Seasonal Coefficient of Variation

Seasonal fluctuation of C_v have been calculated using mean daily discharge data. The eight-year set was grouped into one sample (Tables 4.10 and 4.11). Results between streams are compared using data for similar periods of time.

Season C_v

Seasonal C_vs (1977-1984) indicate Amiskwi River to be the most variable within the study area. The nival basin, Amiskwi obtained the highest C_v (Table 4.10). Both partly glacierized basins, Kicking Horse and Twin Falls had lower C_v figures in view of increasing contributions originating from the ice-melt component July and August (Table 4.11).

Seasonal C_v by Year

Seasonal C_vs by year vary considerably from year to year for

Table 4.10 Mean discharge and streamflow variability of Amiskwi River and Kicking Horse River.

KICKING HORSE, AMISKWI.

SEASONAL Cv (1977-1984)

	MEAN	Cv
KICKING HORSE (501)	43.0	44.8
AMISKWI (501)	11.0	59.7

SEASONAL Cv BY YEAR

YEAR	1977		1978		1979		1980	
DATE	06/10-07/02		06/07-08/01		06/02-06/07 06/11-06/22 07/12-08/03 09/01-09/04		05/21-05/25 05/29-06/02 06/06-08/22 08/31-09/02 09/06-09/22	
	(31)		(56)		(45)		(103)	
	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv
KICKING HORSE	37.2	23.0	55.2	26.3	46.2	46.6	32.7	46.3
AMISKWI	6.2	52.3	5.3	62.7	7.7	75.6	9.3	59.3

YEAR	1981		1982		1983		1984	
DATE	05/24-08/13		05/22-06/09 06/12-07/17 07/23-08/03		06/13-07/11 07/17-07/21 08/03-08/05 08/13-08/14 08/21-08/26		06/11-08/20	
	(77)		(85)		(45)		(76)	
KICKING HORSE	46.6	47.0	44.2	44.0	38.4	36.1	48.9	41.9
AMISKWI	15.1	31.4	17.6	31.0	10.4	33.8	11.7	63.2

SEASONAL Cv BY MONTH

MONTH	MAY (25)		JUNE (185)		JULY (192)		AUGUST (78)		SEPTEMBER (23)	
	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv
KICKING HORSE	31.0	57.9	39.5	47.5	50.2	36.8	44.0	33.2	19.7	32.5
AMISKWI	10.8	23.1	14.1	45.2	9.7	56.6	8.0	58.2	3.0	46.4

NOTE: NUMBER OF DAYS OF OBSERVATION IN BRACKETS.

Mean - Discharge (m^{3}sec^{-1})
Cv - Discharge variability

Table 4.11 Mean discharge and streamflow variability of Kicking Horse River and Twin Falls Creek.

TWIN FALLS, KICKING HORSE.

SEASONAL Cv
(1977-1984)

		MEAN	Cv
TWIN FALLS	(400)	5.0	45.5
KICKING HORSE	(400)	41.6	41.1

SEASONAL Cv BY YEAR

YEAR	1977		1978		1979		1980	
DATE	06/10-06/11 06/14-06/16 06/19-06/23 06/28-07/03 07/12 07/20 07/24-08/13		06/07-08/02 08/10-08/20 09/02-09/15		06/12-06/22 09/02-09/04		05/31-06/22 09/06-09/21	
	(39)		(81)		(23)		(97)	
	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv
TWIN FALLS	5.4	28.0	4.3	40.3	3.0	51.3	5.7	47.3
KICKING HORSE	41.0	23.2	47.5	35.7	40.1	51.5	33.0	42.5
YEAR	1981		1982		1983		1984	
DATE	06/07-08/13		06/11-06/20 07/02-07/09 07/23 08/02-08/03		08/04-08/05 08/13-08/14 08/21-09/04		06/11-07/16 07/30-07/31 08/11-08/16 08/22-08/28	
	(68)		(19)		(19)		(54)	
TWIN FALLS	4.4	54.2	4.9	27.1	6.2	19.5	5.5	42.3
KICKING HORSE	42.3	49.2	51.0	22.7	44.3	25.6	44.0	45.9

MONTHLY Cv

MONTH	MAY (7)		JUNE (139)		JULY (132)		AUGUST (85)		SEPTEMBER (35)	
	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv	MEAN	Cv
TWIN FALLS	1.6	33.2	3.8	59.5	5.8	34.6	6.1	26.7	4.4	38.1
KICKING HORSE	27.9	37.9	39.7	48.8	49.0	33.4	41.4	28.4	25.2	44.0

NOTE: NUMBER OF DAYS OF OBSERVATION IN BRACKETS.

Mean = Discharge (m^3sec^{-1})
Cv = Discharge variability

Amiskwi River. They range from 31.0% to 75.6% (Table 4.10). Summer to summer variability of streamflow at Amiskwi is due to the absence of a perennial ice-covered area in the watershed, variable climate conditions between years and, also, temporal variations of the observation periods used to calculate C_v. Compared with Kicking Horse River, Amiskwi River registered higher C_v for all years except 1981, 1982 and 1983 (Table 4.10). The lower variability values of 1981 are accounted for by the wet summer as precipitation input into the basin was sufficient to keep discharge high. Snow on ground persistence late in spring of 1982 extended snowmelt water production to a later date. The reason for the 33.5% C_v figure in 1983 can only be explained by the fact that most of the data used to compute C_v for that summer was collected when the snowmelt regime was well established. One could expect higher variability values for a complete summer discharge data set for those years. Streamflow variability at Kicking Horse River ranged from 23% to 48.6%.

Streamflow variability figures between Twin Falls Creek and Kicking Horse River are similar (Table 4.11). The results indicate that discharge C_v between summers follows near identical patterns. The 19.5% variability figure obtained at Twin Falls in 1983 occurs because data was collected in late season at a time when snow and ice-melt is well established. Discharge variability figures would likely be slightly lower at Kicking Horse if complete summer data sets were examined.

Monthly C_v

Amiskwi monthly C_v values reveal an increasing C_v value from May to August with a slight drop in September. The contribution of glacial runoff with the disappearance of the snowpack results in sustained streamflow throughout the ablation season and a decline in monthly C_v. The monthly runoff C_v values calculated at Amiskwi are in close agreement with those obtained in the North Cascade while the declining monthly C_v figures observed at both Twin Falls and Kicking Horse follow similar patterns as those obtained by Fountain and Tangborn (1985) for proglacial streams in the North Cascades.

Peak summer runoff delay varies according to the presence or not of a glacier and the extent of glacier coverage. The monthly mean discharge volume figures point to a seasonal discharge peak occurring between mid-May and the end of June at Amiskwi gauging site. At Kicking Horse, it occurs as much as a month later. The higher mean basin elevation of Twin Falls Basin causes peak discharge to occur even later, as late as early August.

Comparison of monthly C_v values between the three catchment areas reflect the transition of hydrological regimes of the basins. Amiskwi River monthly C_v indicate a gradual increase with the progression into summer. Streamflow becomes increasingly variable as the principal source of runoff changes from the snowmelt component to the precipitation and groundwater components in late summer. The increasing supply of snow and ice-melt components in the glacierized basin are reflected in the declining C_v with the progression of summer months. It results in sustained streamflow following snowmelt in the low altitudinal (below 2300m) zones of the basin. Greater regularity in streamflow is achieved in late season as the snowline migrates to higher elevations, thus exposing increasing amounts of ice surface to radiation thereby increasing ice-melt water production. The transition from a snow-melt to an ice-melt regime does not result in major discharge variation and is responsible for the decrease in C_v with the progression into summer.

The seasonal variability figures and monthly C_v trend found in the catchment areas are in close agreement with those which Krimmel and Tangborn (1974) (Figure 4.37) and Fountain and Tangborn (1985) observed in the North Cascades for both nival and partly glacierised basins.

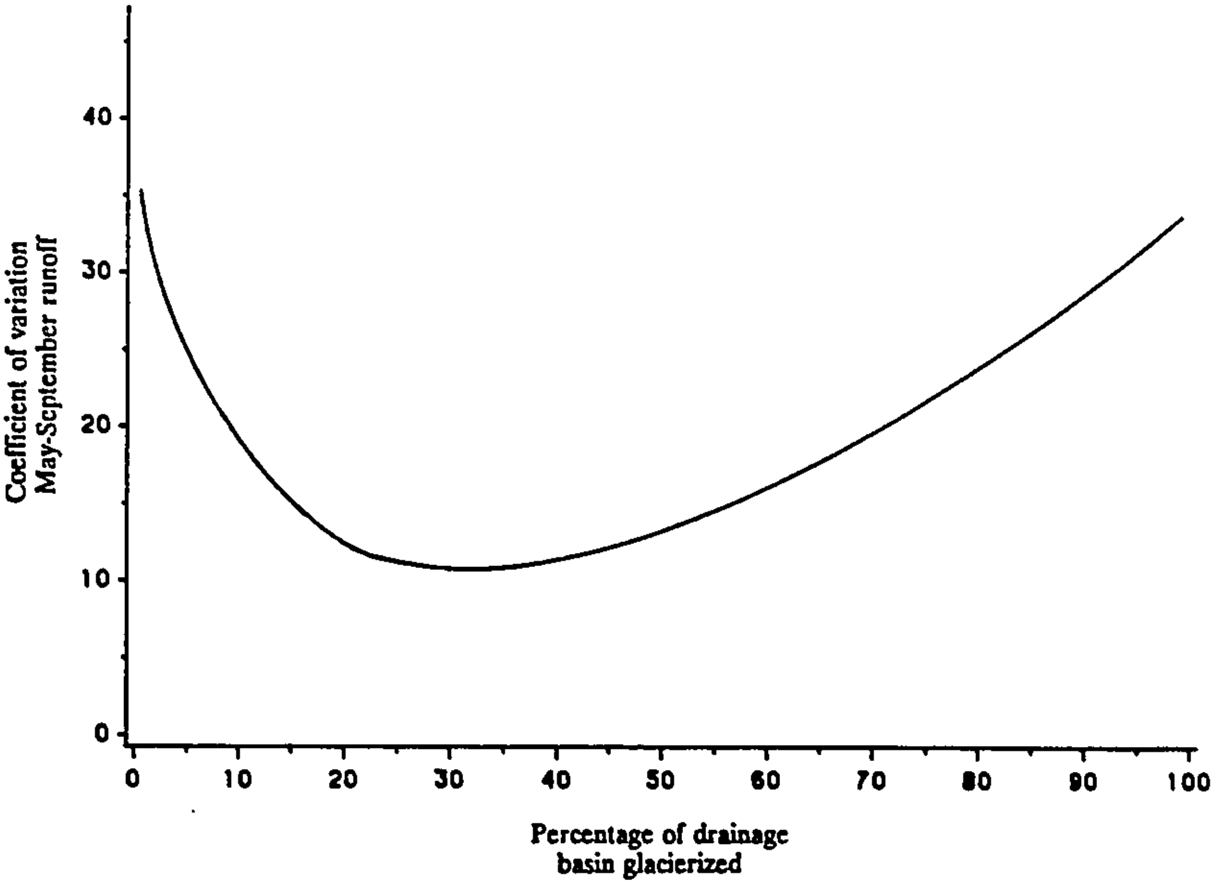

Figure 4.17 Variability of summer runoff in different drainage basins as a function of the percentage of glacial cover for the North Cascades, Washington. Source: Krimmel and Tangborn (1974).

CHAPTER 5

CONCLUSION

This study sought to describe and compare summer (May to September) and short-term flow regimes of three basins with glacial coverages ranging from 0% to 60%. It also attempted to establish climate-runoff links.

In order to achieve these goals, hydrograph analysis between streams was performed. A coefficient of variation analysis was done on runoff data which had the effect of standardizing streamflow variability for comparitive purposes. Simple and multiple linear correlation and regression analysis was utilized to establish climate-runoff relationships.

From the hydrograph trend analysis, two distinct streamflow regimes emerged. An early season snowmelt dominated regime was identified in both nival and glacierized streams in May, June and early July. The gradual depletion of the seasonal snow cover in the basins resulted in a sharp contrast in the shape of the hydrographs. Runoff in the nival stream declined to low flow conditions. It indicated the transition from the snowmelt regime to a precipitation and groundwater regime. Water volumes in the proglacial streams continued to flow at a high rate as glacial melt component contributions to total runoff increased from mid to late summer. Although the pattern tends to repeat itself from year to year, the timing of the transition varied considerably as a result of snow on ground conditions at the onset of ablation and variable climate conditions between years.

It was calculated that the major proportion of annual runoff occurs from May to September in both nival and glacierized streams.

Monthly fractions of discharge indicate a delay of streamflow until later in the summer with increased glacier cover in the basin. The lag is caused by snow melting at a later date with increased altitude. Over the glacierized portions of a basin, snowline movement tends to be less rapid. The gradual migration of the snowline exposes increasing glacial surface and ice melt water production is limited only by energy availability. This along with the gradual release of internally retained meltwaters within the glacier conduits delay peak discharge until later in summer.

Simple linear correlation coefficients between precipitation and temperature indicate no relationship between these climate elements. Coefficients among temperature and sunshine hours, and precipitation and sunshine hours were found to be weak to slightly fair at best. The interpretation of the results of this analysis must be viewed with caution. The statistical significance of these results is questionable due to the limited number of observations used in the computation and the assumption that the relationships between meteorological elements are linear. For these reasons, the results of the correlation analysis remain inconclusive.

During the snowmelt period, fluctuations in streamflow in both glacierized and non-glacierized streams are linked to temperature variations. Squared partial correlation coefficients for the month of May showed temperature accounted significantly for variations in runoff. The figures indicate a decline in the strength of the temperature-runoff relationship with the progression of summer. This decrease occurs as a result of snow cover depletion in the basin. The climate-runoff relationship of proglacial streams shows an increase because more ice surface becomes exposed to solar radiation as the snowline receeds.

Kicking Horse River is least affected in terms of water volume and streamflow variability between summers of extreme hydrometeorological conditions largely due to the regulating effects of the glacial runoff component. Streamflow of Amiskwi River was significantly more variable because it is highly dependant on snow meltwaters in spring and precipitation later in summer.

Monthly summer streamflow variation (C_v) of Amiskwi River tends to increase once the seasonal snow cover has melted while a decrease in variability was observed in proglacial streams as icemelt water contributions commenced later in summer.

The major obstacle encountered in this study is that of runoff data reliability. From 1977 to 1984, data collection stations were relocated following major flood events which destructed water level monitoring sites or bridges. Significant shifts in streambed configuration occurred due to erosion or deposition, a typical phenomenon observed in turbulent mountain and proglacial rivers. The shifts likely modified the rating curves from which discharge data was generated. Few adjustments to the level-discharge curves were carried-out to account for cross-sectional shifts. Stage recorders were replaced by new ones following destruction by a storm. This probably resulted in inconsistent water level readings arising from the use of different instruments. Again, no ajustments were performed. In order to achieve consistency and enhance quality and reliability of data, collection methods and procedures must be maintained to high standards. Errors could have been identified earlier on by simply examining and assessing the data on a regular basis. Steps could have been taken to control errors arising from data acquisition instrumentation and techniques.

A statistical model incorporating climate variables collected at the Boulder weather station to predict runoff of streams with a glacial component would likely give an inaccurate model due to extreme temperature and precipitation regimes which differ significantly over very short distances. A physical model which emphasizes energy balance and network of carefully selected meteorological collection sites at various elevation within a basin in order to establish temperature-altitudinal gradients would probably yield a much more accurate model for forecasting glacial runoff.

The results of this study with those carried out by others reinforce the thought that the presence of a glacier cover has a marked effect on streamflow variability. Regardless of the hydrometeorological conditions, it has been demonstrated that glaciers are important moderators of discharge and ice-melt runoff will more than compensate for the lack of precipitation during dry years, thus providing a reliable source of water throughout summer.

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