OBSERVATIONS ON A

HIGH LATITUDE DRAINAGE BASIN

HYDROLOGICAL AND GEOMORPHOLOGICAL OBSERVATIONS ON A HIGH LATITUDE DRAINAGE BASIN: "JASON'S CREEK", DEVON ISLAND, N. W. T.

by

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SCOPE AND CONTENTS:

"Jason's Creek" drains a small basin in arctic limestone terrain. It is frozen from September to late June, when temperatures rise above the freezing point and snowmelt commences. The spring snowmelt flood lasts for two weeks and is followed by a two-month period during which discharge fluctuates diurnally at a low level in response to meteorological variations, except after rainstorms which produce sharply-defined floods. Transportation of suspended sediment is considerable when the stream is in flood; solute concentration varies inversely with discharge, and at low discharges dissolved load is the major component of total stream load. The solutional capacity of snowmelt water in this high-latitude locality appears to be less than that of water draining limestone terrains in warmer climates.

ACKNOWLEDGEMENTS

I owe a very great debt to my supervisor, Dr. S. B. McCann, for his constant encouragement and friendship since the time of my arrival at McMaster University, and in particular during the field season of 1970 when his powers of persuasion led me to collect much more information than would have resulted without his presence. He has also assisted the production of this thesis in a practical sense by providing funds from grants in aid of research made to him by the National Research Council of Canada and McMaster University. Dr. P. J. Howarth's friendship and interest in my work has also been a source of encouragement, and I am especially indebted to him for the preparation of the map of "Jason's Creek". Dr. McCann and Dr. P. J. Howarth have kindly allowed me to make use of data collected by them in the Radstock Bay area in 1969 and in the basin of the Mecham River in 1970.

Credit for the original conception of this study is due to Dr. F. G. Hannell. Robert "Bob" Taylor deserves special thanks for his work as a tireless and cheerful field assistant, as does Dave Willott for his valuable technical assistance in the early part of the field season. Harold Fritz drew the map of "Jason's Creek" and some of the diagrams, and helped to remedy many of my cartographical inadequacies. Robert Bignell prepared the photographic material for reproduction. I am grateful to Mr. A. J. Arnfield and Mr. J. J. Drake for helpful discussions on the content of the thesis.

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To my wife, Jan, and to my son who gave "Jason's Creek" its name, I give thanks for the endurance of the long periods of time which were spent in the preparation of this thesis and which were rightfully theirs. Without their quiet support this study would have been a much more tedious affair.

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J. Graham Cogley

ABSTRACT

"Jason's Creek" is a stream draining 2.2 km^2 of arctic limestone terrain. Its annual regime consists of a ten-month period in which it is frozen to its bed, a short spring flood which occurs shortly after temperatures cross the freezing-point in late June, and a period of about two months during which discharge is relatively low and fluctuates diurnally in response to inputs of radiative and heat energy to the snowpack. In 1970, the spring flood occupied the first two weeks of July and effected the discharge of some nine-tenths of total annual runoff. The low flow period was punctuated by rainstorms which generated sharply-defined floods: basin response was rapid and efficient, for storm runoff is facilitated over the unvegetated ground and through the shallow active layer above the permafrost table. Covariance and spectral analyses suggest a basin lag time of five hours, both for low discharges of snowmelt water and flood discharge of rainwater. It appears, from the spectra of the time series, that radiation is a better index of snowmelt discharge than is temperature.

Most of the annual removal of sediment from the basin takes place during the spring flood, when the stream is turbid and movement of channel

bed material is vigorous. In the longer period after the flood the main component of stream load is the solute load. The concentration of dissolved material varies inversely while suspended sediment concentration varies directly with discharge. Solute concentrations are lower than those commonly found in limestone streams at lower latitudes, suggesting that in "Jason's Creek" the increased solubility of CO_2 at low temperatures is more than counteracted by a decrease in the rate of solution of $CaCO_3$. There are also indications that the concentration of CO_2 in snowmelt water may be smaller, in absolute terms, than in rainwater.

The role of water is crucial in many processes acting on slopes and delivering detritus to stream channels; rills, for example, remove ions in solution and fine particles in suspension, notably from the base of talus slopes, and lubrication of the active layer after rainstorms generates bowl-slide and mudflow activity.

CHAPTER I

INTRODUCTION AND REVIEW

I. INTRODUCTION

Natural systems which process water through the terrestrial phase of the hydrological cycle are complex in detail and are often immune to hydrological analysis. Modelling and simulation of such systems usually involve simplification and the elimination from consideration of certain aspects of the system. One alternative to simplification is to consider a naturally simple system and subsequently to develop more complete descriptions of related complex systems, having elucidated first the more simple structure.

This dissertation is a first attempt at elucidation of the properties of the arctic drainage basin. The surface hydrology of a high-arctic watershed is simple in two important respects: there is no groundwater, and vegetation is almost completely absent. In the Queen Elizabeth Islands permafrost is universal, and the maximum depth to which the ground thaws in summer is less than one metre; groundwater movement does not take place, and the only components of water flow which need to be considered are overland flow, rill flow and channel flow, together with "interflow" through the active layer. The absence of vegetation implies, firstly, that little hindrance is offered to the movement of water out of the basin, and secondly that the significance of vegetal and soil carbon dioxide is slight. This second point is of some geomorphic importance, particularly in limestone terrains. A further implication is that transpiration may be neglected; evaporation, being difficult to monitor in an area where overnight freezing complicates pan measurement, has also been neglected in this study, although its importance may be greater than has hitherto been imagined.

These simplifying factors give reason for hope that a relatively accurate and rigorous description of the surface runoff system in the High Arctic may be a feasible proposition. This thesis does not contain such a description, but it is believed that it indicates some directions in which investigation will lead to the synthesis of this type of description.

There are three principal foci of study in the thesis: the structure of the snowmelt runoff system, the behaviour of components of the carbonate solution system, and the geomorphic role in general of running water in the cold-climate environment.

The snowmelt runoff system:

Aspects of the snowmelt runoff system, such as the marked diurnal component of variation in snowmelt discharge and the relationship of this variation with meteorological parameters, have been studied with a view to providing the groundwork for a functional description of these relationships. At the diurnal scale the relationships appear to be fairly simple, but the problems involved at the annual scale, such as prediction of the course and timing of the spring flood in terms of the meteorological variables which produce it, may prove more difficult. Interruption of the diurnal pattern of discharge by rainstorm events may be treated by conventional hydrological techniques incorporated with the functional description approach.

The statement that arctic drainage basins are relatively simple systems should not obscure the fact that in this study further artificial simplification has nevertheless been necessary. The most serious over-simplifications which have been made are the neglect of evaporation and the omission of measurements of the movement of water through the active layer and over the ground surface. The latter omission can be partly justified with reference to an early decision to treat the system as a "black box" and to refrain from highly-detailed observation of its internal characteristics; this decision also explains in part the lack of detailed observations on the melt-generating processes occurring above and within the snowpack. All of these should, however, receive attention in future research.

Carbonate solution:

"Jason's Creek" drains an area of limestone bedrock mantled by calcareous till and other loose material, and the significance of the absence of vegetation in the context of carbonate solution has already been mentioned. One problem which has been the subject of debate in the recent past concerns climatic controls over rates of limestone erosion; Corbel (1959) argued that these rates were greater at high latitudes while others, notably Bögli (1960) and Sweeting (1966), contended that such a generalization was unjustifiable and even incorrect. The results of observations on "Jason's Creek" are persuasive against Corbel, and suggest a connection with the findings of Ek (1964, 1966) and Ford (1971, in press) concerning CO_2 - depletion in snow and ice. However, reasonable series of measurements for only three variables (dissolved calcium and magnesium, and pH) were obtained in the present study, and more thorough investigation is warranted, particularly so since the arctic environment provides a "field laboratory" in which the problematical features of limestone solutional processes may be studied without the complicating factor of CO_2 contributions from plants and humus.

Running water in the periglacial environment:

A third purpose of this dissertation is to advance and justify the opinion that the geomorphic role of water, and specifically of running water, has been underestimated in the past, to the detriment of fuller understanding of the periglacial denudation process both as a whole and in detail. Periglacial investigations have hitherto concentrated on obvious and distinctive cryogenic features whereas the more "mundane" aspects of denudation, such as erosion and transportation by fluvial agency, have been all but ignored. It is true that the flow season lasts only for some two to three months (in the Queen Elizabeth Islands), but this period is the same one in which all processes operate; outside of it, geomorphic activity of any kind is usually considered to be minimal. Fluvial transportation of sediment and solutes is an important agent of denudation in periglacial regions, and fluvial landforms develop and become significant features of the landscape at high latitudes just as they do at lower latitudes.

Furthermore, the role of water in the development of landforms which are usually discussed as cryogenic features is often considered as subordinate to those cryogenic features of their development. It has been said that "Permafrost is the common denominator of the periglacial environment" (Péwé, ed., 1969, p. 4), and this is substantially correct, but in processes such as rapid slope movements - mudflows, bowl slides and, very probably, the movement of soliflual lobes - the presence of permafrost is a permissive rather than an active factor. The permafrost table provides a hard, impermeable surface; the processes of movement act over this surface, within the unfrozen active layer.

There is a fourth aspect of this study which should be mentioned. The mere collection of data in a region which happens to be remote is not an especially commendable scientific exercise, and is certainly no justification in itself for a study of this kind. However, knowledge of the surface hydrology and fluvial geomorphology of the High Arctic is undeniably slight, as the sparsity of the literature on these subjects, examined in the next section, will attest. A general, qualitative description can be provided from the work of Cook (1967) and of Pissart (1967), and from similar studies made in Alaska and elsewhere. But actual hydrological and geomorphological data from the region are extremely small in quantity, and this dissertation may go some of the way towards filling this basic gap in knowledge and placing qualitative statements about the area on a firmer and somewhat more accurate footing.

II. REVIEW OF THE LITERATURE

The underestimation of fluvial processes alluded to above is well exemplified in the major geomorphological texts on periglacial forms and processes. Péwé (ed., 1969) does not refer to stream action at all.

Tricart (1970) states that fluvial activity in cold climatic regions is of little importance, while Bird (1967) and Embleton and King (1968) treat the subject in cursory fashion, although they admit that its importance may in fact be appreciable. This cursory treatment may reflect a lack of detailed information rather than errors of judgement.

Work has been done on the hydrology of the Canadian High Arctic by Cook (1967) and Pissart (1967). Cook's research on the R. Mecham established a general picture of the behaviour of this arctic stream (Fig. 1:1), although he gives only measurements of maximum daily stream velocity. There is no indication of how these maxima were arrived at, or of the volume of discharge to which they correspond. The general picture which Cook describes is of a hydrological year separated into five components: a period of snow accumulation from September to June; a pre-melt period in June when snow is lost "chiefly through sublimation"; a period of intense melting, of perhaps a week's duration, between the time when daily mean air temperature rises above $0^{o}C$, and the commencement of flow; a period of catastrophic flood lasting approximately ten days, during which about 90% of total yearly runoff is discharged; and a period of sharply decreased flow from early June until the river freezes to the bottom in September. This final period is punctuated by floods following occasional heavy rainstorms, which characterize arctic summers. Cook's description of the annual regime in the High Arctic is a good one, and suffers only from its general nature.

Pissart, in his paper on runoff activity at Mould Bay, Prince Patrick Island, stresses characteristics such as the melting of the snow while the air temperature remains below freezing, the flow of water beneath

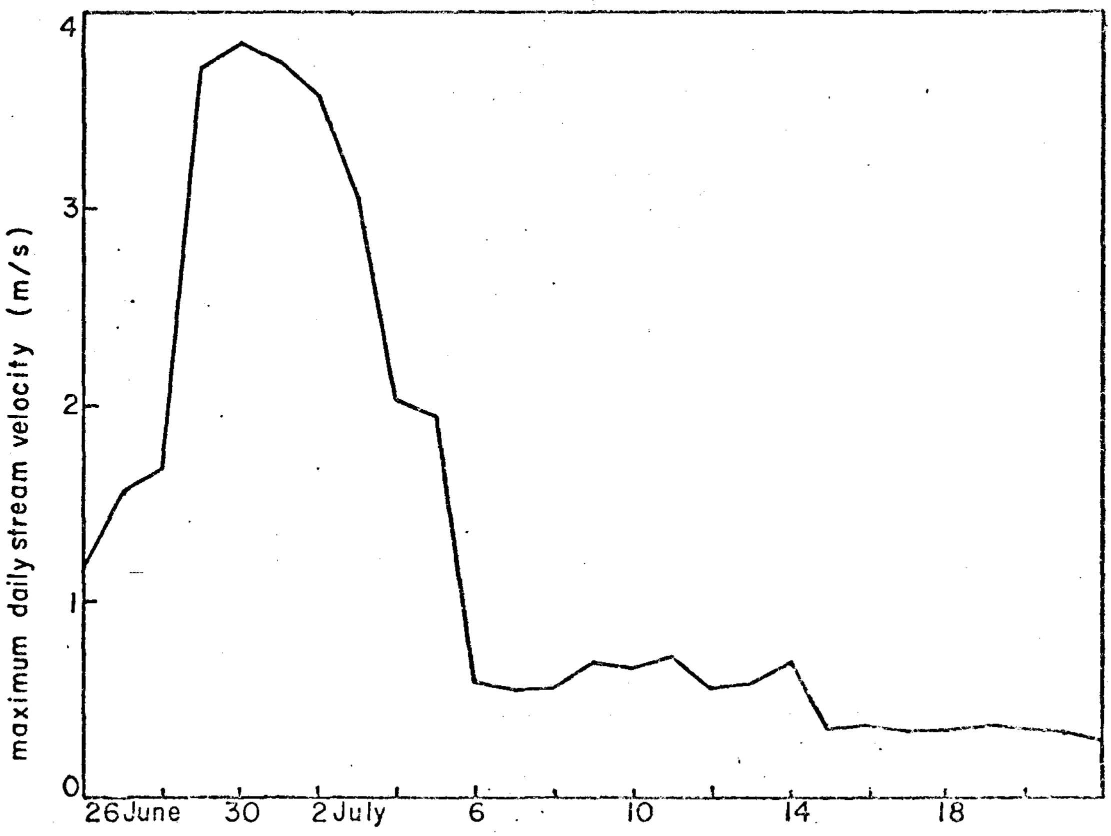


Fig. 1:1 Maximum daily stream velocity, R. Mecham, Cornwallis Island, 1959 (after Cook, 1967).

snow patches which washes the underlying surface, and the flow of water for a substantial part of the flood period in snow-and ice-floored channels. These characteristics are certainly important, but Pissart has underestimated the erosional role of streamflow in the arctic environment. Again, his description is qualitatively accurate but lacking in detailed data.

Czeppe (1965) has published one of the few accounts of the activity of running water in high latitudes outside Canada. His conclusions, also qualitative, agree with those of Cook and Pissart, although his suggestions that sheet flow is more important than linear flow and that running water acts mainly as a redistributing and much less as a removing agent are difficult to accept. These suggestions may or may not reflect real differences between the environments of Vestspitsbergen and the Canadian arctic islands.

Several publications have dealt with runoff hydrology and geomorphology in Alaska. Dingman (1966 A, B) and Brown, Dingman and Lewellen (1968) studied small drainage basins near Fairbanks and Barrow respectively, and produced detailed hydrograph analyses and records of stream water chemistry and sediment concentrations. That the results of these studies differ markedly in some respects from those of the present study can be attributed to differing basin characteristics and to differing environmental conditions. Precipitation and mean temperature are higher in central Alaska; this leads to a diminution in the prominence of the spring flood and to an increase in storm runoff lag time per unit area, for the dense vegetation mat and relatively deep active layer increase basin storage capacity considerably. That different environmental conditions prevail in different circumpolar regions is, of course, a fact which should not be forgotten.

Other studies of Alaskan streams include those on Ogotoruk Creek, north-west Alaska, by Waller (1966), Likes (1966) and Lamar (1966). As in the case of Glenn Creek, the subject of Dingman's study, runoff response to inputs of precipitation was relatively slow and attenuated because of the presence of a vegetation cover. In both Ogotoruk Creek and Glenn Creek a more substantial proportion of annual runoff is derived from summer precipitation than is the case in the High Arctic.

Arnborg, Walker and Peippo (1966, 1967) have worked on the Colville River in northern Alaska, finding that 43% of total annual runoff and 73% of total annual sediment load were discharged during a three-week period in June. The basin of the Colville R. is one of the largest to lie wholly within the Arctic Circle, covering 50000 km^2; maximum discharges reach 6000 m^3/s, and a maximum suspended sediment concentration of 1658 p.p.m. at a discharge of 5050 m^3/s was noted in 1962.

In contexts other than the strictly hydrological, research related to the present study has been done by Mackay (1963) and Henoch (1960) on the fluviomorphic features of the lower Mackenzie R., by Anderson and Hussey (1962) on transportation and deposition of material on alluvial fans in the Sagavanirktok basin, north-eastern Alaska, and by Cawley, Holland and Burruss (1969) on the chemistry of Skjalfandafljót, a river draining basaltic terrain in north-central Iceland.

Several studies of glacier-melt runoff have been made, notably by Keeler (1964) on the Sverdrup Glacier, north-east Devon Island, by Adams (1966) on the White Glacier, Axel Heiberg Island, by Rainwater and Guy

(1961) on the Chamberlin Glacier, Alaska, by Davis and Nichols (1968) on the Surko and Scheuren Rivers, McMurdo Sound, Antarctica, and by Stenborg (1970) on the Mikka Glacier in northern Sweden. These studies have established the dependence of discharge fluctuations of diurnal and longer period on meteorological fluctuations. Østrem (1970) and Gudmundsson and Sigbjarnarson (1970) are currently pursuing research on the correlation of meteorological and glaciohydrological records in southern Norway and Iceland respectively. Østrem indicates that in certain circumstances wind speed and humidity may be highly correlated with meltwater runoff.

A general study of the geomorphology of south-east Cornwallis Island, an area essentially similar to south-west Devon Island, has been made by Robitaille (1959, 1960). His appreciation of the importance of fluvial processes is good, although acquired without measurement:

> "Bien entendu, c'est le gel qui joue actuellement le role prédominant, mais son action se conjugue souvent a celles d'autres processus morphogénétiques. Parmi ceux-ci, les processus fluviatiles ne sont pas les moins importants".

He suggests that the wide valleys found on Cornwallis Island were eroded in the Pliocene, and that the streams occupying them at present are flowing at or just below preglacial base level. The validity of this suggestion is not of concern here; it is fitting, however, to remark that "Jason's Creek" is very probably a stream of post-glacial origin.

Several studies of coastal processes in the Radstock Bay area of Devon Island have been published by members of the McMaster Arctic Research Group (Owens, 1969; McCann and Owens, 1969; Owens and McCann, 1970; McCann and Hannell, 1971). Removal of littoral material by wave action, longshore drift and ice rafting is probably responsible, together with fluvial discharge of solid and dissolved sediment, for the major portion of total transfer of material from land surface to sea in the High Arctic at the present time.

CHAPTER II

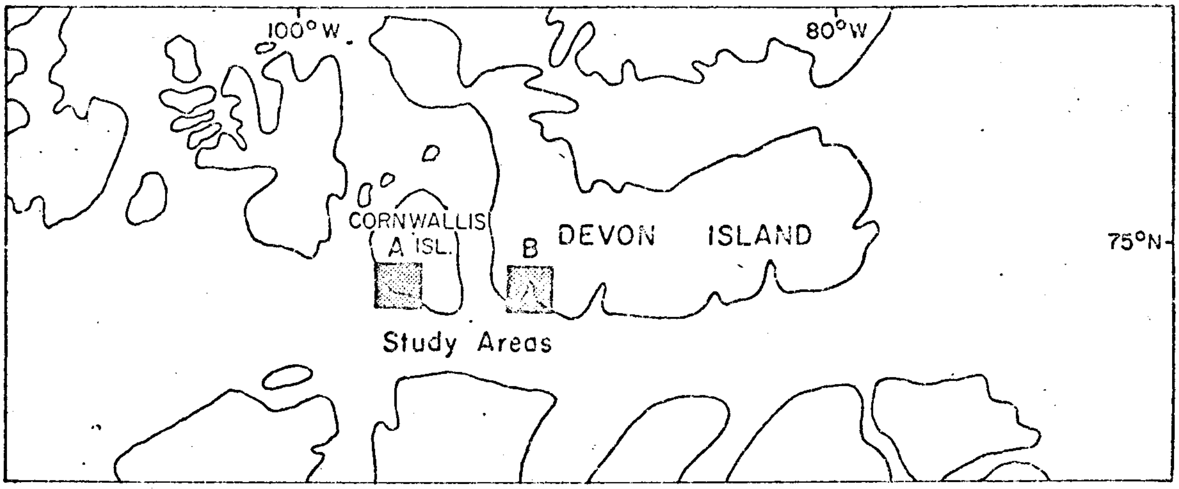
PHYSIOGRAPHIC AND CLIMATIC CHARACTERISTICS OF SOUTH-WEST DEVON ISLAND

Geological history:

Bedrock in the Radstock Bay area of Devon Island (Fig. 2:1) is limestone of the Middle Silurian Read Bay Formation (Fortier et al., 1963). The beds of crinoidal, corallian, dolomitic and argillaceous limestone dip gently to the north-west at angles of c.4^{o}, although in small folds at a scale of a few metres dips are steeper. A plateau in the limestone at 280-320 m a.m.s.l. is thoughtto represent the Barrow Surface, which was developed late in the Tertiary period. The plateau is bounded by steep walls mantled with accumulations of talus. Where basal removal of the talus by wave and current activity is effective, cliffs have formed.

Glaciation of the area during the Quaternary is evidenced by the presence of igneous erratics and deposits of till on the plateau surface. Tracing of the origin of the erratics is being attempted; it is suspected that they come from the east. The till is composed of fine material with occasional shelly fragments, and overlies much of the plateau to a depth equal to or greater than that of the maximum seasonal thaw.

Events following the disappearance of the Quaternary ice are dominated by the changing relationship between sea and land levels. An initial rise in sea level resulting from the melting of glacier ice, and



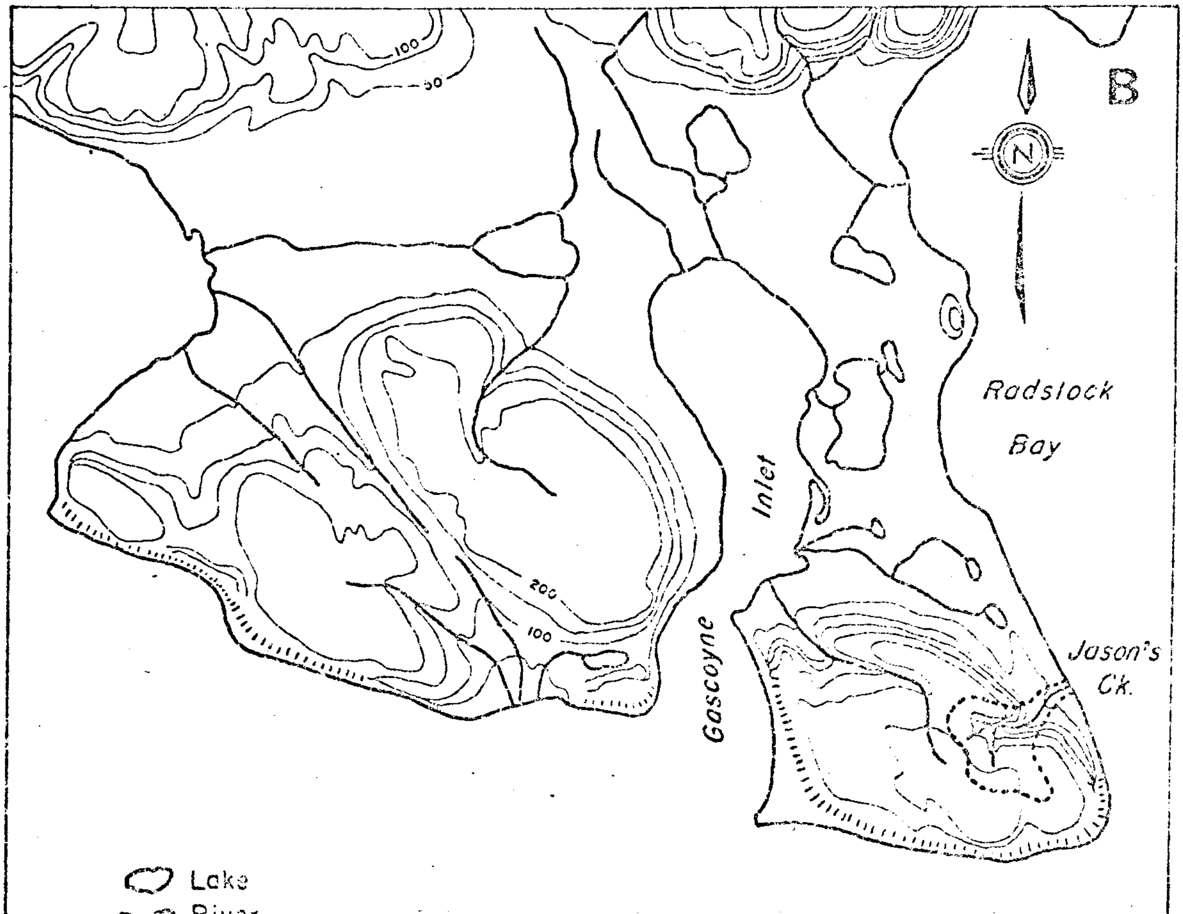


Fig. 2:1 Location of study area; Resolute is located in "Study Area A" on the upper map.

isostatic uplift of the land, have led to the formation of flights of raised beaches descending from 120 m to present sea level. These raised beaches are arranged around the flanks of the plateau. Post-glacial dissection of the plateau by fluvial activity has produced steep-sided valleys such as that of "Jason's Creek".

The "Jason's Creek" drainage basin:

The basin of "Jason's Creek" drains a portion of an outlier of the plateau which lies between Radstock Bay and Gascoyne Inlet (Fig. 2:2). Two strike streams, the "North Branch" and "South Branch", unite to form "Jason's Creek" proper, which occupies a deep rip gully cutting from west to east against the strike (curving from SSW to NW). The raised beach sequence flanking this section of the plateau consists of a series of former spits which grew from the headland of Cape Liddon to the south, at a tangent to the plateau wall. Between the plateau wall and the spit sequence there was a narrow lagoon, into which "Jason's Creek" built a small deltaic fan. With continued isostatic uplift, however, the stream has eroded through the littoral sediments and now flows directly into Radstock Bay. Most of the basin of "Jason's Creek" carries a regolith of till, coarse talus, littoral sediment or soliflual material. Talus is found on the steep walls of the rip gully and on the short stretches of plateau wall located within the drainage basin. Soliflual downslope movement of the regolith is or has been important, and lobate or striped flow features are abundant.

The ground is frozen throughout the area and thaws in summer to an average depth of $^1/2$ metre. Geomorphic activity is concentrated in this

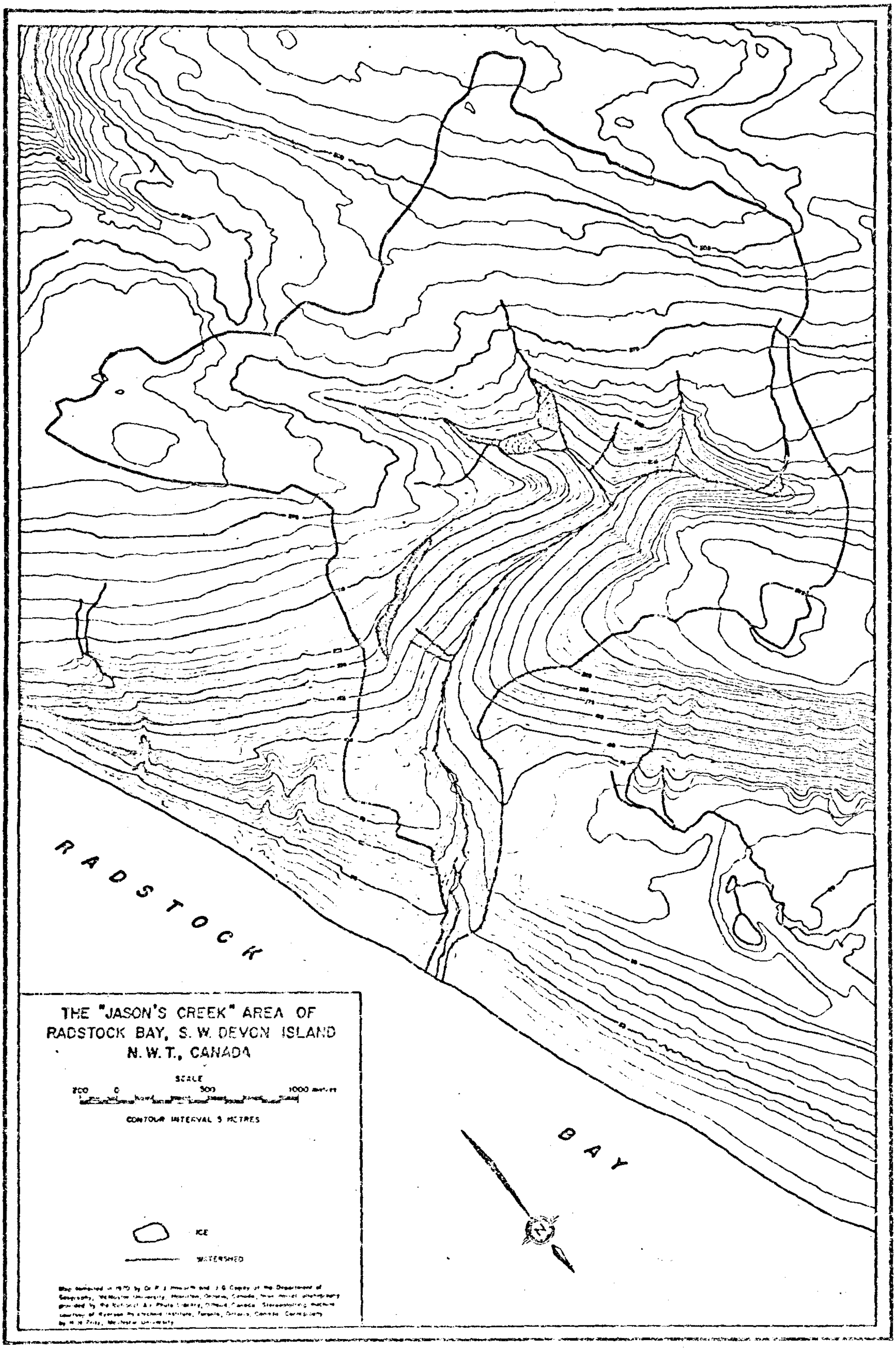


Fig. 2:2 Map of "Jason's Creek", reduced to 1:34500 scale.

shallow active layer. The ground surface is bare, with a very sparse vegetal cover of from one to five percent. Vegetation is localized in areas of greater moisture availability, and low-growing species of moss, grass, poppy and dwarf willow are the only ones present.

Climate:

Climatic control of geomorphic activity is marked at high latitudes in the obvious sense that geomorphic activity is more or less confined to periods when temperatures are above freezing-point. The climatic background to the immediate meteorological variations which are discussed in a later chapter as inputs to the "Jason's Creek" runoff system are, however, deserving of attention, for some significant points are brought to light in such a general treatment.

Winter in the High Arctic is characterized by the early development of an anticyclonic system in the western Arctic. This anticyclone expands eastwards to cover most of the area between the Queen Elizabeth Islands and Hudson's Bay by about November, and remains as a more or less permanent feature of the arctic weather map for the remainder of the winter. In early spring (May), the anticyclone begins to weaken. The general NW - SE circulation of air from the Arctic High to the Iceland-Baffin Low begins to be disrupted as the tracks of eastward-moving depressions are shifted into the Canadian Arctic from their more southerly winter locations. Most of these depressions move over the northern continental mainland or the southern islands (Fig. 2:3). Their passage in the Cornwallis - Devon area is marked by backing of the prevailing NW wind into the S or SE; a period of strong southerly wind is often terminated

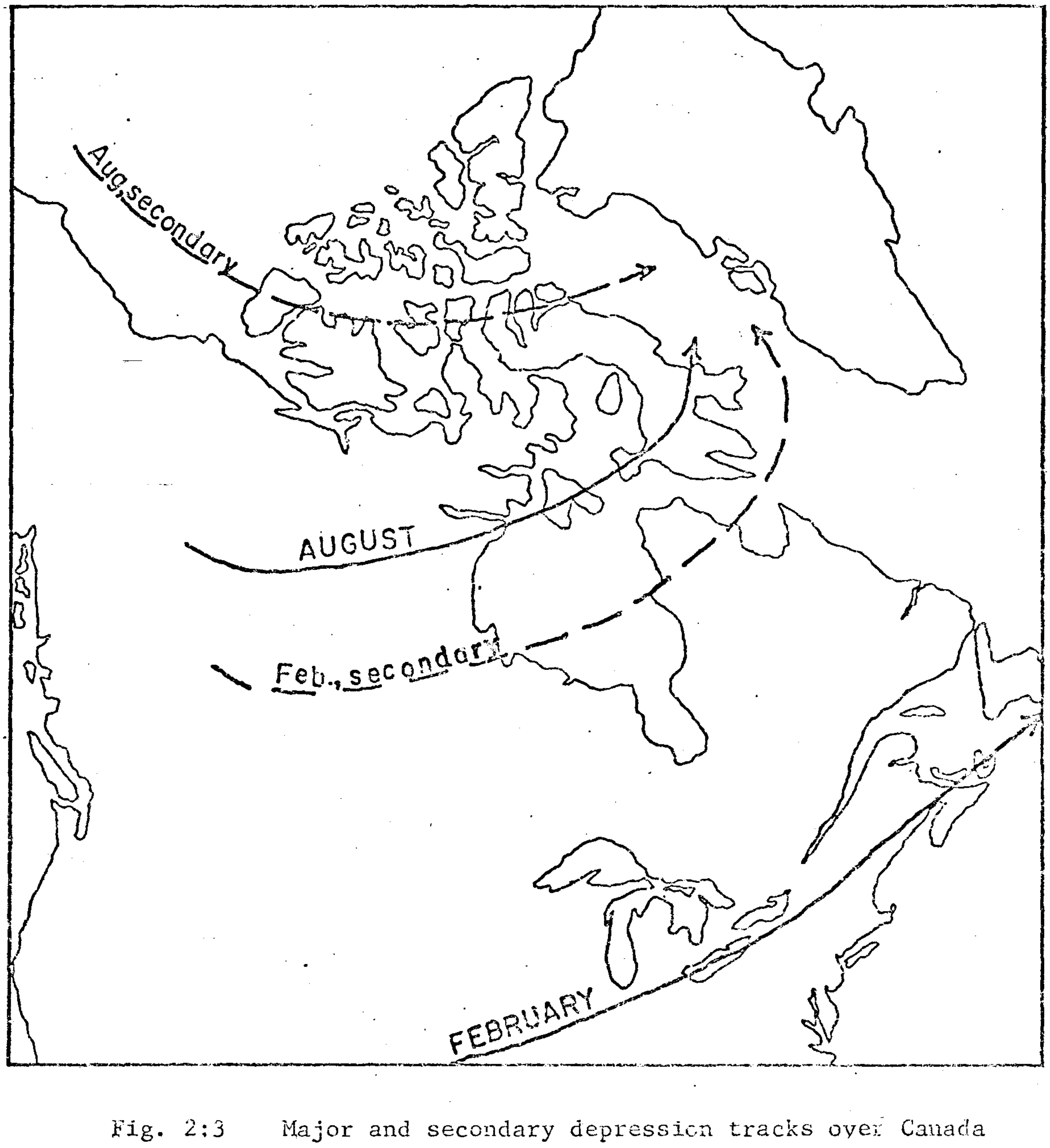


Fig. 2:3 Major and secondary depression tracks over Canada (after Meteorological Branch, D.O.T., 1970).

by a precipitation event, following which winds decrease and veer once more into the NW. In the autumn (September and October), incursions of cold air from the Arctic Ocean and Beaufort Sea over the arctic islands become more frequent. Instabilities result from the passage of these cold air masses over relatively warm land and water surfaces, and September and October are the stormiest months of the year. Almost all of the precipitation on the arctic islands occur in association with cyclonic fronts or unstable situations of the warm ground-cold air type. It follows from this statement that most of the precipitation occurs in summer and autumn. That sizeable proportion (some 47%) which occurs in summer consists almost entirely of rainfall; Thomas and Thompson (1962) discuss an unusually wet summer, that of 1960. The proportion which occurs in autumn falls as snow. In an average year, then, a relatively large amount of the total precipitation (considering that this is itself a small amount) runs off the ground, doing geomorphic work in the process (Fig. 2:4). Most of the rest goes into snowpack storage for eight to ten months of the year before running off in the spring flood. This means that most of the snowpack is "old" by springtime, which may be significant in relation to the solutional capacity of the snowmelt water (Chapter VIII).

The above climatic summary is based on and partly excerpted from "Climate of the Canadian Arctic" (Meteorological Branch, Department of Transport, 1970).

An important point which is not revealed by a brief study of the meteorological records of arctic weather stations is the significance of "trace" precipitation events in high-latitude areas (Cook, 1960; Black, 1954). A "trace" of rainwater is a quantity so small that it fails to

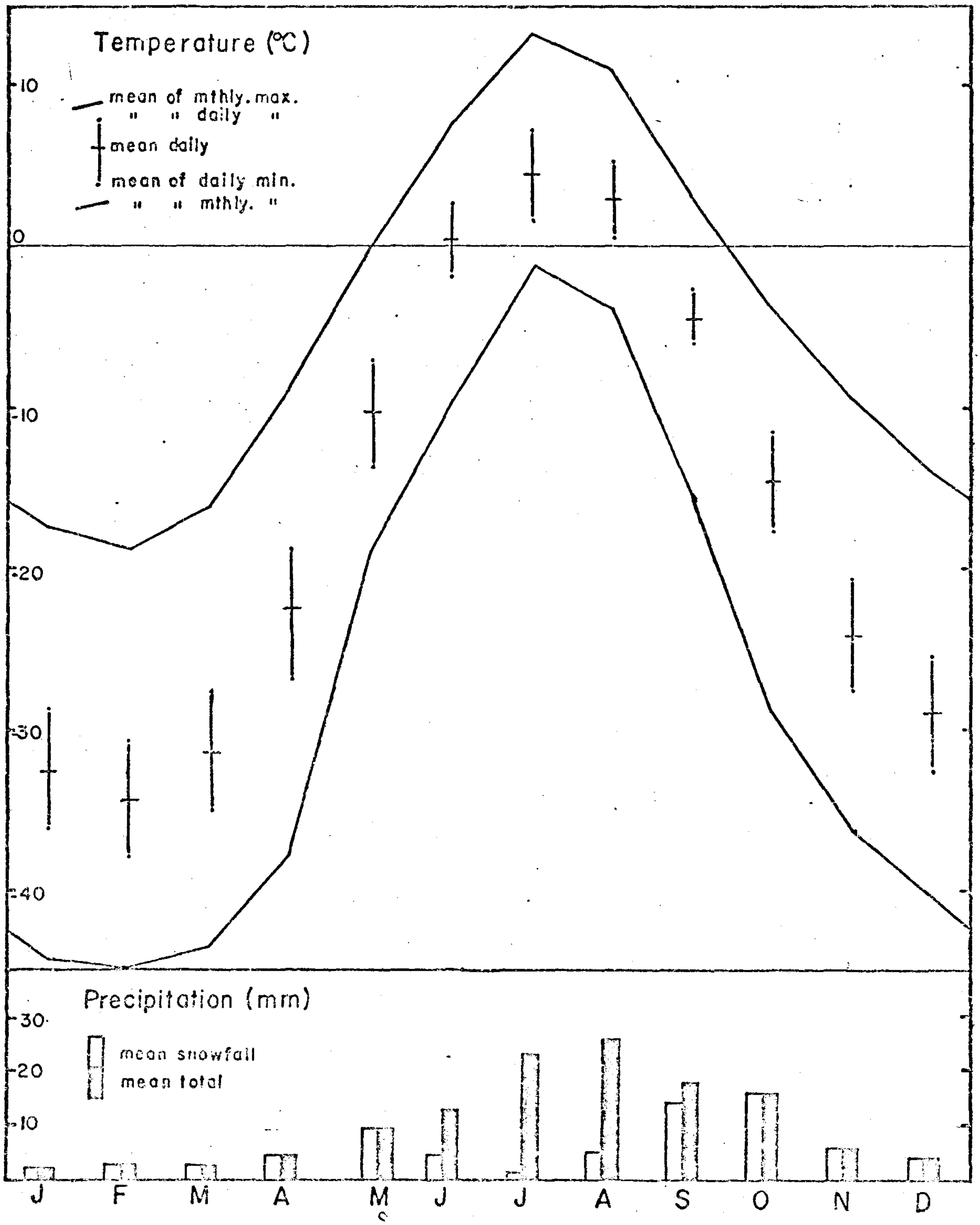


Fig. 2:4 Mean temperatures and precipitation, Resolute A meteorological station, 1947-60.

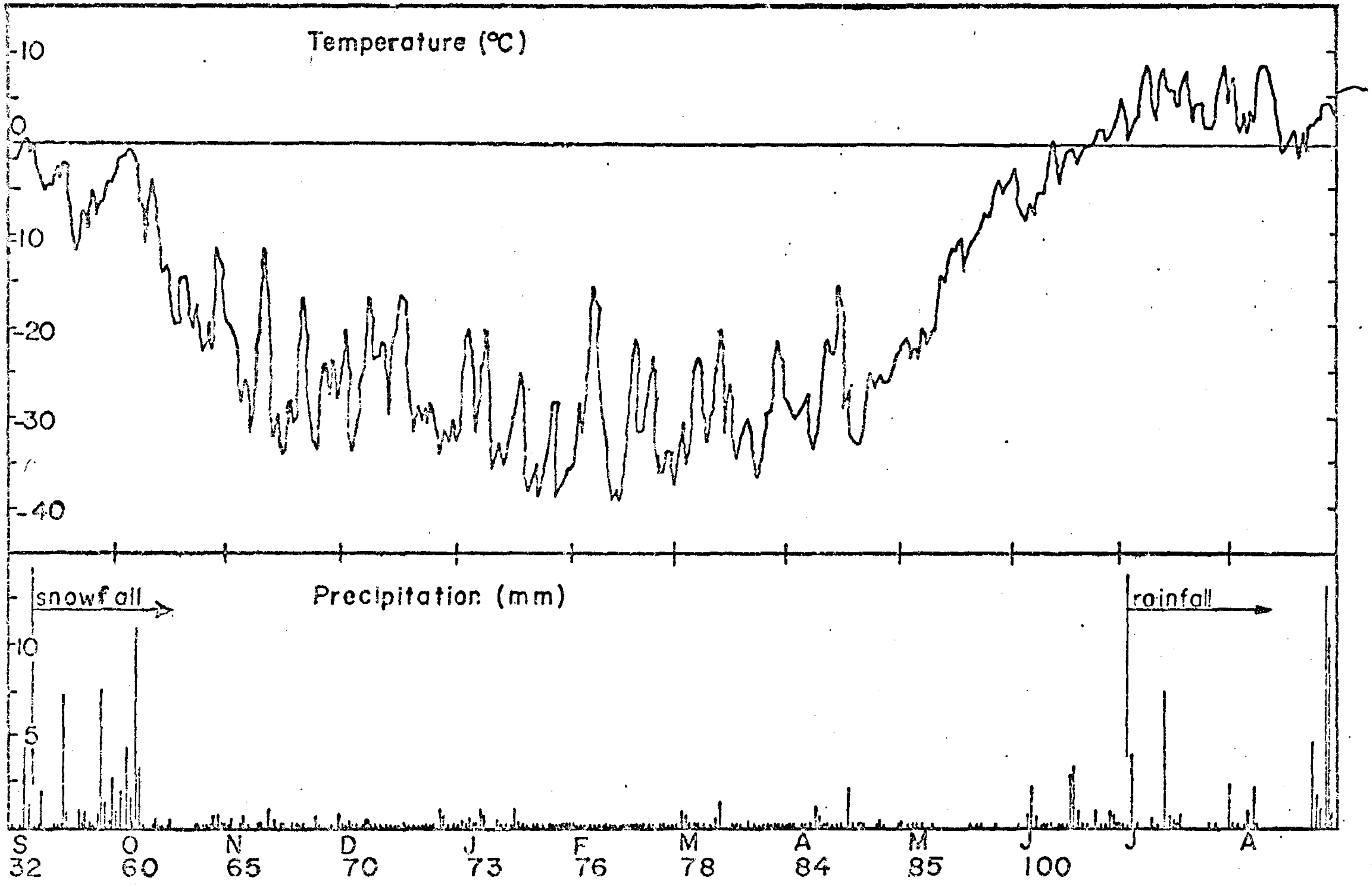


Fig. 2:5 Daily mean temperatures and daily precipitation, Resolute A, September 1969 - August 1970; numbers on abscissa represent cumulative percentages of total precipitation to end of June, 1970.

moisten the ground surface; conventionally, falls of less than 0.005 inches (0.127 mm) are recorded as traces. A trace of snowfall may not moisten the ground surface, but if trace snowfalls accumulate as is the case during the arctic winter, the accumulation may represent an appreciable quantity. Thus, the Resolute A meteorological station recorded traces of precipitation in 396 of the approximately 1100 six-hourly periods in the winter of 1969-70 (Fig. 2:5). Depending on the actual size of each trace, the accumulation of the 396 traces of snow may represent anywhere from perhaps ten to fifty millimetres of water-equivalent precipitation, or from twelve to sixty-two percent of the total recorded precipitation. It can be dangerous, therefore, to work with recorded precipitation in the Arctic if, for example, snowpack volume is of importance in development planning and design, or if total watershed budgets are to be estimated.

CHAPTER III

METHODS OF DATA COLLECTION AND ANALYSIS

The collection of data for this study was organized in terms of the input and output of the "Jason's Creek" watershed, considered as an open system. The inputs in this case are essentially meteorological and the outputs are streamflow parameters. The watershed system was for the most part treated as a "black box", although some qualitative observations are included in this presentation. Systematic measurements were made of one intermediate variable, namely ground temperature in the uppermost one metre, and irregularly collected data on water quality within the basin are used in the discussion on solutional activity.

Meteorological variables:

The meteorological variables monitored were temperature, incoming shortwave radiation, relative humidity, precipitation, wind speed and wind direction.

Temperature and relative humidity were recorded on Lambrecht thermohygrographs mounted in Stevenson screens at 1.3 m above ground level. Calibration of the temperature curve, traced by the expansion and contraction of a bimetallic strip, was done by comparing readings on the chart with readings of a mercury thermometer mounted in the same screen. The hygrograph curve was traced by fluctuations in the weight of a set of tensioned hairs. One of the thermohygrographs was installed at the base camp site at the mouth of "Jason's Creek"; the second instrument was installed at a site in the south-eastern part of the plateau section of the basin, at a height of 275 m a.m.s.l.

Incoming shortwave radiation was measured with a Casella bimetallic actinograph, and hourly values for radiation were derived by planimetering the areas beneath sections of the actinograph curve. The bimetallic strip was protected against changes in ambient temperature by a perspex dome. The accuracy and sensitivity of this instrument are rather low; it was used however, because of its robustness and its trouble-free operation in the field,and because relative if not absolute accuracy was acceptable. Shortwave radiation was also an acceptable surrogate for net radiation since an all-wave radiometer was not available.

Precipitation was collected in a tipping-bucket rain-gauge, which produced a jump in the pen-trace on a recording chart each time one of the buckets tipped. The buckets are tooled so as to tip on the accumulation of 0.01 inches (0.254 mm) of rainwater. The rainwater was collected in the base of the rain-gauge, and the depth of precipitation indicated on the chart record was found to be consistently reproducible by measurement of the total rain-gauge catch in a graduated cylinder.

Wind speed was measured periodically by inspection of the mileage recorded on a Casella anemometer. Cardinal wind direction was noted at each wind speed measurement and also at other times. A log of cloud cover, fog conditions and current weather was also maintained.

With the exception of the temperature and relative humidity records obtained for the "Plateau" station, all meteorological observations were at the base camp site at the mouth of "Jason's Creek", and the meteorological record is taken to refer to this location (Fig. 3:1) unless another location is mentioned.

Ground temperature was measured at six sites on the north and south-facing valley slopes 300 m upstream from the mouth of the creek. The potential difference in millivolts of copper-constantan thermocouples near the ground surface and at 0.1 m intervals from 0.1 to 1.0 m below ground level were measured with a switchbox and potentiometer. Calibration of the copper-constantan wire to evaluate the relationship between millivolts and degrees Centigrade had been performed prior to emplacement in 1969 of the rods bearing the thermocouples.

Streamflow parameters:

The output variables recorded at the mouth of "Jason's Creek" were discharge and stream velocity, concentration of dissolved calcium and magnesium, pH and concentration of suspended sediment. Some thirty water samples were stored and analyzed at McMaster University, on a Perkin-Elmer 303 atomic absorption spectrophotometer, for dissolved sodium, potassium, iron and aluminium.

Chemical measurements:

Calcium and magnesium in solution were measured by titration of 50 ml samples with E.D.T.A. in the presence of Eriochrome Black T indicator and ammonia buffer solution (Schwarzenbach, 1957). Calcium alone was measured similarly using Calcon indicator and sodium hydroxide buffer solution, and the concentration of magnesium was obtained by subtraction of the result of the second titration from that of the first. The accuracy of these measurements is within the range $\pm$ 3 mg/1; most of the

Fig. 3:1 Meteorological station near the mouth of "Jason's Creek".

Fig. 3:2 Stage recorder installation.

analyses were performed within four hours of sample collection and all were performed within twelve hours. A battery-operated Metrohm E280A pH meter, with manual temperature compensation, was used to measure pH. Difficulties were experienced with the acquisition of reliable values for pH because of slow electrode response in the cold water of the samples. The difficulties were partly overcome by allowing the samples to come to tent temperature (approximately 10^{o}C), but this procedure may have introduced errors into the absolute determination of pH. Following the procedure consistently, however, has probably reduced the relative error to acceptable proportions; the measurement accuracy is probably within -0.2 pH units, the tendency being towards underestimation because of the sluggish electrode response.

Several measurements of Ca , Mg and pH were made on samples collected at various times from various points within the "Jason's Creek" basin, in addition to the measurements of regularly collected samples from the creek itself at the mouth of the basin.

Sediment measurements:

Suspended sediment samples were collected with a United States Geological Survey depth-integrating, hand-held DH-48 sampler. The method of collection is to lower the sampler from stream surface to channel bed at a constant rate determined by stream velocity and depth, and on reaching the bed to raise the sample to the surface at the same rate. While the sampler is immersed, stream water passes through a 0.6 mm nozzle into the sample bottle. The 380 - 440 cm^3 sample is capped and stored.

Analysis of the suspended sediment samples for concentration of sediment by weight was performed by adding HCl as floceulent to the samples, filtering, and weighing the accumulation of sediment on the filters. The analyses were made in the laboratory of the International Biological Programme Char Lake Project at Resolute, Cornwallis Island, N.W.T.

Discharge:

Stream velocity was measured with a Price type current meter mounted on a top-setting wading rod and, during periods of low flow, with a pygmy current meter. The pygmy meter operates on the same principle as the Price type meter: stream flow causes cups to rotate about an axis and send acoustic signals to a headphone. It is scaled, however, to two-fifths of the size of the larger meter.

Discharge was calculated by the conventional area-velocity technique. From 17 July to 15 August a Leupold and Stevens Type E stage recorder was maintained (Fig. 3:2), and a rating-curve derived for the stage-discharge relationship by occasional area-velocity measurements of discharge. For this period, therefore, hourly values of discharge are available.

Analysis of data:

Correlation and least-squares analyses have been performed on the principal streamflow variables, and the results of these analyses are discussed in Chapter VIII. The relationships between inputs and output of the "Jason's Creek" watershed system have been investigated with the aid of covariance and spectral analysis. The computer program used for this analysis was the Biomedical program BMD02T, "Autocovariance and Power Spectral Analysis". The analytical techniques are explained in Chapter V, and a detailed description of the program may be found in

"Biomedical Computer Programs", W. J. Dixon, ed., pp. 459-73. In addition to covariance and spectral density functions, the program computes coherence and transfer functions between time series. However, in dealing with weakly Gaussian time series the coherence square, which is an analogue in the frequency domain of the conventional square of the correlation coefficient, is apt to become unstable and to give meaningless values. The transfer functions computed by the program are to a certain extent inapplicable, and neither coherence square nor transfer function results are used in the discussion of Chapters V and VI.

CHAPTER IV

SEQUENCE OF HYDROLOGICAL EVENTS IN 1970

Discharge from "Jason's Creek" in the hydrological year 1970 began on 26 June (Fig. 4:1). Snowmelt commenced at a date somewhat earlier than this, but the process of snowpack ripening was incomplete by 0800 h on 26 June, when a rainstorm which delivered more than 12 mm of rain in five hours commenced. Thermograph records which begin on 24 June indicate that temperature rose above 0°C between 1130 h and 1430 h on 25 June, and snowmelt was observed before that date (Fig. 4:2).

On 19 June snowcover over the basin of "Jason's Creek" was very close to 100%. Near the mouth of the creek, a constricted section of the channel 100 m from the mouth was choked with snow to a depth of 5 m or more, and pits dug 80 m upstream from the mouth and at the mouth itself were 3.43 m and 1.49 m deep respectively. The mean density of ten 500 cm^3 samples of snow from the first pit was 0.495 g/cm^3, and from the second pit 0.498 g/cm^3. No trend was apparent with depth (Fig. 4:3), and the extreme values were 0.564 g/cm^3 (at 0.5 m from the surface of pit no. 1) and 0.384 g/cm^3 (at 1.25 m from the surface of pit no. 2). Temperature in pit no. 2 varied from + 0.3°C at the surface to -0.05°C at the base. Several ice layers from 2 to 10 cm in thickness were present in the walls of each pit. The rather high density values indicate that snowpack ripening was under way by 22 - 23 June, the dates on which the

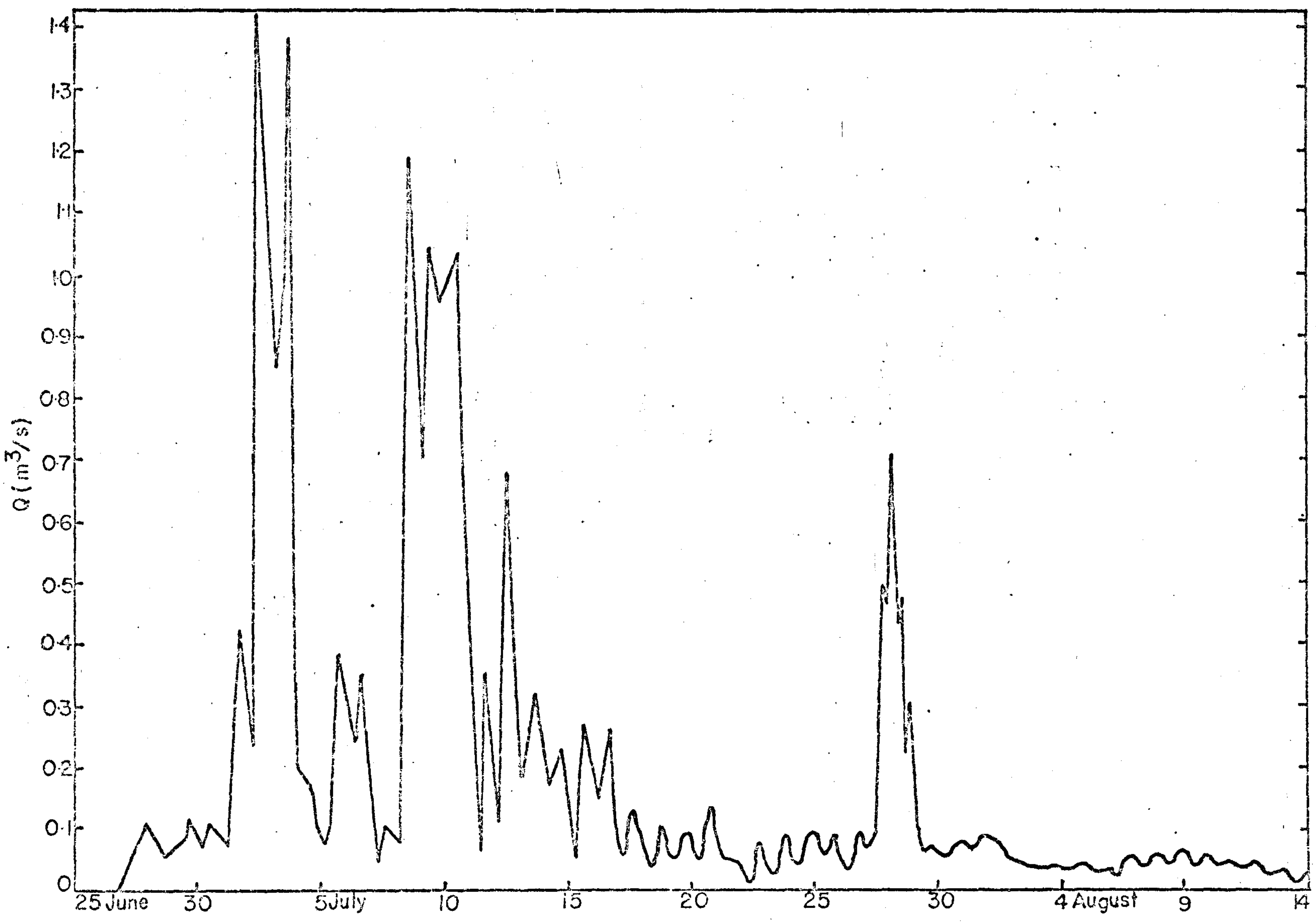


Fig. 4:1 Seasonal discharge of "Jason's Creek", 1970.

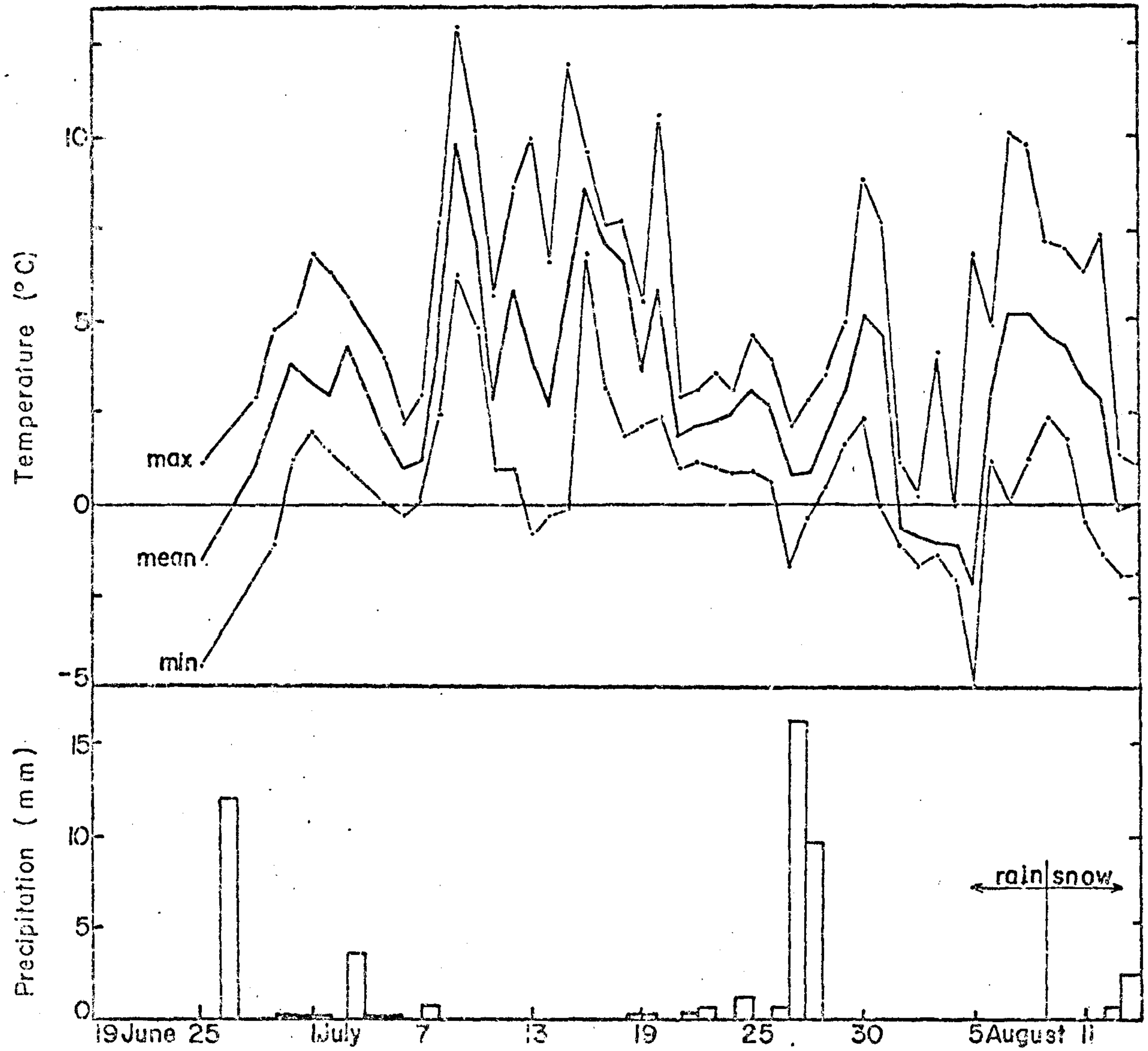


Fig. 4:2 Temperatures and precipitation recorded at "Jason's Creek", 1970.

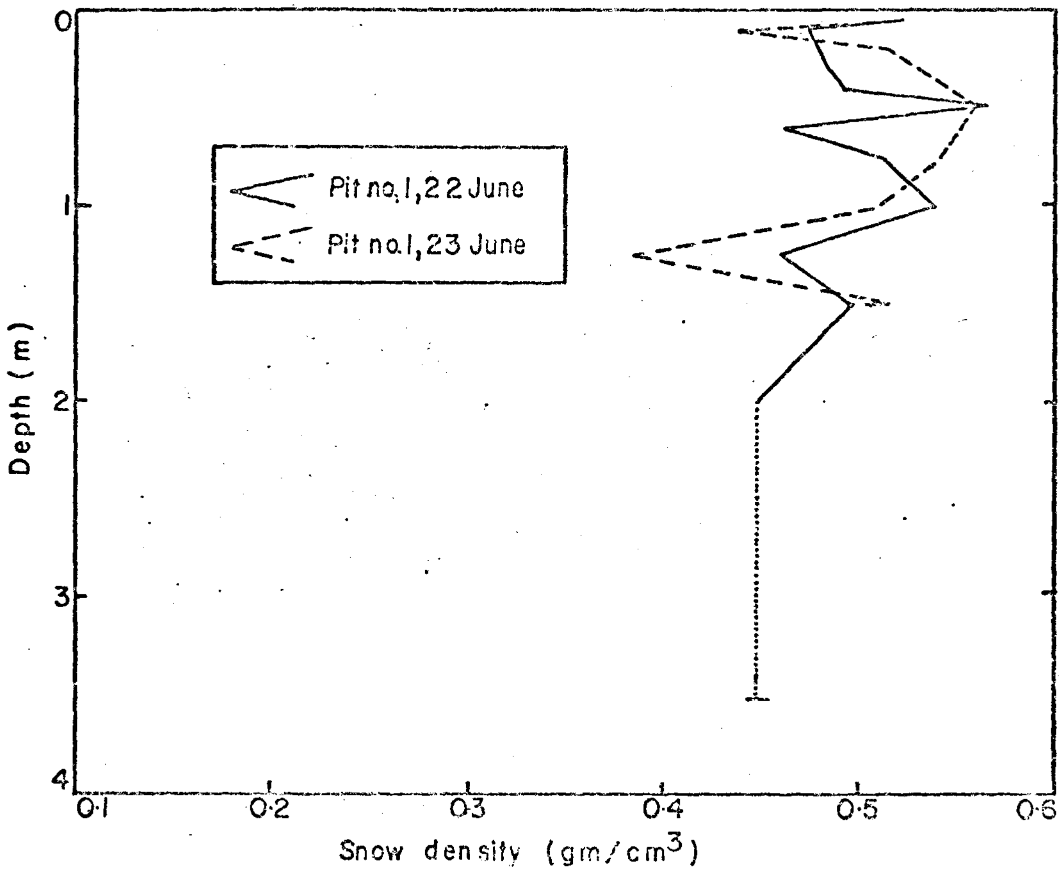


Fig. 4:3 Snowpack density profiles near the mouth of "Jason's Creek".

pits were dug; meltwater was seen to be present in some horizons of the snowpack but it was not possible to make measurements of free water content. After the storm of 26 June, both of the pits became flooded to within 0.25 m of the snow surface, which was slushy. Streamflow over the snow surface was observed at 1600 h on 27 June, disappearing into the lee of the snowdrift which occupied the constricted section upstream of pit no. 1 (Fig. 4:4). Discharge at 2330 h was 0.107 m^3/s.

By 24 June, snowcover in the valley section upstream of the snowdrift had decreased to 75 - 80%. This decrease was accomplished in part through mechanical disintegration of the snowpack and in part through snowmelt. Crevasses representing the outcrops of shear planes were visible in many places, and along the valley walls snow boulders were breaking away from the overhanging cornices at the crests of the valley-wall slopes. The larger snow boulders ploughed considerable amounts of snow before them down the slope (Fig. 4:5).

The retreat of the snow cover revealed the presence of ice layers at the base of the snowpack. These basal ice layers were apparently universal phenomena and were noticeable at all stages of the snowmelt season, being slower to melt than the upper layers of the snowpack and persisting at snowpatch margins for some time after initial melt. Their role in promoting or hindering waterborne removal of material from the ground surface is uncertain. While they prevented access of meltwater to the ground in a few cases, in many others meltwater flowed away from the snowpack in channels cut beneath the basal ice rather than above it (Fig. 4:6).

The storm of 26 June brought the snowpack to free water capacity.

Fig. 4:4 Early streamflow, 27 June; $Q = c.0.1 m^3/s$.

Fig. 4:5 Snow boulder at foot of northern valley slope.

Fig. 4:6 Valley of "Jason's Creek", 30 June; exposures of basal ice layers are discernible around patches of exposed ground surfaces.

However, six days elapsed between the rainstorm and the annual discharge peak on 2 July. Standing water appeared on the snow surface near the mouth of the creek on 29 June, growing rapidly in extent. Water also ponded up between the beach-fast sea ice and the storm bar straddling the mouth of the creek. This bar was thrown up during a storm in autumn 1969.

Discharge increased on 1 July from a level of 0.12 m^3/s to 0.42 m^3/s, and on 2 July reached a level of 1.42 m^3/s, the maximum for the year. Flow over the storm bar commenced on 30 June and became vigorous on 1 July. Dispersion of the discharge was achieved through leads in the sea ice. On 2 July erosion of the storm bar by the snowmelt flood breached the crest of the bar at 1400 h, and erosion of the channel bed at this point proceeded during 2 and 3 July until some 2 m of lowering had been effected. The detritus resulting from this erosion and the transport of material from further upstream as bed load and suspended load was partly deposited on the surface of the sea ice as a lobate delta (Fig. 4:7) and partly removed by continued transport down the leads. Since flow in these leads was effectively confined channel flow,a considerable capacity to carry sediment was maintained in them.

The velocity of flow in "Jason's Creek" reached maxima in excess of 2.2 m/s during the snowmelt flood. At times of peak velocity virtually the entire channel bed was mobile, with cobbles of up to 200 mm diameter in motion. Attempts to measure bed load as a function of the accumulation in metal traps emplaced in the stream bed were unsuccessful, for the traps were washed away with the bed material. In a qualitative sense, the occurrence of bedload movement was correlated with maximum velocities in the channel of 1.8 - 1.9 m/s and greater.

Fig. 4:7 Lobate delta of "Jason's Creek" on beach-fast ice.

Fig. 4:8 Entrance to a sub-nival section of the channel.

During the first six days of the flow season the bed and walls were composed in the main of snow and ice. The stream disappeared into the snowpack at several places (Fig. 4:8), to emerge further downstream. Clearance of snow and ice from the channel continued during these first days but was greatly accelerated during the flood, when blocks of unmelted snow were dislodged and rafted out of the basin. Most of the spring flood water performed work on the ground surface rather than on snow. Where detritus was laid down on a channel floor of snow, snowmelt was accelerated where the detritus was fine and slowed down where it was coarse (Fig. 4:9). In some sections of the valley where snow depth was exceptionally great, the creek abandoned its initial supra-nival course to flow at the base of the snowpack. In three places a snow cover overlying the channel persisted through the entire season.

Effectively, however, the snow cover over the basin as a whole was dissipated by 3 - 4 July, when the areal extent of the cover was about 20 - 25% of the total basin area. From 4 July to 7 July flow decreased, and from 8 July to 12 July a secondary flood peak, almost as large as the first, occurred (Fig. 4:10). The secondary flood commenced abruptly between 1200 h and 1300 h on 8 July, and although 0.76 mm of rain fell on 7 July between 0300 h and 1300 h, there was no immediately apparent explanation for the sudden rise in discharge on the following day. A rainfall of 0.76 mm is insufficient to account for the volume of water discharged during this secondary flood, and the flood was preceded by no remarkable increases in either temperature or incoming radiation.

From 8 July to 12 July lowering and reshaping of the channel bed by bedload movement were resumed. At the mouth of the creek, for example,

Fig. 4:9 "Cast" of abandoned supra-nival stream channel in plateau section of valley; debris constitutes a thin mantle over a core of snow.

Fig. 4:10 "Jason's Creek", 10 June; Q = c.1 m^3/s.

the crest of the storm bar was 3 m above the level of the channel by 12 July, and the stream had eroded a gap in the bar to a width of 5 - 7 m. The highest recorded concentration of suspended sediment, 291 p.p.m., was obtained on 10 July.

From 13 July onward discharge remained low. Snow cover by this time was less than 20%, and the subsequent supply of meltwater was derived from semi-permanent snowpatches. Precipitation of 0.51 mm of rain on 21 July, 0.56 mm on 22 July and 1.02 mm on 24 July failed to produce observable responses on the hydrograph from the stage recorder installed on 17 July. The stream flooded once more, however, in response to a rainstorm which occurred between 1800 h, 26 July, and 2200 h, 28 July. The lag between input of precipitation and discharge output was short, and the stream subsided within ten hours of the end of the rainstorm. This was the only occasion apart from the early period of snowmelt flood when the stream carried bedload.

From 29 July until data collection ended on 16 August discharge declined gradually; from 13 August on, the stream failed to reach the bay as a discrete flow, discharge over the last 25 m of its course occurring as percolation through the loose material of the channel bed. Superimposed on the decline was the regular diurnal fluctuation related to fluctuations in incoming radiative and thermal energy. There was a snowfall of 2.8 mm of snow (as water equivalent) on 14 - 15 August, and on 16 August "Jason's Creek" froze to its bed and ceased to flow. It is not known if there was any flow after 16 August, but it is unlikely that there was any considerable flow.

Ground temperature:

Ground temperatures in summer 1970 were such that the surface layers thawed to depths reaching 0.45 - 0.65 m. Six thermocouple installations, located in a N-S line crossing the valley some 750 m upstream from the mouth of the creek, and referred to as nos. 1 to 6 accordingly, were monitored between 7 July and 16 August. Their elevations ranged from 30 to 75 m a.m.s.l.

Fig. 4:11 shows the temperature profiles obtained from readings at the no. 1 thermocouple rod, located at the crest of the northern valley-side slope. Some of the 19 profiles have been omitted to avoid crowding the graph. The profiles shown, however, reveal the main features of the ground temperature profile and its seasonal changes. These include a constant and relatively small gradient of -0.04 to -0.06 deg/cm below the 0^{o} level, and the location of the maximum gradient and maximum observed range of temperature in the upper 0.2 m (Fig. 4:12 a, b; rods 2 and 3 were located in the middle and at the base respectively of the northern slope; rods 4 - 6 were located at the base, in the middle and at the crest of the southern slope). The highest temperatures are also found in this upper section, and a lowering of the permafrost table over the period of observation may be noted from Fig. 4:12c. The flux of heat into the ground is mainly absorbed in warming of the upper 0.2 m, the effect of changes in heat input being increasingly reduced at depth. Diurnal change appears to be largely damped out below 0.2 m, where only a seasonal warming trend can be detected, and above 0.2 m they are manifested, in some of the individual profiles, as a cooling of the top 0.1 m. After the diurnal temperature maximum a reversal of the direction of heat flux takes place.

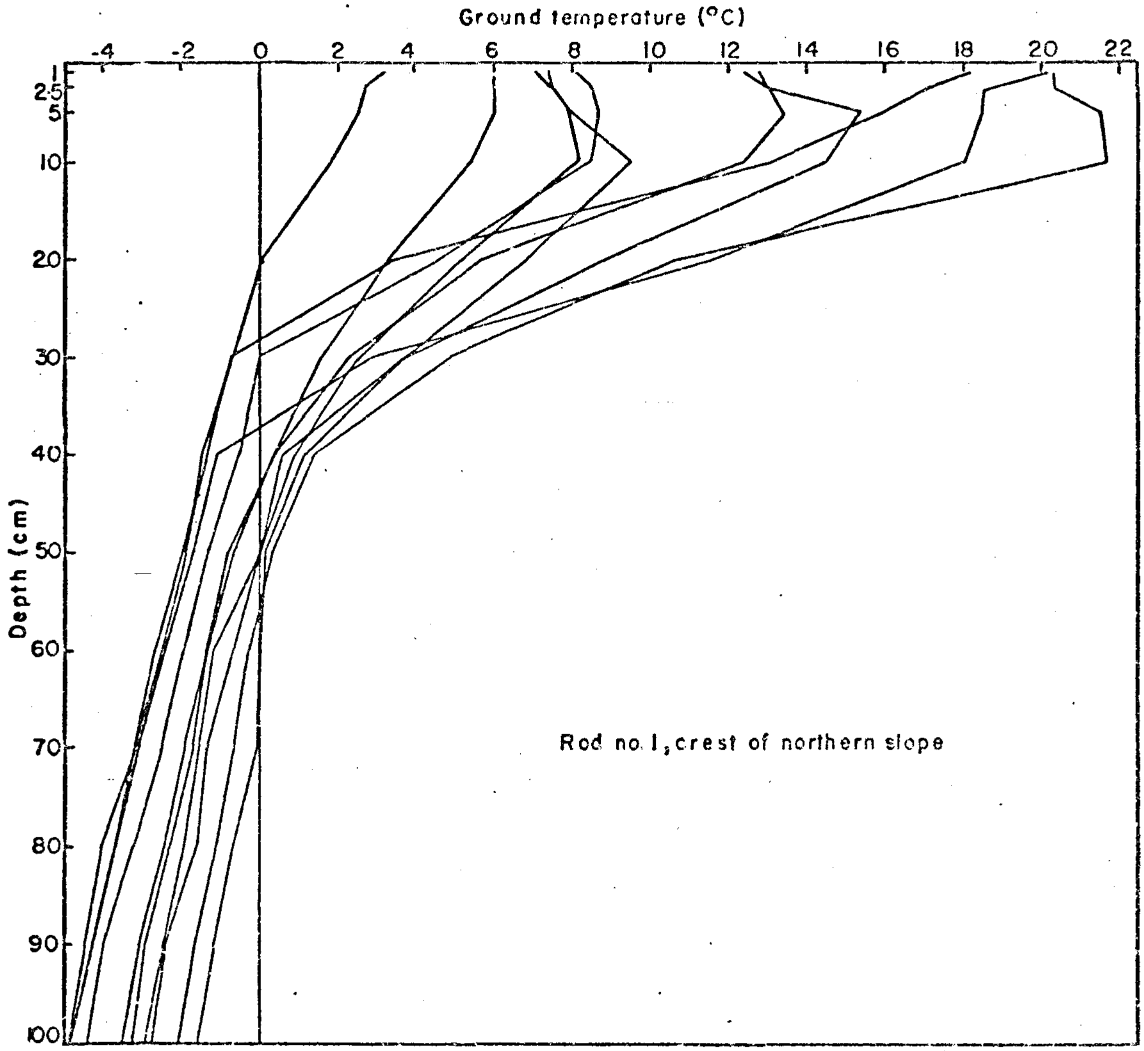


Fig. 4:11 Ground temperature profiles, rod no. 1

7 July - 16 August.

The loss of heat is greatest at the ground surface, and the magnitude and rate of this loss decrease rapidly with depth. In the case of the no. 1 rod this fact is reflected, in Fig. 4:12b, as a mean positive temperature gradient in the top 5 cm; i.e., temperature increases with depth in this layer.

The seasonal trend observed in the lowering of the permafrost table appears to decelerate with time. For most of the curves in Fig. 4:12c, it is true to say that the rate of lowering is fastest between the earlier points on the curve. In all of them the permafrost table is higher on the last day of measurement, due to the snowfall which occurred on the two preceding days. On the first day of measurement, 7 July, none of the rods had been exposed from beneath a cover of snow for more than ten days. The single set of measurements made on rod no. 6, at the top of the southern slope, was taken after approximately two days of exposure and revealed that the permafrost table was located 0.11 m below the surface. Extrapolation backwards in time of the curves for the other rods indicates that surface temperatures at the time of their exposure would have been in the vicinity of $0^{o}C$. This suggests two things.

Firstly, most of the radiative and heat energy absorbed at the snowpack surface must be expended within the snowpack, for if the extrapolation of the curves is valid relatively little heating of the ground can take place prior to its exposure. Secondly, even if a large percentage of the volume beneath the permafrost table were occupied by ice, its rate of melting on any given day could not account for more than a very small proportion of the discharge of the creek on that day, even assuming that runoff of the permafrost meltwater were allowed to take place rapidly

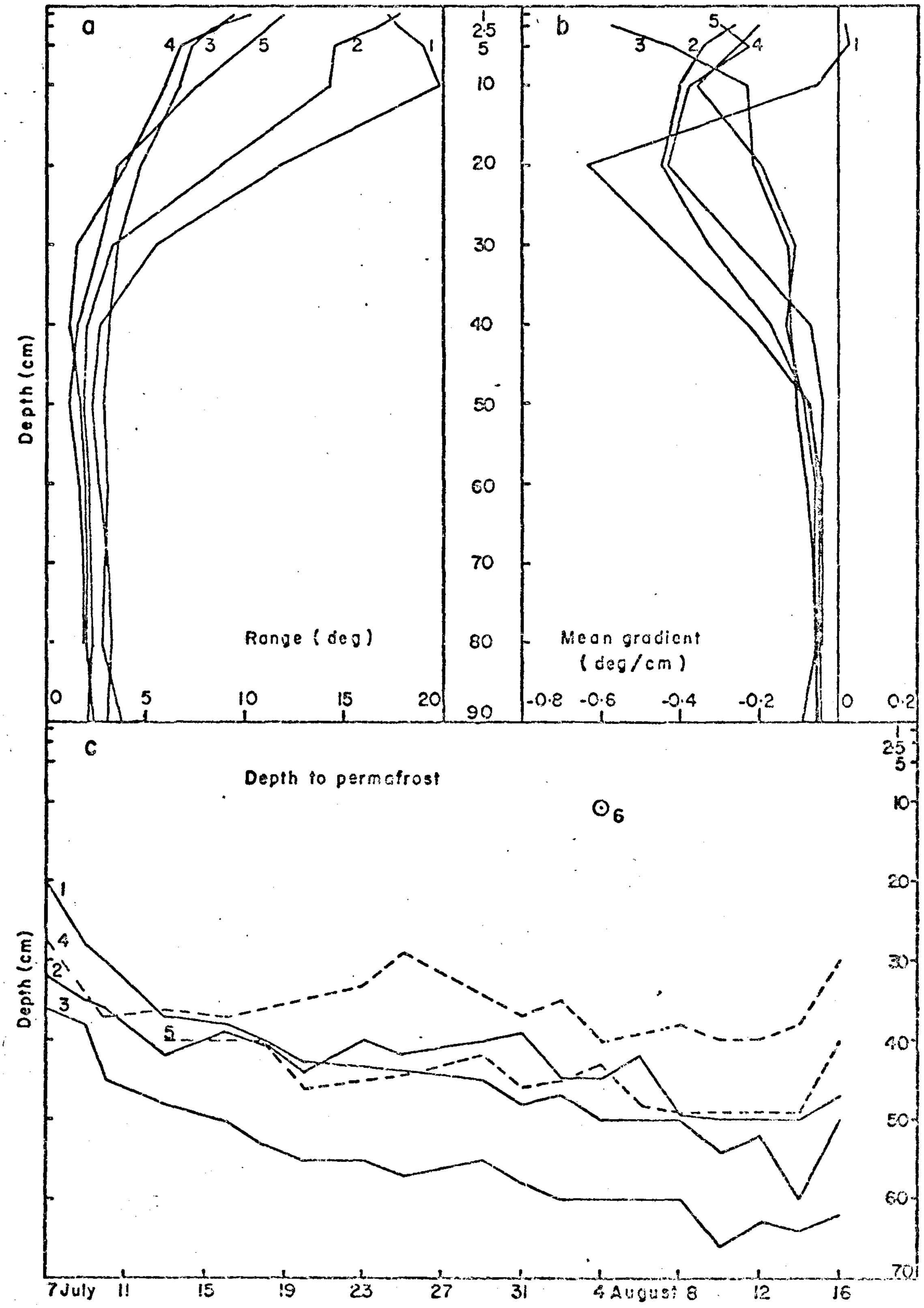


Fig. 4:12 a, observed range of ground temperature; b, mean gradient; c, depth to permafrost.

through the active layer.

Although the study of slope form was not a central aspect of this research, a qualitative correlation may be made between the incidence of mudflows and their location. In the valley section of the drainage basin, most of the mudflows occurred on the north-facing slope. The ground temperature data show that this slope was appreciably colder than its south-facing counterpart. No data are available to indicate whether or not any asymmetry exists between the two slopes; however, the colder north-facing slope preserved a larger remnant snowpatch in the lee of the crest for longer than did the south-facing slope. The greater water supply issuing from this snowpatch may have helped to lubricate the active layer more efficiently on the north-facing side of the valley and thus to promote the incidence of mudflows on that side.

CHAPTER V

RADIATION, TEMPERATURE AND SNOWMELT DISCHARGE

I. TIME SERIES ANALYSIS OF HYDROLOGICAL VARIABLES

Methods of analysis:

A general characteristic of streams nourished by the melting of snow or ice is the correlation between their discharge hydrographs and the curve of the melt-generating function, or in other words a variable such as temperature or radiation. For an appropriate small basin with a mean flowthrough time for overland flow of less than 24 hours, the response of the hydrograph to the input variable is clear. The output has the same frequency as the input, which is general is approximately sinusoidal, but at a transportation lag determined by, among other things, the physical dimensions of the basin. In addition the output function contains a non-linear term which expresses the effect of basin storage.

The relationship between input and output is also non-linear in the sense that basin storage parameters change with time. That is to say, as the snowmelt season progresses, snow cover decreases and with it decreases the ability of the snowpack to store water. In a basin where the snowpack is the major source of runoff, this change with time may have a considerable effect on the response characteristics of the basin. The capacity of any basin to store water depends in general upon its ability to delay the passage of water through it, by retaining the water in surface hollows, between the stems and roots of plants, in capillary spaces in the soil and elsewhere. In an unvegetated, permafrosted basin this type of retention is probably of slight importance relative to snowpack storage. On the scale of a single, discrete runoff response, i.e. to a single rainstorm input or to one day's snowmelt, the effect of basin storage is to impart the characteristic hydrograph shape to the output response, with a steep rising limb and a less steep, protracted receding limb.

The non-linearity of the processes involved thus complicates an attempt to analyze the input-output interaction rigorously. It will appear, however, that without loss of analytical accuracy the processes may be considered to interact linearly for present purposes.

A stationary, Gaussian process occurring through time possesses certain properties, such as period, which have the dimensions of frequency. The relationships between pairs of processes which vary through time may be described by a set of functions which express the relationships in the domains of time and of frequency. If the pair is composed of a generating process and a resultant process, such as radiation and snowmelt discharge, it may then be considered as a system which receives an input and transforms that input into an observed output. The covariance and spectral density functions of the input and output time series are a means of partially describing the transformation effected by the system.

The autocovariance of a single time series is given by

$$\alpha_x(i) = \frac{1}{n-i}\left(\sum_{t=i}^{n-i} x_t\, x_{t+i}\right), \qquad (5{:}1)$$

$$(i = 0, 1, \ldots, m),$$

where

n = number of data points in series,

m = number of lag intervals,

x_t = values of series,

x_{t+i} = values of series at i lags.

The basis of this operation is multiplication of the t^{th} value in series x by the $t + i^{th}$ value, where i is the lag interval, and summation of the products. The resulting i values of α_x give an indication of the occurrence of significant lags within the series. If the number of lags, m, is chosen so as to be greater than the duration of some suspected periodicity in the time series, the periodicity will appear as a relative maximum at the appropriate point in the graph of the autocovariance function.

A potentially more sophisticated measure of frequency is the spectral density function, $S(x)$:

$$S(x) = \frac{2\Delta t}{\pi} \sum_{j=0}^{m} \alpha_x(i) \cos \frac{ji\pi}{m}, \qquad (5{:}2)$$

$$(j = 0, 1, \ldots, m)$$

where Δt = constant time interval between data points, and the other symbols are defined under eq. (5:1). The spectral density function is essentially a Fourier transformation of the autocovariance of the time series, which results in a conversion from the time domain to the frequency domain. The information given by the spectral density function consists of the relative significance of contributions at different frequencies to the total variation in the time series. Typically in this study the most important contribution is that at a frequency of 1 cycle/24 h.

The autocovariance and spectral density functions are measures of lag and frequency within a time series. Analysis of a pair of time series for covariances between the time series at successive lag intervals produces the cross-covariance function

$$\alpha_{xy}(i) = \frac{1}{n-i}\left(\sum_{t=1}^{n-i} x_t\, y_{t+i}\right), \text{ positive time,} \quad (5:3)$$

$$= \frac{1}{n-i}\left(\sum_{t=i}^{n-i} y_t\, x_{t+i}\right), \text{ negative time,}$$

$$(i = 0, 1, \ldots, m),$$

where the x and y denote the two series, and the function is evaluated for y lagging x (positive) and for x lagging y (negative time).

The analogue of the spectral density function in the analysis of pairs of series is the cross-spectrum. Mathematically the cross-spectrum is a complex number, of which the real part is the co-spectrum and the imaginary part the quadrature spectrum.

$$S_c(xy) = C_{xy} - jQ_{xy} , \qquad (j = \sqrt{-1}).$$

When the cross-spectrum is expressed in polar form its magnitude or absolute value is referred to as the amplitude of the cross-spectrum, or as the cross-spectral density function; the angular part or argument of the cross-spectrum is referred to as the phase.

$$S_c(xy) = \left| S_c(xy) \right| e^{-j\theta(xy)} , \tag{5:4}$$

where

$$\left| S_c(xy) \right| = \sqrt{C_{xy}^{\;2} + Q_{xy}^{\;2}}$$

and

$$\theta(xy) = \tan^{-1}\left(\frac{Q_{xy}}{C_{xy}} \right) .$$

The co-spectrum and quadrature spectrum are given by

$$C_{xy}(i) = \frac{\Delta t}{\pi} \sum_{i=0}^{m} \left[\alpha_{xy}(+i) + \alpha_{xy}(-i) \right] \cos \frac{ji\pi}{m} \tag{5:5}$$

and

$$Q_{xy}(i) = \frac{\Delta t}{\pi} \sum_{i=0}^{m} \left[\alpha_{xy}(+i) - \alpha_{xy}(-i) \right] \sin \frac{ji\pi}{m} \tag{5:6}$$

$$(j = 0, 1, \ldots, m).$$

The co-spectrum and quadrature spectrum may be thought of as reflections in the frequency domain of the in-phase and out-of-phase covariance respectively of the series x and y. The quadrature spectrum is evaluated with one of the series shifted relative to the other by one quarter of a period.

The cross-spectral density function yields information about frequency components contributing to both of the crossed series x and y, while the phase values indicate the angular "phase shift" or lag at which these frequency components contribute. Thus at a given frequency a phase value of zero indicates that the series are in phase; a phase value of π radians (180°) indicates that the series are out of phase and inversely correlated; and a phase value of $\frac{\pi}{2}$ radians (90°) indicates that series y lags series x by one quarter of a period.

The equations given above are not presented rigorously but in the operational form used for computation. A full derivation of the equations, with a discussion of their applicability to hydrological time series, may be found in Rodríguez - Iturbe (1967).

The restrictions on the use of the covariance and spectral density functions - namely, that the series under analysis should be stationary (linear) and Gaussian - are severe for many hydrological systems, which tend to be non-linear and to have exponential distributions. There are means by which these problems may be circumvented, but one hydrological situation in which the problems do not arise is that in which the discharge of a stream is a function of the melting of snow or ice, which varies with a regular period of 24 hours. The distribution of data points in this situation is Gaussian. Strictly speaking, however, snowmelt discharge is not a linear process. During the spring snowmelt flood the amount of snowmelt which takes place is achieved by an amount of incoming energy which, relative to the amount of snowmelt, remains more or less constant over the flood period. Since the amount of snowmelt varies substantially as snow cover and snow depth decrease, the relationship between meteorological input and hydrological output is thus non-linear.

For most of the snowmelt runoff season after the spring flood, however, the meteorological agents working on the snow remaining in the basin produce a discharge of meltwater which is, for practical purposes, in proportion with the magnitude of the input. The apparently linear relationship arises because the rate of change of snowpack volume after the spring flood is so small that it may be neglected in the analysis. In physical terms this means that the remnant snowpatches which undergo melting disappear much more slowly than does the snowpack which covers the basin at the start of the runoff season. Little loss of analytical accuracy results from the assumption of constant snowpack volume over short time intervals in the later stages of the snowmelt season.

Assessment and Prospects:

The field of frequency analysis in general appears to offer considerable scope for application to the solution of hydrological problems, particularly, for example, those associated with the accurate determination of drainage basin lag times. The analysis in the case of snowmelt discharge is not beset by the difficulties associated with non-normal or non-linear distribution of the variables. It seems possible, however, that ways may be found around these difficulties in some cases where they do arise. For instance, it is usual in frequency analysis to standardize the time series about their mean values as a preliminary step by an operation of the form

$$x^*(t) = \frac{x(t) - \bar{x}}{\sigma(x)} , \qquad (5:7)$$

where $\bar{x}$ is the mean of the series $x(t)$ and $\sigma(x)$ is the standard deviation of the series. If the series were unitized about their median values prior to the analysis, they would become more nearly Gaussian as a result. A discussion of the potential of this operation is presented in Chapter VI; the series analyzed in the present chapter are quite strongly Gaussian and an actual analysis of these time series in unitized form produced little additional information of significance.

Another approach to the analysis of series which do not satisfy the requirements of existing spectral analytical techniques is to replace the use of Fourier transforms with use of other integral transforms. Consider, for instance, the Laplace transform, which is given by

$$F(s) = \int_0^\infty e^{-st} f(t) \, dt. \qquad (5:8)$$

Multiplication of the time series $f(t)$ by the kernel e^{-st} and integration of the product results in the replacement of $f(t)$ by a frequency function $F(s)$, which is the Laplace transform of $f(t)$. Time is eliminated as a discrete variable and replaced by frequency, the operator s being a complex variable chosen so as to have the dimensions of frequency. The Laplace transform is evidently more versatile than the Fourier sine transform in the sense that the transformation need not necessarily result in a sinusoidal function. Many hydrological series are not physically sinusoidal at all, and a Laplace transform is theoretically obtainable for any series if an equation describing the series can be found.

An important property of the Laplace transform is the following: if x(t) is an input to and y(t) an output of a system, then the ratio of the transform Y(s) of the output to the transform X(s) of the input is the transfer function of the system:

$$\frac{Y(s)}{X(s)} = T(s) \; ;$$

for a linear system in steady state the transfer function is a constant. If equations can be found to describe one input-output pair of a system in steady state, the transfer function of the system can be calculated and used to estimate the output of the system in response to some other type of input. The watershed of "Jason's Creek", for example, represents a system in steady state between 17 and 26 July; the input of the system is represented by the curve of radiation or temperature and the output by the stream hydrograph. If the transfer function of the basin were known it might be possible to use the transfer function and values of rainfall intensity to "predict" the storm hydrograph of 27 - 29 July. An analysis of this sort is not attempted here: the problem of finding the appropriate equations has yet to be solved, and other aspects of the analysis must also be ironed out.

At this stage it may only be said that an approach to the general problem of hydrograph prediction by the use of transfer functions appears to be feasible. It must be stressed that Laplace transforms are strictly applicable only to linear functions, so that their usefulness in the analysis of hydrological non-linearity and time variance may prove limited. Solutions to problems of this type may be found, however, by phase plane analysis, which is an extension of the family of techniques discussed above into the realm of non-linear equations (Coughanowr and Koppel, 1965).

II. TIME SERIES ANALYSIS OF DATA FROM "JASON'S CREEK"

On the first full day of temperature record at "Jason's Creek", 25 June, the mean daily temperature was -1.5° and the maximum temperature was 1.1°. The record for 26 and 27 June was lost following the storm of the morning of 26 June. The mean daily temperature for 28 June was 1.1°. From that day until 2 August there was no day with a mean temperature below 0°. Freezing temperatures occurred for brief periods before 2 August and more frequently thereafter, but on the last day of record, 15 August, the mean temperature was 0.1°. The seasonal maximum of 13.0° was recorded on 9 July. The graph of screen temperature for summer 1970 is presented in Fig. 4:2.

Incoming radiation in summer 1970 appears to have been above average in the High Arctic, although no climatic records are available to substantiate this statement. The maximum value recorded for mean daily incoming shortwave radiation at "Jason's Creek" was 35.8 $mW/mm^2/h$ (0.86 L/min) on 27 June.

The period selected for time series analysis of the records of temperature, radiation and snowmelt discharge, 17 - 26 July (Fig. 5:1),

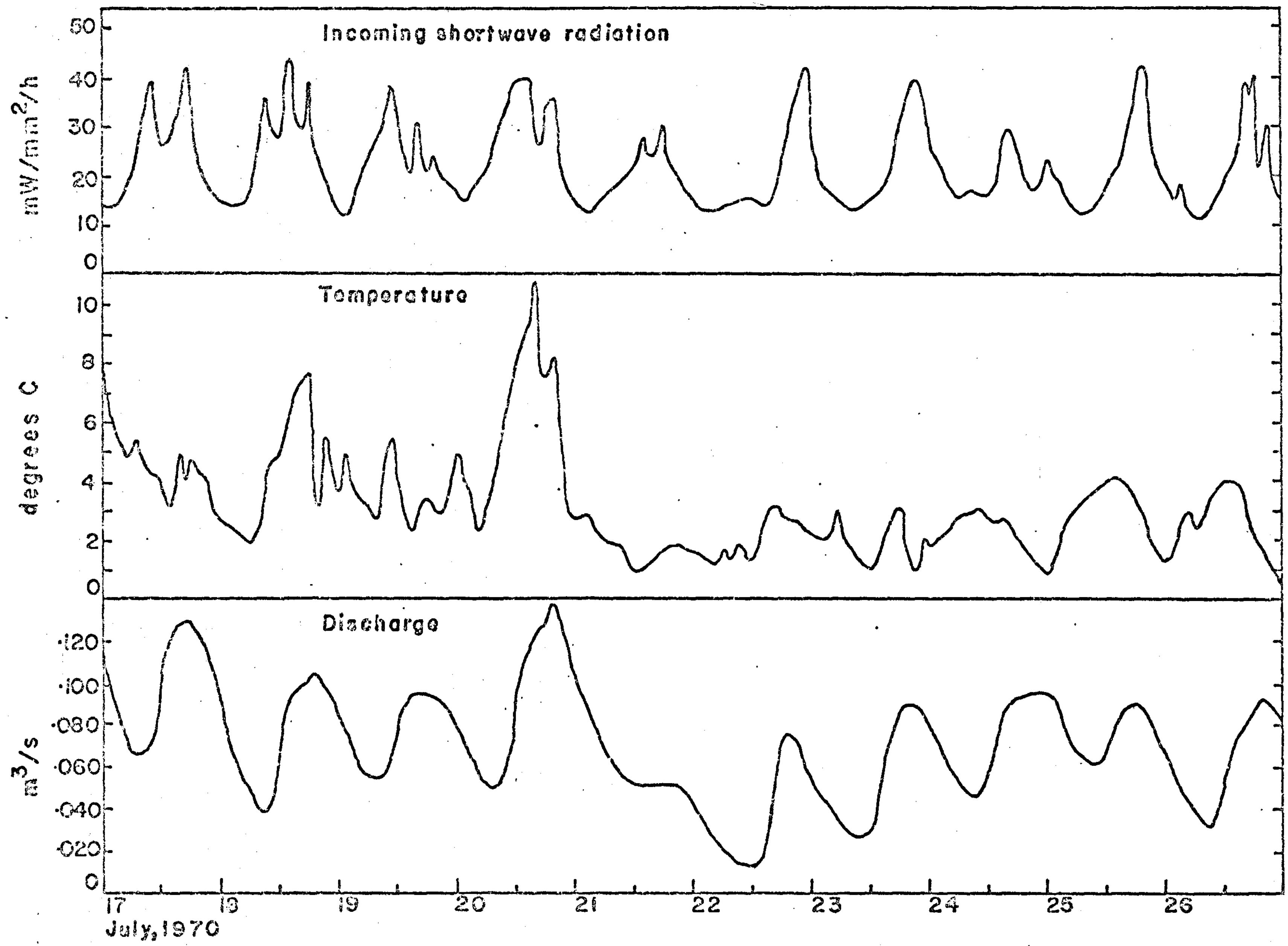


Fig. 5:1 Radiation, temperature and discharge, 17 – 26 July.

covers the ten days prior to the rainstorm and flood of 26 - 29 July. 17 July is also the first day for which a continuous record of discharge is available. The period was one of "baseflow" conditions, and a linear relationship between meteorological inputs and hydrologic output may be said to hold good over the period. (In the accepted sense of the term, of course, "base flow" does not exist in a region of continuous, shallow permafrost such as south-west Devon Island; in the present context the term "baseflow" is used merely to imply "low flow").

A constant time interval of one hour was used in the analysis, yielding 240 data points, and the selected number of lags was 25. The ordinates on the graphs of the functions presented below are dimensionless save for the phase plots, on which the ordinates represent angular phase shift; the abscissae are either time (in numbers of lags) or frequency (in cycles/hour), depending upon the function. On the graphs with frequency on the x-axis, frequency increases towards the right and period consequently increases towards the left.

The autocovariance functions of the three series are plotted in Fig. 5:2. Those for radiation and discharge are similar in form, exhibiting maxima at lags of 24 hours and minima at lags of 12 hours. The temperature function, however, decays up to a lag of 12 hours and exhibits no peak thereafter. The implication of this contrast between radiation and discharge on the one hand and temperature on the other is that the first two series possess strongly marked periodicities of one day while the temperature series is not well correlated with itself at the daily lag. One possible explanation for this contrast may be that temperature is more sensitive to the passage of weather systems than are the

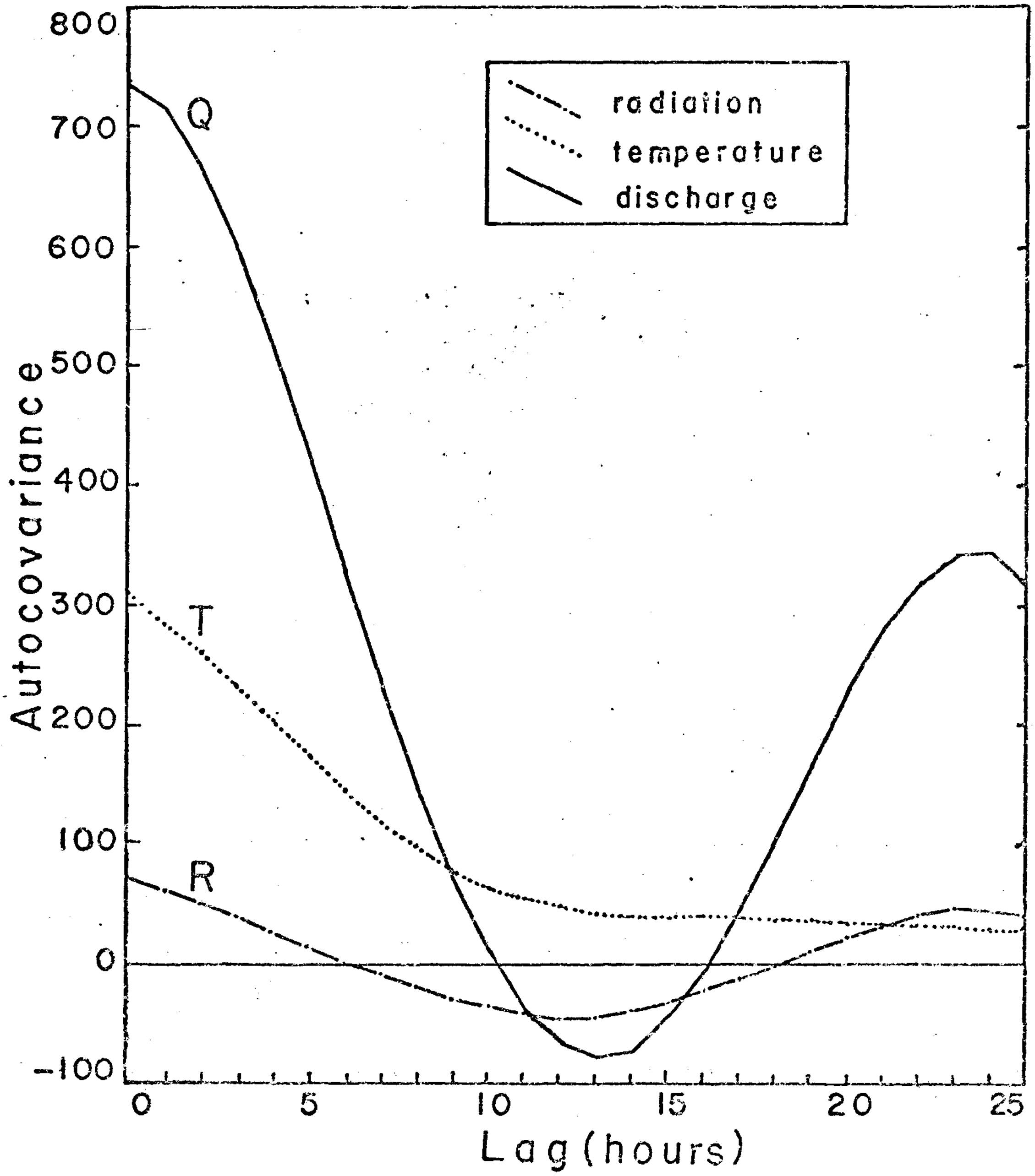


Fig. 5:2 Autocovariance of radiation, temperature and discharge.

other variables, and the effect of these weather systems is to introduce a damping influence on the diurnal component of temperature variation.

The spectral density functions (Fig. 5:3) are all negligibly small at frequencies greater than 1 cycle/12 h. Only radiation shows a maximum at 1 cycle /24 h. The cross-covariances (Fig. 5:4) between the series all have maxima spaced 24 hours apart. The displacement of the central maxima from the central axis of the graph indicates that radiation leads temperature by one hour and that discharge lags behind radiation by five and temperature by four hours. These relationships may be explained from physical considerations; temperature for instance, changes for most of the time in response to inputs of energy, warming or cooling of the air occurring over a period of time after the energy is received. It is of interest to note that the cross-covariance function for radiation and discharge decays more slowly than does that for temperature and discharge, as is indicated by the slopes between maxima of the functions. This may be related to the weakness of the temperature autocovariance function at the 24-hour lag, which may in turn be related to the damping of the diurnal component of fluctuation in temperature which was referred to above.

The cross-spectral density functions (Fig. 5:5) resemble the spectral density functions of the uncrossed series in that they decay rapidly from a maximum value as frequency increases. Of the three plots, that for temperature and discharge slopes most steeply and uniformly; the functions for temperature - radiation and radiation - discharge both reach maxima at 1 cycle/24 h. The contrast between the cross-spectral density function for temperature and discharge, which decreases from a maximum

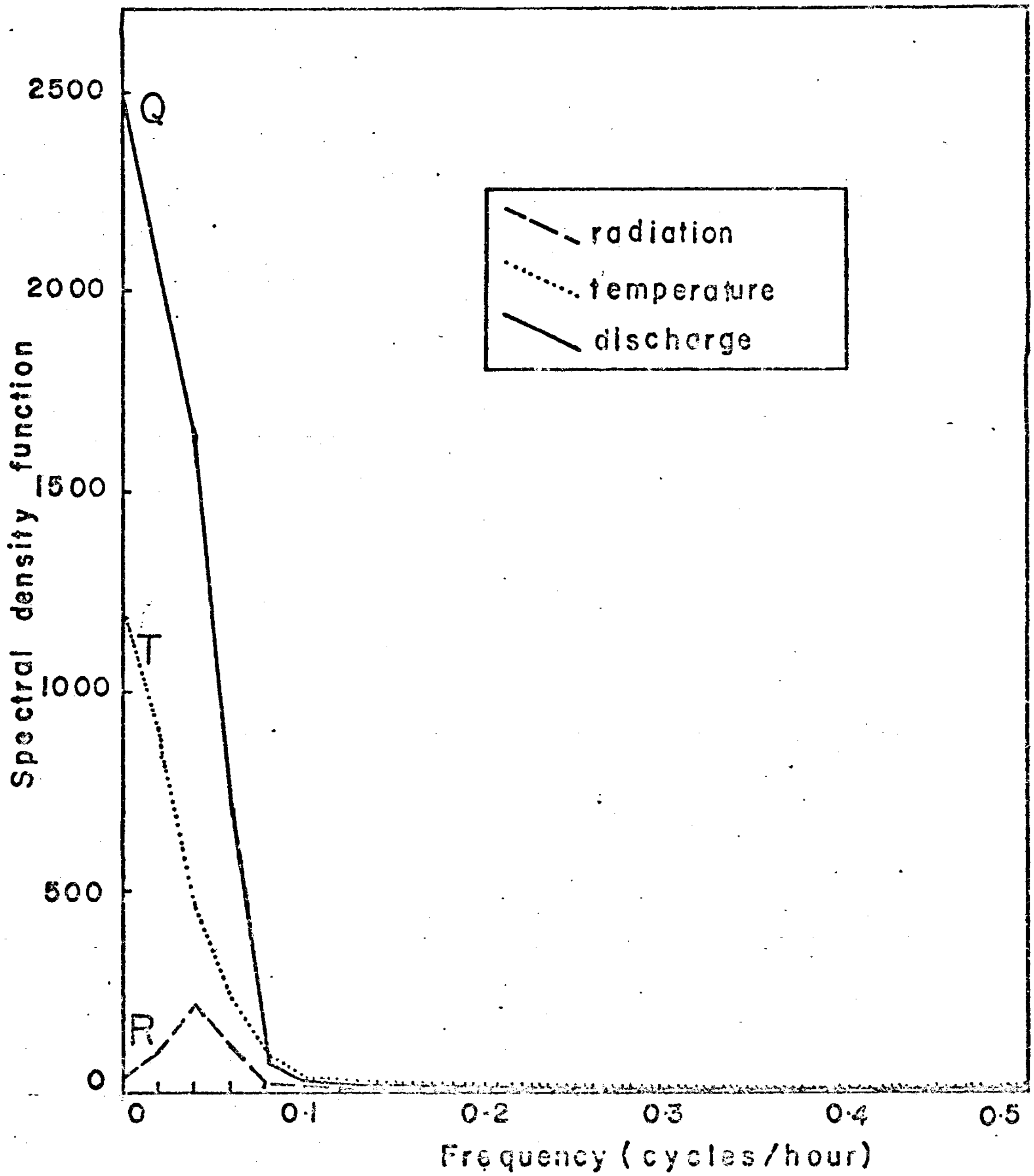


Fig. 5:3 Spectral density functions of radiation, temperature and discharge.

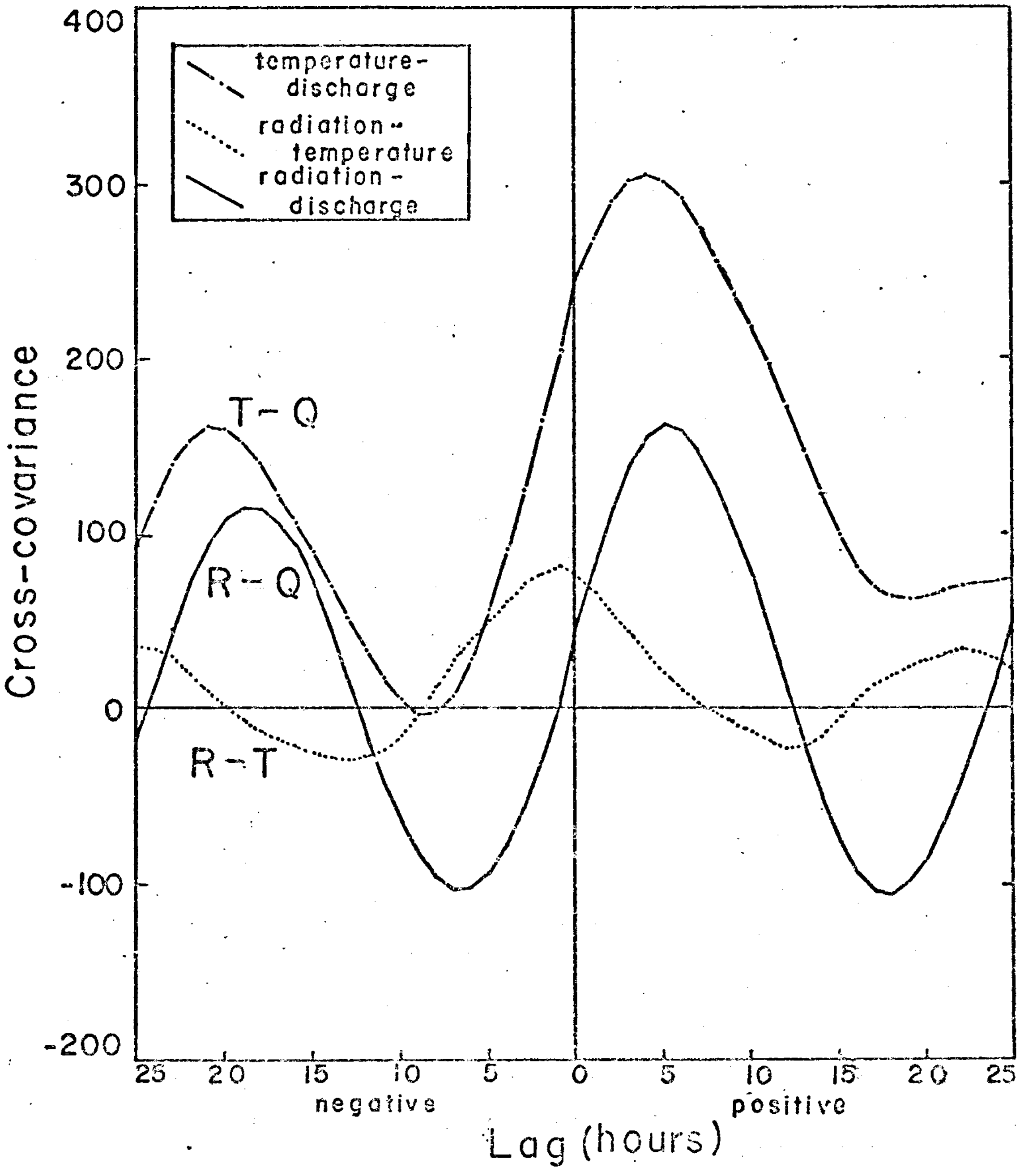


Fig. 5:4 Cross-covariance between radiation, temperature and discharge.

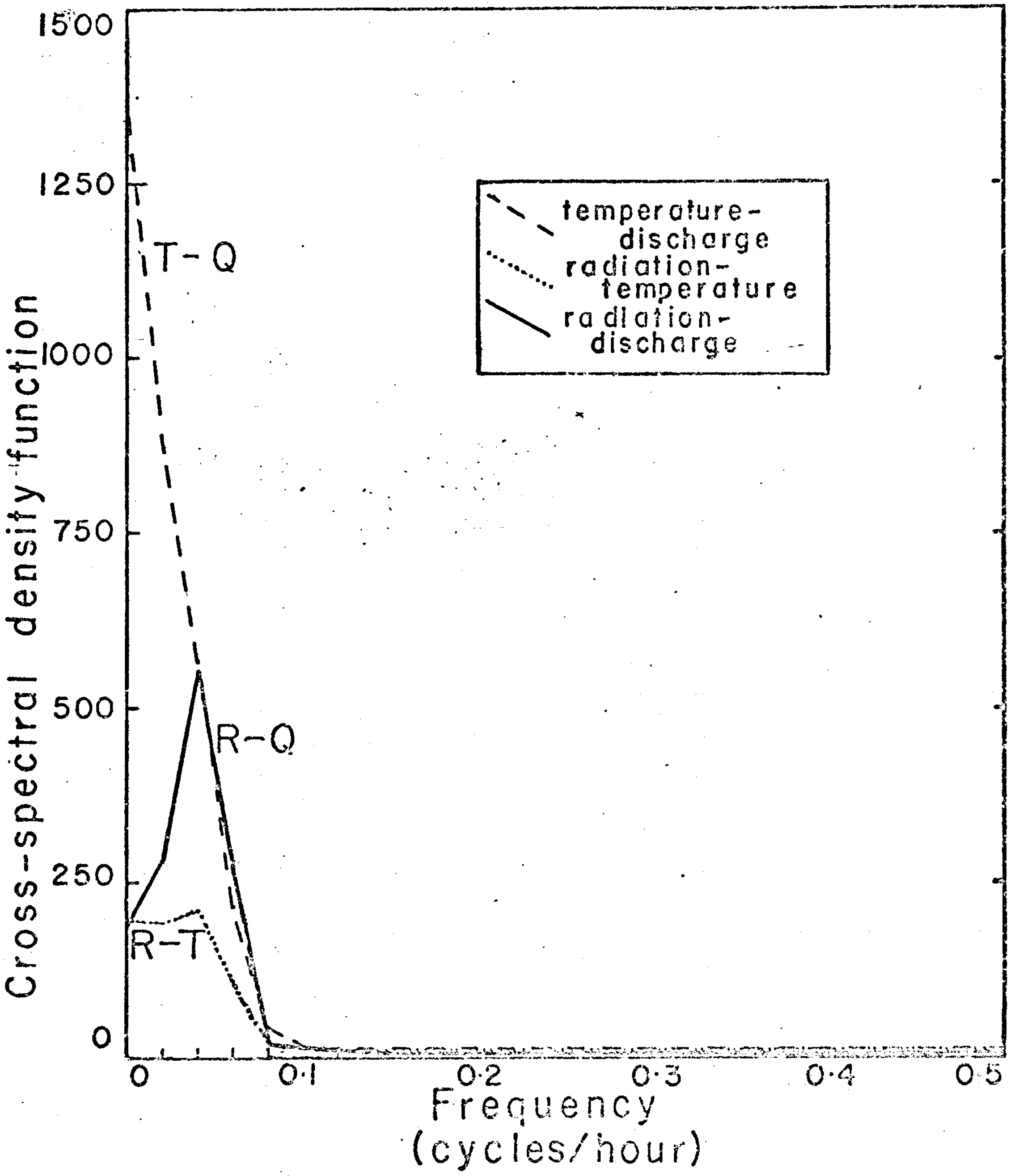


Fig. 5:5 Cross-spectral density functions between radiation, temperature and discharge.

at the zero frequency and shows no evidence of a diurnal frequency component, and that for radiation and discharge, which indicates substantial correlation at the diurnal frequency, suggests that radiation is a better index of snowmelt discharge than is temperature. Consideration of the form of the autocovariance and cross-covariance functions of the time series supports this statement. The weakness of the autocovariance of the temperature series, and the greater slope between maxima of the temperature - discharge cross-covariance as compared with the radiation - discharge cross-covariance, both indicate that the discharge series is more closely correlated with the radiation series than with the temperature series.

The phase diagrams (Fig. 5:6) show that the phase shift of radiation with respect to temperature is negative in most of the frequency range; that is, radiation leads temperature. At the diurnal frequency, which is the only one of interest in the present analysis, the phase shift is -0.29 rad; setting 6.28 rad = 24 h, this shift corresponds to a lead of 1.1 h. The values for shift of discharge with respect to temperature and radiation at the diurnal frequency respectively are +1.05 rad, which corresponds to a lag of 4.0 h, and +1.38 rad, which gives a lag of 5.3 h. These lag times correspond closely with those determined by the cross-covariance analysis.

In summary, the conclusions which may be drawn from frequency analysis of the time series are: firstly, that there is a strongly marked diurnal periodicity in the series of radiation, temperature and snowmelt discharge, but that in the case of temperature this periodicity, which is visually apparent in the records, correlates rather poorly with snowmelt

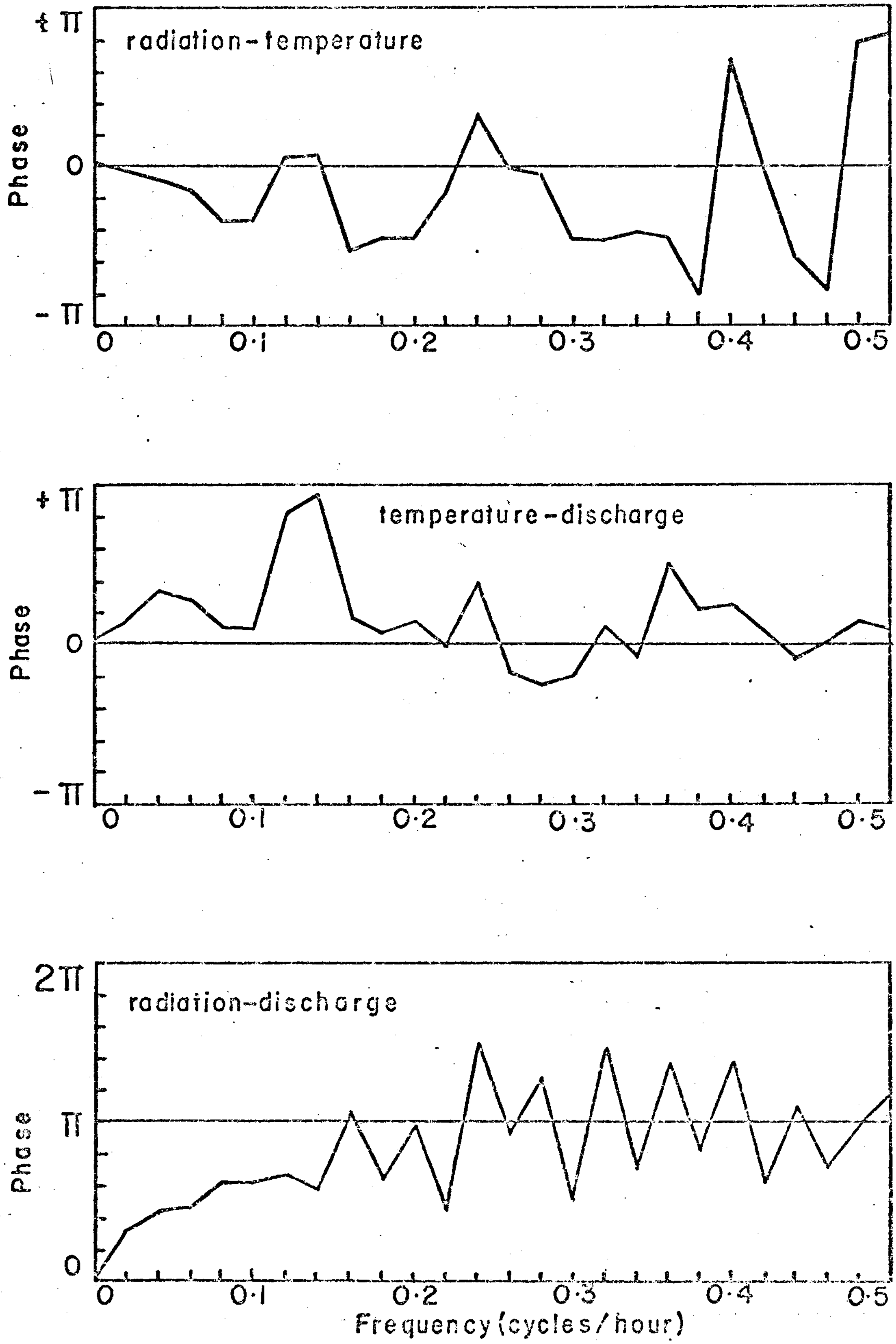


Fig. 5:6 Phase diagrams for radiation, temperature and discharge.

discharge, temperature being subject, for instance, to the influence of passing weather systems which do not necessarily affect the snowmelt process; and secondly, that the snowmelt runoff system may be described, with relatively little loss of information, in terms of incoming radiation as a generating process and stream discharge as a resultant process, with a lag time for the system of, in this case, five hours. It is not possible to state conclusively that in this case radiation rather than temperature effects the actual melting of the snow. The available data afford no possibility of investigating the complex detail of the meteorological processes operating near the snow surface, and therefore nothing is known of the significance of heat flux from air to snow, of evaporation and condensation and of other factors. It was not possible, for instance, to use the relative humidity record in the analysis made above to assess the importance of atmospheric water vapour content, for the record is broken in two places. The question as to which of the two processes, radiation and temperature, is the more important agent of snowmelt is thus not answerable from the existing data; a further complication is the possibility of an instrumental "error" factor, for screen temperatures may differ, at times considerably, from ambient temperatures in the open air. Certainly, however, radiation is a better index of snowmelt discharge than is temperature, and in this respect the suggestion of Megaham, Meiman and Goodell (1967), that net allwave radiation is a more useful index than temperature for the prediction of snowmelt, is substantiated.

Covariance and spectral analysis of the snowmelt runoff system yields useful information on the relationships between the variables in the system, and in particular on the time lag relationships; in this instance the information obtained in the frequency domain happens to be information which in the main is obvious without analysis. The potential for routine determination of lag and frequency relationships of the analytical techniques discussed in this chapter appears to be considerable, where the need for the determination exists and the techniques are applicable. As was indicated earlier in the chapter, the potential of a theoretical approach, based on the derivation of mathematical descriptions of the series, may prove to be yet greater.

CHAPTER VI

"JASON'S CREEK" IN FLOOD

INTRODUCTORY REMARKS

In Chapter V it was noted that "baseflow" in streams fed by snowmelt fluctuates daily in response to inputs of energy to the snowpack. Baseflow was defined rather loosely as "low flow", or as the release of water from snowpack storage after the main snowmelt flood. A more accurate definition of baseflow in the context of snowmelt discharge may be approximated with reference to Fig. 6:1, which is a schematic representation of the radiation - discharge system. At the seasonal scale this system is clearly non-linear, for the input of radiation is almost steady, if the downward trend resulting from the sun having passed the summer solstice is neglected. The output of discharge, on the other hand, bears little relation to the magnitude of the input. There comes a point in this schematic representation, however, where discharge does vary more or less directly with radiation. That is, the principle of superposition applies to the relationship:

$$x_1(t) \longrightarrow y_1(t)$$

$$x_2(t) \longrightarrow y_2(t)$$

$$x_1(t) + x_2(t) \longrightarrow y_1(t) + y_2(t). \qquad (6:1)$$

where x(t) and y(t) represent the inputs and outputs of the basin system.

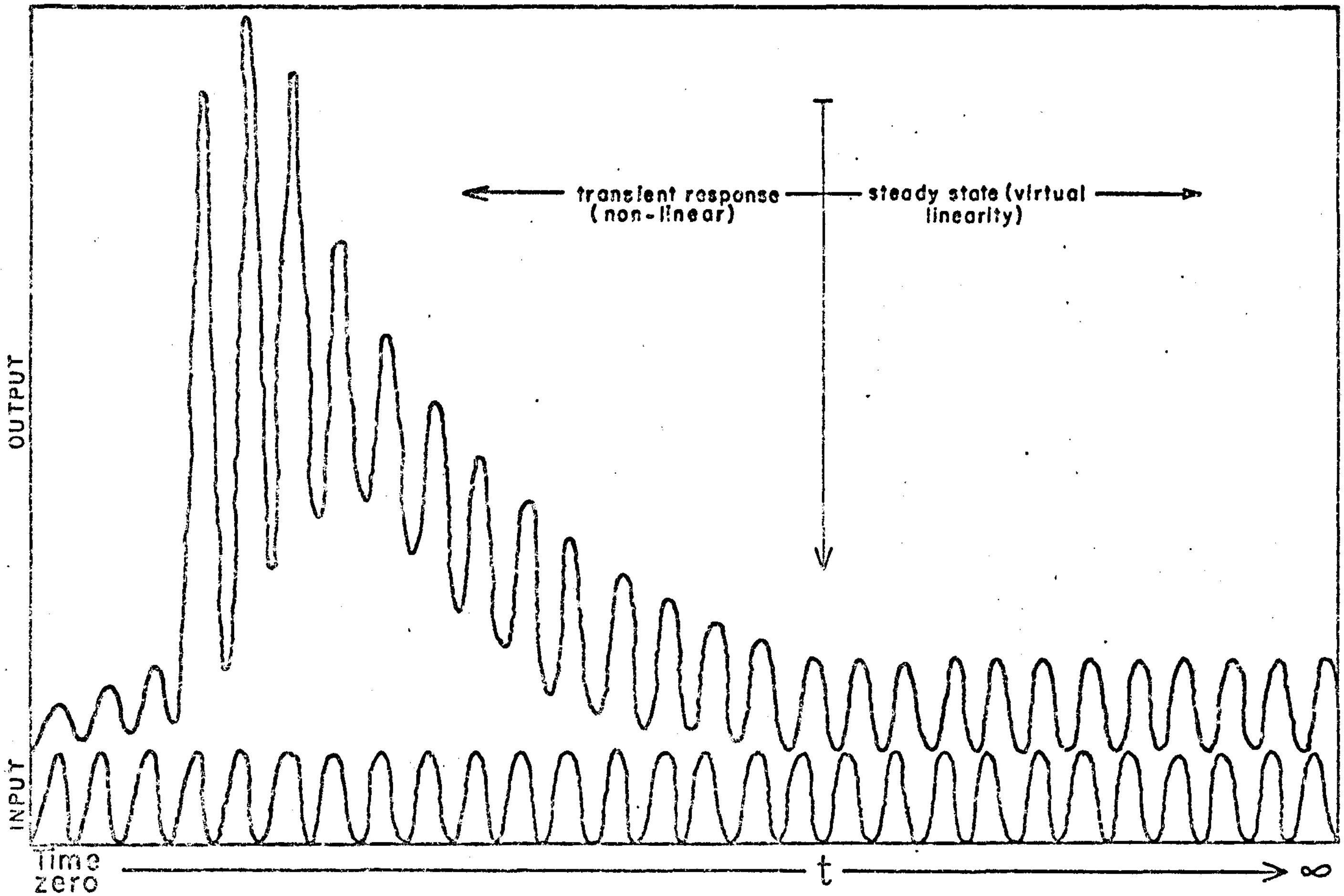


Fig. 6:1 Schematic representation of the seasonal snowmelt runoff system.

The time at which this situation is attained corresponds to the end of the snowmelt flood. From this time onwards the watershed system may be considered to be in steady state. In other words, the system is stable, and "baseflow" prevails. Before this point in time is reached it exhibits a transient response to the radiative or thermal inputs, such that the input "signal" is highly amplified. Analysis of the system for the characteristics of its transient response is possible, but is postponed from the present study for lack of continuous discharge records.

The spring flood:

Baseflow prevails for most of the season, but the major portion of annual runoff is discharged under transient response, i.e. in periods of flood. Unfortunately detailed analysis of the spring flood was not possible because of the lack of a continuous record of discharge. Installation of the stage recorder was not practicable in the early stages of the flow season, for the stream bed was largely formed of ice and snow and in many places the channel also was snow-covered. Where the stream flowed over the ground surface, the channel bed was highly unstable. The salient features of the spring flood, however, may be outlined in descriptive terms.

In general, snowmelt floods tend to last longer than rainstorm floods. The first meltwater produced during the snowmelt season accumulates in the snowpack which, being porous, has a certain capacity to store free water. When the free water capacity of the snowpack is first exceeded runoff begins. However, the snowpack is analogous in some ways to a geological aquifer; Davar (1967) has pursued this analogy in considering the "entire vertical profile consisting of the snowpack, humus or vegetal mat, the ground surface and subsurface formation ... jointly as a complex storage and transmission system". One implication of the analogy is that release of meltwater from the snowpack may not be distributed in anything like the form assumed by runoff "released" by a rainstorm. It is almost invariably true, for instance, that the snow-melt flood is marked by a sudden increase and subsequent asympotic decline in discharge, but this peak in the snowmelt hydrograph may occur at some considerable time after the commencement of snowmelt.

As noted in Chapter IV, the annual maximum discharge of "Jason's Creek" in 1970 occurred on 2 July, at least eight days after the first recorded snowmelt and six days after a heavy rainstorm which precipitated the start of streamflow. This relatively long time of rise is due to snowpack retention, to variations in the intensity of melt (which is a function of the intensity of the meteorological input), and possibly to other factors such as long flowthrough time through the snowpack, and the physical dimensions of the basin. Apart from the fact that a long or large drainage basin will superimpose a relatively long transportation lag on fluctuations in the input to the basin system, there is the added consideration that a catchment in which the range of elevation is substantial will have a long snowmelt season by virtue of the inverse correlation between elevation and temperature. The higher elevation zones in such catchments contribute snowmelt runoff later than do the lower zones.

This is not an important factor in the basin of "Jason's Creek", in which the time base of the snowmelt flood is short when compared with the time bases of floods in, for example, the Western Cordillera. The duration of the "Jason's Creek" flood in 1970 was long nevertheless, for it lasted for between ten and twenty days. The time base of the rainstorm flood discussed later in this chapter was approximately sixty hours. The fact that more than one discrete peak is discernible in the hydrograph of the spring flood (Fig. 4:1) can perhaps be attributed to variations in the intensity of the energy input to the snowpack and, to a much lesser extent, to the elevation factor.

Where more than one discharge figure exists for a given day, the diurnal component of fluctuation in discharge is usually evident. This is the case even for the days of maximum discharge, 2 - 3 July. It is also evident, however, that a lower frequency component of variation is present, representing the course of the snowmelt flood as a whole. This lower frequency component has the general appearance of a long time base flood hydrograph. The amplitude of fluctuations at the diurnal scale approaches fairly closely that of the lower frequency fluctuation, which indicates that even under flood conditions the immediate meteorological control over drainage basin output remains strong.

The rainstorm flood of 26 - 29 July:

Steady-state or baseflow conditions dominate the discharge hydrograph from about 15 - 17 July onwards. Only one disturbance of the steady-state situation affected the watershed after 17 July; this was a result of the rainfall of 26 - 28 July.

Hourly depths of rainfall and cumulative precipitation over this period are plotted in Fig. 6:2; precipitation intensity and stream discharge are plotted in Fig. 6:3. The conversion of the precipitation record from units of depth (mm) in a raingauge to units of volume (m^3/s)

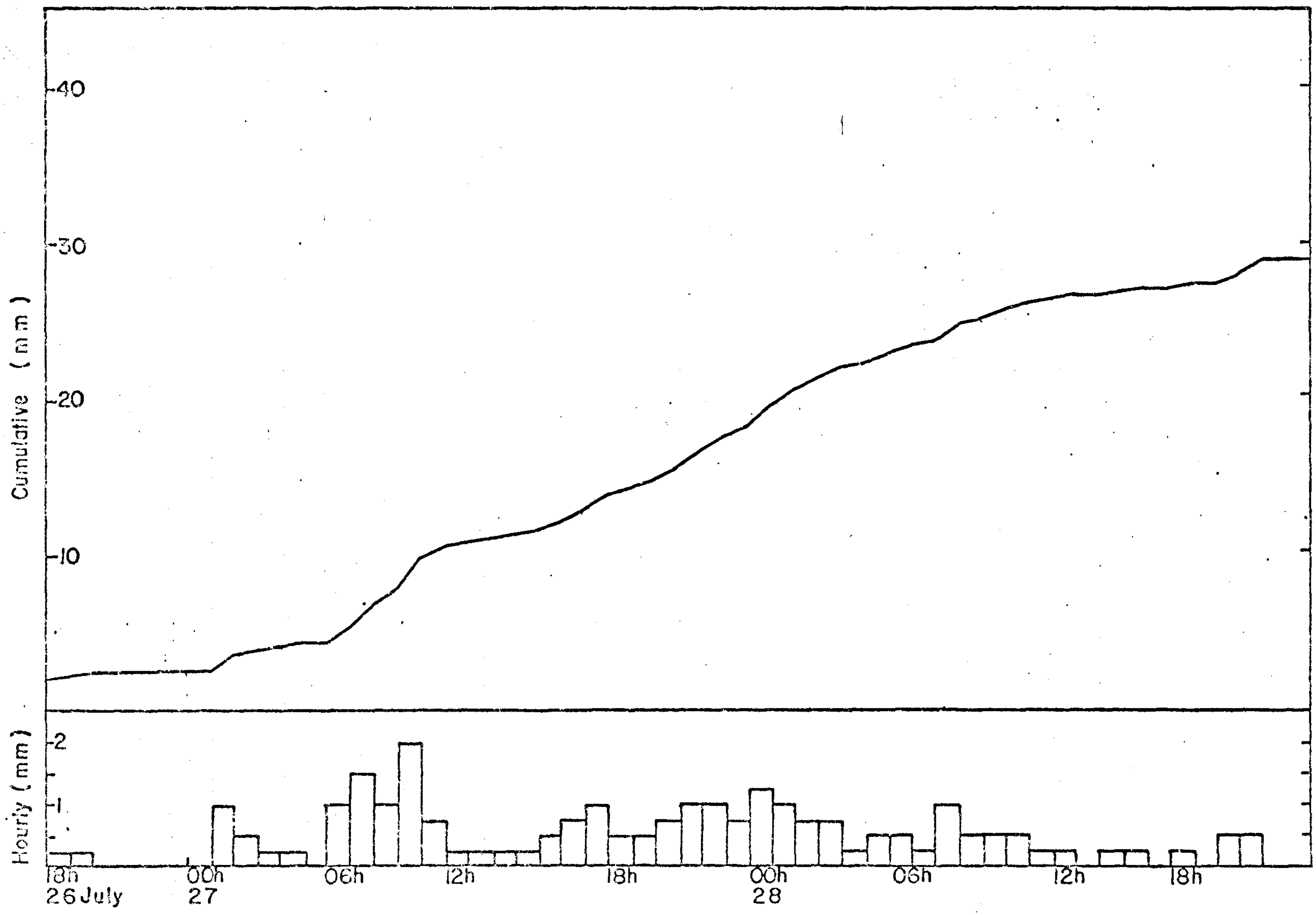


Fig. 6:2 Precipitation during the rainstorm of 26 - 28 July.

entering the basin was made to facilitate direct comparison with the discharge hydrograph. The procedure for the conversion was to assume depth of rainfall to be constant over the area of the basin; the volume of water entering the gauge (depth x area of gauge) was multiplied by the ratio of basin area to raingauge area, and finally divided by an appropriate quantity to give intensity in terms of volume per unit time.

The hydrograph response to the rainstorm was rapid; the time base of the flood was correspondingly short, and stream discharge returned to steady-state levels within some 10 - 12 hours of the cessation of rainfall.

The duration of rainfall was 51 hours, excluding some 6 - 7 hours of drizzle on the afternoon of 26 July. The duration of direct storm runoff, measured on the hydrograph between time of rise and return to pre-storm levels, was between 50 and 66 hours. The inability to give a precise duration for the storm runoff stems from the difficulty in deciding exactly where the storm hydrograph departs from and returns to the snowmelt hydrograph. The latter might have been expected to fall rather sharply after the diurnal peak on 26 July, instead of which the hydrograph trace declined only slowly; the first rise in the trace due clearly to an input of rainwater occurred at about 0400 h on 27 July, but the beginning of storm runoff has been fixed somewhat earlier in the light of the form of the trace during the evening of 26 July.

The first light rainfall was recorded at 1400 h on 26 July, and the first stream response was noted 4 to 5 hours later. The peak in the hyetograph occurred between 0700 h and 0900 h, 27 July, and was followed at 1100 - 1200 h by a sharp increase in discharge. Maximum discharge occurred at 0200 h, 28 July. The lag between hyetograph and hydrograph

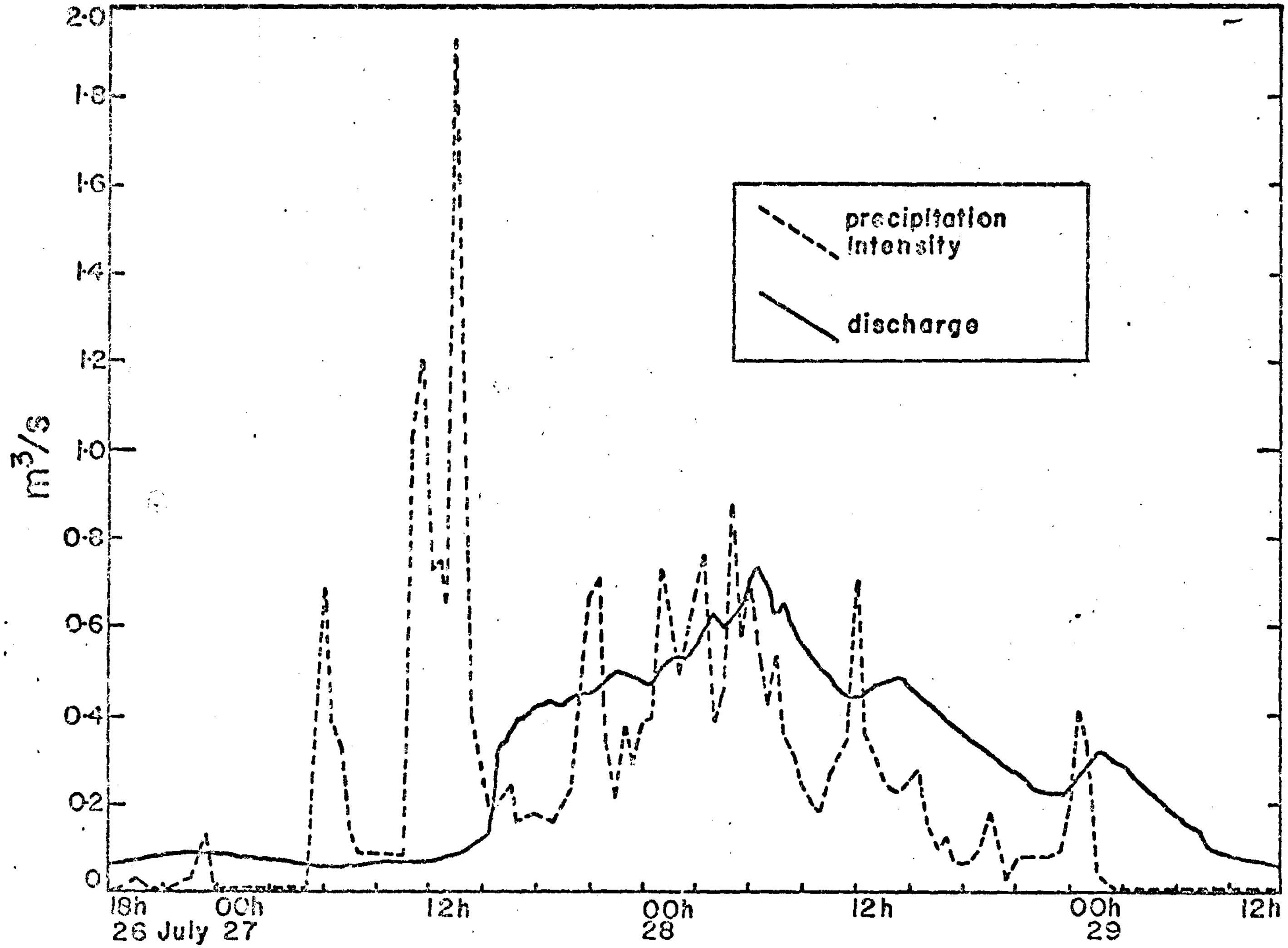


Fig. 6:3 Precipitation intensity and discharge during the rainstorm and flood, 26 - 29 July.

peaks is thus some eighteen hours; this value, however, gives a misleading impression, for the centre of mass of the rainfall input (i.e. the time by which 50% of the total precipitation had occurred) was located only 6 - 7 hours ahead of the hydrograph peak.

The covariance and spectral density functions of the series of precipitation intensity and stream discharge were calculated with a time interval of thirty minutes and fifteen lags, the fifteenth lag thus being 7.5 hours. The number of data points was 132. Since the series of both precipitation and discharge are rather weakly Gaussian, their median values provide better indications of central tendency than do their means; the analyses were performed both with the series standardized conventionally about their mean values and with the series unitized about their median values. The effect of setting the maximum value to +1.0, the minimum value to -1.0 and the median to 0.0 is clearly to disturb the ratios between maxima and minima and thus to alter the amplitude properties of the time series. For the purposes of frequency analysis, however, the series are rendered more nearly Gaussian by this operation, and become easier to analyze.

The autocovariance and spectral density functions of the precipitation series (Fig's. 6:4, 5) suggest periodicities in the series of 5 h, 2.5 h and 1h; however, these periodicities are not evident when the series is unitized about the median (Fig's 6:6, 7). The functions for the discharge series decay as lag and frequency increase, linearly in the case of autocovariance and exponentially in the case of spectral density; no further information is obtained by unitizing the series about the median.

The cross-covariance function of the paired series (Fig. 6:8)

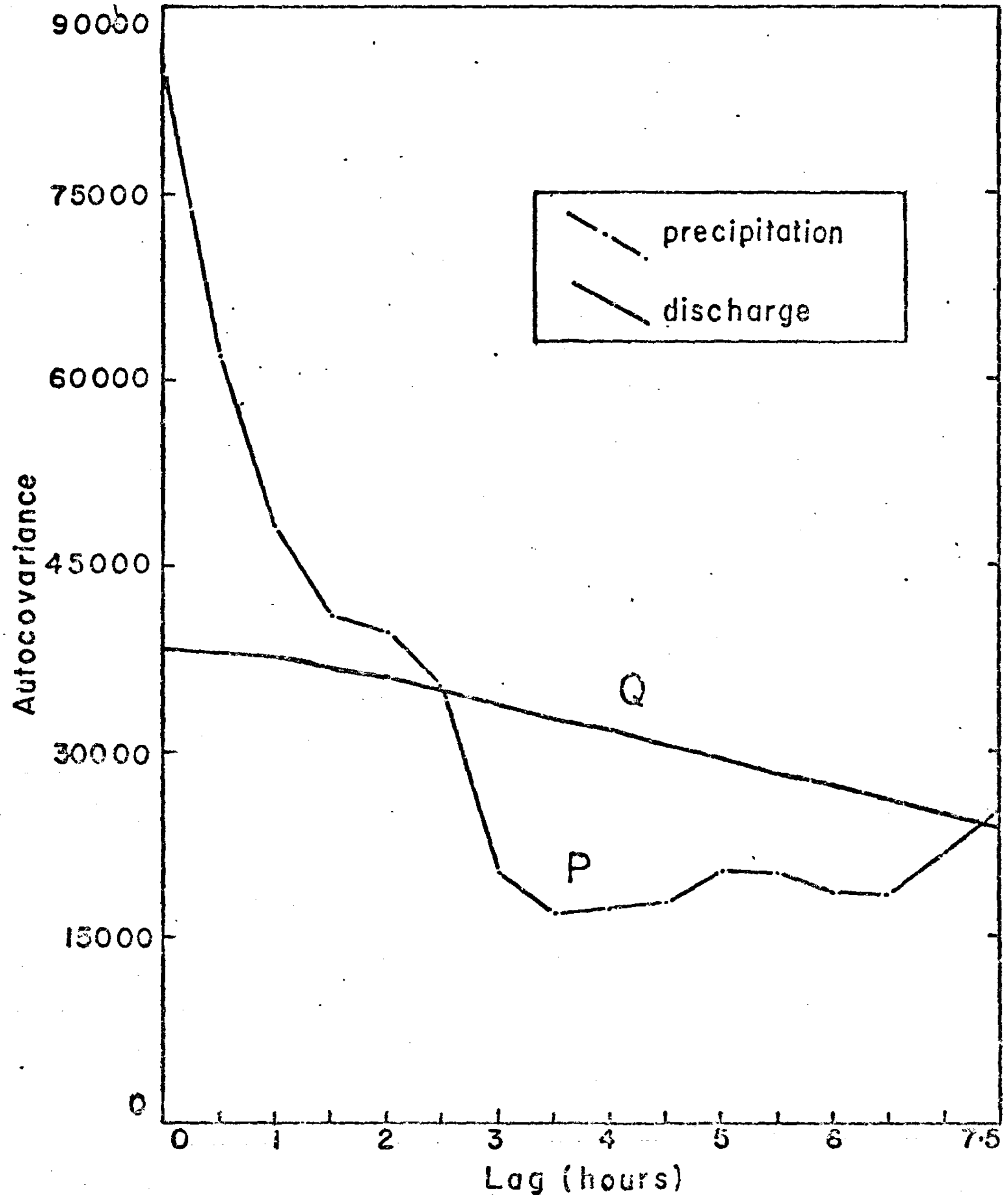


Fig. 6:4 Autocovariance of precipitation and discharge.

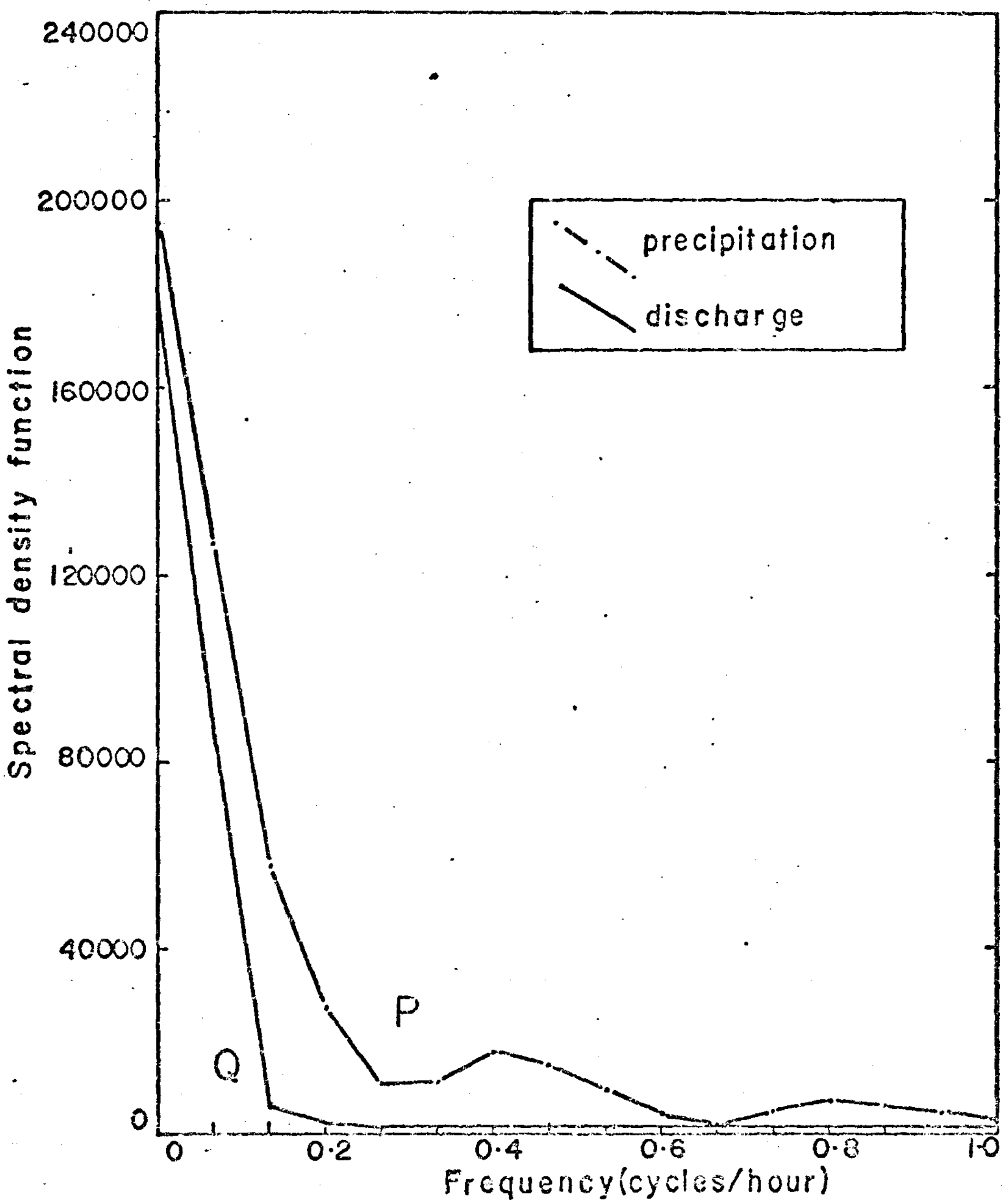


Fig. 6:5 Spectral density functions of precipitation and discharge.

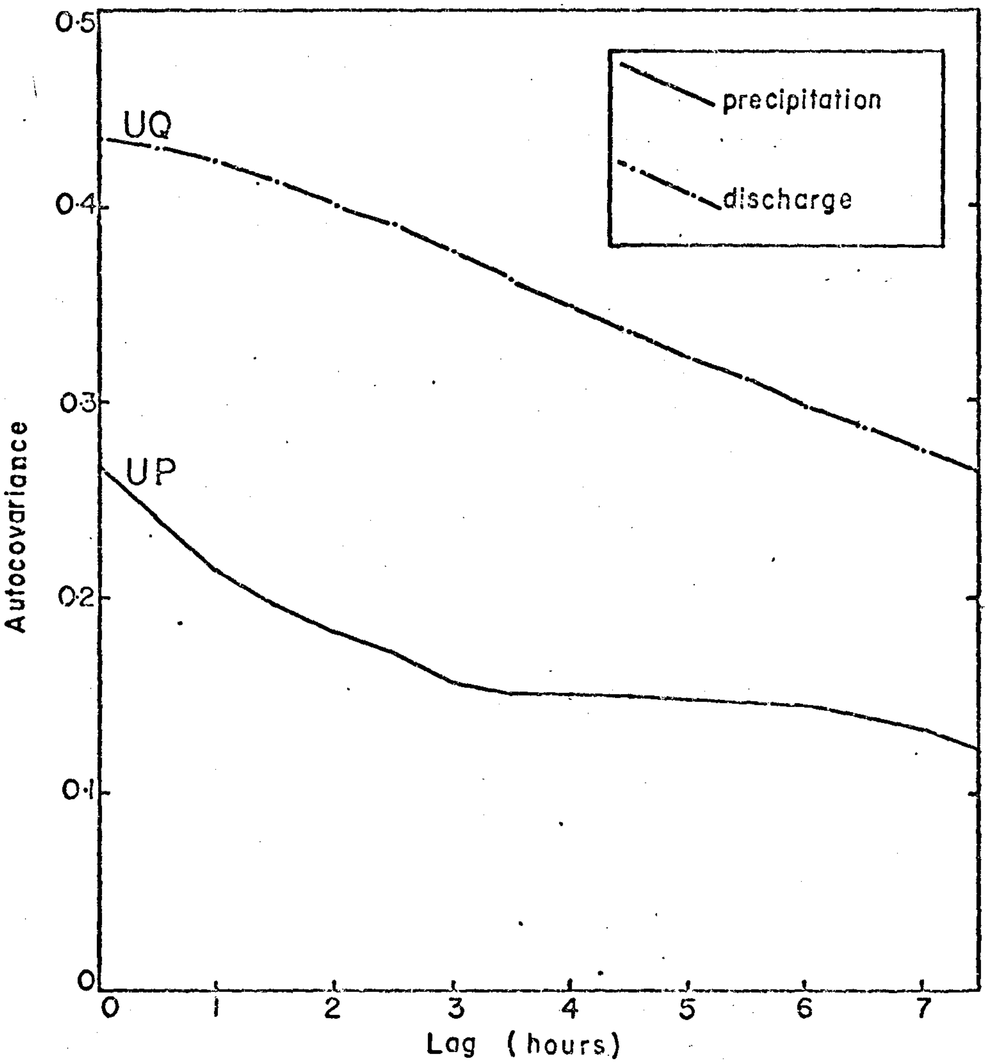


Fig. 6:6 Autocovariance of precipitation intensity and discharge; series unitized about median values.

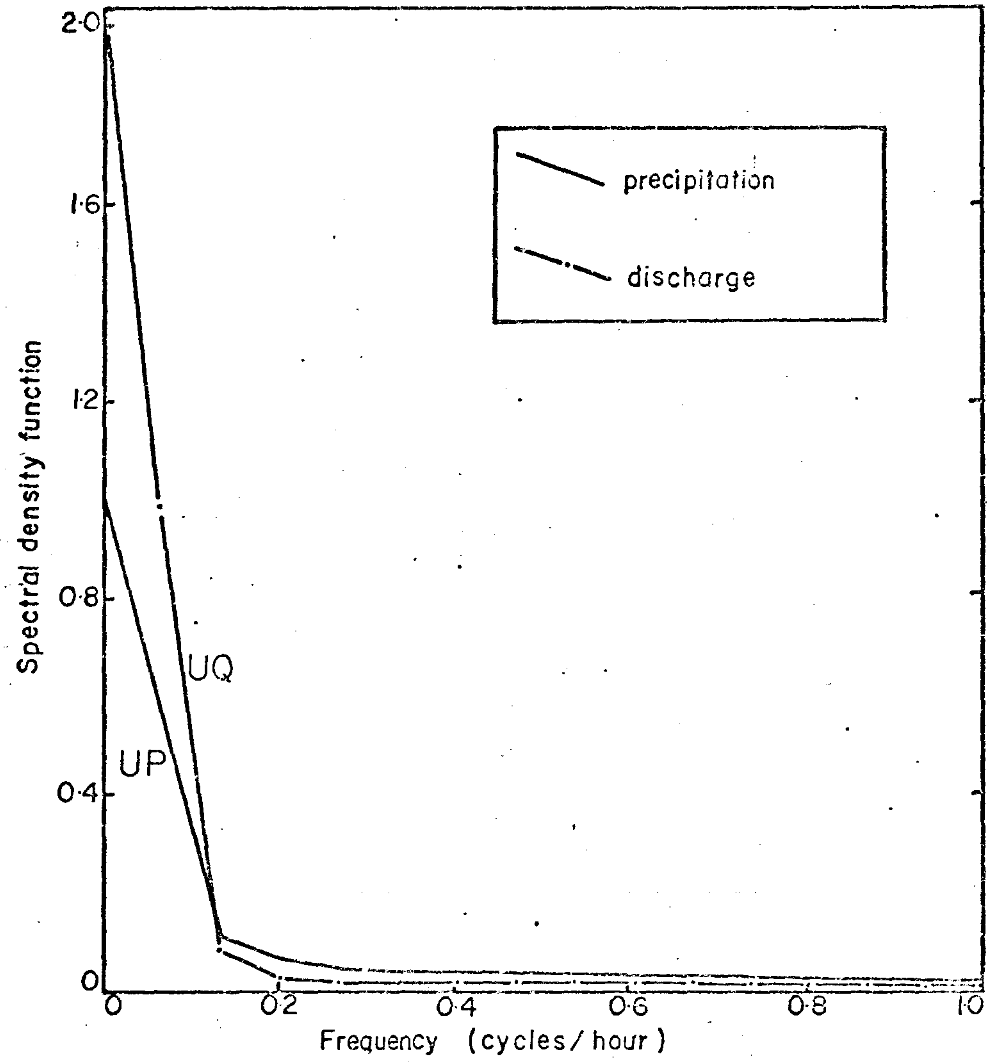


Fig. 6:7 Spectral density functions of precipitation intensity and discharge; series unitized about median values.

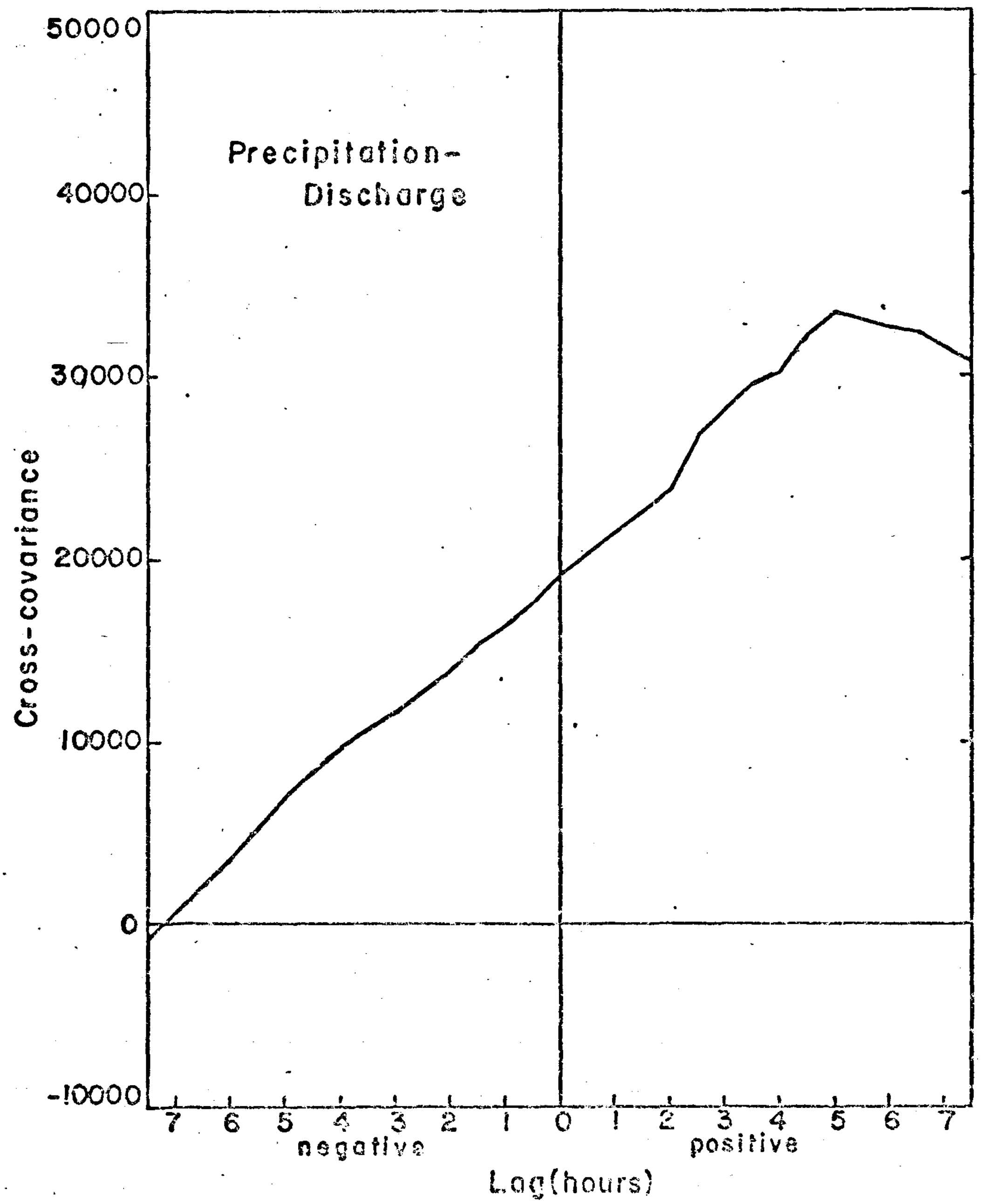


Fig. 6:8 Cross-covariance of precipitation and discharge.

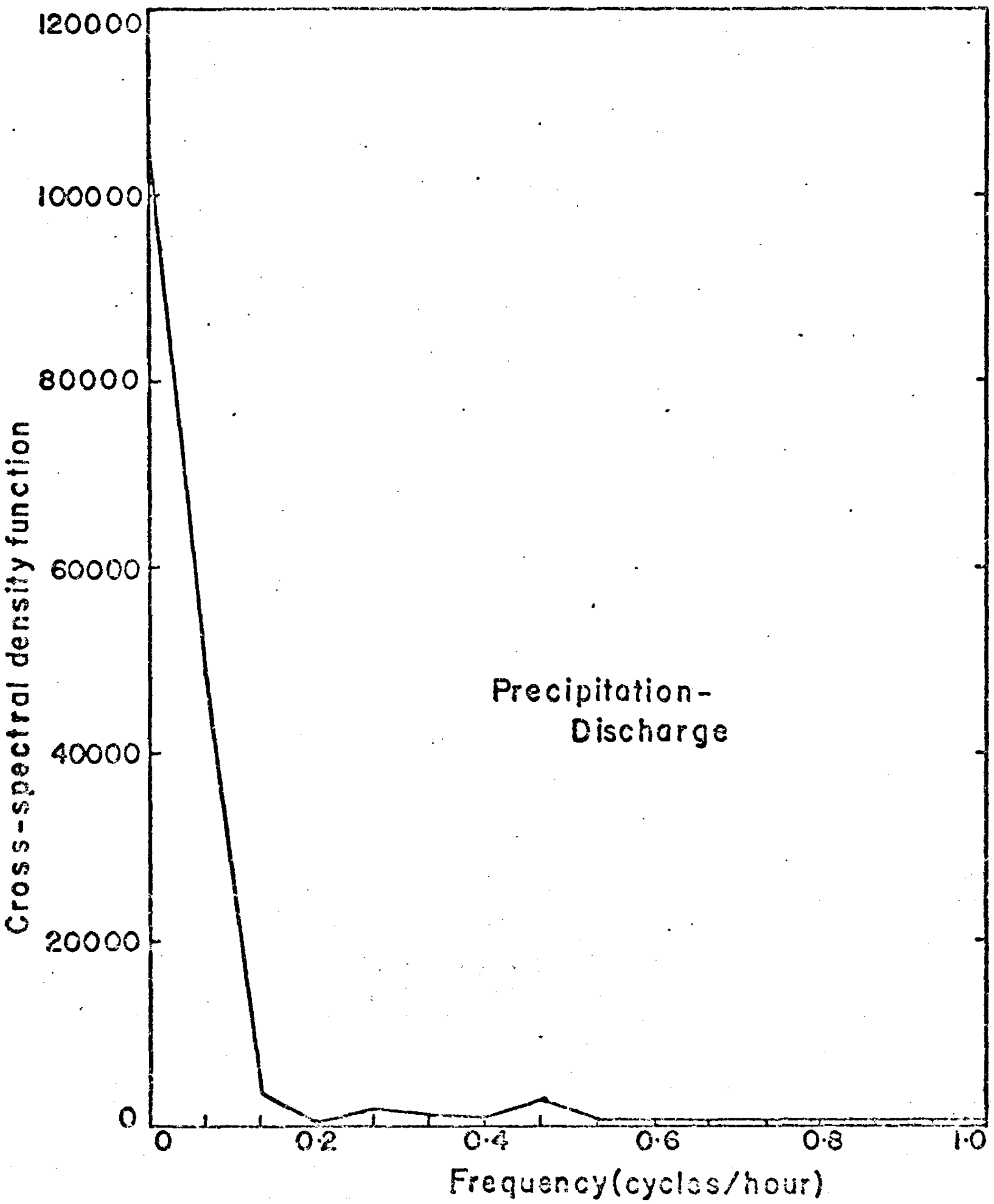


Fig. 6:9 Cross-spectral density function of precipitation and discharge.

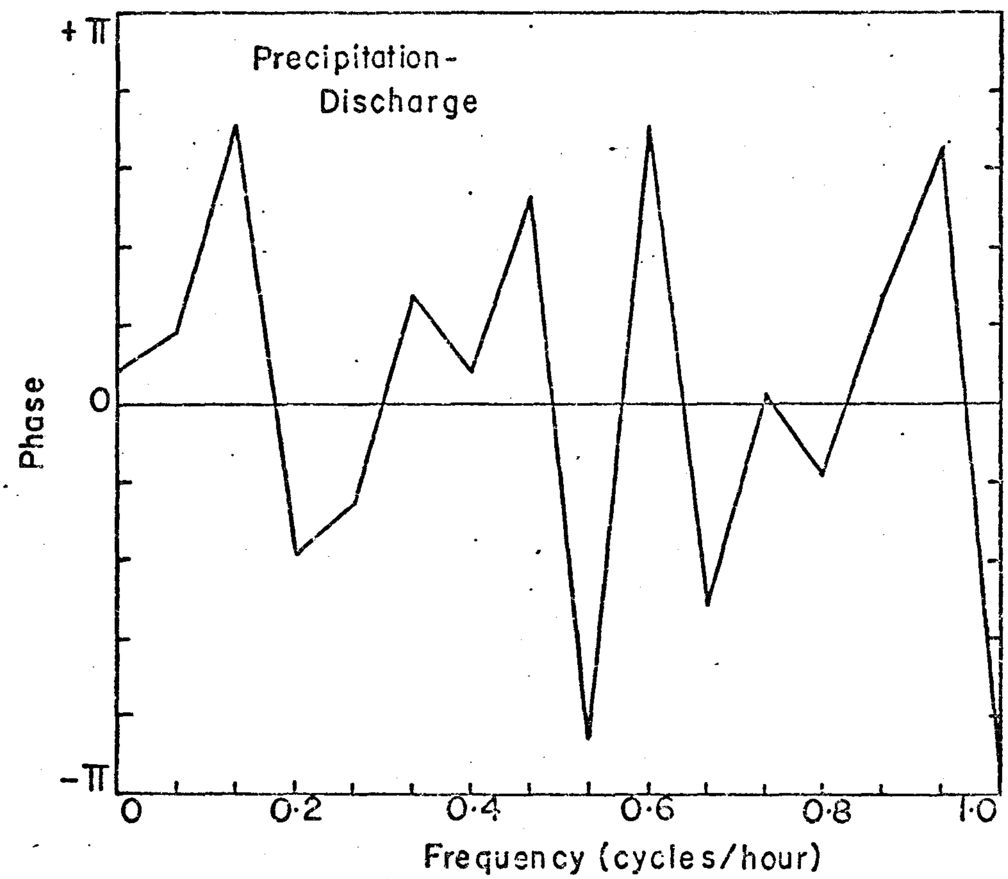


Fig. 6:10 Phase diagram for precipitation and discharge.

exhibits a maximum at +5 h, suggesting that this is the length of time by which discharge lags behind the input of precipitation. It would appear from this value that there is no decrease in lag time as the intensity of the input increases, for the lag is the same for the "low-intensity" series of radiation and discharge as for an input of precipitation and an output of storm runoff at higher intensity. Chiang (1968) maintained that the lag of drainage basin response to a given input should vary inversely with the intensity of that input. The limited evidence presented here from "Jason's Creek" suggests that this may not be the case; certainly the proposition does not hold for the two types of input observed in "Jason's Creek" in July 1970.

The cross-spectral density functions (Fig. 6:9) and phase plots (Fig. 6:10) are uninformative. Since the autocovariance and spectral density functions of the uncrossed series suggest an absence of natural periodicity within the series, it is unlikely that there should be any relationship, in the frequency domain, between the series. The cross-covariance, cross-spectral density and phase graphs for the unitized series have not been included here, for their form is very similar to the graphs for the conventional series. However, the operation of unitization about the median does appear to have some value in smoothing out insignificant maxima in the analytical functions, as in the case of Fig's. 6:4, 5 and 6:6, 7.

Fig. 6:11 is a plot of basin storage during the rainstorm against storm runoff. Storage was calculated as the excess of accumulated precipitation over accumulated runoff, the latter quantity being derived by a subtraction of baseflow from total discharge. Baseflow was arbitrarily

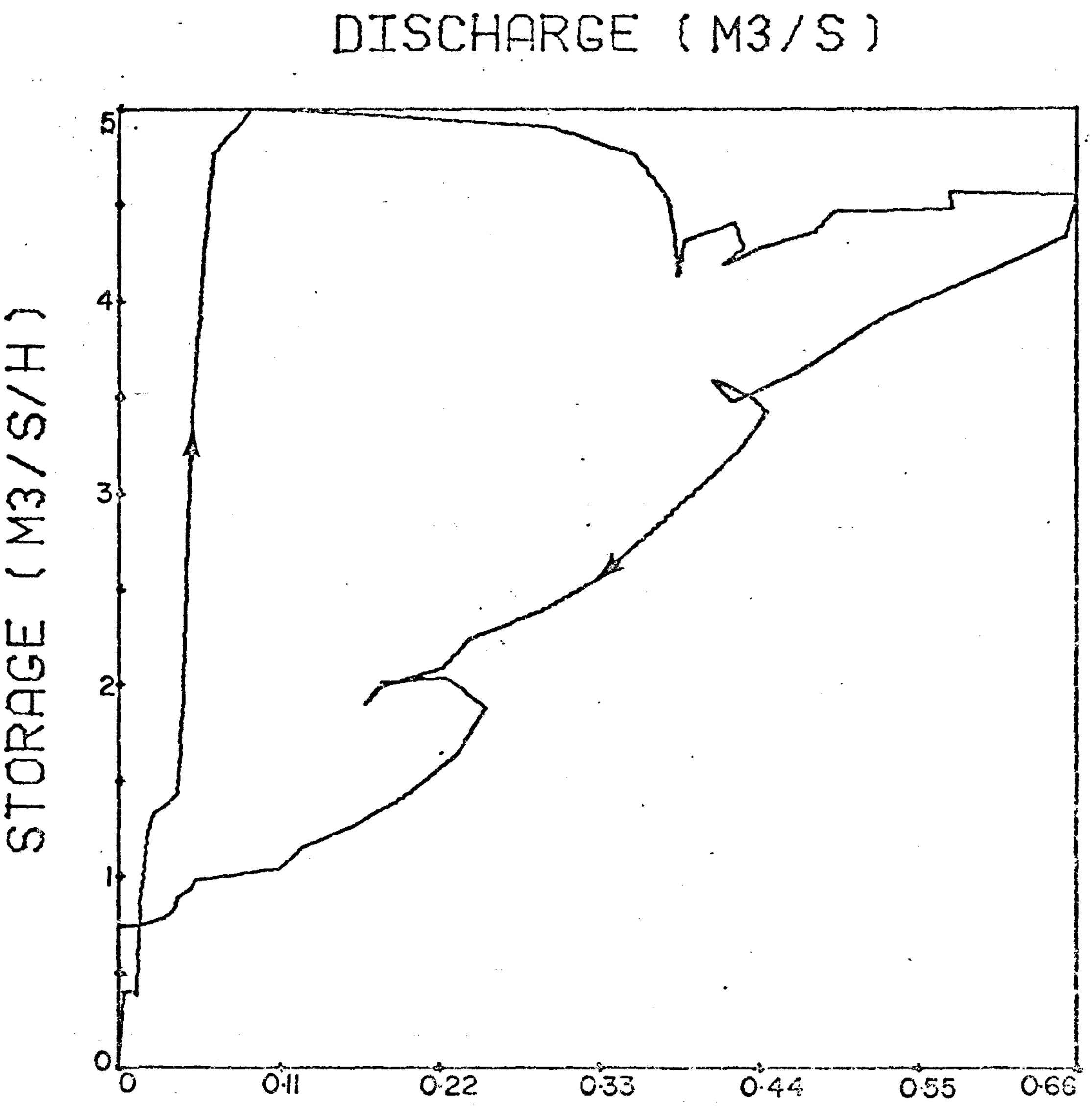


Fig. 6:11 Plot of basin storage against discharge,

26 - 29 July.

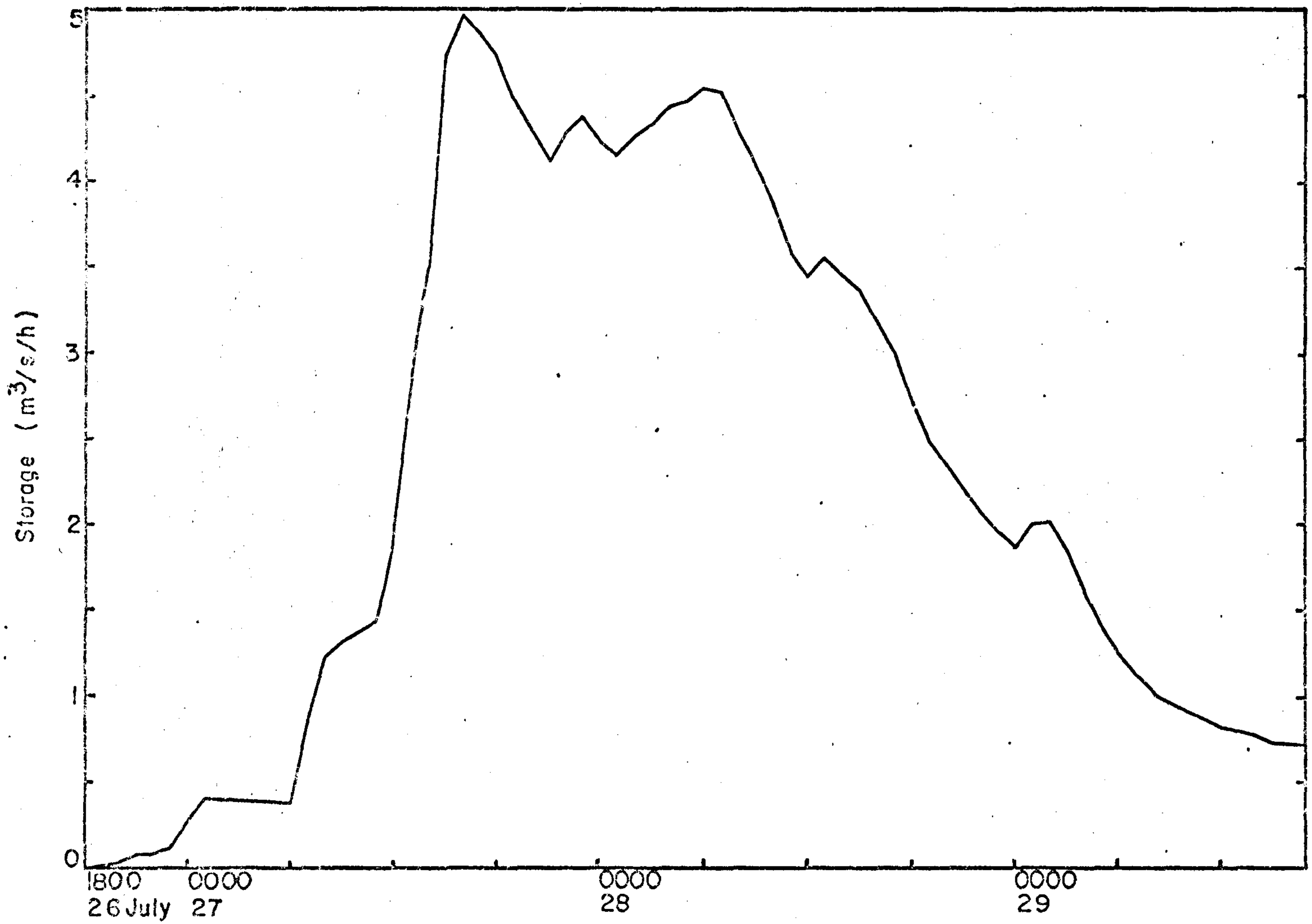


Fig. 6:12 Basin storage, 26 - 29 July.

interpolated beneath the flood hydrograph as an extension of the diurnally fluctuating pattern of snowmelt discharge; this procedure may have introduced error into the calculations, but there is no means of determining baseflow accurately and the adoption of arbitrary values represents an improvement over using no values at all.

The form of the graph results from the lag between input and output. Storage of water within the basin reaches a maximum at or shortly after the time of maximum input, while the maximum discharge occurs several hours later as a result of the transportation lag imposed by the basin. Before the peak flow is reached a non-linear relationship exists between storage and discharge, but after the peak the relationship is linear for each of the three sections corresponding to receding limbs of the discharge hydrograph. The re-entrants separating the linear sections of the storage-discharge graph correspond to discrete peaks in the discharge hydrograph. Essentially the graph reflects three stages in the course of the rainstorm and flood: a stage in which increasing storage is a function of accumulating precipitation and a stage in which decreasing storage is a function of flood discharge, separated by a "plateau" stage of duration approximately equal to the period between the hyetograph peak and the hydrograph peak. This is more clearly illustrated by a plot of storage against time (Fig. 6:12). Chiu and Huang (1970) have proposed an interesting model of the non-linear, time-variant relationship between rainfall and runoff, which makes use of these storage properties in generalized form.

CHAPTER VII

FLUVIAL TRANSPORTATION OF SOLID AND DISSOLVED SEDIMENT

The paucity of the geomorphological literature on periglacial fluvial processes is in part a reflection of the Davisian view that mid-latitude regions with temperate climate are "normal". In "abnormal" regions, attention has naturally been devoted to landforms and processes peculiar to the region. Despite the fact that periglacial landforms are unique in a number of respects, the ultimate removal of material from the periglacial land surface is still effected by streams in the same fashion as in mid-latitude regions. The only other significant agents of removal are littoral processes (including, perhaps, the calving of sediment-laden glaciers); aeolian activity is probably unimportant at the present time in the High Arctic.

No attempt is made in this work to estimate rates of surface lowering as a function of volume of sediment removal. Such estimates have little meaning. However, comparisons of sediment load data with values obtained for mid-latitude streams of sizes comparable with that of "Jason's Creek" indicate that sediment loads are also comparable. This means only that the sediment load values are of roughly the same order of magnitude, considering that the problem of defining comparability is well nigh insuperable.

Movement of bed material:

Of the three fractions of the sediment load of "Jason's Creek", bed load proved the most difficult to measure and, in fact, no values for the magnitude of transportation of channel bed material were obtained. It is known that bed-load transport occurred mainly at maximum stream velocities greater than 1.9 m/s, i.e. for about 2% of the runoff season. At the highest velocities recorded (> 2.2 m/s) the entire channel bed was mobile. Similar observations were made by McCann and Howarth (personal communication, 1970) of bed-load movement conditions in the Mecham R., Cornwallis Island. The abundance of loose, coarse detritus mantling the surfaces of arctic drainage basins is apparently an important factor contributing to the observed high rates of bed-load movement out of these basins. Such high rates are achieved in channels with inconsiderable gradients. Coarse detritus is particularly frequent at lower elevations in the Canadian arctic islands, where isostatic uplift has exposed loose raised-beach material.

Bed-load movement may well be the most important form of fluvial sediment removal from drainage basins in the arctic islands. Since nothing is known of the process in quantitative terms, however, comparative analysis is not possible at present.

Sediment transport in suspension:

Data of suspended sediment concentration are available only for short periods, during which turbidity was usually noticeable (Fig. 7:1). Isolated values of concentration during the periods of low discharge suggest that for much of the time the suspended load of "Jason's Creek" was small or nil. Suspended load was probably carried in quantity only

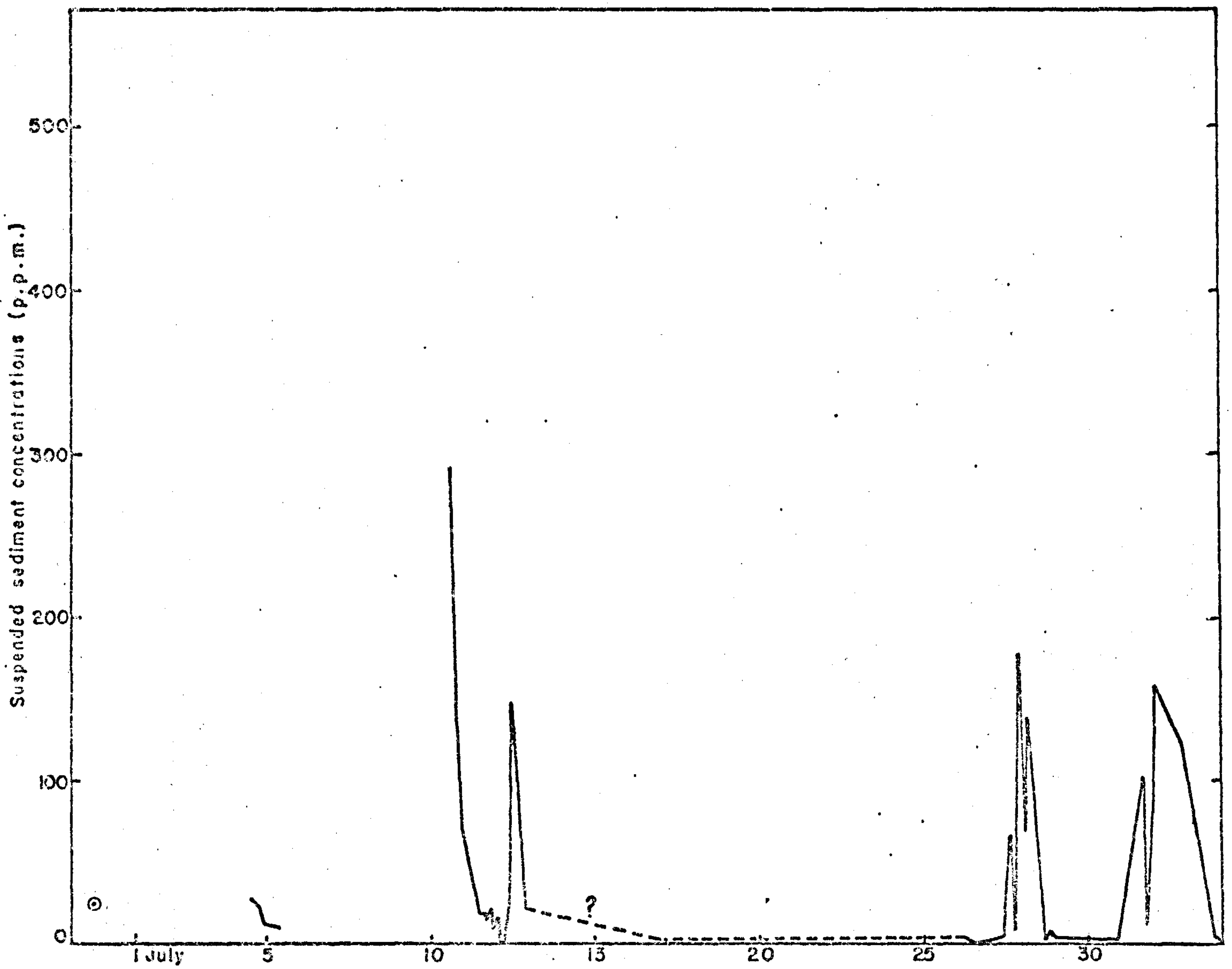


Fig. 7:1 Suspended sediment concentration.

when the stream was in flood, although one anomalous instance of high sediment concentration at low discharge will be discussed below.

A general comment on the suspended sediment record, sporadic as it is, concerns the variability in concentration over short periods. Both the amplitude and rate of fluctuation are much greater in the case of suspended sediment than in that of dissolved sediment. Suspended sediment concentrations of zero or trace were recorded for several samples, and the maximum recorded concentration was 291 p.p.m.; concentration of dissolved calcium and magnesium varied between 46 and 102 mg/l $CaCO_3$. The variability of the suspended sediment concentration, suggesting imperfect longitudinal mixing of the water-sediment body in the stream channel, would fatally complicate any attempt to compute annual removal of material from the basin in terms of depth of surface lowering/unit time, such as millimetres per thousand years. Fig. 7:2 provides an illustration of this short-term variability during the flood of 27 - 29 July. It also indicates that suspended sediment concentrations were greater than solute concentrations for approximately twelve hours at the height of the flood, and that the maximum concentration of suspended sediment occurred some time before maximum discharge. The latter observation probably reflects faster travel through the basin of the sediment wave relative to the flood wave. The former observation illustrates the direct correlation of suspended sediment concentration with stream velocity. As noted above, this correlation appears to be qualitatively applicable in the case of bedload movement, and similar remarks apply to suspended sediment with the qualification that the critical velocity, at and above which sediment is taken up as load, is lower. Table 7:1 shows values for suspended sediment and solute

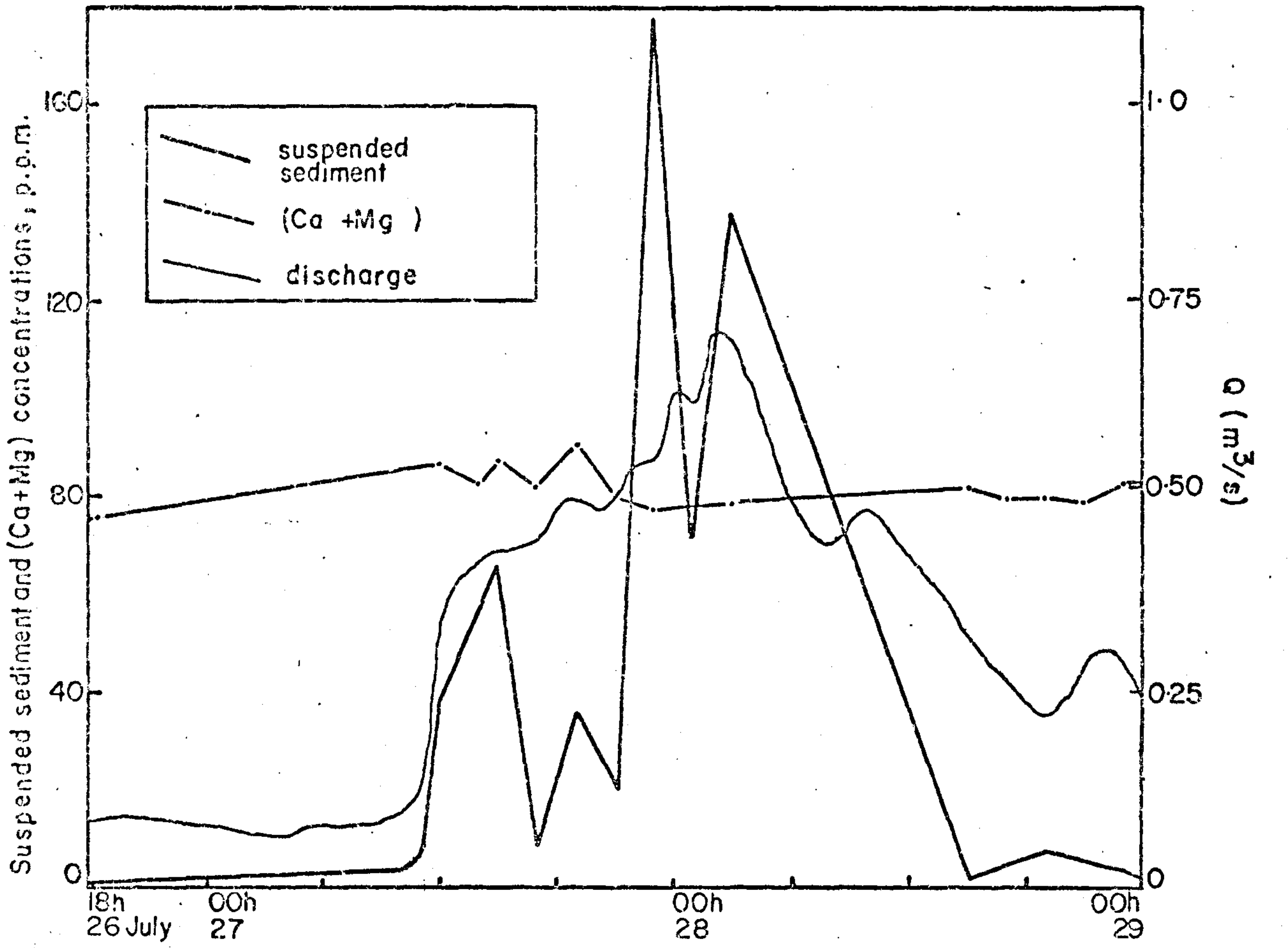


Fig. 7:2 Sediment and solute concenteations and discharge, 26 - 29 July.

concentration converted into values of load/unit time.

The high concentrations of suspended sediment recorded on 31 July and 1 August were associated with no extraordinarily high discharge or velocity. They resulted, in fact, from the occurrence of a mudslump and mudflow on the southern slope of the valley some 120 m upstream from the mouth of the creek. The slump and resulting flow began between 0815 h and 0830 h on 31 July and remained intermittently active for at least forty-eight hours (Fig. 7:3). The slope on which the slump occurred consists of a pair of convex sections separated by a concave section; below the lower convex section is the stream channel, while above the upper convexity there is a smaller concave section, occupied at the time of the mudslump by a snowpatch. This smaller concavity lies immediately below the crest of the slope.

The slump began as a failure along a shear plane in the active layer near the base of the upper convexity. The shear plane became the locus of the slump headwall, which began to enlarge and recede over the permafrost table, attaining a maximum width of 5 m and a maximum height of 1 m. The collapse material was delivered to a reservoir of mud in the intermediate concave section and from this reservoir of mud an overflow, consisting of a mixture of water, fine and aggregated sediment, and stones of gravel and cobble size, drained periodically through two channels over the lower convex section and into a mud lobe. This lobe encroached on "Jason's Creek", which removed the mud, for most of the time at a rate slightly less than the rate of arrival of the mud from the slope above. The mud diffused across the width of the channel over a length of 20 - 30 m and was transported away by the stream in suspension, accounting for

TABLE 7:1

CONCENTRATION AND LOAD OF SUSPENDED AND DISSOLVED

SEDIMENT IN "JASON'S CREEK", JUNE - AUGUST 1970

Date	Time	Discharge	Suspended sediment		Dissolved calcium		Dissolved calcium plus magnesium	
	(E.S.T.)	(m^3/s)	conc (ppm)	load (g/s)	conc (mg/l)	load (g/s)	conc (mg/l)	load (g/s)
June 27	2330	0.107			58	6.21	78	8.35
28	1800	0.056			68	3.81	96	5.38
29	1600	0.116	24	2.78	58	6.73	74	8.58
30	1330	0.110			54	5.94	72	7.92
July 1	1900	0.424			48	20.35	68	28.83
2	1830	1.424			36	51.26	46	65.50
3	1800	1.382			32	44.22	48	66.34
4	0900	0.338			32	10.82	51	17.24
	1200	0.201	27	5.43	40	8.04	50	10.05
	1430	0.211			40	8.44	59	12.45
	1700	0.174	24	4.18	38	6.61	66	11.48
	1930	0.161			44	7.08	54	8.69
	2100	0.143	11	1.57	42	6.01	55	7.86
	2330	0.109			44	4.80	60	6.54
5	0130	0.076			57	4.33	64	4.86
	0400	0.118			48	5.66	72	8.50
	0600	0.078			51	3.98	62	4.84
	0900	0.116	10	1.16	53	6.15	63	7.31
	2230	0.385			46	17.71	74	28.49

TABLE 7:1 continued ....

July 6	1900	0.351			49	17.20	62	21.76
7	1430	0.104			54	5.62	71	7.38
8	1300	0.500			50	25.00	64	32.00
9	1900	0.965			39	37.62	48	46.32
10	1300	1.184			43	50.91	62	73.41
	1500	0.94 (est.)	291	275 (est.)				
	1700	0.82 (")	149	120 (")				
	1900	0.722	93	67.15	49	35.38	59	42.60
	2100	0.678	72	47.42	34	23.05	56	37.97
11	1130	0.067	20	1.34	38	3.89	83	5.56
	1330	0.167	19	3.17	55	9.18	70	11.69
	1530	0.223	16	3.57	51	11.37	69	15.39
	1730	0.328	21	6.89	48	15.74	69	22.63
	1830	0.314	10	3.14	48	15.07	67	21.04
	1930	0.288	13	3.74	50	14.40	68	19.58
	2130	0.243	12	2.92	50	12.15	69	16.77
	2330	0.283	3	0.85	46	17.02	67	18.96
12	0230	0.169	TR	0.17	55	9.22	73	12.34
	0530	0.118	TR	0.12	49	5.78	70	8.26
	0730	0.152			47	7.14	62	9.42
	0930		24					
	1130	0.634	147	93.20	43	27.26	57	36.14
	1530	0.676			43	29.07	54	36.50
	1930	0.487	23	11.20	47	22.89	60	29.22
	2330	0.373			48	18.90	64	23.87
13	1830	0.322			48	15.46	64	20.71
14	2130	0.226			53	11.98	68	15.37
15	1830	0.274			48	12.15	60	16.44
16	2100	0.175			52	9.10	69	12.08
17	1900	0.127			58	7.37	78	9.91
18	2130	0.100			58	5.80	81	8.10
19	2130	0.093			58	4.79	86	8.00

TABLE 7:1 continued ....

July 20	2130	0.131			53	6.94	73	9.56
21	2030	0.053			79	4.17	100	5.30
22	2200	0.067			70	4.69	102	6.83
23	2230	0.083			58	4.81	79	6.56
24	1930	0.096			58	5.57	76	7.30
25	1900	0.090			62	5.58	80	7.20
26	1830	0.088	TR	0.09	56	4.93	76	6.69
27	1200	0.334	38	12.69	62	20.71	87	29.06
	1400	0.421			61	25.68	83	34.94
	1500	0.430	66	28.38	69	29.67	88	37.84
	1700	0.447	9	4.02	61	27.27	82	36.65
	1900	0.498	36	17.93	60	29.88	91	45.32
	2100	0.504	21	10.58	62	29.89	80	40.32
	2300	0.549	178	97.72	62	34.04	78	42.82
28	0100	0.623	70	43.61	58	36.14	80	49.84
	0300	0.699	138	102.46	61	42.64	79	55.22
	1500	0.331	2	3.97	64	21.18	82	27.14
	1700	0.277			62	17.17	80	22.16
	1900	0.229	8	1.83	62	14.20	80	18.32
	2100	0.280			60	16.80	79	22.12
	2300	0.283	4	1.16	64	18.11	83	23.49
	2400	0.249			60	14.94	83	20.67
29	2030	0.072			60	4.32	79	5.69
30	1000	0.062	TR	0.06	64	3.97	88	5.46
	2000	0.073	TR	0.07	72	5.26	91	6.64
31	1600	0.076	103	7.83	62	4.71	81	6.16
	1900	0.073	12	0.88	66	4.82	81	5.91
	2100		23					
	2300		80					
	2330a*	0.088	2	0.18				
	2330b	0.088	158	13.90				
August 1	1930	0.062	124	7.77	68	4.22	94	5.83

TABLE 7:1 continued ....

August	2	1830	0.045	4	0.18	68	3.06	88	3.96
	3	2030	0.033			70	2.31	96	3.17

*sample collected above mudflow

the high sediment concentrations recorded at the mouth of the creek. Samples collected from the stream above and below the mudflow at 2330 h on 31 July had respective concentrations of 2 p.p.m. and 158 p.p.m.

Kerfoot (1969) provides an account of slump and flow features similar to that described above from Garry Island, off the Mackenzie River delta. Although the features on Garry Island are appreciably larger than the "Jason's Creek" slump, they appear to be analogous. Kerfoot's description, with appropriate dimensional modifications, applies equally well to the "Jason's Creek" slump. One feature not emphasized by Kerfoot is the erosive role of the mudflows. On leaving the mud reservoir the two flows issuing from the "Jason's Creek" mudslump carved channels up to 0.7 m in depth through the active layer of the lower convex slope section. Mudflow discharge fluctuated rhythmically at a period of from five to at least thirty minutes, the fluctuation being related to periodic blockage of the mud channel. Four samples of the mud-water flow mixture, taken from the foot of the mudflow on 31 July at 2145 h, 2150 h, 2155 h and 2300 h, revealed considerable variation in rate of discharge and ratio of water to solid (Table 7:2).

Although the suspended load of "Jason's Creek" during the 31 July - 1 August period was not high in comparison with the loads carried during the flood periods, the summation of many geomorphic events of this type may account for a significant proportion of the total denudation achieved over long periods of time. Events of this type also account for much of the detail observed in the microrelief of the land surface. A connection was made in Chapter IV between the incidence of mudflows and northern aspect; the example discussed above was much the largest of

Fig. 7:3 Mudslump and mudflow on southern slope of valley, 31 July.

Fig. 7:4 Stone-and-mud stream on southern slope over mossy vegetation cover; note basal ice exposure in background.

several occurring in 1970, but a number of older slump and flow features of comparable size can also be found on the southern slope of the valley of "Jason's Creek". Examples of other types of discrete, semi-solid flow forms appear also to occur preferentially on the southern slope (Fig. 7:4). The implications of this preferential distribution are not speculated upon further in this work.

TABLE 7:2

MUDFLOW DISCHARGE AND COMPOSITION, 31 JULY

Time of collection	Duration of sample intake (s)*	Weight of sample (g)	Mudflow discharge (g/s)	Concentration of solids (p.p.m.)	Solid load (g/s)
2145	5	377.58	75.52	210000	15.9
2150	3	906.77	302.26	861000	260.2
2155	5	450.84	90.15	533000	48.0
2300	15	415.88	27.73	19000	0.5

*Samples collected in polyethylene bags held into flow beneath overhanging rock ledge; sealed water-tight until analysis.

Dissolved load:

The concentration of dissolved material in "Jason's Creek" was basically in inverse relationship with the discharge (Fig. 7:6). The principal series of data collected in 1970 consist of values for concentration of calcium and magnesium, and for pH. Calcium and calcium plus magnesium are reported in mg/1 of $CaCO_3$; unless otherwise stated

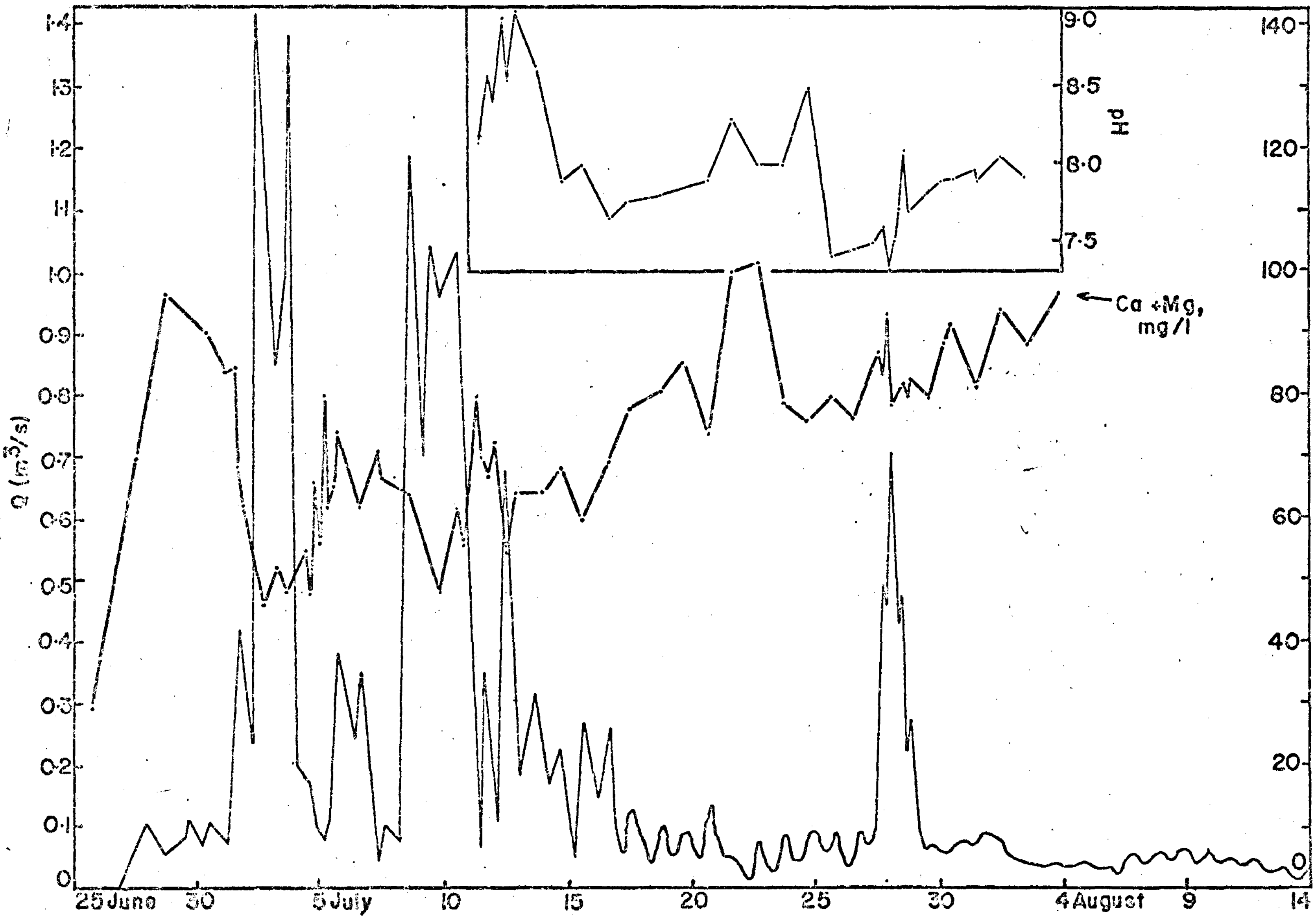


Fig. 7:5 Seasonal variations in solute concentration, pH and discharge of "Jason's Creek".

"solute concentration" refers to the concentration of dissolved calcium plus magnesium. Samples were also analyzed for dissolved sodium, potassium, aluminium and iron at McMaster University, and occasional measurements of water temperature were made. The range of these latter measurements was from 0° to 1.5°C.

(Ca + Mg) concentrations increased over the flow season as a whole, reaching high values immediately preceding the snowmelt flood and decreasing to<50 mg/l during the flood itself. As snowmelt discharge decreased after the flood peak, corresponding solute concentrations increased until, at the end of the sample period in early August, they were in the 85 - 95 mg/l range. The seasonal maximum, 102 mg/l, was recorded on 22 July, which was a day of low incoming radiation and low stream discharge. During the rainstorm flood solute concentrations increased at first to 91 mg/l, then decreased to c. 80 mg/l and remained at that level for the remainder of the flood. The values recorded during the rainstorm are in direct contrast with those recorded during the snowmelt flood, when for comparable discharges the solute concentrations were lower by up to 30 - 40%.

Readings of the pH of the stream water were taken between 11 July and 2 August. The readings ranged from 9.05 on 12 July down to 7.3 during the rainstorm flood. The general seasonal trend of pH was downward, and the coefficient of correlation between pH and Ca concentration was found to be -0.592 (for fifty readings, significant at the 0.01 confidence level).

Thirty-two samples, collected between 11 July and 15 August, were brought back to McMaster University and tested for dissolved Na, K, Al and Fe on a Perkin-Elmer 303 atomic absorption spectrophotometer at the end of the 1970 field season. Although some of the samples were eight weeks old

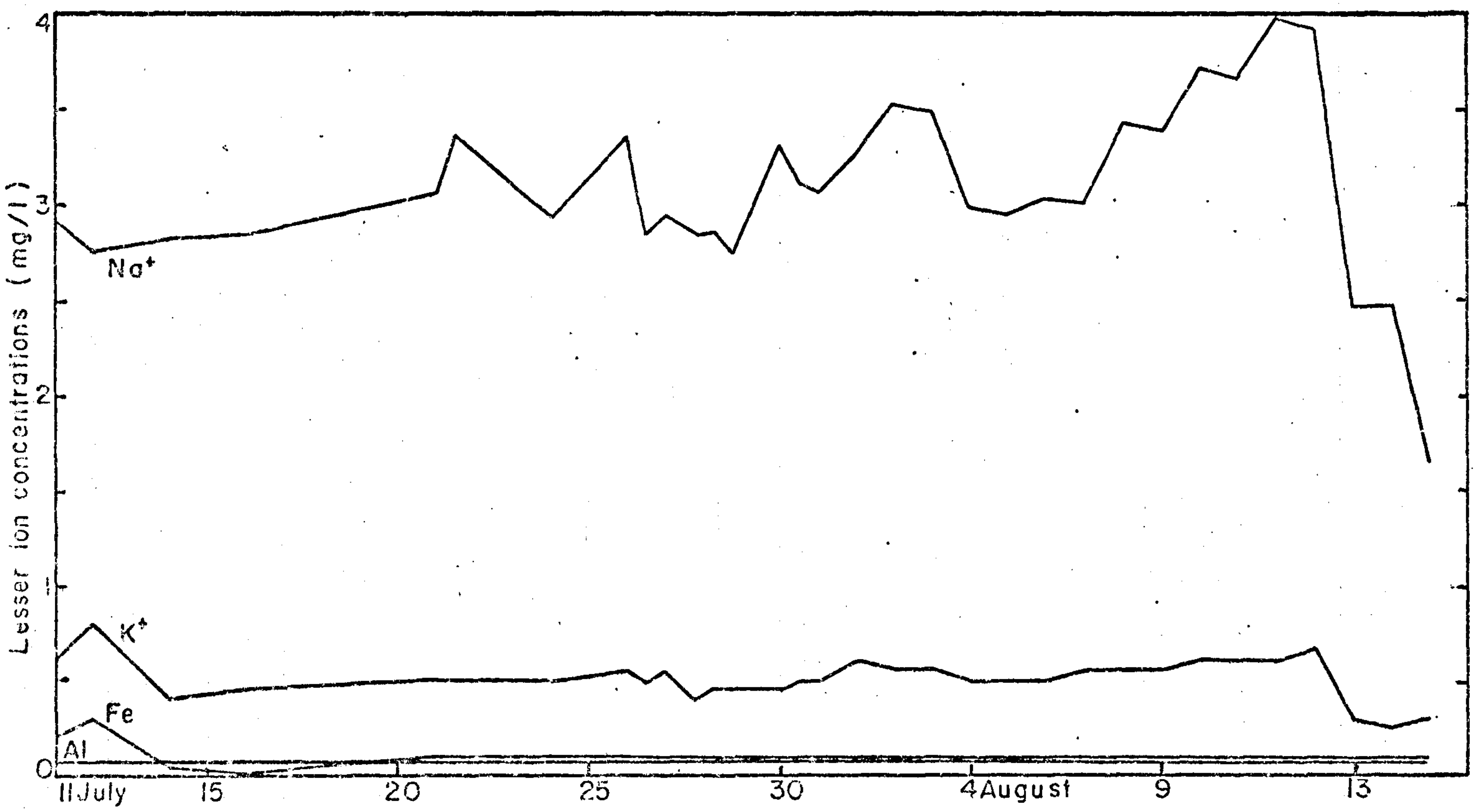


Fig. 7:6 Concentration of lesser ions in solution in "Jason's Creek".

by the time they were analyzed, they were stored in tightly-capped polyethylene bottles and deterioration is not thought to have been excessive. The results provide a general indication of the smallness of the concentrations of these ions: Na^+ ranges from 1.66 to 3.98 mg/l, K^+ from 0.25 - 0.8 mg/l, while Al and Fe were either not detectable at all or present only in trace quantities.

Table 7:1 illustrates the predominance of dissolved load over suspended load for the greater part of the 1970 flow season. Transportation of dissolved calcium and magnesium is much greater during flood periods than during periods of low discharge, but flood transportation of suspended material is greater still (cf. the data for 10 July). It is not possible to derive meaningful figures for the realtive significance of the two modes of removal over the entire season, considering the lack of suspended sediment data for the snowmelt flood and the short-term variability of suspended-sediment concentration. However, for the period of the 27 - 29 July flood, calculations using the existing data give arithmetic means of 24.7 g/s for suspended load and 30.6 g/s for dissolved load. The significance of these figures is uncertain, but they suggest that the quantity of calcium and magnesium removed in solution was comparable with and possibly somewhat greater than the total amount of material removed in suspension. In the case of the snowmelt flood suspended sediment transport was probably rather greater than solute transport, for concentrations of Ca and Mg in solution were proportionately lower in the snowmelt flood than in the rainstorm flood.

Suspended and Dissolved Sediment in the Mecham River:

Partially complete records of discharge, suspended sediment concentration and solute concentration were obtained in 1970 from the Mecham River, south-east Cornwallis Island. These records are graphed in Fig. 7:7. Making suitable alterations to allow for the larger size of the Mecham R., remarks made about the hydrologic and geomorphic behaviour of "Jason's Creek" apply to both streams, and observations made on the Mecham R. corroborate the account given of the activity of "Jason's Creek".

The maximum discharge of the Mecham R. in 1970 was at least 26.6 m^3/s on 8 July. The spring flood was slower to reach its peak than was the case with "Jason's Creek"; it commenced on 2 July, when the stream burst through an ice dam blocking its course and generated a short-lived "flash flood". Flood discharge continued after the subsidence of this flash flood for some two weeks, the annual maximum discharge being attained thirteen days after the commencement of flow and six days after the start of the flood.

Well-marked diurnal fluctuations in discharge were observed during the period 14 July - 16 August, when a stage recorder was in operation, as well as during the flood period. Diurnal discharge maxima occurred at approximately 2200 - 2300 h (E.S.T.), suggesting that the basin lag time was 8 - 9 hours rather than 5 hours as in "Jason's Creek".

Suspended sediment concentration reached a maximum of 571 p.p.m. at 1125 h on 2 July, at the height of the flash flood; by 1140 h concentration had decreased to 328 p.p.m., and by 2100 to 111 p.p.m. A concentration of 540 p.p.m. was recorded on 8 July. Sampling was discontinued on 13 July but was resumed between 4 and 13 August, during which period concentration was never greater than 5 p.p.m. Concentration

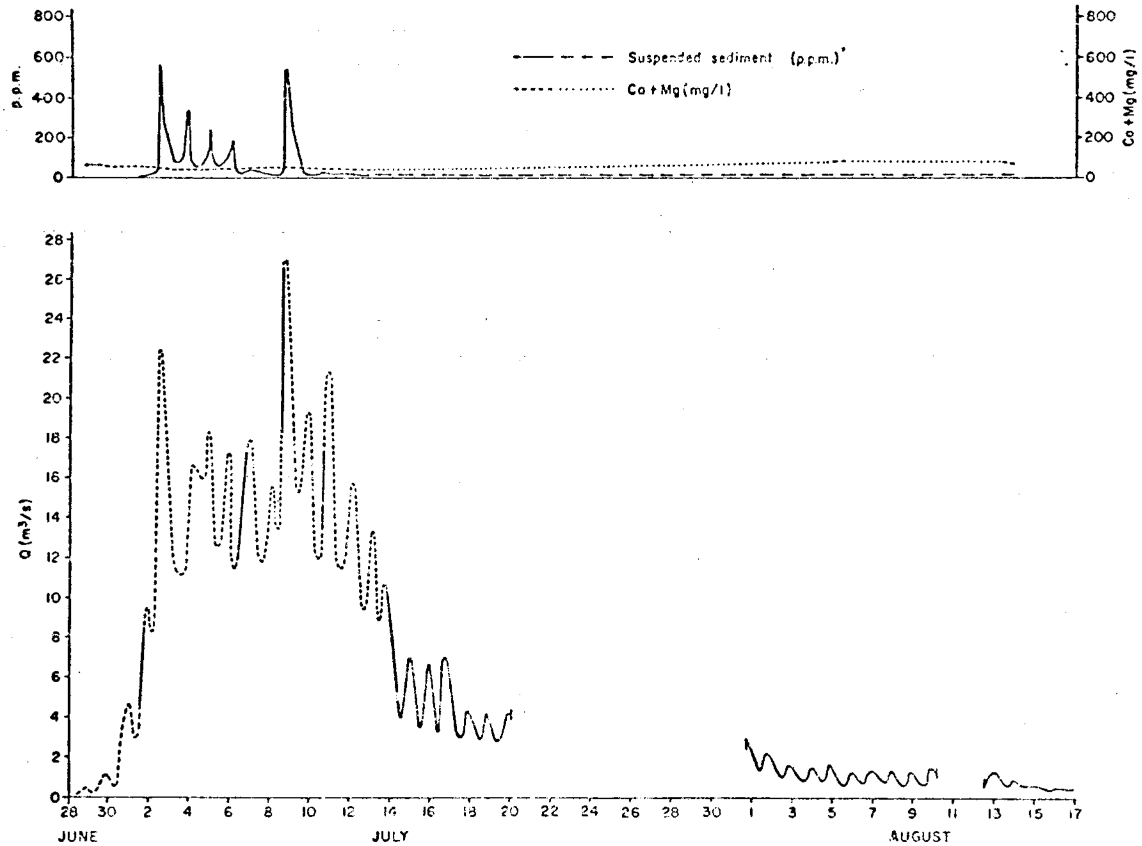


Fig. 7:7 Discharge, suspended sediment and solute concentrations, Mecham R., 1970. Dashed sections of hydrograph interpolated on basis of qualitative observations.

of dissolved Ca and Mg ranged from 33 to 90 mg/l. In the period preceding the spring flood the range was from 50 to 60 mg/l, and during the flood from 33 to 50 mg/l. Between 4 and 13 August concentrations recorded were between 70 and 90 mg/l. The relationship of solute concentration to discharge is discussed in Chapter VIII.

The load carried by the Mecham R. was naturally greater than that carried by "Jason's Creek"; maximum observed values were 8350 g/s for suspended load and 818 g/s for solute load. Estimates of the load at peak discharge on 8 July (probably greater than 30 m^3/s) are 16200 g/s for suspended load and 1350 g/s for solute load.

CHAPTER VIII

SOLUTIONAL ACTIVITY IN THE BASIN OF "JASON'S CREEK"

The inverse relationship of solute concentration to discharge referred to in Chapter VII, is non-linear in the sense that discharge increases more rapidly than solute concentration decreases (Fig. 8:1). The basis of the relationship is the well known dilution effect which results as the volume of water passing over a relatively constant surface area (viz., the channel perimeter) is increased: a lesser proportion of the water comes into contact with the channel perimeter and opportunities for solutional reaction become relatively fewer. The tendency for velocity to increase with discharge has an effect on the relationship; product-moment correlation yields a coefficient of -0.539 between (Ca + Mg) and maximum stream velocity, as against -0.346 between (Ca + Mg) and discharge. The increase in channel perimeter area with rising stage also has an effect, but the relationship is fairly well described by a power curve. A series of least-squares-fitting operations on the data collected in 1970 produced the following equations for the curve:

$$Ca = 42\ Q^{-0.118} \quad , r = -0.797, \qquad (8:1)$$

$$Q = 3.51 \times 10^{8}\ Ca^{-5.4} \quad , \text{"} \quad ; \qquad (8:2)$$

$$(Ca + Mg) = 56\ Q^{-0.118} \quad , r = -0.825, \qquad (8:3)$$

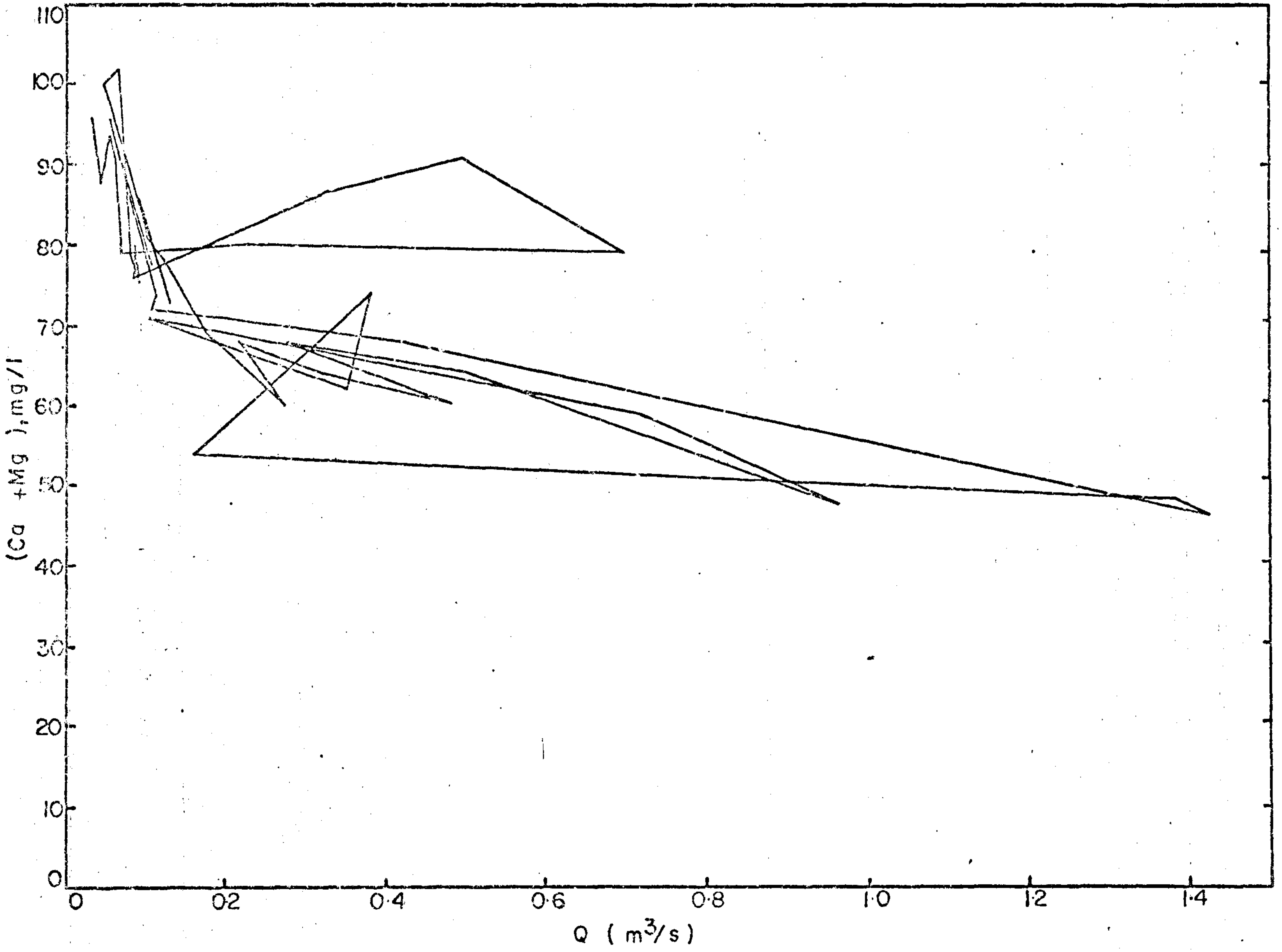


Fig. 8:1 Plot of solute concentration against discharge; data points are connected in temporal sequence.

$$Q = 9.04 \times 10^{9} \quad (Ca + Mg)^{-5.8} \quad , \quad " \quad ; \qquad (8:4)$$

where Q = discharge in m^3/s and Ca, (Ca + Mg) denote solute concentrations in mg/l $CaCO_3$; r = correlation coefficient, number of observations = 72. Ca and (Ca + Mg) are plotted against discharge in Fig. 8:2 and Fig. 8:3 respectively.

The equations were derived for waters sampled at the mouth of "Jason's Creek" over the 1970 flow season and at the mouth of the Mecham R., Cornwallis Island, during the 1970 spring flood. The latter group of samples was collected and analyzed by S. B. McCann and P. J. Howarth, who have permitted their use in the present discussion. Since the basin of the Mecham R. is larger than that of "Jason's Creek" its discharge is proportionately greater. The two basins are eroded into the same lithological units and are physiographically rather similar, and these factors may be reflected in the fact that it is possible to describe the solute-discharge relationship for both streams with a single equation.

Calcium/Magnesium Ratios:

The similarity of the exponents in eqs. 8:1 and 8:3 suggests a fairly constant relationship between concentrations of Ca and of (Ca + Mg), and by extension between Ca and Mg. This suggestion is confirmed by Fig. 8:4, in which the two are plotted against each other. It is clear that although there is considerable variability in the ratio Ca/Mg, the mean ratio does not change as the sum of these two increases. The mean of all the sample ratios is close to 3.2. For "Jason's Creek" the mean is slightly less, approximately 3.0, while for the other sample groups the

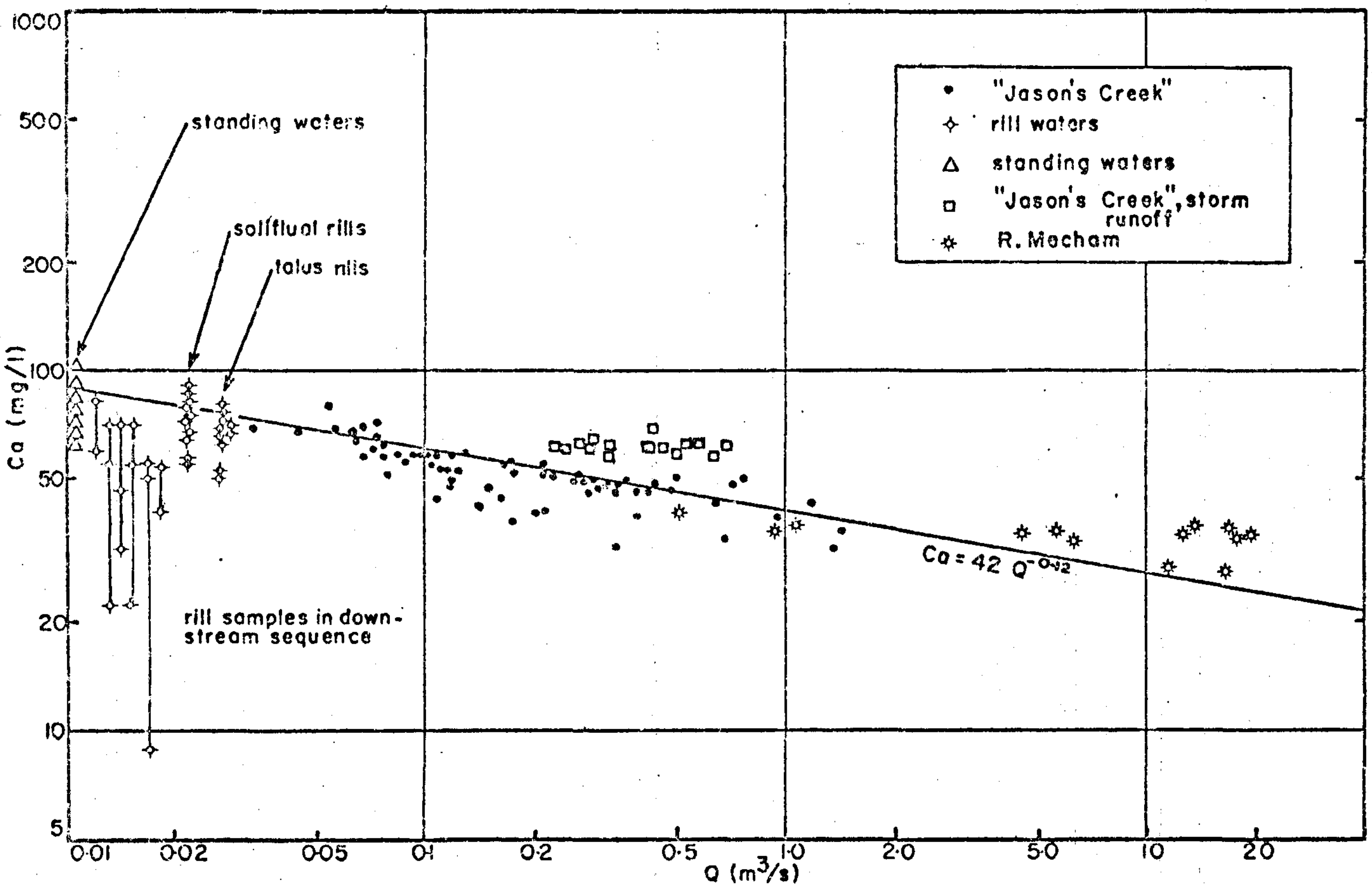


Fig. 8:2 Ca concentration against discharge; logarithmic plot.

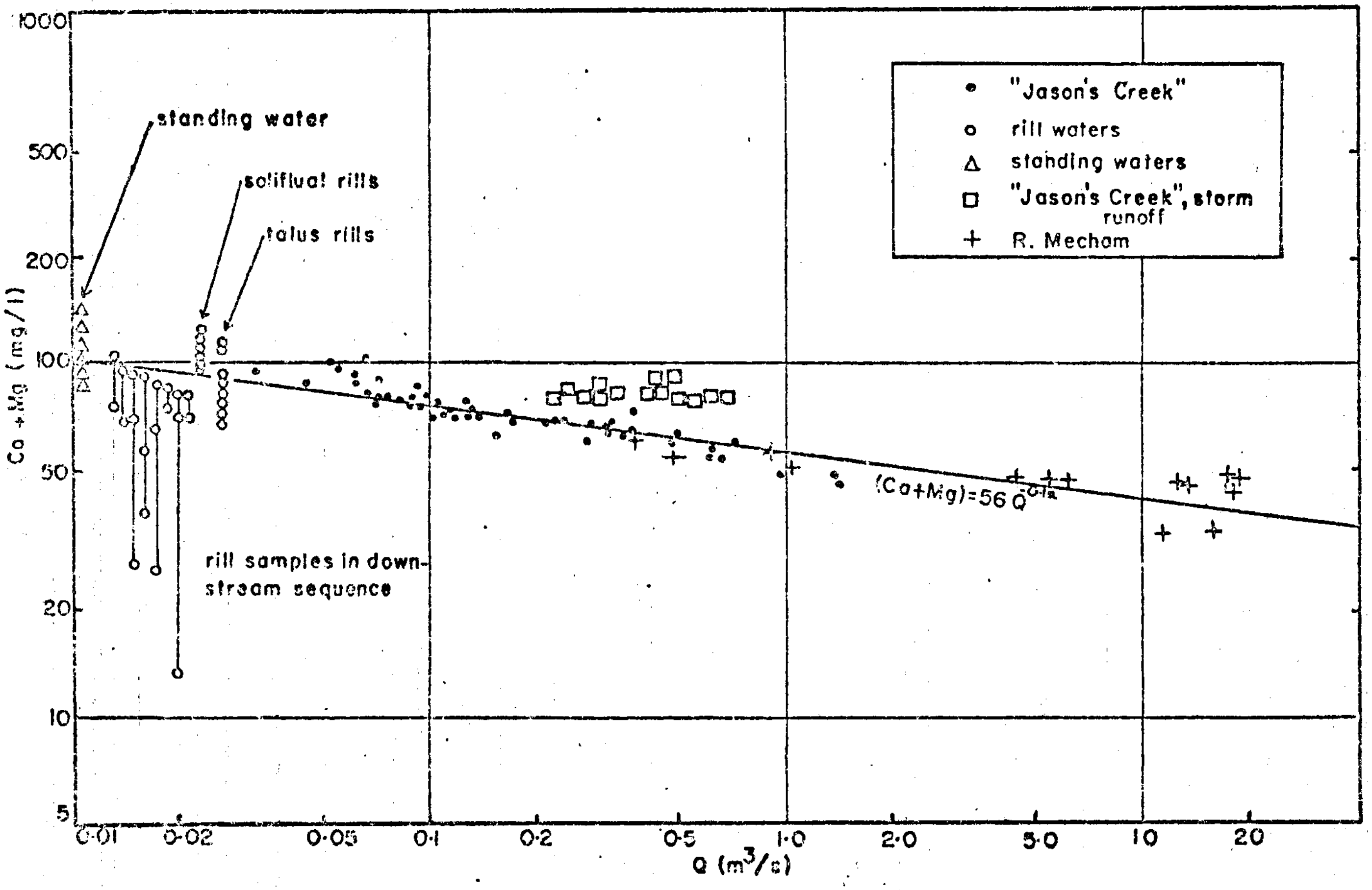


Fig. 8:3 (Ca + Mg) concentration against discharge; logarithmic plot.

mean ratio is higher, ranging up to 3.8 in the case of rills draining talus slopes. No trend with time can be distinguished in the waters of "Jason's Creek" (Fig. 8:5), and the Ca/Mg ratios for individual samples appear to be normally distributed about the mean value (Fig. 8:5, inset). The Ca/Mg ratio appears to be a property shared by all the waters of the region, and it is probably determined primarily by lithology. Ford (1971, in press) came to a similar conclusion with reference to limestone waters in the Rocky Mountains, where deviations from a regional mean of 2.5 could be explained in terms of differences in the rock types over and through which the waters had passed.

Features of the Limestone Solution Process:

Apart from the "Jason's Creek" and Mecham R. samples plotted on Figs. 8:2 and 8:3, there are five other groups of samples on these graphs: samples from standing water bodies, from rills draining soliflual terrain, from rills draining talus slopes and from "Jason's Creek" during the 27 – 29 July flood, together with several sets of rill samples taken in downstream sequence. Some of these samples were collected in 1969 by S. B. McCann from areas adjacent to the "Jason's Creek" catchment. The anomalous behaviour of "Jason's Creek" during the rainstorm flood is well illustrated by the isolation of the samples collected at that time from the rest of the "Jason's Creek" samples lying on the slope of eqs. 8:1-4. Discussion of this anomaly is postponed for the present.

The location of the rill water and standing water samples with respect to the discharge axes of Figs. 8:2 and 8:3 is entirely arbitrary. The discharges which correspond to the given Ca and (Ca + Mg) concentra-

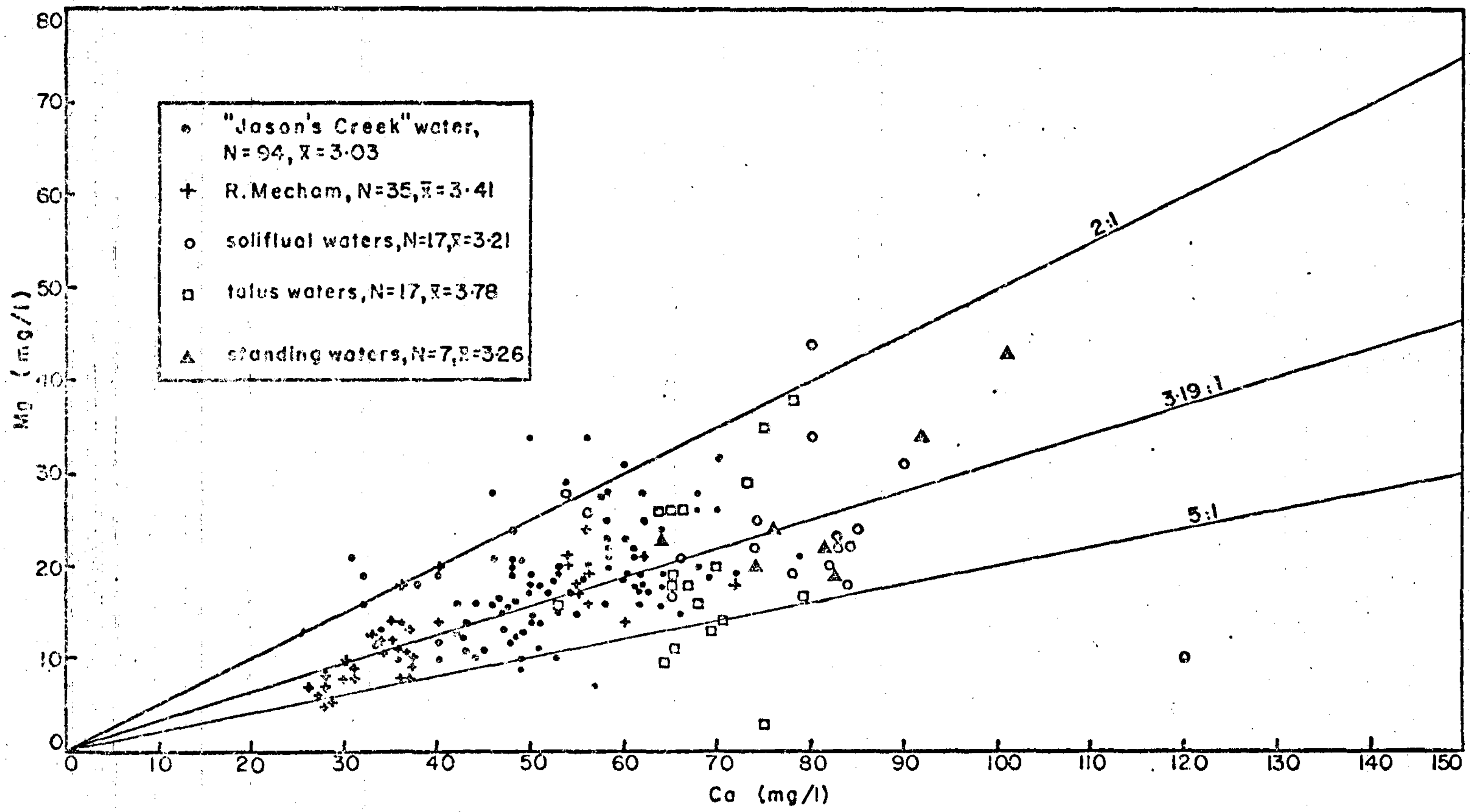


Fig. 8:4 Ratio of Ca to Mg.

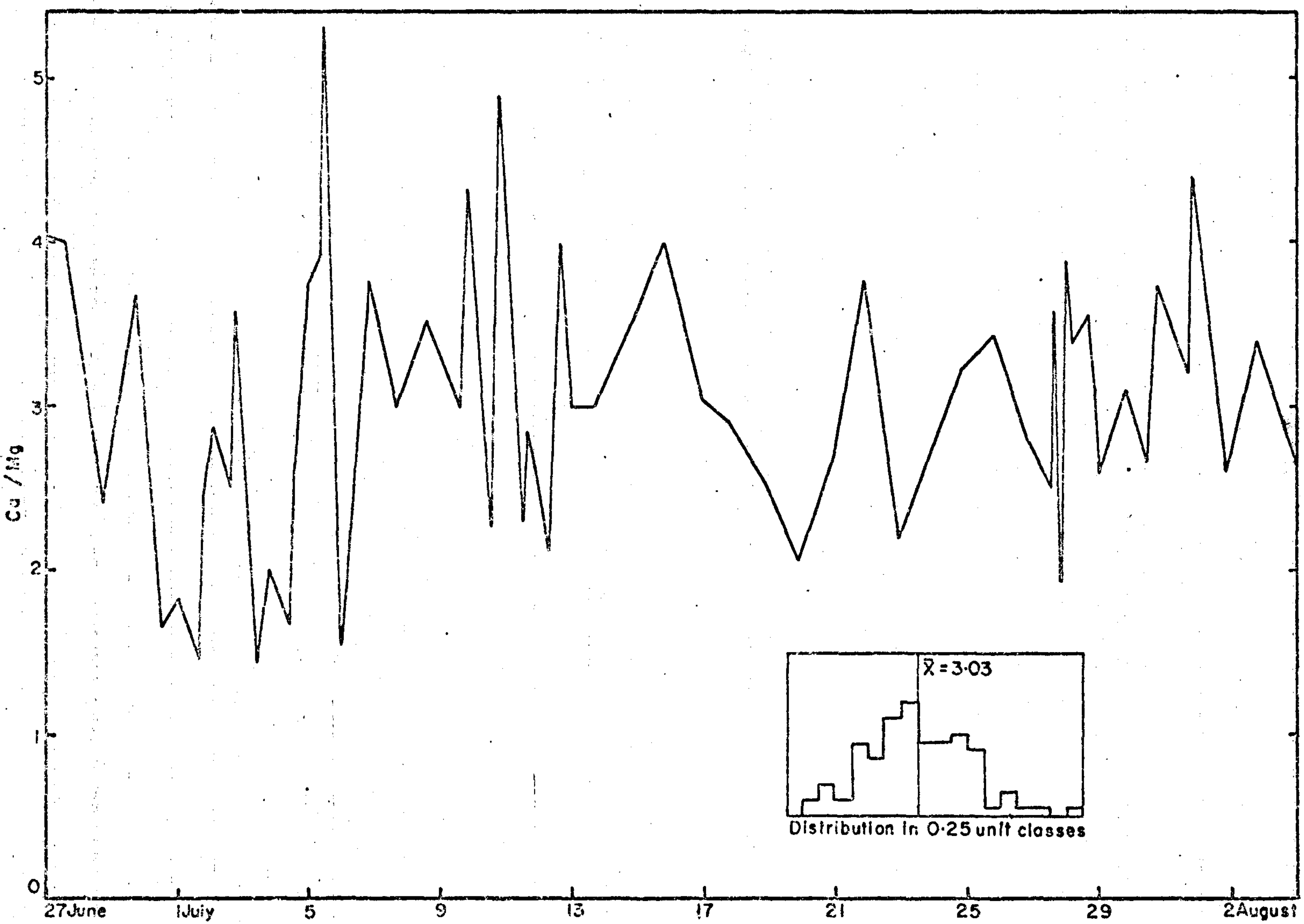


Fig. 8:5 Plot of (Ca /Mg) against time for "Jason's Creek".

tion are unknown, and the positions of the different sample groups thus serve illustrative purposes only. One noteworthy feature of the distribution of solute concentrations in the rills and standing water bodies is that talus rills exhibit lower concentrations than do soliflual rills, which in turn have concentrations lower than those found in standing water. A number of possible explanations may be proposed for the distinction between talus water and soliflual water: the finer nature of the soliflual material may afford greater opportunity for solutional reactions to take place, for example, or the CO_2 supply from vegetation may be more abundant on soliflual terrain, or the observed distinction may have arisen by change.

Considered as a whole, the highest concentrations among all of the samples in Fig's. 8:2 and 8:3 are found in standing water samples. This observation, and the general form of the solute-discharge graphs, suggest that a relationship exists whereby solute concentration becomes a function of the duration or distance over which solution occurs, probably approaching some limiting value as an asymptote. Consideration of the results of the downstream sequences of sample collection indicates that rates of solution are initially rapid, for the downstream sequences extend over no more than 150 m in any one case, and most extend over less than 100 m. If these sets of samples are taken to belong to the same population as the other rill samples, and if the asymptotic relationship between solute concentration and duration or distance of solution holds true, it would appear, from the concentrations observed at the downstream end of each sequence, that solution is substantially "completed" in the first 100 - 150 m of rill flow.

For the relationship between concentration and length of contact to remain valid, initial conditions and bounding conditions must remain constant. Where initial conditions differ or bounding conditions change the suggested relationship would be disturbed. In this context discharge, for instance, may be thought of as a bounding conditions. If discharge increases the dilution effect expressed by eqs. 8:1 and 8:3 comes into operation, reducing the rate of solution per unit volume of solvent.

Initial Conditions, Aggressivity and Saturation:

The importance of changes in initial conditions is particularly apparent in the search for an explanation of the anomalous features noted during the 27 - 29 July flood. Fig. 8:6 depicts the relationship of dissolved calcium with the hydrogen ion concentration for samples taken at the mouth of "Jason's Creek". The range of the y-axis of Fig. 8:6 is from pH 10.0 to 7.3, the $[H^+]$ values (in moles/litre) having been multiplied by 10^{10}.

Three separate samples are also plotted on the graph. Two of these samples are of snowmelt water dripping directly from snowpatches, collected on 12 July and 1 August; the third was taken from the rainwater which fell on 28 July. The first snowmelt sample had a pH of 7.85 and a concentration of 6 mg/l; the corresponding values for the rainwater were 6.0 and 6. The $[H^+]$ of the rainwater was thus two orders of magnitude greater than that of the meltwater, with Ca concentration being the same in both. The second snowmelt sample had a pH of 6.6 and Ca = 9 mg/l. It is thought, although it cannot be conclusively demonstrated, that the higher $[H^+]$ observed in this sample is due to dilution of the meltwater proper by the rainwater.

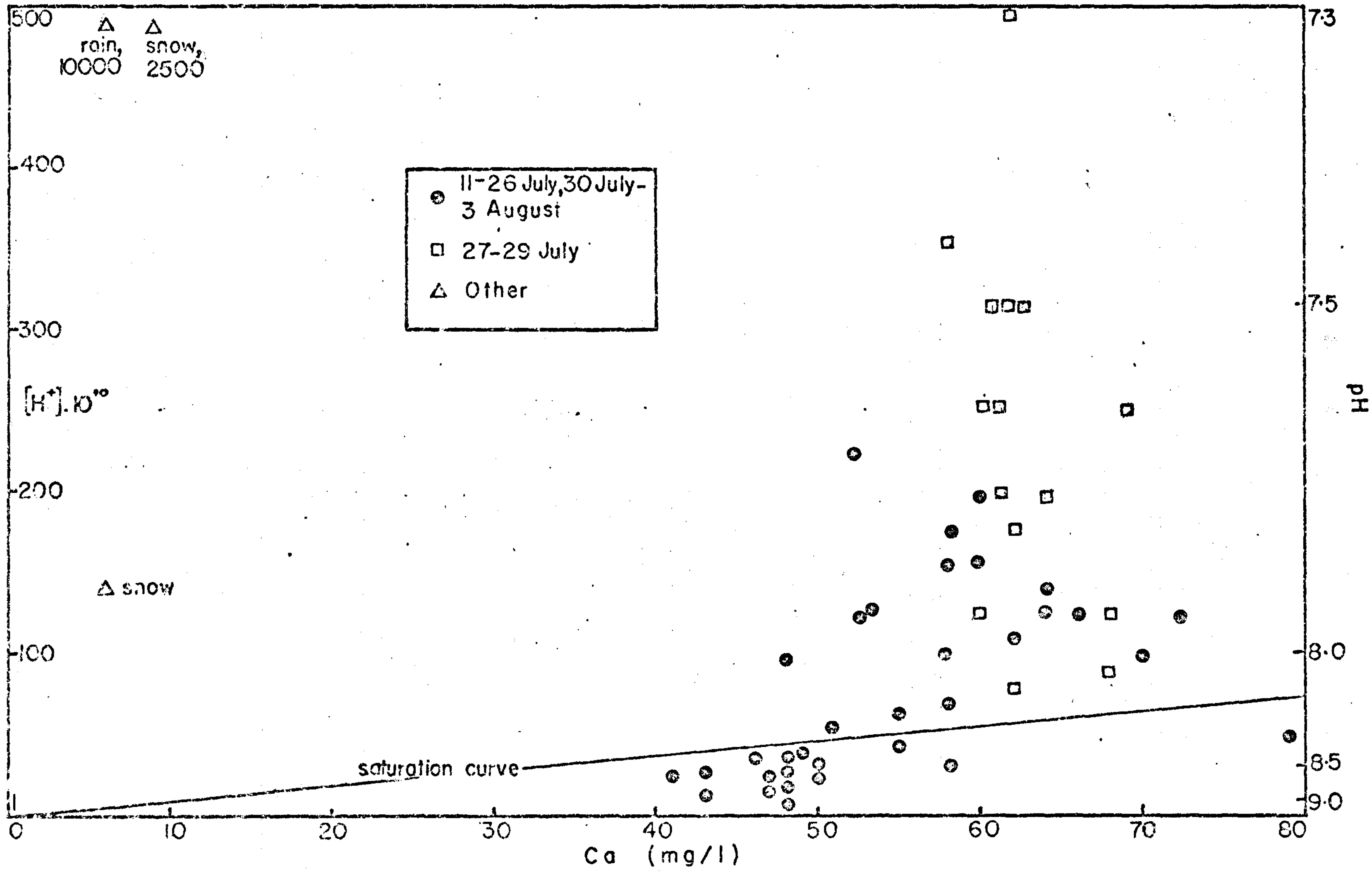


Fig. 8:6 Ca concentration against H^+ concentration, "Jason's Creek".

The solutional behavior of the rainwater runoff samples on Fig. 8:6 appears to be quite different from that of the snowmelt runoff. Within the range of the graph, Ca concentration is unrelated to $[H^+]$ for the rainwater runoff, in which Ca ranges from 58 - 69 mg/l. In the case of the snowmelt runoff $[H^+]$ is initially relatively low and changes little upon contact with the ground; there is, moreover, a positive correlation between Ca concentration and $[H^+]$ (v. Ch. VII, Dissolved Load).

A saturation curve has been drawn onto Fig. 8:6 using Picknett's values (1964) for the solubility products. (Because pH increases downward on the y-axis, points below the curve are supersaturated.) Supersaturation with respect to calcite is indicated for several of the "Jason's Creek" samples; all but two of these supersaturated samples were collected between 11 and 13 July. None of the rainwater samples fall below the curve, and it appears that the rainwater was considerably more aggressive towards calcite than the meltwater. Fig. 8:7 is a graph of $[H^+]$ against discharge, with unsaturated and supersaturated samples differentiated from each other; as a generalization it is true to say that the supersaturated snowmelt samples occur at higher discharges than the unsaturated snowmelt samples.

No sound explanation can be offered for this fact. Clearly the reason why the supersaturated samples contain less Ca than the others is the higher discharge with which they are associated; the influence of the dilution effect expressed by eq. 8:1 is noticeable here. To rephrase the problem, however, the reason why the waters which contain less Ca should be supersaturated rather than unsaturated remains unclear. When snowmelt discharge is relatively low the metlwater is evidently able to dissolve

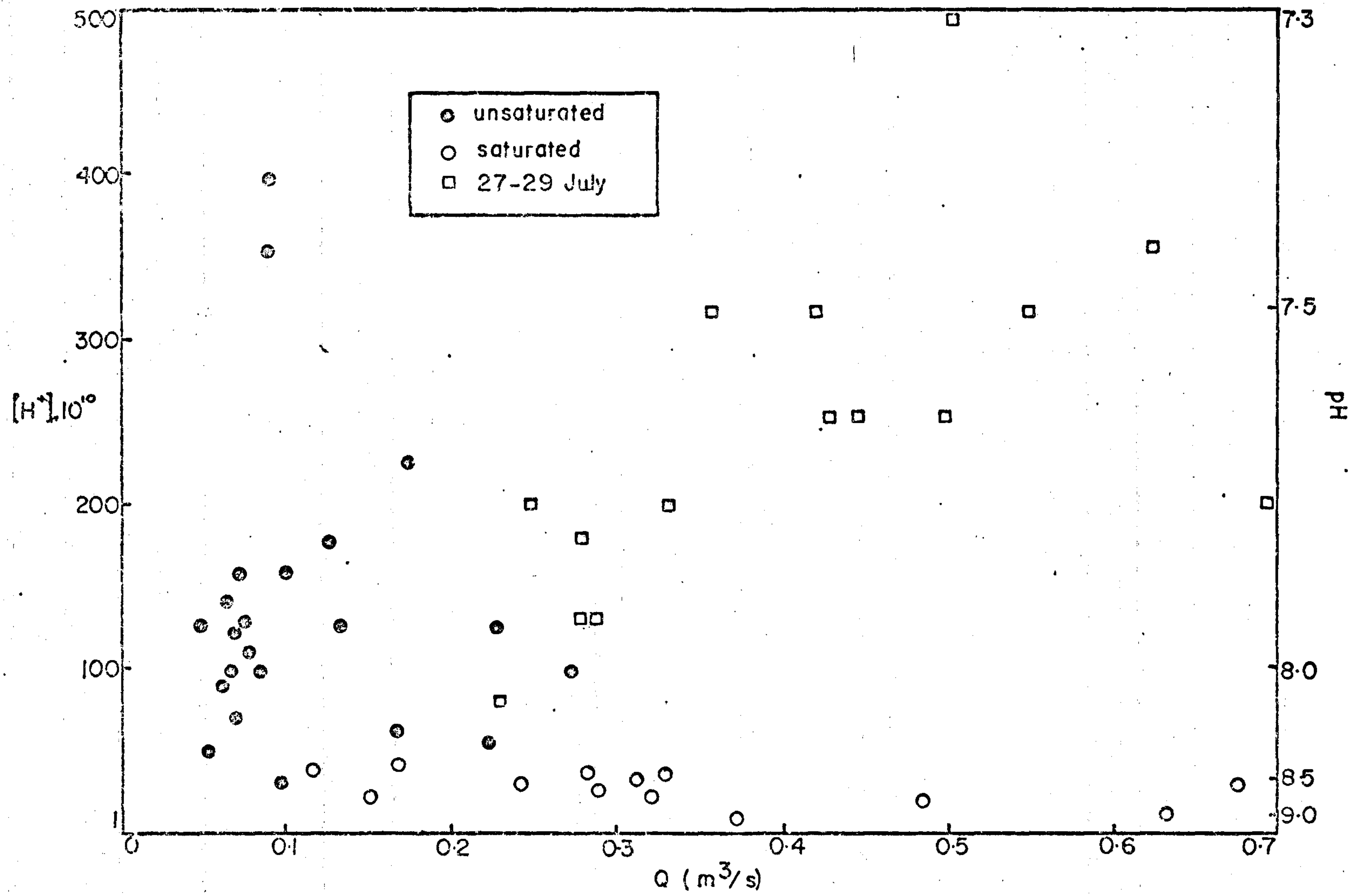


Fig. 8:7 H^+ concentration as a function of discharge, "Jason's Creek".

proportionately more calcite without reaching saturation. This observation may reflect some temperature-dependent process, but on the basis of the data collected in 1970 it is not possible to provide an answer to the problem.

The disparity between the hydrogen ion concentrations of meltwater and rainwater, and the apparent solutional results of this disparity, probably reflect a disparity in the concentration of "free" CO_2. The availability of aqueous CO_2 and its derivatives is more significant in limestone solution than is the concentration of the hydrogen ion itself, and it is reasonable to postulate a good mutual correlation between the two.

Comparisons with related results from other studies:

The tendency for rainwater to be acid is well known, and can be explained in terms of equilibriation at or near the mean atmospheric concentrations of CO_2 and other ions. Values quoted in the literature (e.g. Gorham, 1955) range from pH 4.0 to 7.0. The pH of melting snow appears to be more variable. Ek (1964, 1966) found the pH of melting snow and ice in the Savoy Alps and the Italian Dolomites to lie between 7.65 and 8.9, attributing these relatively high values to expulsion of CO_2 from the snowpack upon densification. Clement and Vaudour (1968), in contrast, found the pH of melting snow and ice in another region of the French Alps to range from 4.4 to 7.0 about a mean of 5.4. Their samples were collected in winter (December to April) from very clear snow, whereas Ek's were collected in autumn (September) from glacier fronts which were old, and probably transformed and dirty. Moreover, Clement and Vaudour observed a distinct seasonal trend in their values, the mean pH of December samples being 5.1 and that of April samples being 5.8, together with a correlation between the age and type of the snow and its pH. The variation in the April samples was from 4.8 to 7.0, April being a month of considerable new snowfall. pH also increased from fresh through wet to granular snow.

Ek drew a distinction between ice meltwater and snow meltwater, the former having higher pH. He observed decreases in pH from the glacier front up-glacier and downstream, the up-glacier decrease being more marked with values as low as 7.35 occurring in the firm zone. The meltwater issuing from the glacier front, he argued, was likely to be derived largely from the snout itself, the oldest part of the glacier. Expulsion of CO_2 from the ice would have proceeded farthest in the oldest ice, which would thus have been the least aggressive.

The evidence of Ek's results and those of Clement and Vaudour, taken with the evidence from "Jason's Creek", suggests that the pH of newly-fallen snow may in general be comparable with that of rainwater, both being equilibriated with respect to CO_2 roughly about the atmospheric concentration of this compound. As the fallen snow ages it loses CO_2 and becomes reduced in aggressivity, until by the time it melts its ability to dissolve calcite may be appreciably less than that of rainwater falling at the same time. Ek doubted that this effect would be marked in the case of snow, but in "Jason's Creek" this does indeed appear to be the case. As noted in Chapter II the age of the bulk of the snow lying on "Jason's Creek" in spring is 9 - 10 months; in other words, most of it dates from the previous autumn. Melting and regelation processes in the snowpack remnants, once temperatures have crossed the freezing point, may accelerate the escape of CO_2 from snow which has already undergone a full season of densification.

Ford (1971, in press) has published one of the relatively few accounts of solutional activity which include data on the CO_2 - content of limestone waters. Dealing with limestones of the Canadian Western Cordillera, his calculations from alkalinity tests indicate that snow and clear-ice meltwaters above the treeline have P_{CO_2} (partial pressure of CO_2) values two or more orders of magnitude below the global atmospheric mean of 3×10^{-4} atm (Ford, 1971, Fig. 14). In contrast, forest waters below the treeline have P_{CO_2} one to two orders of magnitude above the global mean, while for vegetated tundra and turbid glacial streams the value tends to be near to the global mean. The corresponding ranges of calcium concentration within which these waters saturate with respect to calcite are < 50 mg/l (snowmelt water, saturating in some cases at ≤ 25 mg/l), 100 - 140 mg/l (forest water) and 50 - 90 mg/l (tundra water).

Concluding discussion:

The role of aqueous CO_2 in the solution of limestones has received considerable attention. One aspect of this role is that CO_2 is potentially three times more soluble in water at $0^\circ C$ than at $35^\circ C$. Kauko and Laitinen (1935) determined experimentally that its solubility in snow could range up to 40 times greater than that in water at $0^\circ C$. Essery (1952) found the solubility of CO_2 in snow and ice to be at a maximum in the range -7° to $0^\circ C$.

Corbel (1959) made use of some of these facts to argue that rates of limestone erosion were greater under cold climatic conditions than under temperate or tropical conditions. His paper prompted several theoretical and empirical criticisms. Bögli (1960) pointed out that the effect of enhanced solubility would be counteracted by a decrease in the rate of the $CaCO_3$ - solution process. Sweeting and Gerstenhauer (1960) and Sweeting (1966) argued for the importance of non-climatic variables, such as lithology, as controls on the rate of solution. Douglas (1968) discussed some of these other variables, instancing vegetation type, rainfall regime and ground water and surface runoff regimes, and stressing the importance of CO_2 supply from overlying soil in the solution of bedrock. Pitty (1966, 1968), has also emphasized this latter factor. One of the empirical refutations of Corbel's arguments has come from D. I. Smith (1969), who showed that dissolved calcium and magnesium in the waters of north-west Somerset Island, N.W.T., were present in quantities which were low relative to those commonly observed at lower latitudes.

Although Muxart, Stchouzkoy and Franck (1969) have recently written in support of Corbel, the concensus of opinion has formed against him. The empirical evidence from "Jason's Creek", and theoretical extrapolations made from that evidence, are also persuasive against Corbel. It may be concluded as a result of the controversy, not so much that Corbel was in error, but rather that limestone solution systems are far more complex than he suspected. A general theoretical account of limestone solution as a geomorphic process must consider many variables rather than few. Unsolved questions remain even in the relatively simple case of the high-latitude solution system.

CHAPTER IX

CONCLUSION

During the eight to ten weeks of the annual thaw season, "Jason's Creek" and streams like it in the High Arctic play important geomorphic roles in the active landscape. The quantity of solutes and detritus removed by them is appreciable, and their geomorphic significance greater than is implied by the amount of attention hitherto paid to them.

The source of runoff for "Jason's Creek" is the melting of snow accumulated in winter, and rainwater falling during the thaw season. The former accounts for the spring flood, in which the greater part of annual runoff is discharged, and a diurnally-fluctuating discharge during the remainder of the thaw season. This diurnal fluctuation has been shown to be related to meteorological inputs to the snowpack, with a basin transportation lag of five hours. Radiation provides a better index of snowmelt discharge than does temperature.

Spring and summer rainfalls generate rapid basin response, observed in the form of sharply-defined and short-lived flood hydrographs. The presence of permafrost and the absence of vegetation encourage this rapid and efficient response. The basin lag time for a rainstorm at the end of July was five hours, the same as for the day-to-day discharge of meltwater.

TABLE 9:1

SUMMARY OF EVENTS DURING THE 1970 FLOW SEASON

	"Jason's Creek"	Mecham R.
First day of streamflow	26 June	25 June
First major flood peak	2 July	2 July
Snowmelt flood period	2 - 17 July	2 - 16 July
Maximum discharge (m^3/s)	1.42 (2 July)	26.6 (8 July)
Maximum recorded suspended sediment concentration (p.p.m.)	291 (10 July)	571 (2 July)
Maximum suspended load (g/s)	275 (est., 10 July)	16200 (est., 9 July)
Maximum recorded solute concentration (mg/l $CaCO_3$)	102 (22 July)	90 (5 August)
Maximum solute load (g/s)	73.4 (10 July)	1350 (est., 8 July)
First freeze-up	16 August	-

Most of the geomorphic work done by "Jason's Creek" is probably done during the spring flood and the occasional rainstorm floods. At high stream velocities movement of bed load is considerable but difficult to sample quantitatively. Suspended sediment transport is only significant at high velocity but reaches maximum values much greater than those for movement of dissolved sediment.

Solute concentration varies inversely and non-linearly with discharge, and is also partially a function of duration or distance of contact between solvent and solute surface. Rainwater is a more effective solvent than old, melting snow. Meltwater issuing from the snowpack is less aggressive towards calcite than is rainwater, probably because CO_2 is lost from the snowpack as it ages. Limestone solution processes, and fluvial processes in general, behave in the High Arctic in ways which are essentially similar in kind to those observed elsewhere, although they differ in degree and in detail.

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