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AN INVESTIGATION OF THE EFFECTS OF GEOMORPHOLOGY ON STREAM HYDROCHEMISTRY

by

Russell L. Smith

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

UNIVERSITY OF OTTAWA

UNIVERSITÉ D'OTTAWA
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CHAPTER 1

INTRODUCTION

1.1 Context and approach

Geomorphology--the study of landforms.

This general definition of geomorphology has been interpreted in two different ways. Traditionally the discipline has been the study of the origin and evolution of landforms, concerned primarily with historical interpretations. It has provided hypotheses for the recent chapters of geological time. Many contemporary geomorphologists, while observing the description component, also recognize the importance of process. This second interpretation is more quantitative and research has shifted to studies with an applied component. Leopold et al. (1964) stated that the discipline was at the stage where adequate translations from the dynamics of process to the historical interpretation could not be made, and this is probably still the case today. Investigation of landform process relationships contributes to the development of such translations. The need for more information on geomorphic processes has been voiced by a number of researchers. Understanding present-day processes improves the interpretation of those acting in the past and the estimation of the future (Carson and Kirkby, 1972; Leopold et al., 1964; Pitty, 1971; Ritter, 1978).

Gregory and Walling (1973) identified three sources of information which are basic to both of the interpretations of geomorphology: First, mapping and measurement of the form of the land and the spatial distribution of the landforms; second, understanding the processes which fashion the surface of the earth at the present time; third, the analysis of deposits to provide understanding of past processes and a chronology of events. Different approaches have emerged in the discipline based on one of these lines of enquiry. These apparently diverse approaches, however, are united as Brown (1970) pointed out, by the increasing attention being devoted to the spatial distribution of contemporary physical processes. Integration within geomorphology has stemmed from emphasis on the understanding of present systems, their content, mechanics and spatial variation, as a basis for studies of the past and prediction of the future (Gregory and Walling, 1973).

Landforms originate from denudational processes, depositional processes, or from combinations of both. Geomorphology is primarily the study of the exogenous processes as they shape the earth's surface. But endogenous forces cannot be overlooked when dealing with models of the origin and development of landforms (Leopold et al., 1964). A variety of concepts have been developed to address the question of the external agents acting within the lithosphere, many of which are based on the general systems theory of von Bertalanffy (1950). The theory has been discussed at length in the geomorphic context by Chorley (1962). Chorley defined a system as

> . . . a structured set of objects and/or attributes. These objects and attributes consist of components or variables (i.e. phenomena which are free to assume variable magnitudes) that exhibit discernible relationships with one another and operate together as a complex whole, according to some observed pattern.

Systems are classified by Chorley and Kennedy (1971) as isolated, closed and open. Isolated systems possess clearly defined boundaries closed to the input and output of both mass and energy (e.g. a laboratory experiment). Closed systems assume boundaries which prevent the import and export of mass, but not of energy. Open systems involve a constant exchange of both mass and energy across their boundaries. A steady-state condition is produced when the outflow of mass and energy from the system equals the inflow. This balance occurs through self regulation, the adjustment of the system's components and their interrelationships. Gregory and Walling (1973) claimed that it is this concept of adjustment which constitutes the strength of the approach:

> The advantages of the open system approach arise from the facts that it places emphasis upon adjustment and upon relationships between form and process, upon the multivariate character of the many geomorphic phenomena, and upon the total physical environment.

However, the theory's utilization in geomorphology has not been without dissent. Howard (1965) viewed the theory as more a collection of complementary concepts than a theory. Smalley and Vitafinzi (1969) refered to its use in the discipline as an unnecessary complication, and Chisholm (1967) criticized the precision in the definition of its terms.

Deductive and inductive arguments are the two established modes to understanding a system. The former builds models based on physical laws. The latter involves the measurement of the components at sample points and statistical analysis of the data (Carson and Kirkby, 1972). Leopold et al. (1964) held the viewpoint that qualitative geomorphologists may interpret landforms and deposits in terms of the past processes, but qualified their statement

> . . . we believe that the genetic system breaks down when it is subjected to close scrutiny involving quantitative data.

Pitty (1971) claimed that given the perplexity and irregularity of forms and processes which are complicated further by changes with time, a qualitative method should be employed in approaching many geomorphological problems. However, he pointed out that :

> . . . since 1945 there has been an increasing realization that in some instances forms and particularly processes are sufficiently regular

> for more exact approaches and, in other instances, that qualitative analysis has proceeded as far as it can go.

Yet quantification has not been without opposition. Spate (1960) cautioned that expertise in a particular quantitative technique can act as a smoke-screen of formulae for the elaborate discovery of the well known. Poverty of thought and limited data collection may be disguised through the use of computer statistical analysis. Macklin (1963) voiced similar concerns:

> If the measurements are complicated involving unusual techniques and apparatus and a special jargon, things can be said in equations, impressively, even arrogantly, which are so nonsensical that they would embarrass even the author if spelled out in words.

It has also been expressed that quantitative techniques dull one's geomorphological common sense and perceptiveness (Pitty, 1971). Geomorphic approaches have, however, moved from the qualitative works of early observers to advanced quantitative assessments such as Bakker and Leheux's slope analysis (1946, 1947, 1950, 1952) or Scheidegger (1961a, 1961b, 1966). The fashion is presently inductive involving specific practical studies based on field measurement. Hydrological examples range from water contamination (e.g., Johnson and Eaton, 1980; Lewis et al., 1980; Millette et al., 1980; Platts et al., 1980; Wolfberg et al., 1980; Zack, 1980) to water balance studies (e.g., Bagdasaryan and Chilingaryan, 1979; Bajsavowicz and Welton, 1979; Hibbert, 1979; Nikitin et al., 1978).

Theories are developed by passing through a combination of deductive and inductive steps (Figure 1.1). For the initial stage in an investigation Carson and Kirkby (1972) cautioned that

> . . . it may be preferable to aim at generating models after collecting and analysing data which are considered relevent to a range of possible models.

An inherent difficulty with the inductive approach lies in the acquisition of a large number of reliable measurements. The limits of the sample size create practical problems for the verification and generation of models. Carson and Kirkby (1972) believed that sample points should be selected within slope profiles or basins, resulting in suitable sample clusters as well as suitable spatial systems. Gregory and Walling (1973) pointed out that information may be obtained from drainage basins, from laboratory models, or from knowledge of physical or statistical laws by analogy.

This thesis examines the effect of geomorphology on the hydrochemistry of several small streams in the headwater basin of Gladstone Creek, southwest Yukon Territory (Figure 1.2). The research studied a cascading system (Figure 1.3) within an inductive framework. The

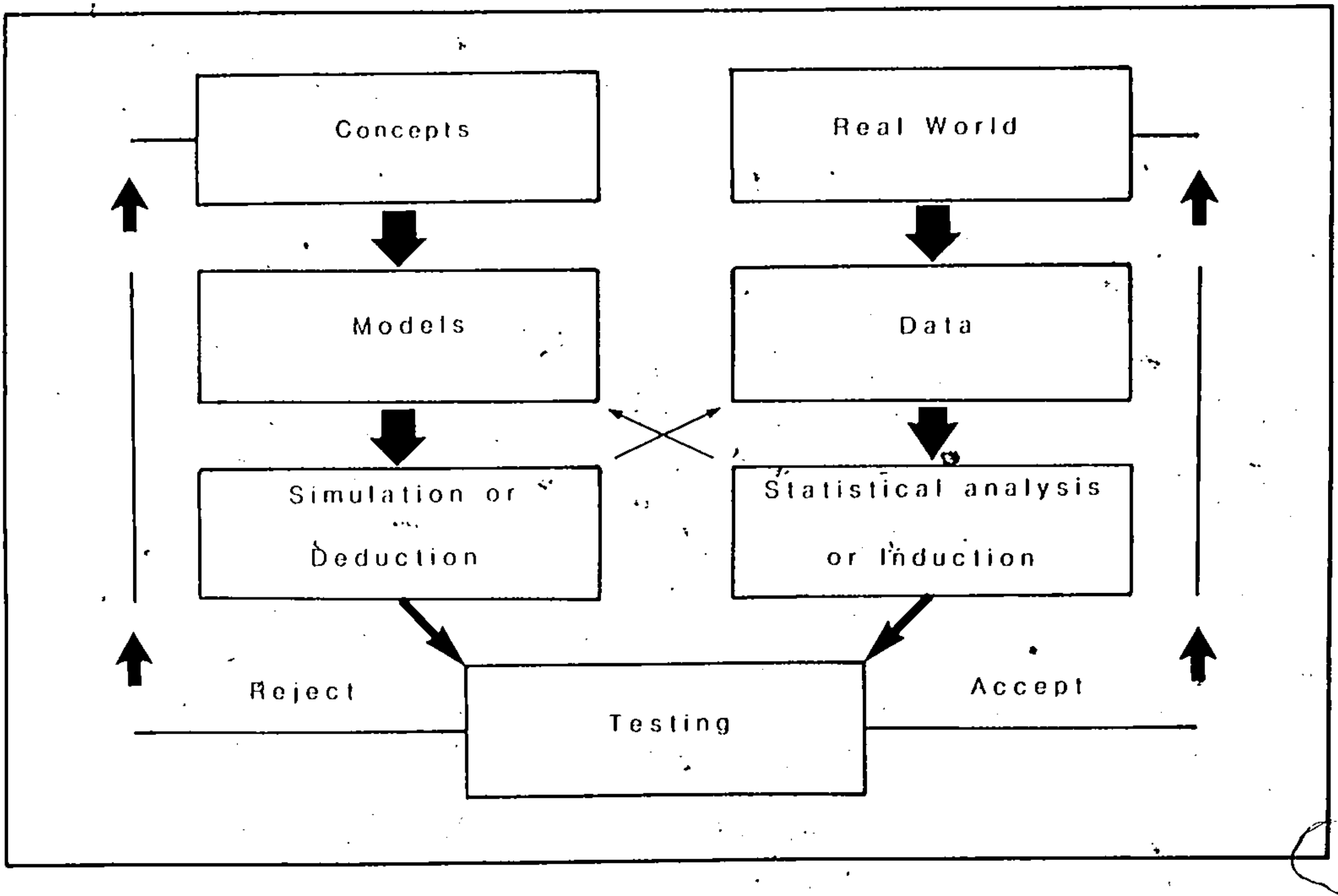

Figure 1.1 The inductive-deductive model building process (Carson and Kirkby, 1972).

Figure 1.2 Headwater lake of Gladstone Creek, southwest Yukon Territory.

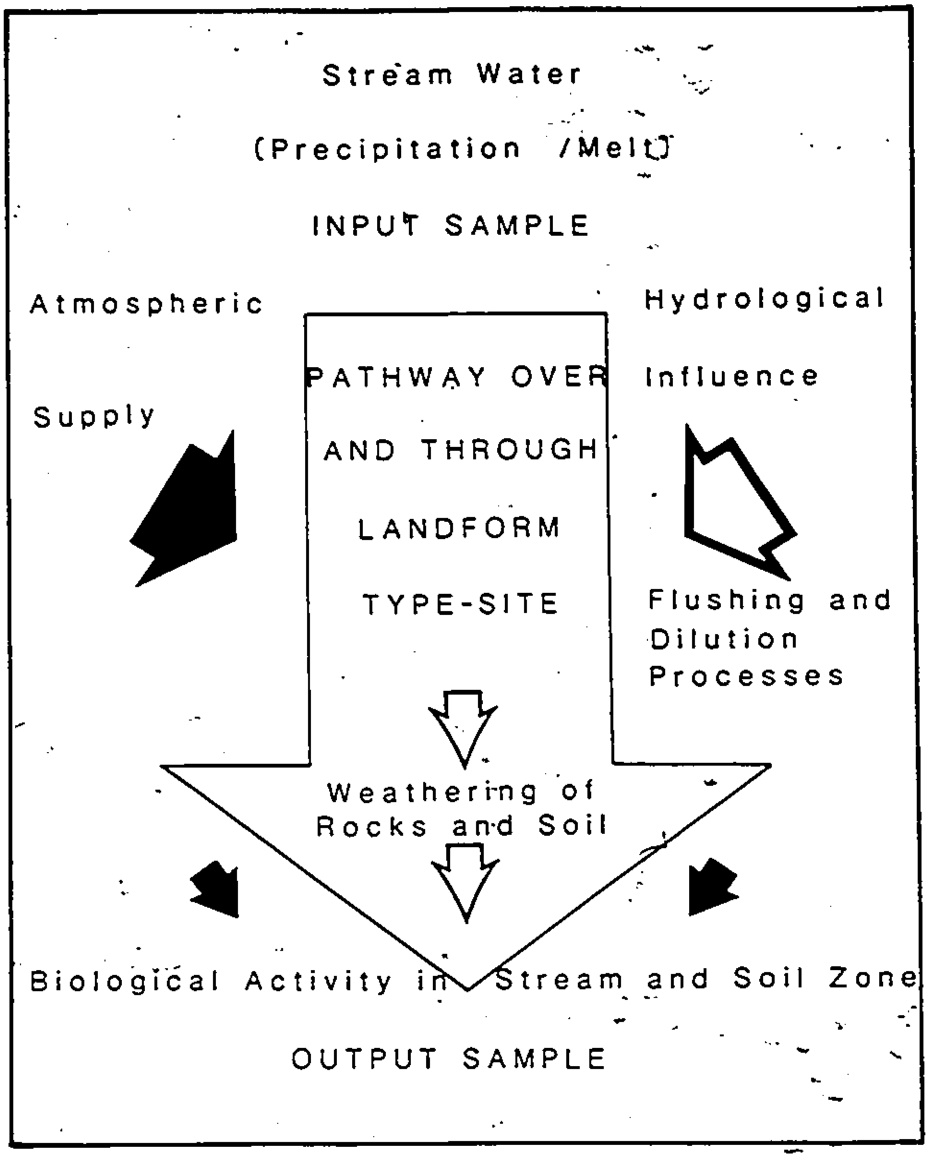

Figure 1.3 Factors influencing solute dynamics.

thesis objective is to investigate the influence of the headwater lake's surrounding landforms on the hydrochemistry of the streams running over and through the forms.

1.2 The study hypothesis and justification

The hypothesis involves the concept of independent/dependent variables. The landforms surrounding the headwater basin act as the independent variable while stream character is the dependent variable. Temporal and spatial solute variation were used to test the hypothesis:

> The varying morphologies and diverse lithologies of unconsolidated deposits along the valley sides of Gladstone Creek headwater basin influence to varying degrees the hydrochemical loading of the streams feeding the lake (Figure 1.3).

Within the working hypothesis the emphasis is on process. Process may be seen as the method by which one thing is produced from something else, and as the vehicle by which a quantity of one system is transferred into, and participates in, the mechanics of another system (Ritter, 1978). Studies on rates and modes of operation of contemporary process have flourished over the past decade, thereby increasing our understanding of process mechanisms and interrelationships (Walling, 1977). Walling and Webb (1980) pointed out that, in particular, growth has occurred in the hydrological literature, with an increasing number of studies focused on solute investigation.

Studies have concentrated on the various factors which influence ionic concentration. Documentation has included the general effects of geology (e.g., Feth et al., 1964; Garrels and Mackenzie, 1967; Johnson and Reynolds, 1977) to the specific role of the biota (e.g., Lee and Hoadley, 1967; Leonard et al., 1979; Olafsson, 1979). Short term solute behavior has been interpreted through hydrological and meteorological variables (e.g., Foster, 1978; Lewis and Grant, 1979; Oborne et al., 1980; Pilgrim et al., 1979; Walling and Foster, 1975). Stream source and pathway have been documented as major controls. Limited research has investigated how landforms within the same drainage basin affect solute concentration (Burt, 1979; Foggin and Forcier, 1977; Walling and Webb, 1980). The hypothesis utilizes hydrochemical variation over time and space as an indicator of landform effect on surface and nearsurface streams.

The importance of hydrochemical investigation has been voiced by Freeze and Cherry (1979):

> In the study of landscape evolution the assumption is commonly made that the physical processes of mechanical erosion, thermal expansion and contraction, frost action and slope movements are the dominant influences, but on closer examination it is often found that chemical processes in the groundwater zone are the controlling influence.

Carson and Kirkby (1972) have expressed similar concern, claiming that the rate of hillslope solutional erosion may exceed that of all mechanical process combined.

The study was confined to the summer months. Field research was conducted from June 25 to July 15, 1980, and between June 1 and August 23, 1981. The latter data collection commenced immediately following melt of the lake ice for academic and practical reasons. Measurement of spring solute loads and runoff were required from an investigative viewpoint, while access to the site was dependent on ice free conditions. Collection was terminated in late August due to reduced stream input to the lake. Research was limited to one drainage basin as recommended by a number of researchers (Garrels and Mackenzie, 1967; Gorham, 1961; Reid et al., 1981; Webb, 1976). Selected streams which route different landforms around the headwater lake, and its sole surface outflow were subjected to investigation.

The temporal and spatial constraints create limitations for the study. It is a specific enquiry with limited comparison for both time and space. The working hypothesis can only serve as an insight into the nature of the processes investigated. However, since drainage basin systems do not function at a constant rate over short periods, the hypothesis is testable. Immediate and summer trends can be observed for the study, but explanation remains speculative.

1.3 The study area

1.3.1 Location and physiography

The headwater lake of the Gladstone Creek system (Figure 1.4) is located in the Ruby Range of the Yukon Plateau, northeast of Shakwak Trench (north latitude 61°24', west longitude 138°24'). The headwater lake was selected due to the following local features:

(1) Alluvial fans, rock glaciers and taluses are located around the basin;

(2) although regional climatic variation occurs due to orographic effects, the local climate is homogeneous;

(3) the basin is characterized by one outflow stream and one inflow stream. The two channels are located at the west end of the lake 50 metres apart.

The area was located by airphoto analysis and field checking during the pre-study year of 1980.

The physiography of the region has changed little since the Pleistocene with little contemporary erosion or aggradation taking place (Muller, 1967). It is characterized by rounded uplands with elevations of 1200 to 1800 metres a.s.l. and some peaks reaching elevations of 2100 metres. Finger lakes, swamps and sluggish streams

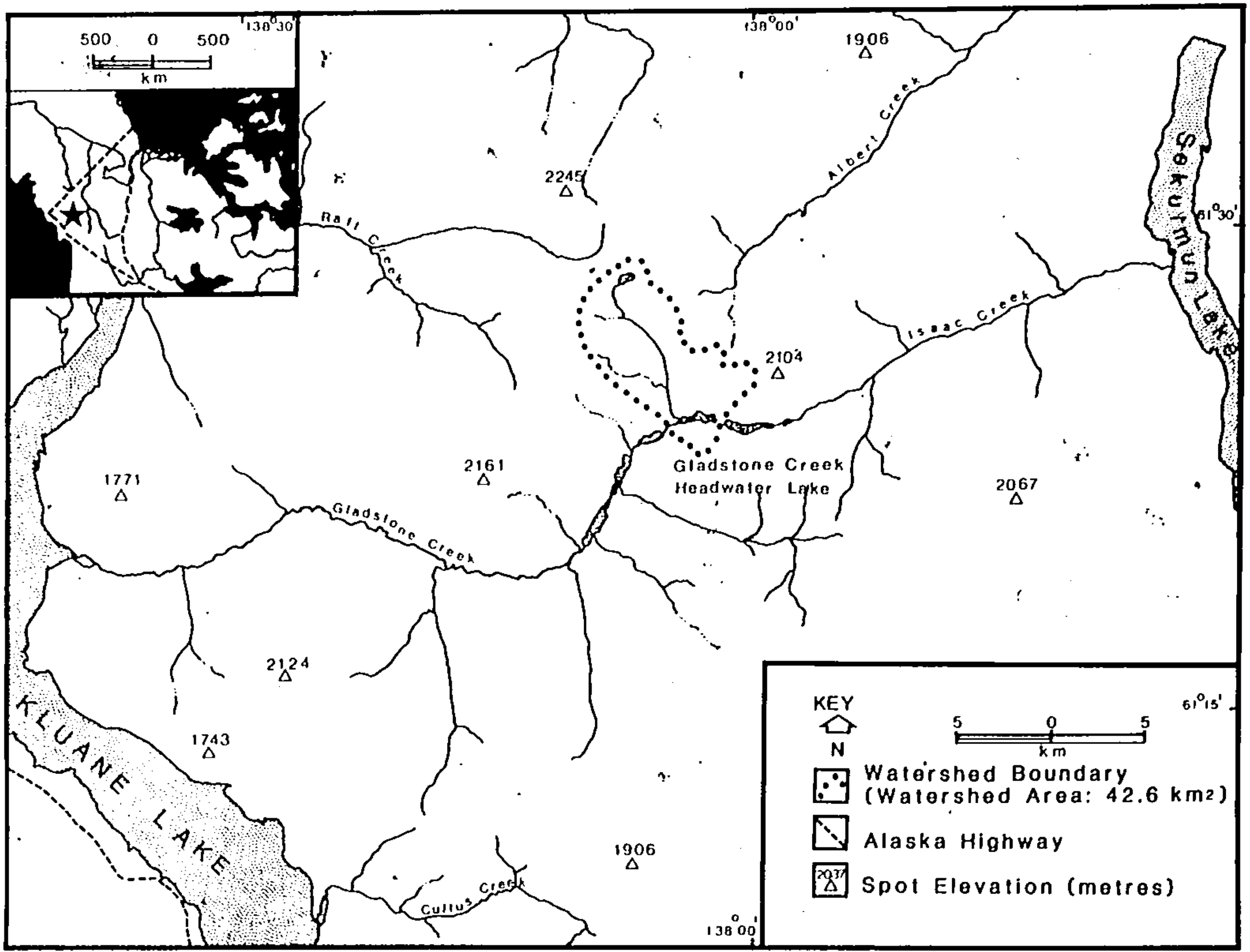

Figure 1.4 Study area map: Gladstone Creek headwater lake, southwest Yukon Territory.

are found in the range's glacial valleys (Bostock, 1948; 1952).

1.3.2 Climate and vegetation

The region lies northeast of the St. Elias Mountains which form a barrier to relatively warm moist air from the Pacific Ocean. The area, therefore, has a continental climate (Hare and Thomas, 1974; Kendrew and Kerr, 1955). During winter, the region is influenced primarily by the extremely cold and dry Mackenzie High from the Beaufort Sea. The summer climate is dominated by moist air from deep lows that move into the Gulf of Alaska (Marcus, 1974). The region has long winters, with periods of daylight shortening to less than six hours, and short summers with the sun above the horizon for nineteen or more hours (Kendrew and Kerr, 1955). The systems trend south to north following the Shakwak Trench with orographic effects generating local valley winds at right angles to this regional weather pattern. Burwash Landing weather station is located 50 kilometres west of the study area. Meteorological data from July 1980 to July 1981 (Environment Canada, 1980; 1981) quotes the winter minimum at -47°C (mean -20°C) and the summer maximum at 27°C (mean 10°C). The precipitation was recorded at 270mm.

Forest cover in the region is light, with an upper limit at about 1200 metres a.s.l. (Terasmae, 1967). The main forest species are: black spruce (<u>Picea mariana</u>), white spruce (Picea glauca) and balsam poplar (Populus balsamifera). Aspen (Populus tremuloides), white birch (Betula papyrifera), alpine fir (Abies lasiocarpa), tamarack (Larix laricina) and lodgepole pine (Pinus contorta var. latifolia) can also be found (Muller, 1967; Terasmae, 1967). The non-timbered parts of the valleys are covered commonly with grass ('niggerheads' or 'bunchgrass'), groundbirch and willows (Muller, 1967). Above 1500 metres a.s.l. this vegetation is sparse.

1.3.3 Geology and glaciation

The Ruby Range (Figure 1.5) is composed of granitic batholith intrusions (Bostock, 1948; Douglas et al., 1980; Muller, 1967). The batholith consists mainly of hornblend-biotite granodiorite and quartz diorite. Quartz monzonite, quartz diorite and minor granodiorite gneiss also occur (Douglas et al., 1980; Muller, 1967). The hornblend-biotite granodiorite is a medium to coarse grained granitic rock with a mafic mineral content varying from 5 to 20 per cent. The hornblend-biotite diorite is generally finer grained with a higher mafic content between 15 and 30 per cent (Muller, 1967). Two distinct ages for the granitic rocks of the Ruby Range batholith have been identified by Muller (1967): some very early Jurassic and some very early Tertiary or late Cretaceous.

During the late Pleistocene (Figure 1.6) the region was covered with ice by both the Nisling and Ruby

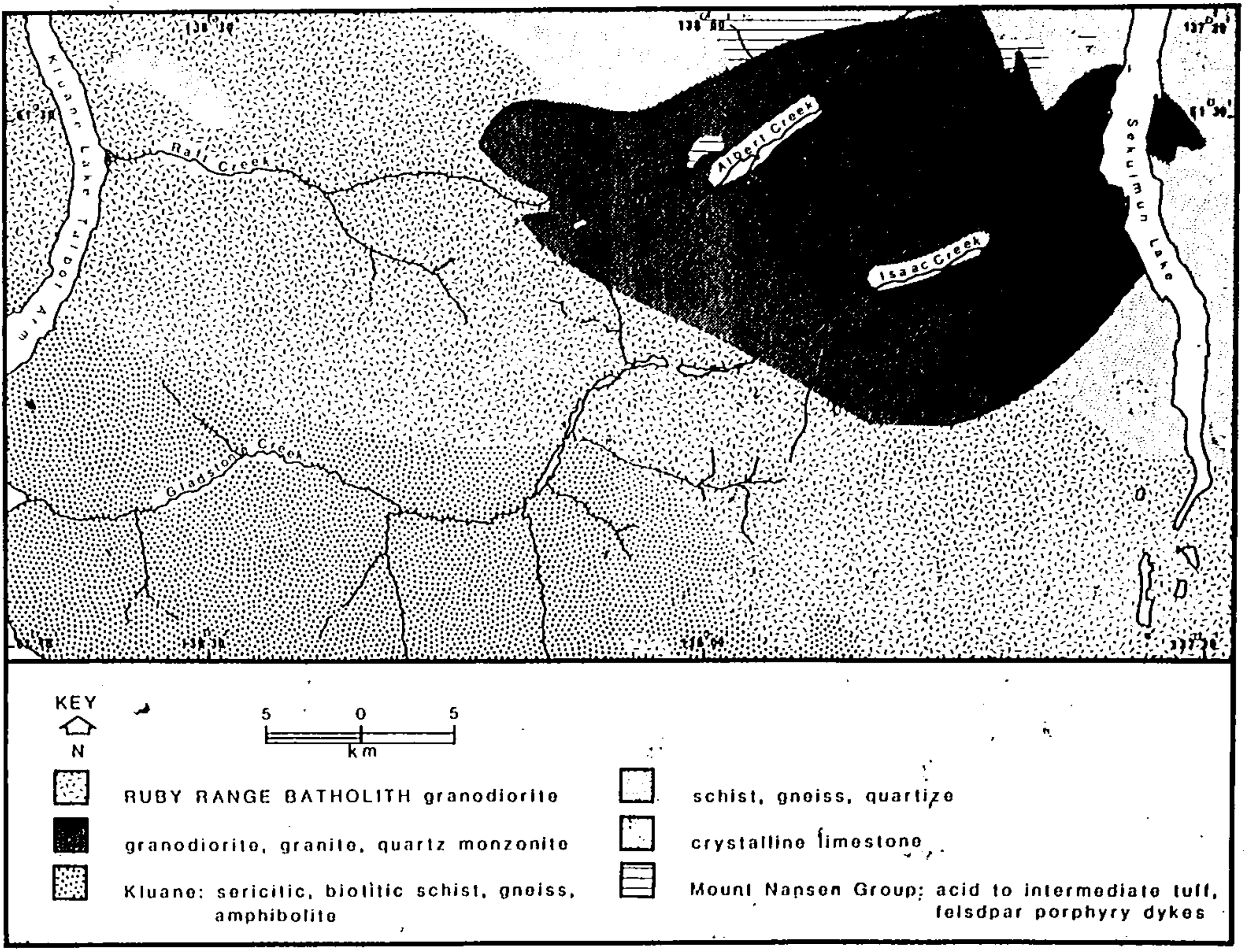

Figure 1.5 Geology of study area (Douglas et al., 1980).

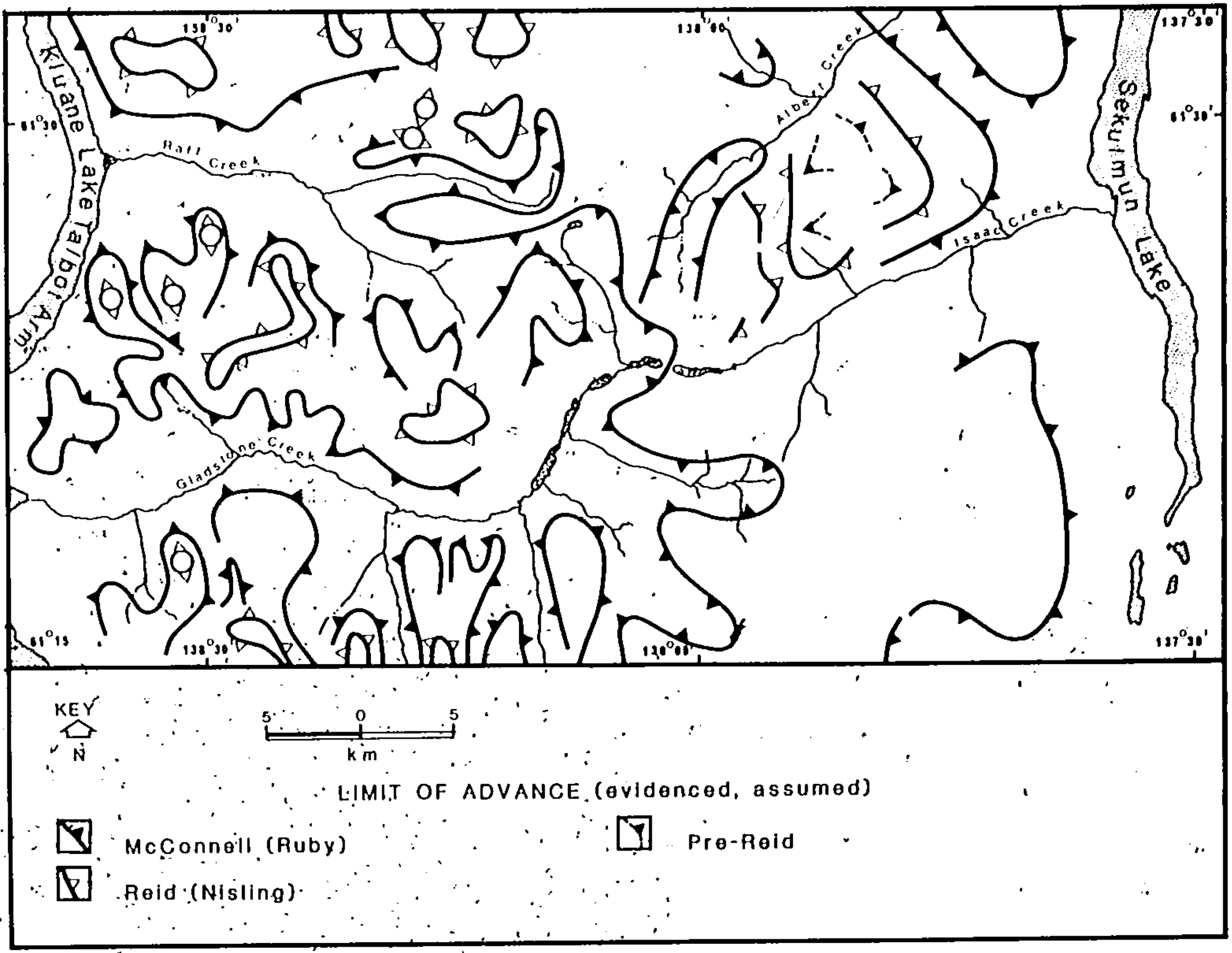

Figure 1.6 Glaciation history of study area (Hughes et al., 1969). [The triangle symbols are on the ice covered side of the advance limit.]

ice sheet advances (Muller, 1967). During the Nisling advance ice flowed across the Shakwak Valley to the west and covered the Kluane, Nisling and Ruby ranges to elevations of 1500 to 2100 metres a.s.l. The Ruby advance covered essentially the same region with a height limit 150 to 300 metres lower. The Nisling and Ruby advances are correlated with the Reid and the McConnell advances of the Cordilleran ice (Hughes et al., 1969). Depositional features marking ice limits are either poorly preserved or lacking, causing difficulties in the delineation of glacial limits. Evidence for local Holocene glaciation is found in many of the valleys of the Ruby Range (P. G. Johnson, personal communication, 1981). Surficial deposits of the Gladstone region are primarily composed of Quaternary age sand and gravel deposited in varied thickness and extent by glacial meltwater. Lacustrine clay and sand was laid down in the glacial lakes that were associated with glacial withdrawal. At present, deposition occurs in lake basins and along stream courses in the area.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Natural waters attain their chemical composition through a variety of chemical reactions and physico-chemical processes (Stumm and Morgan, 1981). This composition is under continual change as natural waters circulate in the hydrological cycle. Solute studies have increased markedly over the last decade due to increasing interest of the hydrologist in the operation of fluvial processes (Walling, 1977) and growing environmental concern for water quality (Reuter and Perdue, 1977; Walling and Webb, 1980; Wilson, 1979). A number of studies have evaluated denudation systems and the development and modification of landforms by suspended sediment and solute concentration description (e.g., Logan, 1977; Oxley, 1974; Subramanian, 1979; Walling, 1974; 1977). Their contribution to geomorphology has been assessed by Gregory and Walling (1973):

> The documentation of sediment and solute dynamics within a drainage basin is important to the geomorphologists in providing an index of the effects of water on the landscape and the rates of operation of fluvial processes.

The majority of works, however, have reported on the sources and controls of solute concentration.

Documentation is reviewed within the following discussion on weathering of rocks and soils, hydrology, atmospheric supply and biota. This investigation examines the hydrochemistry of several small alpine streams which drain different landforms and associated surficial materials. These factors, as well as the effects of man and time, interact to influence the composition of and concentrations in stream water.

2.2 Weathering of rocks and soils

Weathering is the alteration of rocks at the earth's surface through a complex of interacting physical, chemical and biological processes (Ollier, 1969; Press and Siever, 1978; Ritter, 1978). The intensity of weathering is dependent on climate, tectonics, original lithologic composition and time (Press and Siever, 1978). Weathering decomposes rock into an unconsolidated mass, which, weathered sufficiently, can sustain the growth of rooted plants (Freeze and Cherry, 1979). This residue of weathering is defined as soil (pedological definition). It has been generally accepted that the main source of ions in fresh waters is weathered rocks and soils (Gorham, 1961; Hem, 1970; Freeze and Cherry, 1979).

Krauskopf (1967) stated that weathering can be perceived as the approach to equilibrium of a system involving rocks, air and water. When water comes into contact with minerals, chemical reactions occur and continue until equilibrium concentrations are attained in the water or until all the minerals are consumed (Freeze and Cherry, 1979). In natural systems chemical equilibrium is rarely achieved due to changing environments, fluctuating concentration of reactants and products and the presence of other ions in solution (Drever, 1982). Chemical processes involved in rock decomposition (i.e., solution, oxidation and reduction, hydration and hydrolysis, chelation, ion exchange) have been discussed in many works (e.g., Gorham, 1961; Krauskopf, 1967; Ollier, 1969; Ritter, 1978). Water is strongly influenced by the soil zone it infiltrates and passes through. The most important effects occur as a result of the processes illustrated in Figure 2.1. Geochemical and pedochemical weathering processes are mentioned as they pertain to the studies reviewed.

Feth et al. (1964) studied the sources of the mineral constituents of the spring waters of the Sierra Nevada. The researchers concluded that the dissolved content of the springs comes almost entirely from attack of CO_2-rich soil water on silicates (primarily plagioclase feldspars). Garrels and Mackenzie (1967) extended the research illustrating spring compositions with a model in which the primary rock-forming silicates are altered in a closed system to soil minerals plus a solution in steady-state equilibrium with these minerals. The

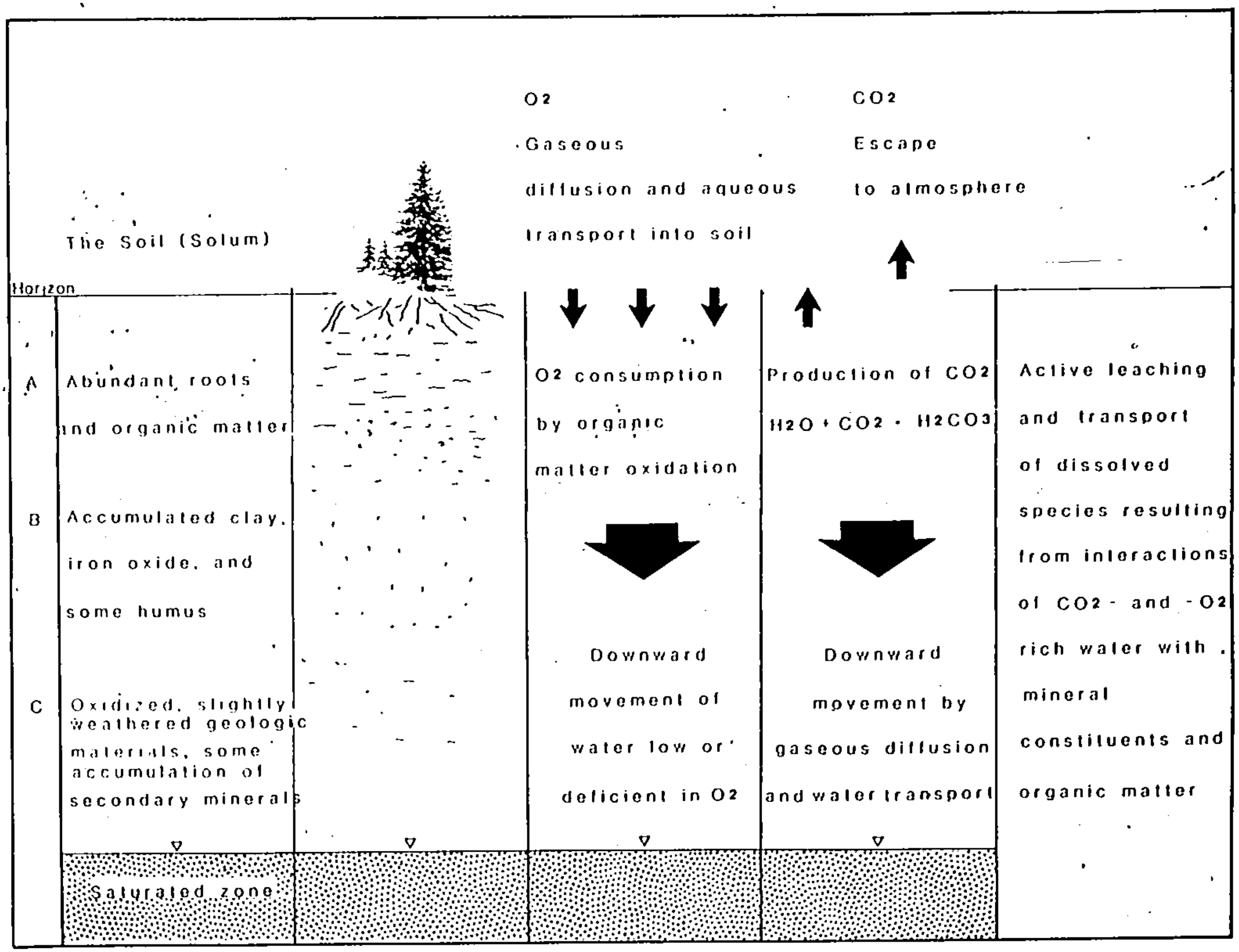

Figure 2.1 Schematic representation of major hydrochemical processes in the soil zone (Freeze and Cherry, 1979).

research supports the weathering reactions identified by Feth et al. (1964). Addressing the origin of the compositions of groundwaters from igneous rocks, Garrels (1967) arrived at similar conclusions:

> Many of the waters have compositions broadly consistent with what can now be predicted as the result of adding water rich in CO_2 to primary rock minerals and permitting reactions to take place in a closed system.

Miller (1961) investigated the solute content of stream waters draining single igneous rock types in the Sangre de Cristo Range, New Mexico. Based on stream chemistry uniformity regardless of change in slope, soil, vegetation and hydrology, a steady-state relation for the various weathering mechanisms is implied. Comparison between soil and rock composition and soil and surface water chemistry has been reported by Appello (1974) for an alpine granitic watershed in Italy. The research shows the organic layer acts as a cationic buffer against dilution during precipitation. Rapid infiltration during rainfall, however, causes general lower concentrations in the lower soil horizons. An equilibrium with vermiculite in these horizons controls Ca, Mg and SiO_2, while K and Na diffuse slowly out of parent rock fragments. These five solutes dominate the ionic content (99%) of the runoff from a granitic basin in the Pacific Ranges of the British Columbia Coast Mountains (Zeman and

Slaymaker, 1975). The researchers attribute the concentrations to the influence of lithospheric sources.

Carbonate weathering has received attention to a similar degree to that of igneous rock-water systems. Much of this attention has been directed toward aquifers. Navarre et al. (1977) demonstrated that the predominance of Ca and HCO_3 in the spring waters of the Dyle Basin, Belgium, reflects the tertiary calcareous sandstone of the aquifer. The origin of ions in the groundwater of the western and central Galilee aquifer of Israel is attributed to dissolution of carbonate rock (Nadler et al., 1980). Krothe (1976) claimed the same process governs the water chemistry of Slab Cabin Run, a stream which drains a carbonate region in Pennsylvania. These conclusions are supported by quantitative investigations on the stability of carbonates under solution (e.g., Garrels et al., 1960; Langmuir, 1968).

Contrasting rock types present within and surrounding a carbonate region, however, influence solution. Halliwell (1979) and Bortolami et al. (1979) have shown that this physical control directly affects groundwater flow and solute concentration. Depetris (1980) considered this factor in an explanation of the dissolved inorganic constituents of the Negro River, Argentina. Solution of evaporites and carbonate rocks, and weathering of metamorphic, igneous rocks and varied non-calcareous sediments account for hydrochemical loadings.

Weathering of rocks and soils as principal source and control of solute concentration has been expressed by researchers in terms of the geology of an area. Miller (1974) and Steele et al. (1975) studied streams in southwestern Montana and northern Arkansas respectively. Conclusions stated a relationship between water chemistry and geology. Russian researchers Kutseva and Kopovilov (1975) investigated the water-rock relationship for drainage basins in northern Caucasus. The results indicated that the river water chemical compositions correspond to the rocks composing the drainage basins. Depetris (1976) reported the same conclusions for the Parana River, which has the second largest drainage basin in South America (2.6 x 10^6 km^2).

Spatial variation of solute conditions explained by changes in geology has been documented by a number of investigators (e.g., Feller and Kimmins, 1979; Johnson and Muir, 1977; Oborne et al., 1980; Walling and Webb, 1980). Hughes and Edwards (1977) considered the complex geology of Cyron watershed, South Wales (Great Britain), as the cause for downstream variation of Na, K, Mg and Ca concentrations. A study in Vermont and New Hampshire identified spatial differences in stream chemistry due to bedrock type. Johnson and Reynolds (1977) reported that the streams draining plutonic bedrock have lower concentrations of dissolved solids (12.8 - 18.6 ppm) and are more acidic (mean pH 5.5) than those draining metamorphic bedrock (TDS = 32 - 224 ppm; mean pH 7.2).

Many researchers have identified processes in the soil as the most important control on surface water chemistry. The presence of soluble material (solution) in the soil and its interaction (ion exchange) with runoff have received much attention. For example, Miller and Drever (1977) claimed that the most important control on the chemistry of the North Fork Stream, Absaroka Mountains, Wyoming, is solution of readily soluble salts from the soil zone. Reid et al. (1981) documented similar conclusions for the river water from Glendye catchment, Scotland. Ca, Mg, Na, HCO_3 and SiO_2 concentrations are influenced by ion exchange and chemical weathering of silicate minerals in the soil zone. Fe, TOC, Mn and Al concentrations are affected by the translocation of these elements down the soil profile (podzolisation) and are released into the river at times of high discharge. According to the researchers, nitrogen demand and mineralization in the soil zone control the concentration of NH_4 and NO_3 while P, SO_4, K and Cl appear to be conservative solutes.

The residence time of water in the soil is an important factor in determining the degree of influence the soil zone has on the water passing through it. In general, long time of contact promotes high ion concentration and short residence time results in lower solute content (Freeze and Cherry, 1979; Foster, 1978; Gorham, 1961; Oxley, 1974; Walling, 1974; 1977). Researchers have investigated this relationship (e.g., Pilgrim et al., 1979; Sonzogni et al., 1976) and measured the movement of solutes through undisturbed field soil (e.g., Shuford et al., 1977; Van de Pol et al., 1977) and multilayered soils (Gureghian et al., 1979; Selim, 1978; Selim et al., 1977). Residence time influence on soil zone buffering capacity and solute availability is primarily controlled by hydrological processes (Section 2.3).

Assuming no atmospheric nitric and sulphuric acid from anthropogenic sources, the principal driving force in weathering reactions is carbonic acid. The acid-base reactions cited below illustrate carbonic acid as the acid reactant. Equation [1], the chemical reaction for weathering of biotite to kaolinite, is typical of areas dominated by silicate rocks.

$$\begin{aligned} &KMg_3AlSi_3O_{10}(OH)_2 + 15/2\ H_2O + 7CO_2 \rightarrow \\ &K^+ + 3Mg^{++} + 7HCO_3^- + 2H_4SiO_4 + 1/2Al_2Si_2O_5(OH)_4 \end{aligned} \quad [1]$$

Equation [2] is typical of weathering occurring in carbonate areas.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{++} + 2HCO_3^- \quad [2]$$

Bricker and Garrels (1967) have examined the control of such weathering reactions on water composition and concluded that Ca, HCO_3, pH and, to a lesser degree, Mg, are influenced by the dissolution of carbonate rocks. Na, K, SiO_2, Ca and Mg are effected by the dissolution of silicates.

Stream chemistry reflects the interaction between gases, water and lithologic materials. Reactions occur because certain elements are unstable in the presence of others and therefore react to form more stable configurations. Whether and how reactions occur and their rate and extent are reflected in the equilibrium relationships of the rock/soil-water system. Generation of solutes for stream water is thus a function of rock and soil composition and weathering processes. Spatial or temporal change of the factors can cause stream chemistry variability. Additional controls operating in an area interact with the factors to further mediate water composition.

2.3 Hydrology

Hydrology primarily acts as a regulator of delivery of solutes from rock and soil horizons to the watercourses. Discharge, antecedent moisture condition and runoff component type of a watershed are strongly controlled by precipitation frequency, intensity and magnitude.

Investigations have uncovered relationships between discharge and solute concentration. An inverse relationship between stream discharge and solute concentration has been documented by many researchers (e.g., Burt, 1979; Edwards, 1973; Feller and Kimmins, 1979; Foster, 1978; Hem, 1970; Lewis and Grant, 1979; Miller and Drever, 1977; Oborne et al., 1980; Oxley, 1974; Reid et al., 1981; Walling, 1974; 1977; Walling and Foster, 1975; Walling and Webb, 1980). This has been explained by a dilution process. At low discharges streamflow originates as baseflow from the rock and soil. High solute concentration is achieved in stream water due to its long storage residence time in the rock/soil mantle. At times of high flows due to precipitation, baseflow is diluted by overland flow and rapid throughflow. Runoff possesses a lower solute content because of its shorter residence time and reduced contact with rock and soil (Oxley, 1974; Reid et al., 1981; Walling, 1974).

Research has shown that the decrease in concentration can be preceded by a rise, or that the initial drop may be followed by an increase before giving way to subsequent decrease (e.g., Burt, 1979; Foster, 1978; Hendrickson and Krieger, 1964; Leonard et al., 1980; Miller and Drever, 1977; Oxley, 1974; Walling, 1974; 1977; Walling and Foster, 1975). The overland flow component is the first to contribute to the storm runoff and causes the initial decrease. The subsurface flow component, which consists of water that has been in contact with the soil longer, is flushed out by storm throughflow and a rise in runoff solute content results. As throughflow continues, soil water entering streams becomes more dilute by the increasing contribution of precipitation.

The increase of solute concentration is explained by the flushing of accumulated soluble material in the surface and subsurface layers of the soil profile by the initial phases of storm runoff (Foster, 1978; Loughran and Malone, 1976; Oxley, 1974; Pilgrim et al., 1979; Walling, 1974; 1977; Walling and Foster, 1975). Weathering, leaching, decay of organic matter and evaporation, during the period after the previous runoff event, account for the build-up of soluble material in the soil zone. Water held in the soil during this period can reach an equilibrium concentration of solutes (Pilgrim et al., 1979). Hence, during a storm, the source of throughflow can be changed from stored water in equilibrium with the soil system to less concentrated rainwater (Oxley, 1974).

Flushing effect and the time required for dilution to take place are highly dependent upon the antecedent soil moisture conditions of the catchment and storm magnitude (Foster, 1978; Lewin et al., 1974; Oxley, 1974; Pionke and Nicks, 1970; Walling and Foster, 1975). During conditions of low soil moisture status, the ground surface and upper horizons of the soil contain accumulations of readily soluble material. Dilution commences when this supply of solutes has been exhausted by flushing mechanism. Under conditions of high soil moisture status the supply of readily soluble material is likely to have been depleted by previous storm events. Dilution of stream flow begins with the onset of the storm.

Results from several studies have supported this phenomenon. Lag measurements between hydrograph peak and solute concentration trough (e.g., Glover and Johnson, 1974; Foster, 1978; Spraggs, 1976; Walling and Foster, 1975) reflect the rate and operation of flushing and dilution processes. The researchers have suggested that the lags are inversely related to antecedent moisture condition and storm intensity. Maximum lags are associated with dry antecedent conditions, while shorter lags occur with high moisture status. Lewin et al. (1974) illustrated solute concentration variation between a wet and dry period for a watershed in mid-Wales, Great Britain. The researchers found generally higher values of dissolved constituents in the runoff from the single rainfall which followed the dry spell. Pilgrim et al. (1979) recorded shorter contact time results for water within soils with high soil moisture, thus explaining the decreased solute concentration when the water is flushed out by subsequent rainfall.

Investigations on solute behavior during storm periods have demonstrated clockwise and anticlockwise hysteretic effects. Hysteresis is the looped relationship when the trend of solute concentration is plotted against discharge for a specific storm event (Gregory and Walling, 1973). Hendrickson and Kreiger (1960) interpreted the clockwise curve, which involves higher concentrations on the rising stage, by flushing and subsequent dilution. Following the storm, concentration begins to increase again and discharge continues to drop as baseflow becomes the dominant runoff component. The less documented occurrence where concentrations are lower on the rising stage produces an anticlockwise loop. Flood runoff from more distant parts of the watershed cause higher concentrations on the falling stage since these waters peak later and have had longer contact with catchment rock and soil (Cleaves et al., 1970; Toler, 1965; Walling and Webb, 1980).

Stream water chemistry although highly influenced by interaction with rocks and soils along its flow path, is also a function of the hydrological regime of the watershed of which it is a part. Several runoff characteristics tend to affect the chemical composition of stream water: runoff source and volume, runoff types (overland flow, throughflow and baseflow) and their subsequent mixing as streamflow, as well as the antecedent soil moisture condition.

2.4 Atmospheric supply

While the major source of ions to inland waters are rock and soil weathering, research has revealed that the atmosphere is an additional source. Sources of atmospheric solutes include sea spray aerosols, sulphur and nitrogen oxide emissions and wind blown terrestrial dust (Gorham, 1961; Reid et al., 1981). Gorham (1961) reviewed the literature on factors influencing the supply of ions to natural waters and claimed that the significance of atmospheric contribution has been underestimated. Investigations have supported Gorham's viewpoint. Mineral materials are transferred from the atmosphere to surface waters by rain and snow or by dry fallout (Gorham, 1961; Wilson, 1979).

Likens et al. (1967) identified bulk precipitation (wet and dry deposition) as the primary source of Ca, Mg, K and Na nutrients for six watersheds in New Hampshire (Hubbard Brood Experimental Forest). Cleaves et al. (1970) concluded that over a third of solute input to Pond Branch catchment, Maryland, is derived from atmospheric supply. Based on a four year study for Rawson Lake, Ontario, Schindler et al. (1976) stated that atmospheric input significantly influences P, N, Ca, Mg, Na, K, Cl and SO_4. Schindler and Nighswander (1970), Lavandier and Mur (1974), Tuffey and Trama (1975) and Peters (1977) have indicated that precipitation can also be the primary source of P. Bulk precipitation for upland catchments has also been shown to effect solute concentrations (e.g., Crisp, 1966; Cryer, 1976; Leonard et al., 1979; Sutcliffe and Carrick, 1973; White et al., 1971; Zeman, 1975). Precipitation has also been documented as a main source of inorganic ions to the rivers of eastern Australia (Douglas, 1968; Muir and Johnson, 1978) and southeastern United States (Beck et al., 1974).

Acidification of precipitation, as a result of natural and anthropogenic influences, causes upward trends in the input of H, NO_3, NH_4 and SO_4, and a decrease of HCO_3 concentration in surface water. Lewis and Grant (1980) have shown that the soil-water and acidic rain do not simply mix but react. Inputs of nitric and sulphuric acid from atmospheric transport (Cogbill and Likens, 1974; Forland, 1973), resulting in a significant downward trend in pH, have been recorded by several researchers (e.g., Glover et al., 1980; Henricksen and Wright, 1977; Lewis and Grant, 1980; Likens and Bormann, 1974; Roffman, 1980; Wright and Gjessing, 1976). Because of this phenomenon, carbonic acid, as the principal weathering agent, is replaced by the stronger acids, causing increases in weathering rates (i.e., if pH is less than 4.5).

In areas where a large portion of the precipitation is snow, dissolved ions accumulate in the snowpack and are released during spring thaw. Physiography and meterological factors influence the variation of snow composition on the ground (Matreyer, 1964; Wright and Dovland, 1978). The snowpack contains interstitial air which, in turn, contains gaseous contaminants of natural and anthrogenic origin (Zeman and Slaymaker, 1975). Wind blown terrestrial and vegetative particles enrich the composition of the snowpack (Dovland and Eliassen, 1976; Zeman and Slaymaker, 1975). Johannessen and Henriksen (1978) postulated that further concentration may result from freeze-concentration process during snow recrystallization and melting in which contaminants accumulate preferentially at the surfaces of ice particles. Hence, although snow crystals may be formed in relatively clean air and wash the air less efficiently than rain, snowmelt in the spring contributes to surface water solute concentrations. Researchers have studied this contribution and found that a high percentage of the pollutant load is released in the first fractions of snowmelt, these fractions containing 2-5 times the concentration of the snowpack itself (Johannessen et al., 1977; Johannessen and Henriksen, 1978; Skartveit and Gjessing, 1979). Snowmelt mineral content increases since it is subject to limited buffering as it washes over frozen soil and biological material and enters the watercourses. Acidification of the snowpack can cause radical change in surface water pH during the spring melt. Acute depression of pH during snowmelt in lakes and streams has been recorded for central Ontario (Jeffries et al., 1979), New York State (Schofield, 1975), Finland (Haapala et al., 1975), Sweden (Hultberg, 1977) and Norway (Henriksen and Wright, 1977; Johannessen and Henriksen, 1978). Cl as the dominant constituent in snowmelt, derived from sea spray, can also occur. Zeman and Slaymaker (1975) found Cl amounted to 50-60 per cent of the dissolved matter in snowmelt for an alpine basin of the British Columbia Coast Mountains. The snow composition of areas unaffected by sea spray or sulphuric and nitric acid deposition, however, has been recorded to have a dilute solute nature (e.g., Feth et al., 1964; Miller, 1961).

Wet and dry fallout from the atmosphere are sources of solute supply. Air mass transport of pollutants determines, to a large degree, the influence of atmospheric supply on surface water chemistry.

2.5 Biota

While the concentration of an element in natural water is determined by the thermodynamics and kinetics of its chemical reactions, biological activity in the stream itself and in the soil zone can alter reaction rates and equilibrium concentrations. The cycling of elements in water and soil is largely the result of biochemical reactions which can cause shifts in equilibrium, significantly influencing stream dissolved constituent concentration (Duvigneaud and Denaeyer-De Smet, 1970; Lee and Hoadley, 1967; Leonard et al., 1979; Likens et al., 1977). Biological activity is discussed in terms of processes acting in the channel itself and those operating in the soil zone and surrounding area.

Biochemical investigations have shown that biota within the stream have dominant roles in influencing water chemistry. Nutrients may be utilized or released by aquatic vegetation or by the activity of biotic organisms. Lee and Hoadley (1967) reviewed the literature and documented the influence as direct or indirect. Direct effects include:

(1) Those elements that are principal components of cellular materials such as C, N and P; and

(2) those elements which form the major constituents of the hard part of organisms, for example, Ca in molluscs or Si in diatoms.

The indirect influence is the result of sorption or excretion of compounds (mainly organic) that react with elements in the water. The most important indirect influence is the change in CO_2 content of the water caused by respiration and photosynthesis. Change in CO_2 by large populations of biota causes pH variation (in poorly buffered systems) which, in turn, affects those reactions influenced by pH.

Research has supported the interpretation of Lee and Hoadley (1967). For example, Olaffson (1979) investigated the annual cycle of plants and nutrients in Lake Myvatn, Iceland. Olaffson (1979) observed that the growth of planktonic diatoms and chrysophyceans algae in June was limited by the concentration of inorganic nitrogen. In July however, a bloom of nitrogen fixing blue-green algae developed which was limited by the availability of phosphorus. Associated with the mid-summer algae blooms was variations in pH as reflected by changes in the CO_2 content of the basin. Cleaves et al. (1970) reported similar pH variation for Pond Branch watershed, Maryland. Olaffson identified new blooms of phytoplankton diatoms and chrysophyceans which occurred in August in response to the decomposition of the organic matter, which caused inorganic nitrogen to enter solution again. The utilization of Si constituent by benthic and planktonic diatoms was observed.

Although aquatic organisms do influence water composition, the processes are very complex, involving many components, and are highly dependent on their environment. Hence, as Lee and Hoadley (1967) pointed out, few studies have led to reliable estimates of the extent of this influence.

Biological effects on solute concentration also originate from biological activity in the soil/litter zone and forest area. The cycling of nutrients within the forest ecosystem influences stream solute concentration through (a) the removal and retention of ions by root and wood biomass systems and (b) the release of nutrients by nitrogen fixation or the washing of litter, organic debris and forest canopy (Duvigneaud and Denaeyer-De Smet, 1970; Likens et al., 1977).

Documentation of biological activity in the soil zone is extensive and, as in water bodies, the processes are complex, involving a series of inter-relationships. For example, Leonard et al. (1979) investigated the processes of nutrient release and transport for the watershed of Ward Creek, California. The researchers reported removal of NO_3-N by the soil-vegetation system. This resulted in an anticlockwise hysteretic effect between NO_3-N concentration and discharge during the snowmelt period. NO_3-N in the area, however, is not derived from bulk precipitation alone, since concentrations are increased by inputs from biological nitrogen fixation. Biological activity also affects the PO_4-P concentrations of the watershed. While PO_4-P is removed from throughflow in the soil by absorption to soil particles (Keup, 1968; Ryder et al., 1973), biological processes in the root zone enhance the PO_4-P retention (Graustein et al., 1977). Biological sequestering mechanisms are countered by nutrient release from biological leaching processes. Ions are returned to the soil by precipitation washing of litter (organic debris), forest canopy (throughfall) and tree bores (stemflow). A number of researchers have documented the release of ions (H, Ca, Mg, K, Na, HCO_3) by decomposed plant litter (e.g., Attiwill, 1968; Cleaves et al., 1970; Gosz et al., 1973; Johnson et al., 1968; Slack and Feltz, 1968), while others have discussed throughfall and stemflow contributions (e.g., Aulitzky, 1967; Eaton et al., 1973; Hoffman et al., 1980). Biological leaching processes are highly dependent on the hydrological regime of the watershed (Section 2.3).

Although the cycling of nutrients in water/soil systems is strongly governed by biochemical reactions which affect the concentration of certain elements present in surface water (e.g., PO_4-P, NO_3-N), our ability to gauge this influence is still in the developmental stage. Due to the complexity of biological processes, much additional investigation is needed before the extent of biological influence upon natural water chemistry can be fully appreciated.

CHAPTER 3

HYDROLOGICAL REGIME

3.1 Introduction: Water balance equation

The importance of hydrology in affecting solute dynamics has been discussed in Section 2.3. The hydrological regime of Gladstone Creek headwater lake was monitored from June 3 to August 21, 1981. The study was designed to determine the lake water budget components, in particular the overland flow, throughflow and baseflow contribution of water from the unconsolidated valley side deposits. Discharge fluctuation of this direct runoff from the landforms surrounding the basin reflected the rate and operation of flushing and dilution processes.

The water balance of the headwater lake was evaluated during the study period by employing the continuity equation from Ferguson and Znamensky (1982):

$$Is + Il + Iss + P - E - Os - Oss - \Delta s = 0$$

where Is = main surface inflow into the lake
Il = lateral inflow (direct runoff from surrounding land area)
Iss = groundwater inflow
P = precipitation on the surface of the lake
E = evaporation from the lake
Os = surface outflow from the lake
Oss = underground outflow
Δs = change in the water storage of the lake

The components of the water balance are illustrated in Figure 3.1. The equation is modified to estimate the ungauged lateral inflow (Il), groundwater inflow (Iss) and underground outflow (Oss). Hence:

$$Is + P - E - Os - \Delta s + Ic = 0$$

where Is = main surface inflow into the lake
P = precipitation on the surface of the lake
E = evaporation from the lake
Os = surface outflow from the lake
Δs = change in the water storage of the lake
Ic = unknown component: Il + Iss - Oss

The parameter Ic was estimated as the residual in the water balance equation. The calculation provides an indication of the contribution made by surface and subsurface direct runoff from surrounding land area (watershed area was calculated as 42.6 km²) and the withdrawal by subsurface outflow (Appendix A).

3.2 Techniques and results of lake water balance

3.2.1 Main surface inflow into the lake (Is)

As suggested by Ferguson and Znamensky (1982) the total surface water inflow into the lake was subdivided, for convenience, into main inflow and lateral inflow. The main inflow stream of Gladstone Creek headwater lake

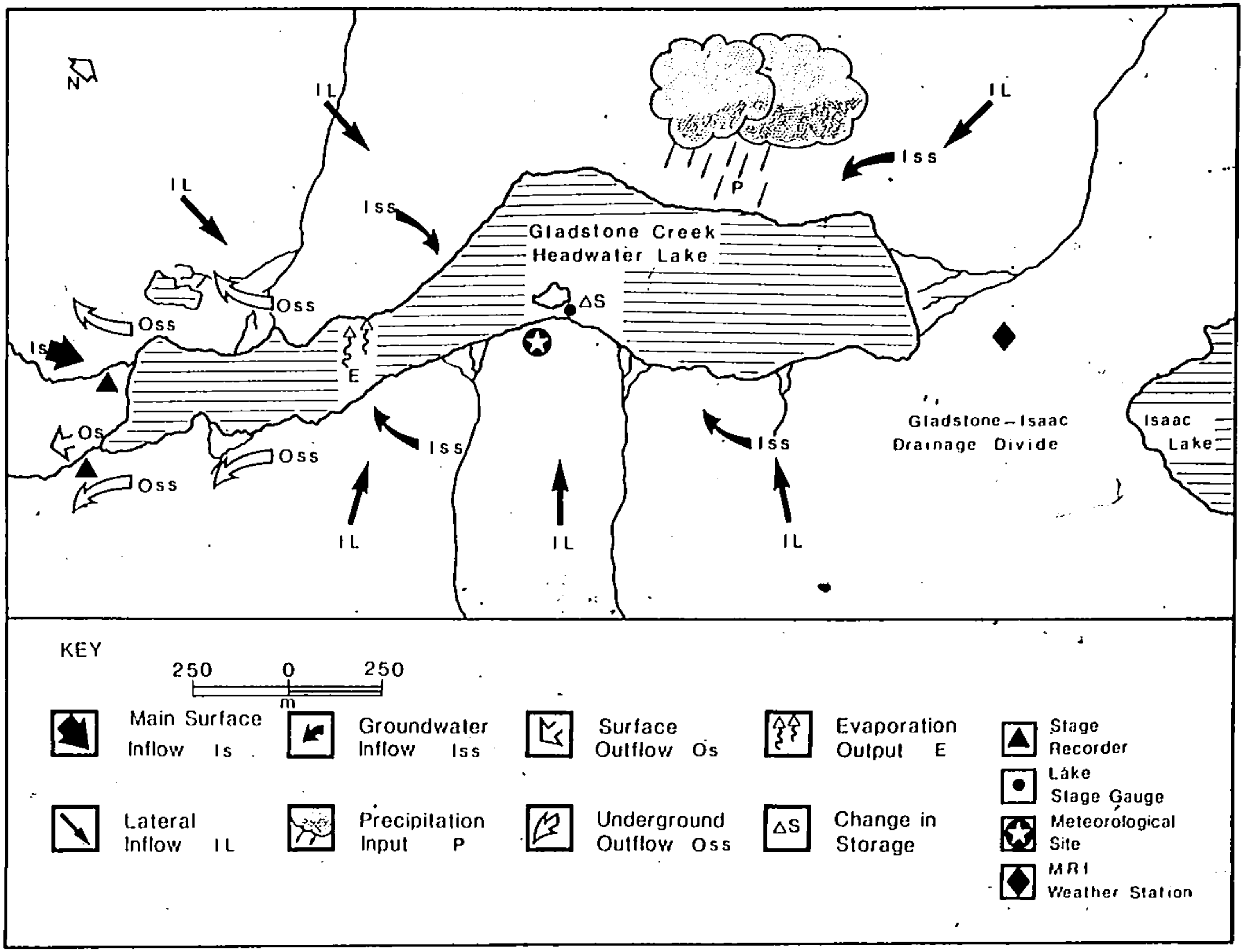

Figure 3.1 Water balance components, Gladstone Creek headwater lake.

is illustrated in Figure 3.2. A record of discharge from the open channel was obtained using the velocity-area method (Gregory and Walling, 1973; Lambie, 1978). Twenty-seven discharge measurements were made during the study. The channel was divided into thirteen segments, for each of which the mean velocity, the cross-sectional area and the section discharge were determined. Total discharge for the point in time was computed as the sum of the section discharge values.

The current was measured at varying flow conditions using an A. Ott Kempen small current meter model 10.150 (Figure 3.3) as outlined by Charlton (1978), Church and Kellerhals (1970) and Pierce (1941). The 0.6 of the depth from surface velocity method was employed as recommended by Gregory and Walling (1973) when measuring shallow streams. Continuous stage for the stream was recorded using an A. Ott. Kempen Type X Horizontal Water Recorder. The stage recorder was installed and operated as described by Church and Kellerhals (1970) and Lambie (1978). The cross-section of the stream bed was measured on a three-day cycle using a standard fiberglass survey staff and a Jena-N 025 level and tripod (Figure 3.4) as illustrated by Gregory and Walling (1973) and Smoot (1978). Cross-sectional areas were obtained by plotting point in time stage values on a graphic representation of the stream bed morphology. No significant alteration took place in its characteristics during the study period.

COLOURED PICTURES
Images en couleur

Figure 3.2 Main surface inflow (S_6) and surface outflow (S_5). (S_5, S_6 refer to the hydrochemical sample identification.)

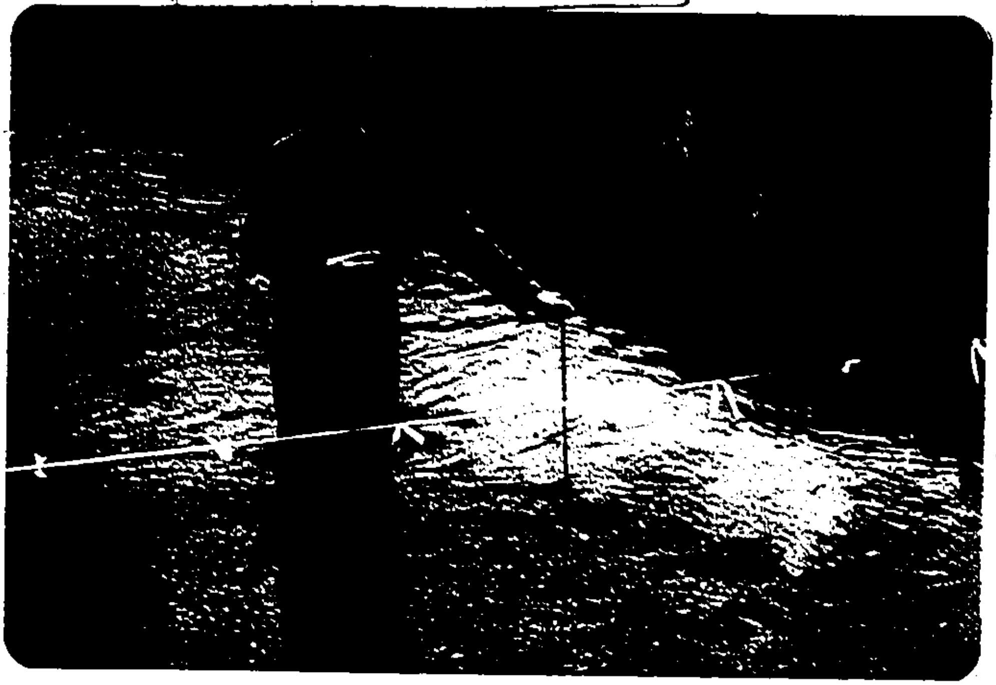

Figure 3.3 Current measurement of surface outflow.

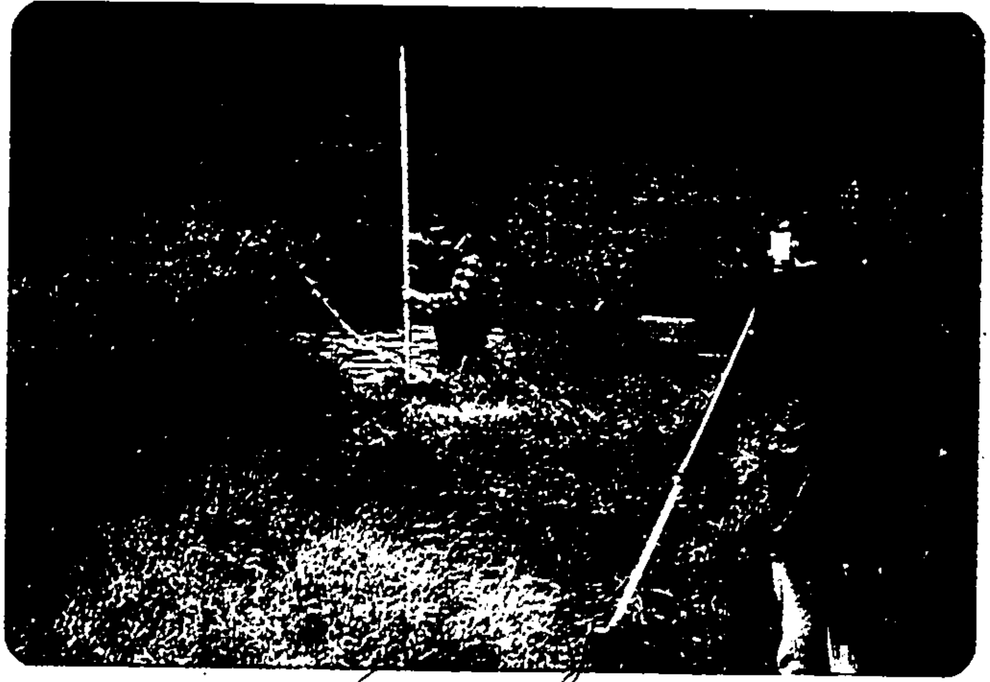

Figure 3.4 Cross-sectional measurement of main surface inflow.

Daily discharge measurements were made by indirect means dependent on the relation between monitored discharge and stage. The relation was determined by correlating measurements of discharge with the corresponding observations of stage (Appendix A) using the least-squares method (Gray, 1972; Lambie, 1978; Haan, 1977). The main surface inflow stream hydrograph is illustrated in Figure 3.5.

3.2.2 Surface outflow from the lake (Os)

Surface outflow from the lake is directed through a single natural channel located 50m south of the main inflow stream (Figure 3.2). The short distance between the two streams made it possible to obtain close in time discharge recordings. The monitoring of discharge of the surface outflow followed the same procedure as that outlined for the main surface inflow.

The channel was divided into eleven segments and possessed a different morphological character than that of the main inflow. Unlike the stream bed of the main surface inflow, which is composed of coarse unconsolidated deposits, the surface outflow stream bed consists of sand, silt and clay. Since the stage-discharge relation holds good only so long as no significant changes take place to the channel bed (Barnes and Davidian, 1978; Lambie, 1978), the morphology of the two streams were under

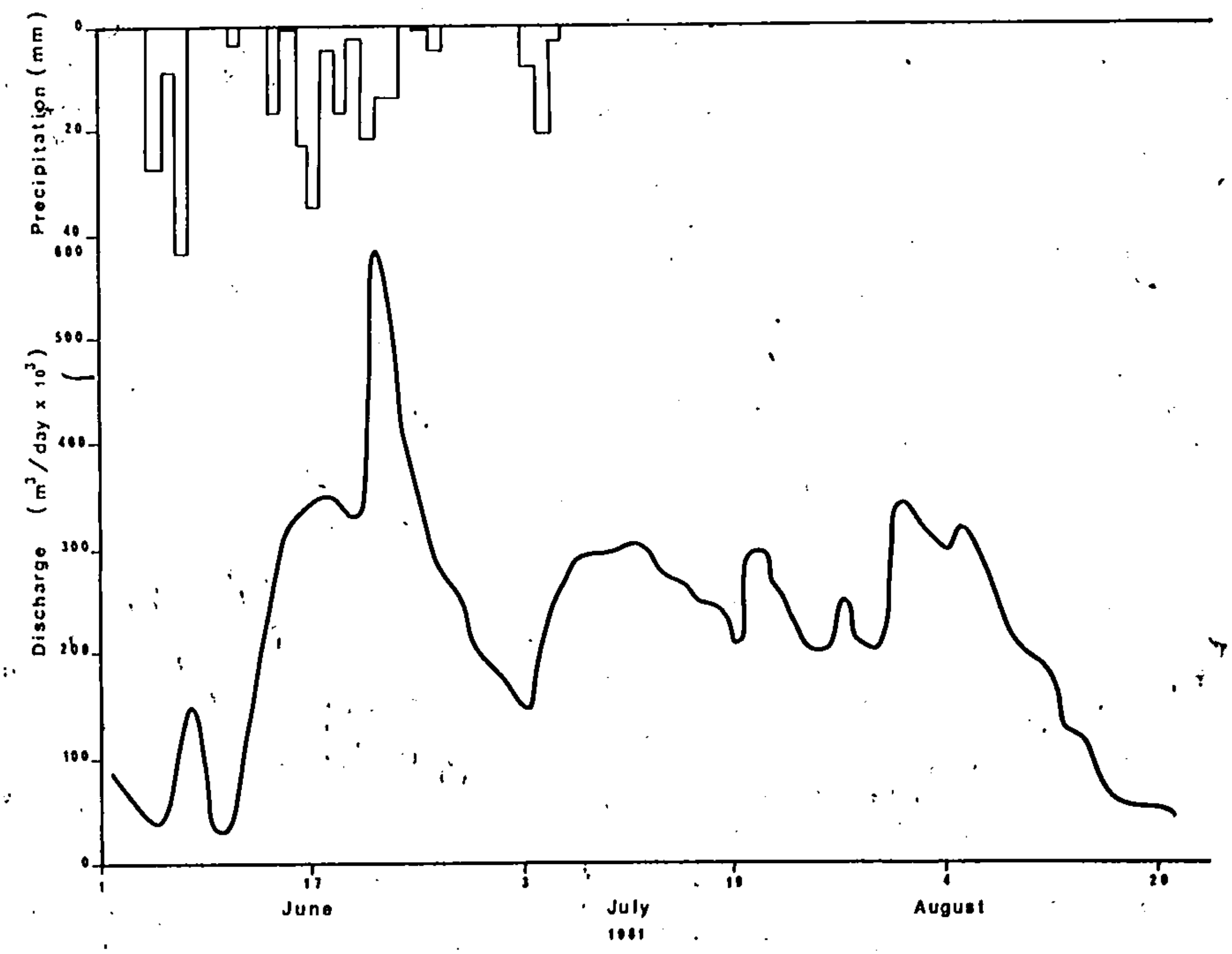

Figure 3.5 Stream hydrograph: main surface inflow.

continuous review. The surface outflow stream bed, although less stable than that of the main inflow, showed signs of only gradual change. The stream hydrograph is illustrated in Figure 3.6.

The velocity-area technique, although the most widely used method for point in time measurements of discharge (Gregory and Walling, 1973), has limitations as reported by several researchers (e.g., Barnes and Davidian, 1978; Herschy, 1978a; Pilgrim and Cornish, 1975). The types and performance of current meters have been reviewed by Charlton (1978) and Herschy (1978b).

3.2.3 Precipitation on the surface of the lake (P)

The importance of precipitation as an input to the hydrological regime and the techniques for its measurement have been documented by many authors (e.g., Ahrens, 1982; McKay, 1972; Ward, 1975). Areal precipitation values over the surface of the lake were obtained as the product of lake area and point precipitation.

The area of the lake was calculated as 0.6km^2 using a Precision compensating polar planimeter on an enlargement made from airphoto number A25193-70. Point precipitation was recorded by a tipping bucket rain gauge which was stationed on the Gladstone-Isaac Drainage Divide (Figure 3.1). The gauge, which was less than 20m above lake surface height, was part of the M.R.I. 'Mechanical

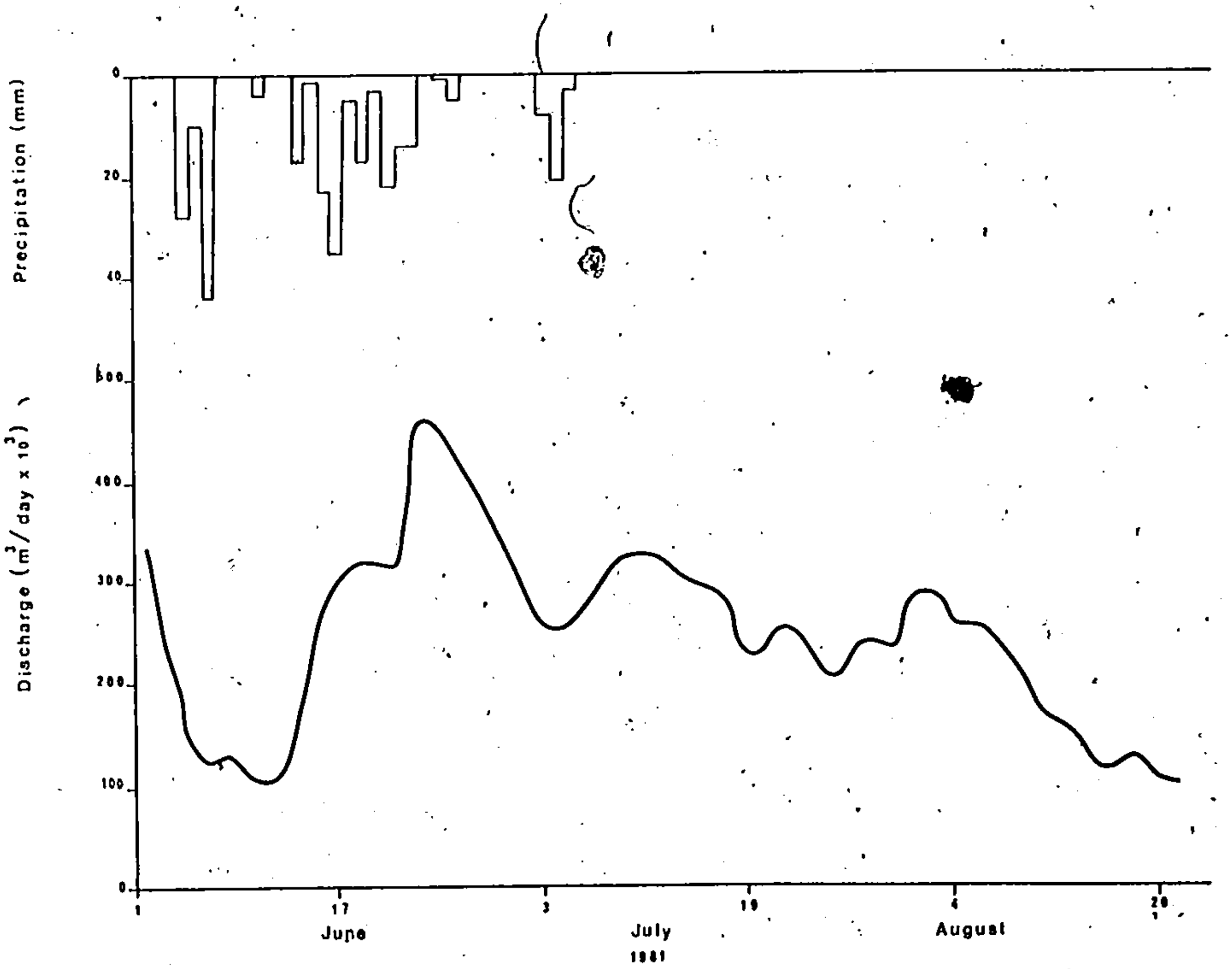

Figure 3.6 Stream hydrograph, surface outflow.

Weather Station model 1087 operated during the study period by Dr. D. Lagarec of the University of Ottawa. A number of researchers have reported on the importance of gauge site location and siting to minimize errors due to exposure of the gauge (e.g., Brown and Peck, 1962; Harrison and Newson, 1978; Larson and Peck, 1974).

Given the size of the lake only comprises 1.4 per cent of the total watershed area, the relative importance of the precipitation component in the water balance was minimal and hence the single rain measurement was used (Ferguson and Znamensky, 1982; Nezikhovskij, 1976). While the precipitation gauge itself was subjected to a variety of interferences (i.e., wind and splash effects) additional uncertainties lie in the spatial variability of the rainfall. Although precipitation variability has been recorded over small areas (e.g., Woo et al., 1981) monitoring such variability would have been impractical. The single rain gauge provided adequate accuracy for the determination of areal values over the surface of the lake for the period between June and early July (instrument failure July 7, 1981). Field notes were taken to complete the record.

3.2.4 Evaporation from the lake (E)

Numerous authors and research associations have described and compared the various techniques which estimate the amount of evaporation from a free water surface (e.g., Australian Water Resources Council, 1970; Chow, 1964; Gray et al., 1972; Webb, 1975). Efforts to simplify evaporation evaluation involving modification of the existing methods have been documented (e.g., Bowen, 1926; McCuen and Asmussen, 1976; Morton, 1979; Priestly and Taylor, 1972; Stewart and Rouse, 1976).

Evaporation estimates from the lake were derived using the nomograph of Kohler et al. (1955) and lake area. Daily point evaporation values are read from the graph, provided solar radiation, air temperature, dew point temperature and wind run are known. The importance of these meteorological factors affecting lake evaporation has been voiced by a number of researchers (e.g., Ferguson and den Hartog, 1975; Ward, 1975).

Excluding wind run (measured by the M.R.I. weather station), meteorological observations were recorded from the shore site identified in Figure 3.1 (data provided by D. Lagarec, Appendix A). The location represented lake conditions since it was assumed that limited modification occurred to the variables over the surface of the lake. The daily evaporation estimates for the headwater lake are shown in Figure 3.7.

The water balance output due to evaporation, like the precipitation input component, was partly a function of lake size. Therefore, its importance in the water balance equation was reduced due to the small area of

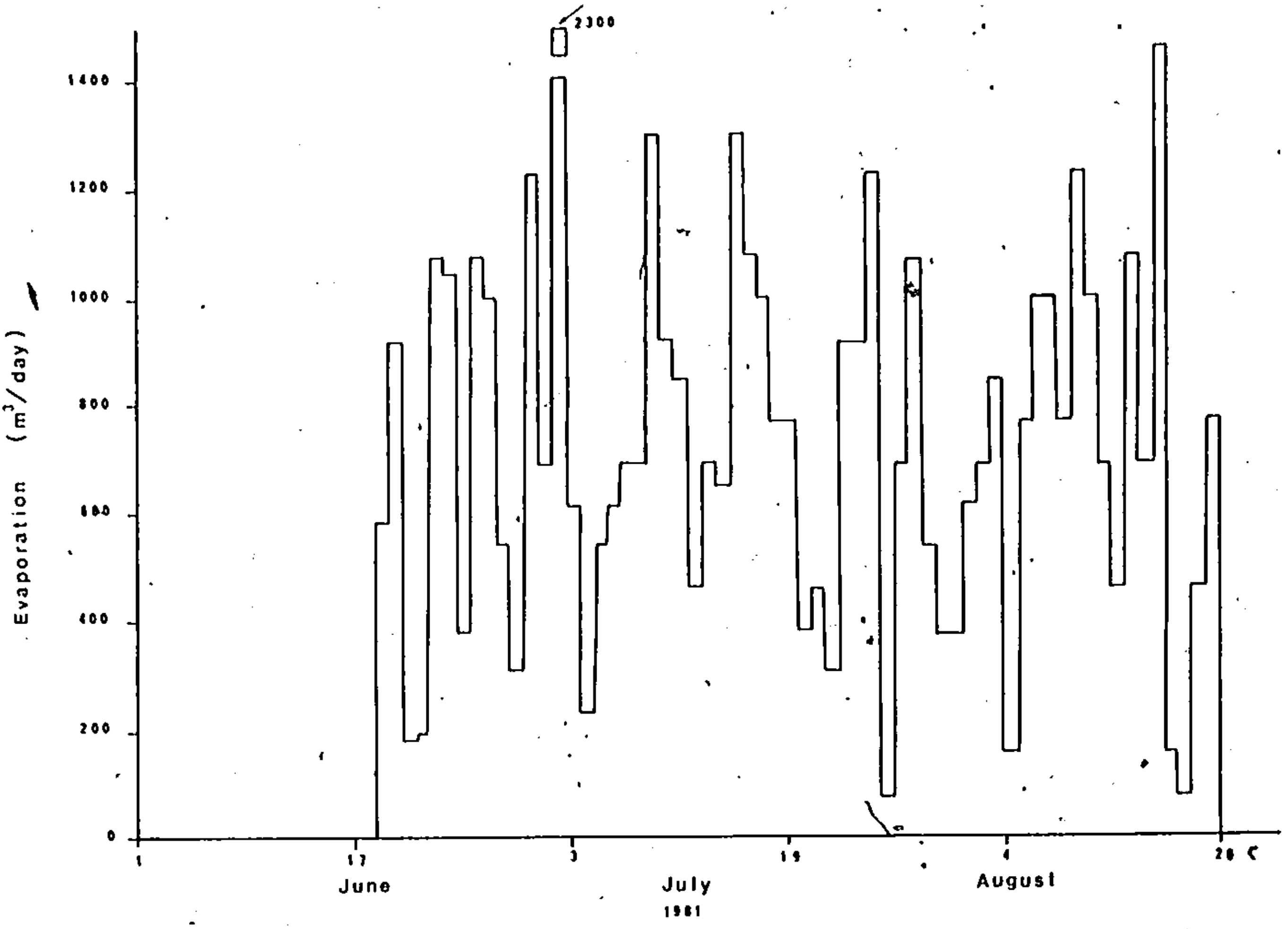

Figure 3.7 Evaporation estimates, Gladstone Creek, headwater lake.

the lake. Thus, although limitations existed in the determination of evaporation estimates, the use of a more elaborate technique would not have been justified.

3.2.5 Change in the water storage in the lake (Δs)

The change of the water volume in the lake was calculated as the product of lake level fluctuation and lake area. Daily lake level change was recorded from an accessible lake stage gauge. The survey staff was located near the axis of equilibrium of the lake (Figure 3.1) as recommended by Ferguson and Znamensky (1982). The axis of equilibrium refers to the zone where stage fluctuations resulting from wind effects do not influence the stage level and where the level is close to the mean level of the water body. Given the size of the lake and the fact that it is void of distinct bays or gulfs, only the one stage gauge was installed and monitored. The lake storage fluctuation is illustrated in Figure 3.8.

3.2.6 Ungauged parameters (Ic): Lateral inflow (Il), groundwater inflow (Iss), underground outflow (Oss)

As stated in Section 3.1 the parameter Ic (unknown component) was the residual term of the water balance equation (terms previously defined),

$$Is + P - E - Os - \Delta s + Ic = 0$$

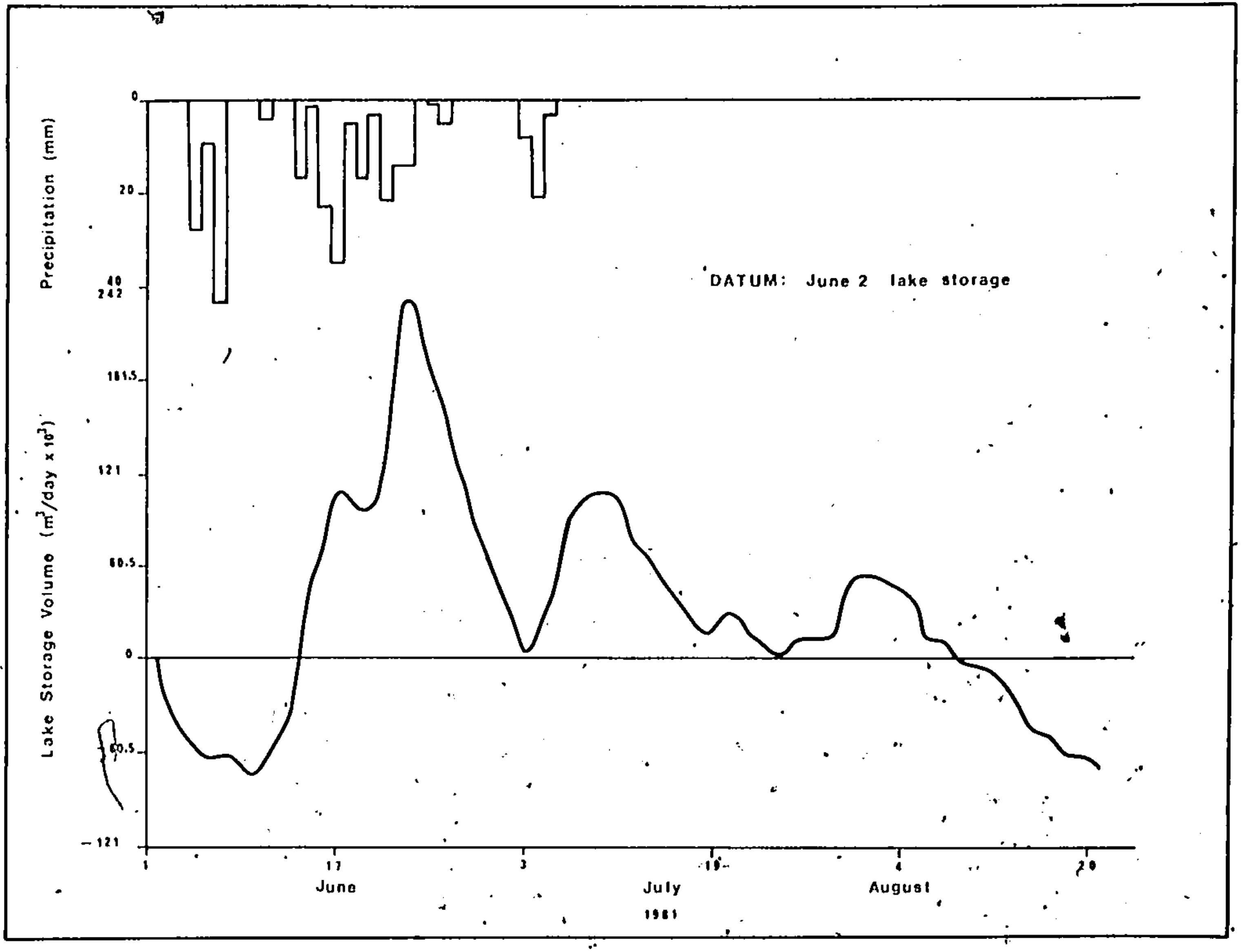

Figure 3.8 Lake storage fluctuation, Gladstone Creek headwater lake.

A positive residual would suggest a greater contribution made by lateral and groundwater inflow than by underground withdrawal. Conversely, a negative residual may indicate dominant underground outflow. The results are relative figures since no attempt was made to separate the Ic components. Discrepancies and errors of the gauged water balance parameters were also unknown. Therefore, balance discrepancy was an additional component of Ic. Hence:

$$Ic = Il + Iss - Oss \pm \sigma$$

where Ic = residual component of water balance equation
Il = lateral inflow (direct runoff from surrounding land area)
Iss = groundwater inflow
Oss = underground outflow
σ = cumulative effect of the errors in the gauged water balance components

The variation of Ic for the headwater lake is illustrated in Figure 3.9.

3.3 Discussion

The results obtained illustrate the general hydrological picture of Gladstone Creek headwater lake for the period in question. The results provide useful background knowledge for the evaluation of landform influence on stream hydrochemistry (Chapter 4). Through the use of a water balance equation, the lake water

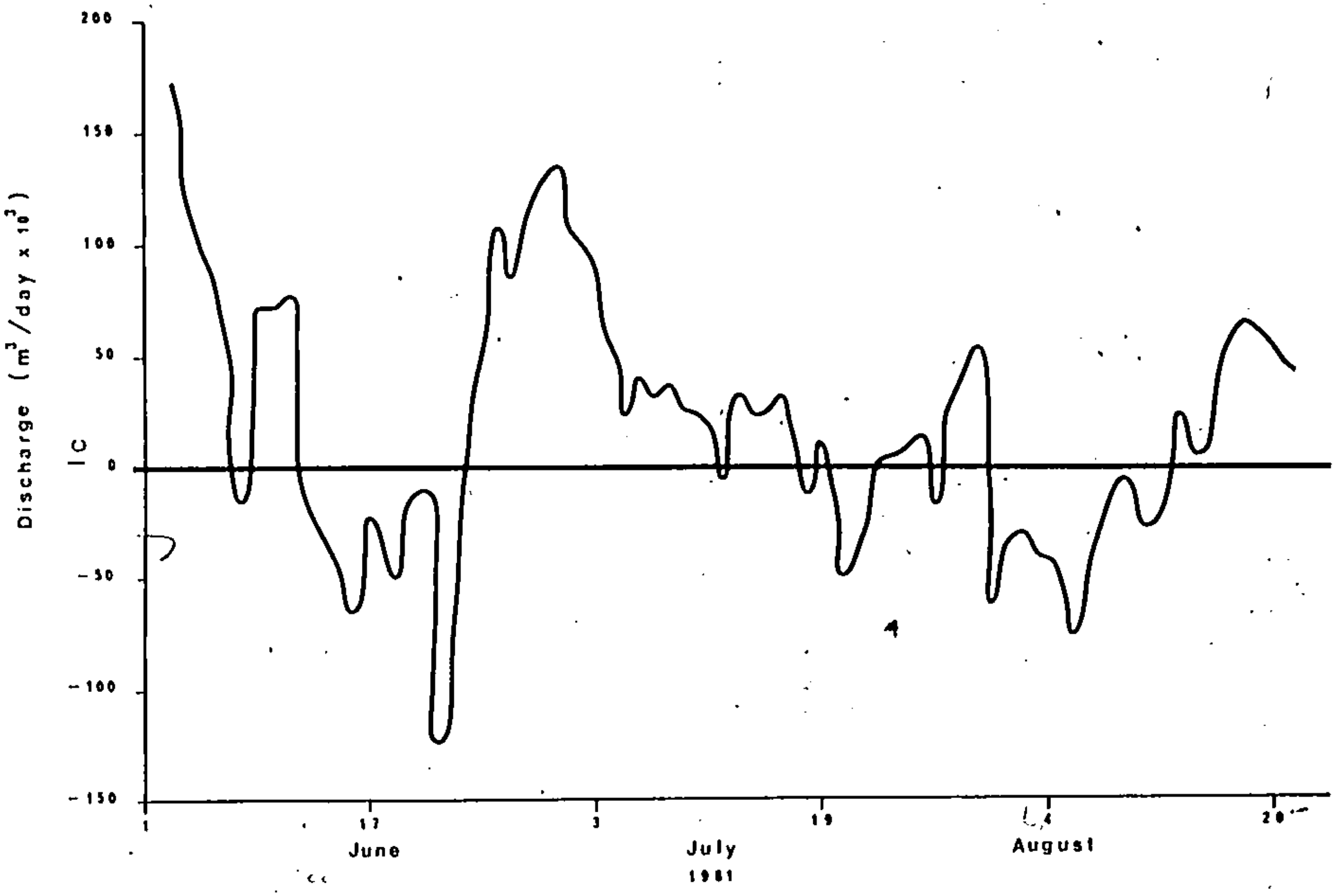

Figure 3.9 Seasonal variation of component Ic.

budget components were determined. Based on the observations the following remarks can be made:

(1) Residual figures (Figure 3.9) suggest that the headwater lake was partially fed by lateral and groundwater inflow, and characterized by a subsurface outflow.

(2) Precipitation had a strong effect on the seasonal regime of the lake. Rainstorms dominated between June 5 and July 6. The precipitation for the remainder of the season was light. Hydrological response to the precipitation events is illustrated by the occurrence of hydrograph peaks (e.g., Figure 3.5).

(3) Catchment response indicates lag times between water balance components. Comparing the lake's main surface inflow (Figure 3.5), surface outflow (Figure 3.6) and storage fluctuation (Figure 3.8) hydrographs, estimates of lag time were made. The lag of storage fluctuation and surface outflow behind the main surface inflow was 1 and 2 days respectively. It follows that the surface outflow lagged storage fluctuation by 1 day.

(4) A positive relationship existed between lake storage and subsurface outflow. Increases in lake storage volume resulted in increased subsurface outflow due to the pressure exerted by hydrostatic head (Figures 3.8 and 3.9).

The hydrological investigation was successful in identifying the lake water budget components, but failed to isolate lateral inflow (runoff from landforms surrounding the lake). Difficulties in monitoring the groundwater component (Ferguson and Znamensky, 1982; John and Lock, 1977) led to the estimate of parameter Ic. It should be noted that the values obtained for this daily estimate are large. The figures are relative to the water balance equation (gauged parameters) and must be regarded cautiously until more research is done to measure the Ic components. Lateral inflow discharge fluctuation (a function of precipitation intensity, duration and frequency) was important since it affected the flushing and dilution of stream solutes. These processes are considered in Chapter 4.

CHAPTER 4

STREAM HYDROCHEMISTRY

4.1 Introduction: Study design

The study was designed to investigate the effects of the landforms of the basin on the water chemistry of the surface and subsurface streams. Hydrochemical analysis was used to indicate the spatial and temporal solute behavior of the investigated streams. The spatial enquiry contained five type-sites identified as a representative sample of the landforms surrounding the headwater lake. Temporal behavior was observed for June 2 to August 22, 1981, corresponding to snowmelt through to reduced stream input of the lake respectively.

To observe the changes in hydrochemistry due to the routing, both an input and output sample for the landform was essential. The investigation to locate type-sites to meet this condition was accomplished during the pre-study. The location of sampling sites and the frequency of sampling were established from the study design (Environment Canada, 1983; Hem, 1970; McBean and Bushert, 1978; Rainwater and Thatcher, 1960; Rodda, 1980; Wilson, 1979). The landforms selected included one rock glacier, one talus and three alluvial fans. In addition to monitoring the five landform streams, the inflow and outflow of the lake were sampled. Refer to Figure 4.1 for location and

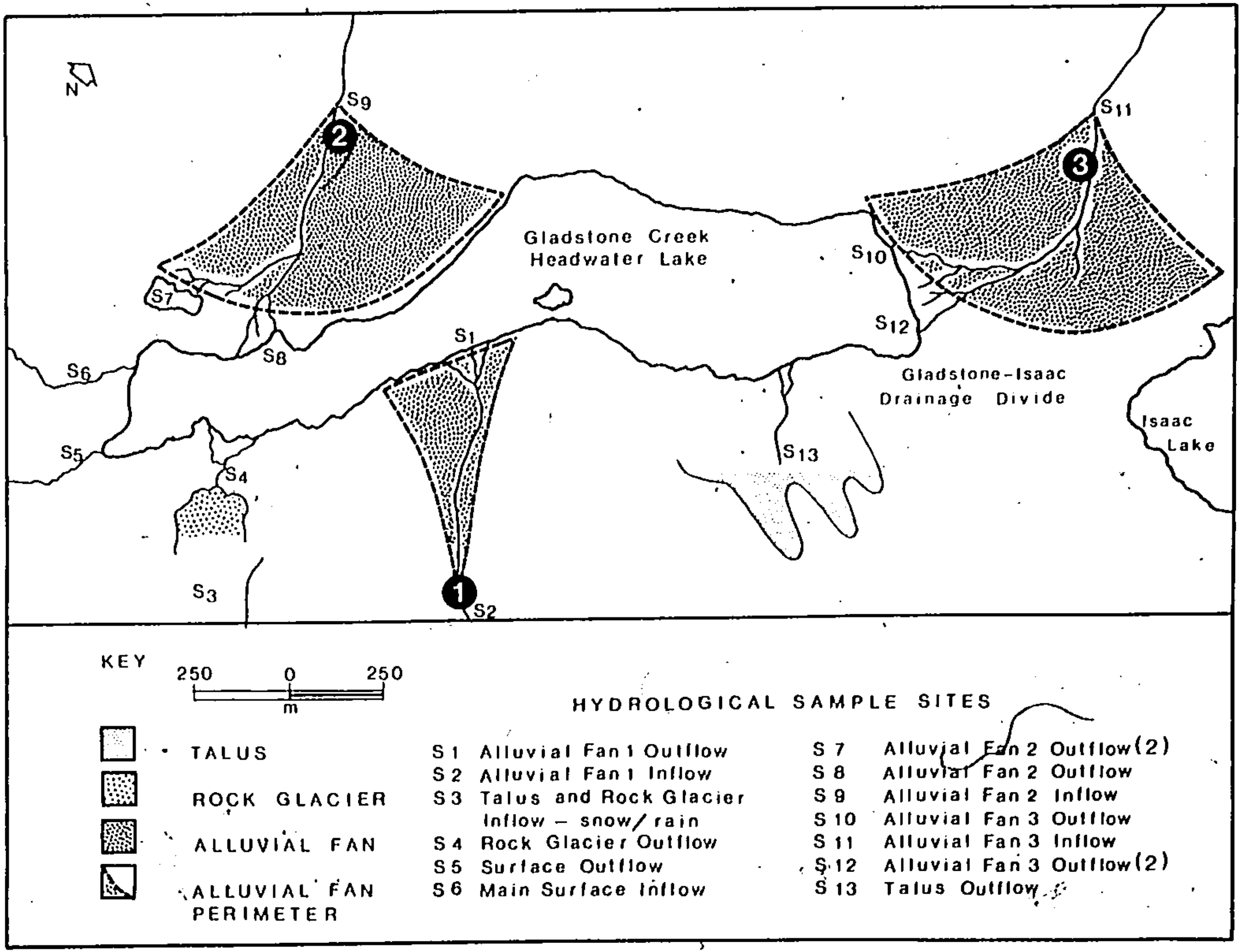

Figure 4.1 Hydrochemical sample location diagram.

identification of sample sites.

The sites were sampled every three days to document solute levels and their general pattern of variation through the field season of 1981. This frequency of sampling resulted in twenty-eight sample set collections. Hydrological measurements (Chapter 3) indicated flushing and dilution processes associated with precipitation and increased discharge (Burt, 1979; Feller and Kimmins, 1979; Lewis and Grant, 1979; Oborne et al., 1980; Reid et al., 1981; Walling and Foster, 1975; Walling and Webb, 1980). The three day cycle was, however, insufficient for detailed appraisal of the temporal and spatial variability of the system, particularly during precipitation events when continuous records or frequent sampling is required (Walling, 1977). Several researchers (e.g., Burt, 1979; Feller and Kimmins, 1979; Foster, 1978; Miller and Drever, 1977; Oxley, 1974; Pilgrim et al., 1979; Reid et al., 1981; Walling 1974; 1977; Walling and Foster, 1975; 1978; Walling and Webb, 1980) have discussed rapid short-term solute fluctuations during storm events. Houston and Brooker (1981) claimed that variations in behavior of this nature are unlikely to affect substantially seasonal trend assessment of temporal and spatial variation of water concentrations.

4.2 Techniques and discussion of landform type-site descriptions

The landforms differ in aspect, slope, composition and vegetation cover. The aspect of the landform sites was determined by Brunton compass. Slope measurements at 10m intervals up the alluvial fans were recorded using an abney-level. 300gm grab samples were obtained to compare the stratified sediments of the fans (Kellerhals and Bray, 1971). Cross-sections were cut at the base, at two mid profiles, and at the apex of the landforms. Grain size analysis was performed on the sediment samples using the dry sieve method (Folk, 1974). The type and thickness of vegetation was recorded for each alluvial fan. (Longitudinal transects were run at 10m intervals.)

Rhodamine WT dye was used to identify the pathways of the streams. Tracing was performed to verify that an output site corresponded to the input sample. Rhodamine WT for water tracing has been recommended by Smart and Smith (1976) and Smart and Laidlaw (1977). Nestmann et al. (1980) identified biological problems associated with the use of Rhodamine B. Omoti and Wild (1979) recommend Pyranine; however, its use is confined to short-term laboratory experiments (Smart and Laidlaw, 1977; Omoti and Wild, 1979). One per cent Rhodamine WT concentration allowed for pathway and lag time investigation for the alluvial fans. Procedures followed those recommended by Wilson Jr. (1968) and Hubbard et al. (1968).

4.2.1 Talus type-site

Talus is colluvial accumulation of variable rock debris from exposed rock faces of mountain valley walls. Debris is transported by gravity, rainwash or snow meltwater, or by avalanching snow (White, 1981). Talus has been studied extensively in many areas: for example, northern Sweden (Rapp, 1960), Soviet central Asia (Sosedov, 1974), the Colorado Front Range (White, 1971), the Canadian Rockies (e.g., Gardner, 1973; Luckman, 1977; Rampton, 1981), and eastern Baffin Island (Church et al., 1979).

The talus (Figure 4.2) is of the rockfall type of White's (1981) classif[illegible]tion of alpine mass movement forms. Of Johnson's (1983) seven proposed talus profiles, the slope is sublinear having been produced by gravity debris accumulation. Rock disintegration by physical weathering has primarily occurred by wedging effect of ice in jointed or fractured rock. The talus is composed mainly of angular fragments of hornblend-biotite granodiorite and quartz diorite. Sorting by fractions during sliding has resulted in particle size increase with distance travelled downslope (surface). Grain size decreases with depth (subsurface). Smaller particles have been washed down and sorted vertically. While the surface is characterized by high porosity, fine fractions located near bedrock hold water longer due to slow filtration rates.

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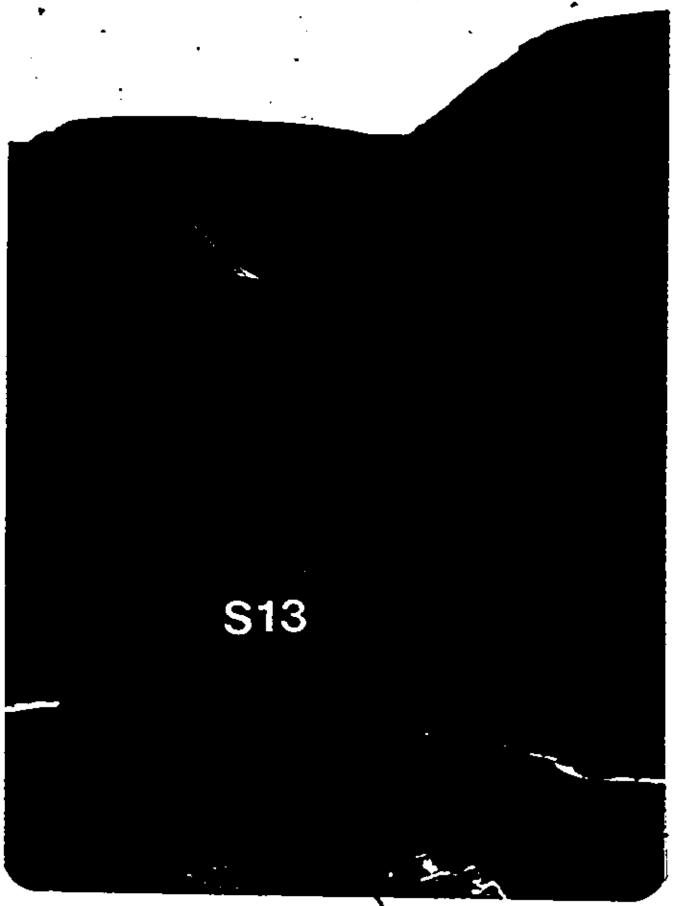

Figure 4.2 Talus site, northfacing slope (S_{13}).

Due to the mature vegetation cover (willow, spruce and grass) which has developed at the base of the form and the absence of fresh rockfall material, it is evident that the slope is not undergoing significant development. The upper section of the talus is characterized by subsurface drainage (percolation flow). This develops into a distinct incised stream course at the foot of the form (S_{13}).

4.2.2 Rock glacier type-site

The documentation of rock glaciers first appeared in the literature around the turn of the century (e.g., Capps, 1910) and has increased to the present. A number of ice type content theories have been developed to explain the internal structure and origin of flow of the landforms. These include glacier and snowbank ice cored systems (e.g., Barsch, 1971; Johnson, 1980a; Potter, 1972), interstitial ice formations (e.g., Johnson, 1978; Wahrhaftig and Cox, 1959) and relict features devoid of ice content (Johnson, 1980b; Whalley, 1974). Rock glaciers have been classified according to this continuum, with debris covered glaciers at one end to cemented interestitial ice and no ice content at the other (e.g., Ommanney, 1976; Rampton, 1981; Whalley, 1974). Designation has also been inferred by the origin of the rock and debris mass, such as rock glaciers at the base of taluses or below terminal moraines (e.g., Barsch, 1971; Johnson, 1978; 1983).

The rock glacier (Figure 4.3) can be classified as either a lobate rock glacier (Wahrhaftig and Cox, 1959; White, 1981) or a talus derived type (Johnson, 1978). Rock-debris acquired from high angle talus has accumulated at the base of the slope and moved outward from the valley wall (compressional zone). At this extension of the talus (flow lobe) there is a sharp change of slope angle. The form has a coarse surface litter of weathered rock blocks. At depths of 2m there is a gradual decrease of particle size due to summer rainfall washing the fine fractions down into the rock glacier. The drainage pattern is subsurface. Seepage of water (precipitation and melt) occurs through the rock mass as there are no distinct surface water courses. Percolation through the rock glacier resurges at the terminus of the flow lobe (S_4). Its continuous flow suggests hydrostatic head from water build-up in the rock. Interstitial ice (frozen rain and refrozen melted snow) was encountered in the top 2m of the landform. Deformation of this ice due to pressure and the weight of the talus behind the landform have caused the mass movement of the rock glacier.

4.2.3 Alluvial fan type-sites

In areas with high relief and glacial over-steepening of valley walls, alluvial fans form where creeks

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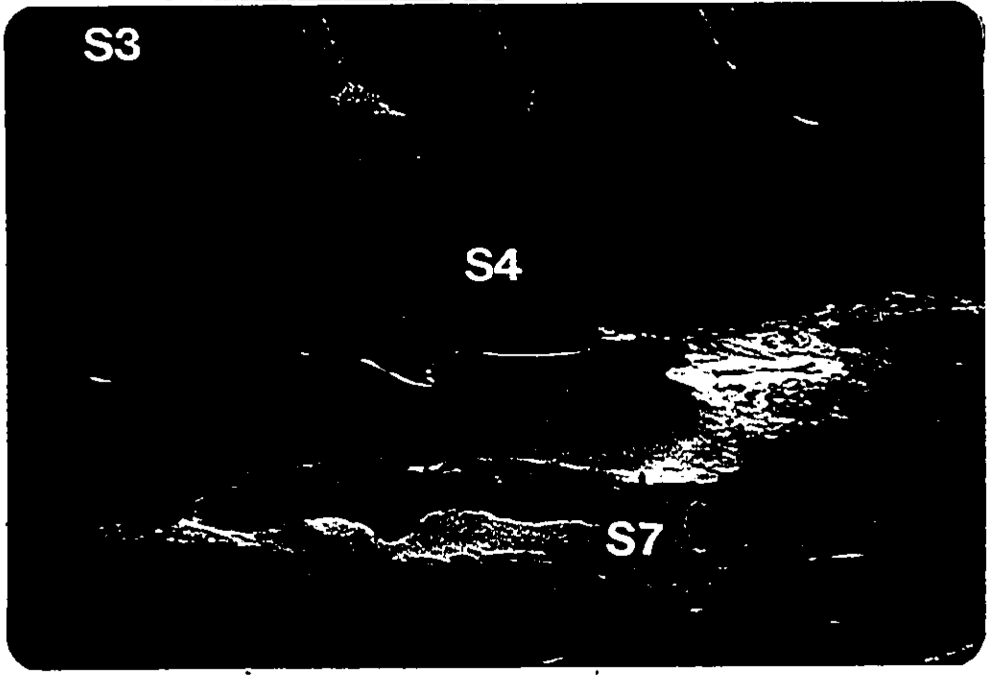

Figure 4.3 Rock glacier, northfacing slope (S_3, S_4). The back-water lake (S_7) in the foreground and main inflow and sole outflow at the west end of the lake are also shown.

with rapid rates of descent flow out onto the flatter bottoms of major valleys (Rampton, 1981). Several alluvial fans have developed around the headwater lake.

Three of these fluvial landforms were investigated (Figures 4.4, 4.5 and 4.6). The forms differ in a number of respects. Alluvial fan 1 covers a slope distance of 540m with a frontal base of 310m, compared to 480m by 1080m and 470m by 1100m for alluvial fans 2 and 3 respectively. The large fans (2 and 3) feature gentle slopes which contrast the steep slope of the smaller fan (Table 4.1). The single active channels which flow the upper sections of the forms (S_2, S_9, S_{11}) become distributed with decrease in slope angle and distance travelled downslope. These braided streams are surface to nearsurface flows which drain into the headwater lake (S_1, S_8, S_{10}). This drainage pattern of the lower sections is pronounced on fans 2 and 3. The vegetation which has developed on the forms suggests that although small changes occur in the stream channels, the landforms are stable (Table 4.1). Deposition of sediment was probably greatest shortly after the Quaternary glaciations which influenced the region. Fan sediments are tabulated in Table 4.2. Gravels and sands dominate the profiles A–C. The White River Ash is present in the C profile of all fans. The 1230 14C YR BP volcanic deposit's chemical composition (wt %) is $SiO_2 = 67.4$, $Al_2O_3 = 15.1$, $TiO_2 = 0.5$, $MgO = 2.0$, $FeO = 2.0$, $Fe_2O_3 = 2.2$, $Na_2O = 4.1$, $K_2O = 2.5$ and $CaO = 4.1$

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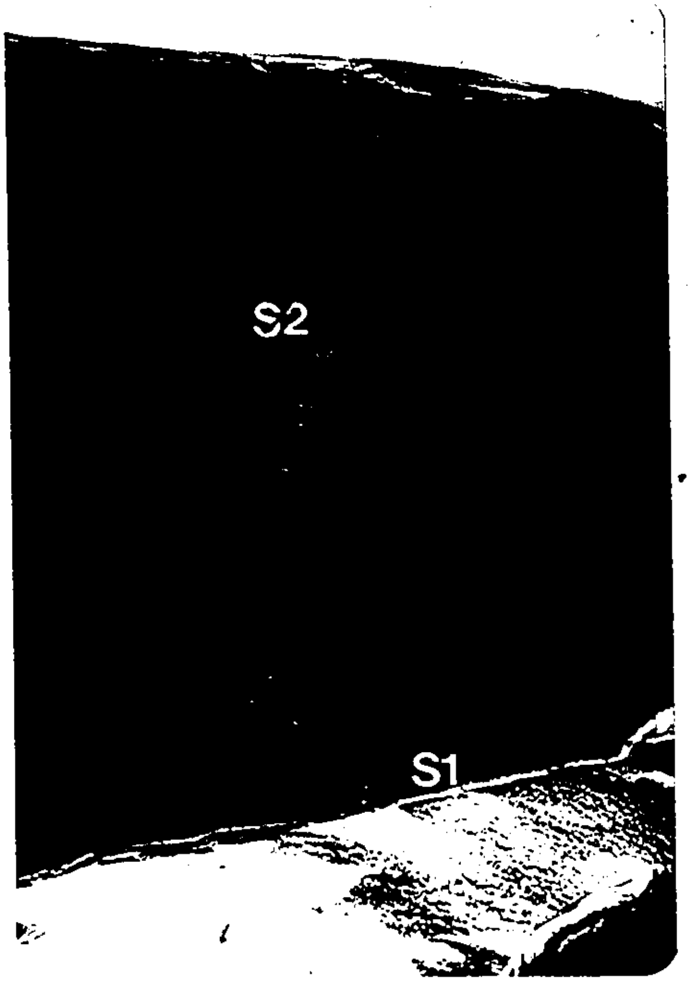

Figure 4.4 Alluvial fan 1, northfacing slope (S_1, S_2).

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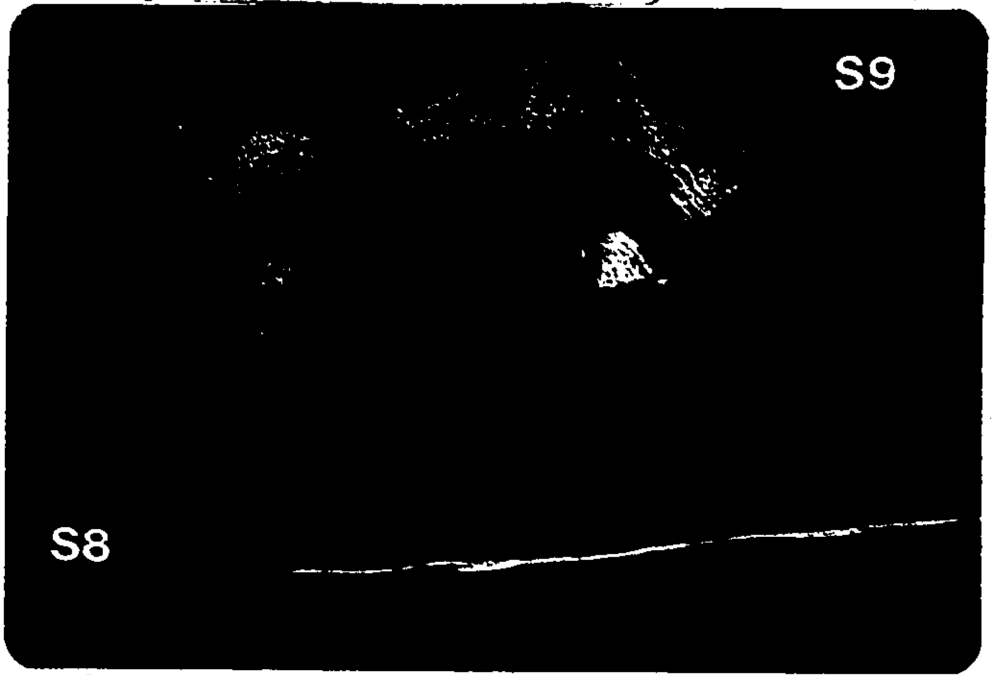

Figure 4.5 Alluvial fan 2, southfacing slope (S_8, S_9).

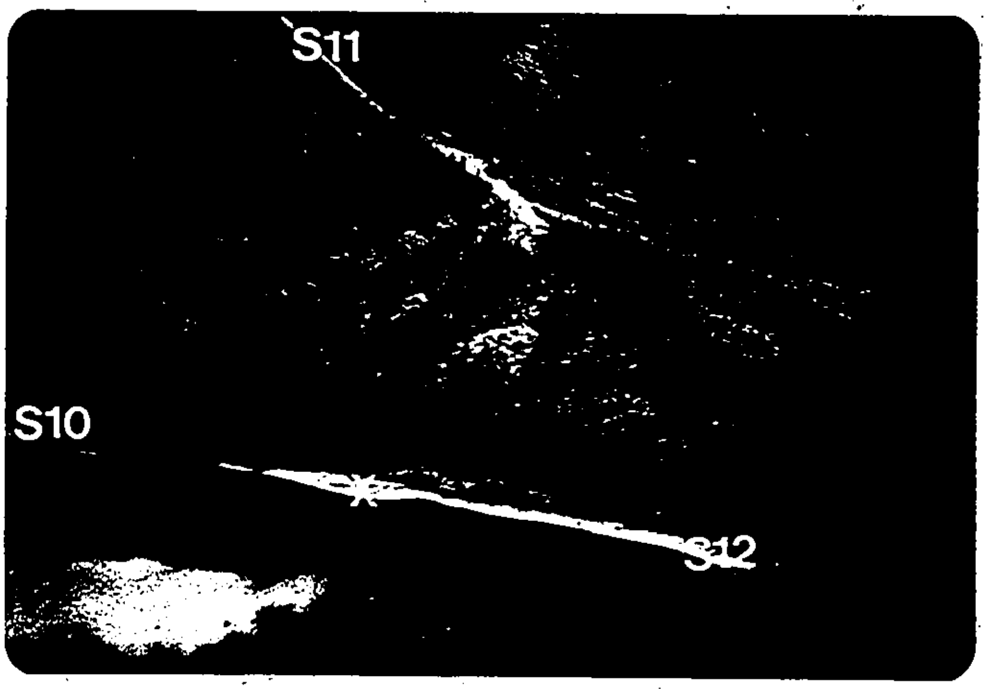

Figure 4.6 Alluvial fan 3, Gladstone-Isaac Drainage Divide (S_{10}, S_{11}, S_{12}). (x) marks an intermittent stream.

Table 4.1

Average slope, vegetation and vegetation thickness observations from longitudinal transects of the alluvial fans.

Location	Slope Angle (°)	Vegetation Association	Vegetation Thickness (cm)
A_1	21	Dispersed willow and grass	<1
A_2	14	Balsam poplar, willow and grass	10
A_3	10	Dispersed spruce and willow	4
B_1	18	Dispersed willow and grass	5
B_2	12	Balsam poplar, willow and grass	9
B_3	9	Dispersed spruce and willow	1
C_1	18	Bog, willow and white birch	19
C_2	6	Dispersed willow and bog	11
C_3	7	Dispersed willow and spruce	3
D_1	12	Bog and willow	38
D_2	3	Willow, bog and spruce	32
D_3	3	Willow, bog and spruce	50

Note: The transects were divided into four equal portions where A = Apex section, B = Upper section, C = Lower section and D = Base section.

Table 4.2

Particle size analysis of sediment samples from alluvial fan longitudinal transects.

Location	Silt % <0.063mm	Sand % 0.063-2.0mm	Gravel % >2.0mm
A_1	0	54	46
A_2	2	38	60
A_3	1	43	56
B_1	32	68	0
B_2	2	39	59
B_3	2	50	48
C_1	9	74	17
C_2	1	44	55
C_3	3	56	41
D_1	1	99	0
D_2	35	61	4
D_3	49	51	0

Note: The transects were divided into four equal portions where A = Apex section, B = Upper section, C = Lower section and D = Base section.

Denton and Karlén, 1977; Lerbekmo and Campbell, 1969). The lowest section (D) is composed of smaller sand fractions and silts. This trend is strongest on alluvial fans 2 and 3 (alluvial fan 1 is primarily composed of sand size deposits) Rhodamine WT dye tracing verified stream pathways (output and input sites corresponded) and determined flow residence times for the landforms (Figure 4.7). The steep sloped, sand sized derived, alluvial fan 1 lag was measured on June 27, 1981 at 65 min over a stream course distance of 570m. The gentler sloped, heterogeneous alluvial fans 2 and 3 measured on July 21 and July 22, 1981, recorded times of 95 min by 250m and 115 min by 450m respectively (surface flow measurement).

4.3 Techniques and discussion of hydrochemical results

The Gladstone Creek headwater basin surficial deposits are primarily gravel and sand derived from granite based rocks (SiO_2). The lithologic debris, deposited during the Quaternary glaciations (Section 1.3.3), is related to the bedrock. The predominant minerals are quartz, feldspar (plagioclase and orthoclase form) biotite and hornblend (R. Kodybka, personal communication, 1983). The chemical composition and weathering products of these minerals are shown in Table 4.3. The concentration of inorganic constituents in the streams is affected by the availability of elements and operation of geochemical processes in this unconsolidated mantle (i.e., solution

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Figure 4.7 Rhodamine WT dye tracing on alluvial fan 1.

Table 4.3

Weathering products of the common minerals found in the Gladstone Creek Region (modified from Cargo and Mallory, 1977).

Mineral	Chemical Composition	Weather Products	
		Soluble	Insoluble
Quartz	SiO_2	none	quartz grains
Plagioclase	Na, Ca, Al, SiO_2	Na, Ca, SiO_2 (silica)	clay with K^+
Orthoclase	K, Al, SiO_2	K (minor), SiO_2 (silica)	clay with K absorbed on it
Biotite	K, Fe, Mg, Al, SiO_2	K (minor), Mg, SiO_2 (silica)	clay, hematite and/or limonite
Hornblend	Ca, Fe, Mg, Al, SiO_2	Ca, Mg, SiO_2 (silica)	clay, hematite and/or limonite

and ion exchange).

The output of solutes from the surficial deposits to the watercourses is regulated by the hydrological regime (Section 2.3). The general hydrological picture of the Gladstone headwater catchment for the study period was as follows (Chapter 3):

(1) June 2 to July 8 represented the wet period. Snowmelt and precipitation during this time caused increased runoff flows and peak lake storage.

(2) The remainder of the season (July 9 to August 22) was characterized by light precipitation, reduced stream discharge and a decrease in lake storage. With the exception of the precipitation events of late July which resulted in a discharge response on July 31, the period was dry.

The results presented in this chapter serve as an indicator of the effect of geomorphology on alpine stream hydrochemistry. The study was designed to identify landform influence on stream hydrochemical concentration. Therefore, the lake's main inflow (S_6), main outflow (S_5) and secondary outflows from alluvial fans 2 and 3 (S_7, S_{12}) have not been considered. Hydrochemical results for all sample sites were graphed according to concentration over time. Descriptive statistics were calculated for the wet and dry periods and overall season (Appendix B). Comparisons of the graphs and statistics were used to assess temporal and spatial solute trends. The results were tested at a 0.95 confidence interval using the t distribution (Haan, 1977). The solute trends, (a) an increase of concentration was exhibited between the input and output samples of the type-sites; (b) output samples from different landforms illustrated significant differences in concentration; and (c) higher solute concentrations occurred during the snowmelt and precipitation period, are presented to test the hypothesis:

> The varying morphologies and diverse lithologies of unconsolidated deposits along the valley sides of Gladstone Creek headwater basin significantly influence the chemical loading of the streams feeding the lake (Section 1.2).

4.3.1 Water sampling and analysis

The importance of sample collection in water analysis has been expressed by Hume (1973) and Hamilton (1976). Natural waters are mixtures containing biological species and chemical ions in dynamic equilibrium. Batley and Gardner (1977) pointed out that

> . . . the mere act of sampling, when the water sample is brought into contact with oxygen and container walls, or subjected to physical changes of temperature and pressure, is often sufficient to disturb this equilibrium.

A number of researchers and research associations have recommended sampling procedures: for example, Batley and Gardner (1977), Brown et al. (1970), Environment Canada (1983), Hem (1970), Rainwater and Thatcher (1960) and the United States Army Corps of Engineers (1977).

Stream samples were obtained for all sites with the exception of the input sample for the rock glacier and talus landforms (S_3). Samples were collected in 250ml acid-washed polyethylene bottles. The bottles and caps were soaked in 6N HCl, flushed with tap water and carefully rinsed twice with deionized water. The bottles were shaken dry and capped. The containers were rinsed with several sample aliquots before sample collection. Throughout this procedure care was exercised not to touch the inside of the bottles or caps. Individual containers were assigned to a specific site for use throughout the field season. Grab samples were taken at the centroid of flow, facing the container upstream, collecting a representative water sample for the site (Batley and Gardner, 1977; Brown et al, 1970; Environment Canada, 1983; Hem, 1970; Rainwater and Thatcher, 1960). Oguss and Erlebach (1976) and Kleiber et al. (1978) have discussed the limitations of infrequent single grab samples representing mean water quality. Given the size of the streams and frequency of sampling, such limitations did not exist.

Additional techniques are established for the collection of surface and nearsurface water samples. Surface sampling devices range from simplistic sampling irons (Environment Canada, 1983) to sophisticated automatic water samplers which operate more frequently when solute concentrations are most variable (O'Loughlin, 1981). A number of nearsurface sampling apparatus also exist. Stainless steel or plastic troughs can be installed at various depths of the soil profile or adjacent to the vegetation mat to sample nearsurface flow (Lewin et al., 1974; Pilgrim et al., 1979). Shallow groundwater samplers commonly consist of a variety of sampling probes inserted into the groundwater profile (Hansen and Harris, 1980; John et al., 1977; Pickens et al., 1978). Patterson et al. (1978) modified and simplified a coring and squeezing technique. Subsurface water samples are obtained by placing short sections of sediment cores in a mechanical squeezer and applying pressure.

During June and early July snowmelt runoff constituted the major input for the rock glacier and talus type-sites (S_3). Snow samples were obtained from the snowpack on the north facing ridge, located directly above the rock glacier. A grab sample taken at the interface of the snowpack and ground surface was collected in a 1ℓ polyethylene container (Galvin and Cline, 1978; Zeman and Slaymaker, 1975). Debris present on the ground or dust accumulation on the snow cores was not included in the sample. The aliquot acted as the input sample for both landforms. Other methods of snowpack sampling include the removal of a snow core using clear plastic piping (Wright and Dovland, 1978) to the more elaborate use of a field lysimeter, buried in the ground prior to winter (Johannessen and Henriksen, 1978).

By July 8, no snow remained, and precipitation became the major source of input to the landforms. From this date until the end of the field season, bulk precipitation was collected to represent this source. Bulk precipitation collection refers to a combination of unknown proportions of both dry and wet fallout (Whitehead and Feth, 1964). The collector used was a continuously open plastic 10ℓ container, fitted with a drain mechanism. The collector, with a collecting area of $0.25m^2$, was mounted 3.0m from the ground surface. The use of such a large collector has been employed by Likens et al. (1967), Lewin et al. (1974); Cryer (1976) and Lewis (1981), and recommended by Lewis and Grant (1978). Following a rainfall event the bulk precipitation was drained into a clean 250ml polyethylene bottle. This procedure resulted in no significant loss due to evaporation. Individual rainfall samples were integrated every three days corresponding with stream sampling frequency. Combining the events which occurred in the three day period ensured that enough sample was obtained for chemical analysis. The bulk precipitation technique used is a modification of the polyethylene system described by Likens et al. (1967) and Lewis and Grant (1978). The system consists of an uncovered funnel, tubing (vapour barrier) and reservoir.

Numerous researchers have documented the analytical methods available for water analysis (e.g., Brown et al., 1970; Golterman and Clyme, 1969; Levinson, 1974; Minear and Murray, 1973; Rainwater and Thatcher, 1960). Trace metal ionic concentrations were determined by colorimetry, using Lamotte model M-TRL colorimeters. The colorimeter consists of a light source, sample holder, photocell and a meter which displays the photocell's response. An ionic concentration determination is based upon a reaction to form a colored solution which indicates the amount of a specific solute present in the solution (Levinson, 1974; Sandell, 1950; Thomas and Chamberlin, 1980). The intensity of the color is measured by the colorimeter. The results are given in per cent transmittance and calibration charts convert these values into concentration of solutes. The M-TRL units are pre-calibrated, therefore the preparation of standard solutions and standard curves is not required.

Colorimetric methods were used because analysis could be performed in the field while still providing adequate accuracy (2 per cent transmittance) to test the hypothesis under investigation. The technique eliminated the need for sample transport and storage.

Studies have documented interferences which change the solution equilibrium after collection. Contact of the dissolved fraction with suspended sediment can change the ion concentration distribution, with adsorption and desorption equilibrium times of less than 72h (Duke et al., 1968; Gardiner, 1974; Lorrain and Souchez, 1972; Murray and Murray, 1972). Similar effects have resulted due to bacterial interference (Lee and Hoadley, 1967; McLerran and Holmes, 1974). Storage of samples can also cause contamination (Batley and Gardner, 1977; Benes and Steinnes, 1975; Bernhard and Zattera, 1975; Johnson et al., 1975; Rainwater and Thatcher, 1960). Filtration or centrifugation, to remove particulate matter, and the addition of preservation reagents, to keep dissolved constituents in solution, act to minimize such interferences (Batley and Gardner, 1977; Environment Canada, 1983; Henrikson and Balmer, 1977; Rainwater and Thatcher, 1960).

Inorganic species present in surface and subsurface water is commonly classified as major, minor and trace constituents (e.g., Davis and De Wiest, 1966; Faust and Aly, 1981; Gorham, 1961; Hem, 1970). An example of this classification is given in Table 4.4. Ions from each of these categories were selected for analysis. Specific electrical conductivity was measured in microsiemens (μs) using a Lamotte model DA multirange conductivity meter. pH was measured on a pH scale with a Lamotte model HA pH meter. Both instruments were equipped with manual

Table 4.4

Classification of dissolved inorganic constituents in groundwater (Davis and De Wiest, 1966).

Major Constituents (>5mg/ℓ)	Minor Constituents (0.01–10.0mg/ℓ)	Trace Constituents (<0.1mg/ℓ)	
Bicarbonate	Boron	Aluminum	Molybdenum
Calcium	Carbonate	Antimony	Nickel
Chloride	Fluoride	Arsenic	Niobium
Magnesium	Iron	Barium	Phosphate
Silicon	Nitrate	Beryllium	Platinum
Sodium	Potassium	Bismuth	Radium
Sulfate	Strontium	Bromide	Rubidium
		Cadmium	Ruthenium
		Cerium	Scandium
		Cesium	Selenium
		Chromium	Silver
		Cobalt	Thallium
		Copper	Thorium
		Gallium	Tin
		Germanium	Titanium
		Gold	Tungsten
		Indium	Uranium
		Iodide	Vanadium
		Lanthanum	Ytterbium
		Lead	Yttrium
		Lithium	Zinc
		Manganese	Zirconium

temperature compensation. Ionic concentrations were measured in parts per million (ppm). Total hardness, calcium, magnesium and chloride were determined using titration techniques. Total hardness was measured using the sodium ethylene diamine tetraacetate method (EDTA), murexide indicated calcium concentration (EDTA), and magnesium was derived from the difference between total hardness and calcium. Chloride concentrations were obtained using the potassium dichromate-silver nitrate method. The remaining tests were determined colorimetrically. Ammonia nitrogen by the nesslerization method (Golterman and Clymo, 1969), chromium, copper, flouride, iron, manganese and nickel through diphenylcarbohydrazide, diethyldithiocarbamate spadns, bipyridyl, periodate and dimethylglyoxime methods respectively. Nitrate was determined by cadmium reduction (Bendschneider and Robinson, 1952; Wood et al., 1967) with nitrite being measured by diazotization. Phosphorus fractions were monitored by ascorbic acid reductions (Murphy and Riley, 1962; Golterman and Clymo, 1969) and silica was determined by heteropoly blue method (Armstrong and Butler, 1962; Brown et al., 1970). Dissolved sulphate was measured using barium chloride method (Kato et al., 1955; Golterman and Clymo, 1969) and sulphide by methylene blue. Zinc concentrations were obtained using the zincon method. Samples were analyzed within 24h of collection. This procedure, combined with low suspended sediment loads, involved no filtration or acidification requirements.

Seventeen of the 20 tests performed gave positive results, with flouride, manganese and zinc being the elements which were not present.

4.3.2 Landform effect

Contact between water and the thermodynamically unstable minerals which compose the type-sites initiated dissolution which continued until equilibrium concentrations were attained in the water or until all the minerals were removed. For example, during precipitation, reaction rates with weathered minerals would have initially been rapid but soon would have decreased with effective equilibrium being rarely reached (Cleaves et al., 1970; Freeze and Cherry, 1979). Dissolution caused (a) the water to acquire a different concentration of solutes as it drained the landform, and (b) the unconsolidated deposits to change mineralogically. The rates and amounts of ions removed from the landforms depended on ion mobility, ion exchange and the flow regime and pathway of water.

The change of solute concentration between the input and output samples of the type-sites for the wet and dry periods are illustrated in Table 4.5 and 4.6. During the wet period the majority of stream ionic concentrations increased and pH became more acidic with passage over and through the landforms. This trend was strongest on the talus where all the tests except Fe showed increases.

Table 4.5

Evidence of landform influence on stream solute concentration during the wet period (June 02-July 08).

			Hydrochemical Analysis (ppm)														
			Hardness			Solutes											
Landform Site	SEC	pH	Total	Ca	Mg	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus $S_3 \rightarrow S_{13}$	I	A	I	I	I	I	I	I	I	X	I	I	I	I	I	I	I
Rock Glacier $S_3 \rightarrow S_4$	I	A	I	I	I	I	I	I	I	X	I	I	X	X	I	I	X
Alluvial Fan 3 $S_{11} \rightarrow S_{10}$	I	A	I	I	I	X	I	X	X	I	X	I	I	I	I	I	X
Alluvial Fan 2 $S_9 \rightarrow S_8$	I	A	I	X	I	I	X	X	X	I	X	I	I	X	I	X	I
Alluvial Fan 1 $S_2 \rightarrow S_1$	I	A	I	I	X	X	X	I	X	I	X	I	I	I	I	X	I

Note: (I) indicates solute increased and (X) denotes solutes decreased with passage over and through the landform site. pH: A = acidic; B = basic. SEC = measured in microsiemens.

Figure 4.6

Evidence of landform influence on stream solute concentration during the dry period (July 09-August 22).

			Hydrochemical Analysis (ppm)														
			Hardness			Solutes											
Landform Site	SEC	pH	Total	Ca	Mg	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus $S_3 \rightarrow S_{13}$	I	B	I	I	I	X	I	I	I	I	I	X	I	X	I	I	I
Rock Glacier $S_3 \rightarrow S_4$	I	B	I	I	I	X	I	I	I	I	I	I	I	X	I	I	I
Alluvial Fan 3 $S_{11} \rightarrow S_{10}$	X	A	I	I	I	I	I	I	I	I	X	I	I	X	X	X	I
Alluvial Fan 2 $S_9 \rightarrow S_8$	X	A	X	X	X	X	I	I	I	I	I	I	I	X	X	I	X
Alluvial Fan 1 $S_2 \rightarrow S_1$	X	B	I	I	I	I	X	X	X	X	X	I	I	X	X	I	X

Note: (I) indicates solute increased and (X) denotes solutes decreased with passage over and through the landform site. pH: A = acidic; B = basic. SEC = measured in microsiemens.

The rock glacier and alluvial fans displayed the same effect but for fewer solutes. This landform influence on stream hydrochemistry continued during the dry spell with the exception of alluvial fan 1 (9 of 16 tests decreased and pH became more basic).

Figures 4.8 to 4.11 (graphs and t-tests) illustrate this change of solute concentration of the streams which drained the landforms. These examples have been selected since they demonstrate the major facets of solute response with passage over and through the forms. The concentration of SiO_2 for the talus and rock glacier inputs and outputs (Figure 4.8) indicates that snowmelt and precipitation passing through these forms picked up SiO_2 along its flow path. The weathering of silicate minerals (Table 4.3) acts as the lithospheric source for the solute. This acquisition of soluble silica in surface and nearsurface water has been recorded for granitic areas by a number of investigators (e.g., Appello, 1974; Cleaves et al., 1970; Feller and Kimmins, 1979; Zeman and Slaymaker, 1975). The weathering of silicate minerals has been discussed in detail by Bricker and his colleagues (e.g., Bricker and Garrels, 1967; Bricker et al., 1968).

Figure 4.9 presents the temporal variation of Ca for alluvial fan 1. This cation can be considered to be essentially terrestrial in origin as shown by the landform influence during the wet period. The output was greater than the input in response to cation acquisition

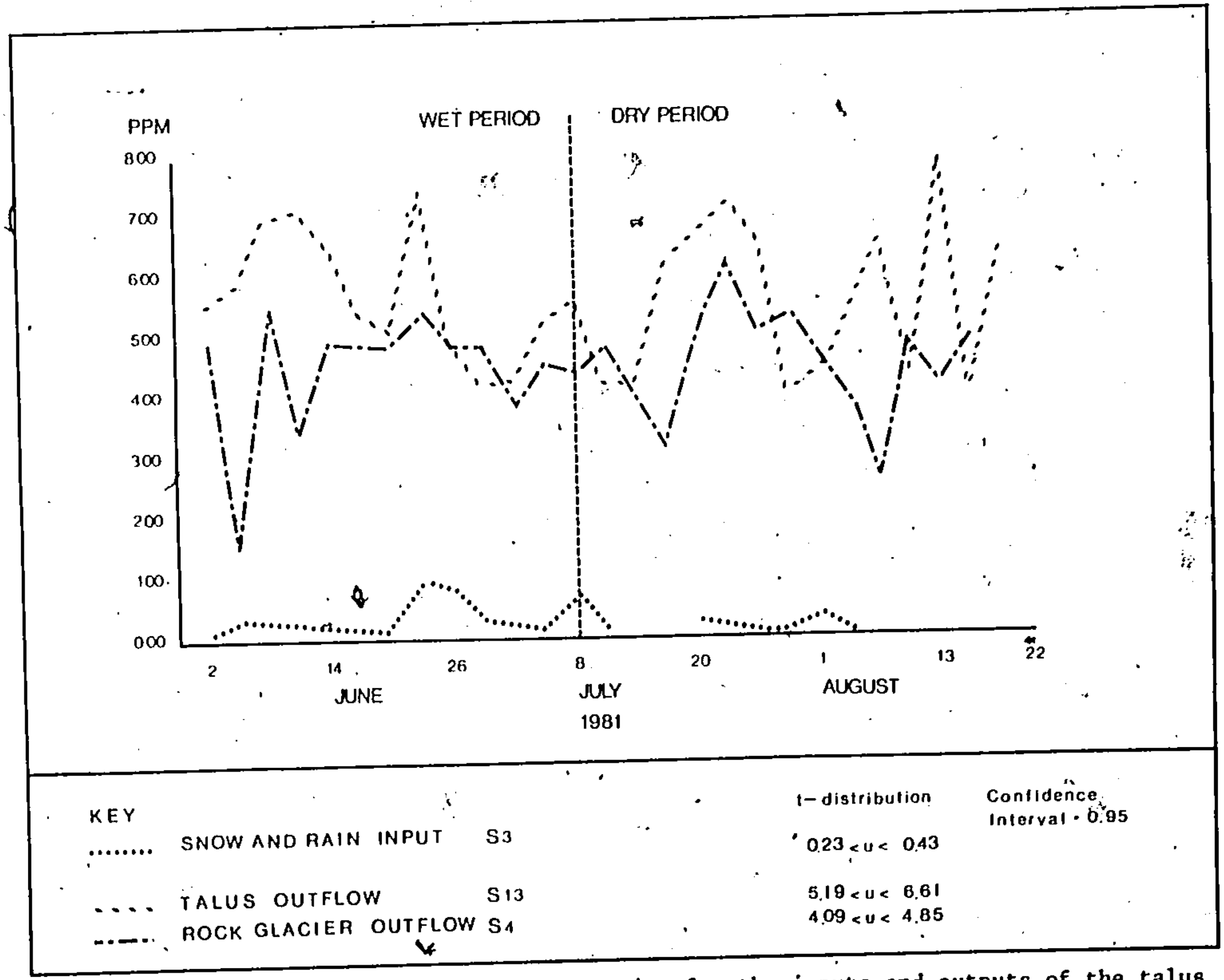


Figure 4.8 The trend of SiO_2 concentration for the inputs and outputs of the talus and rock glacier landforms.

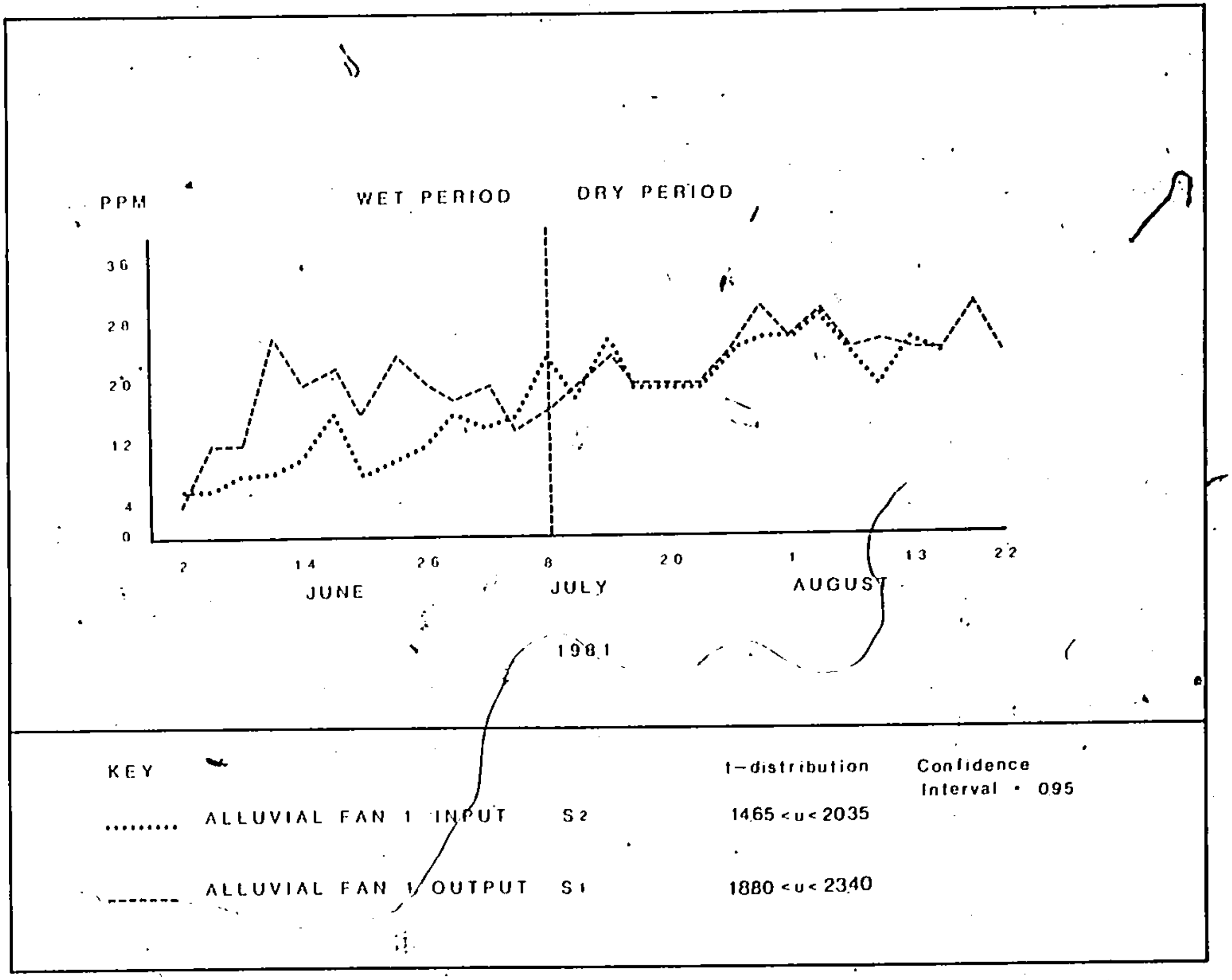


Figure 4.9 Temporal variation of Ca levels for input and output of alluvial fan 1.

from weathered minerals encountered en route. The Ca concentrations for both sites rose during the dry spell in response to reduced discharge. Higher concentrations were achieved due to reduced dilution and longer residence time in the unconsolidated mantle. This reduction of streamflow, however, was greater at the input site of the landform, as it ran dry on August 16. This resulted in a greater Ca increase for the input site. Hence, the landform influence was masked during this period.

The seasonal variation of Mg for alluvial fan 3 (input and output) is presented in Figure 4.10. Both the wet and dry periods were characterized by an increase of stream Mg concentration with drainage through the form. This increase of Mg, like Ca, is attributed to the release of ions by the dissolution of silicates. Research has shown that feldspar can act as a mineral source of Ca, while Mg can be derived from the weathering of biotite and hornblend (Bricker and Garrels, 1967; Bricker et al., 1968; Cleaves et al., 1970; Freeze and Cherry, 1979; Garrels and Mackenzie, 1967). During the wet period the Mg concentrations were greater and more variable. This trait suggests that flushing and dilution processes operated and is discussed in Section 4.3.4 (Hydrological influence).

Figure 4.11 demonstrates the difference of Fe concentration between the input and output samples for alluvial fan 2. Possible sources of Fe, with stream

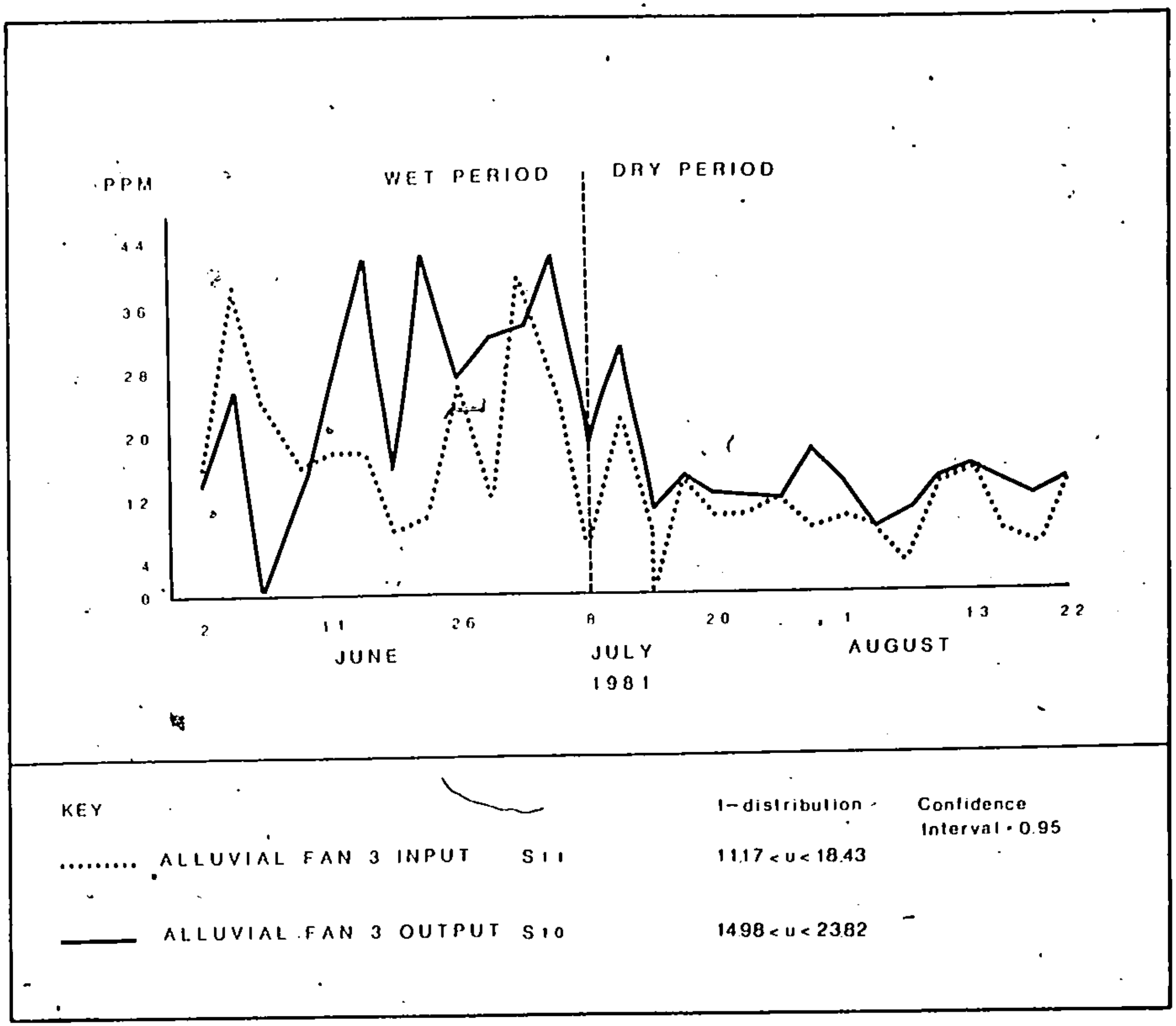


Figure 4.10 Temporal variation of Mg concentration, input and output of alluvial fan 3.

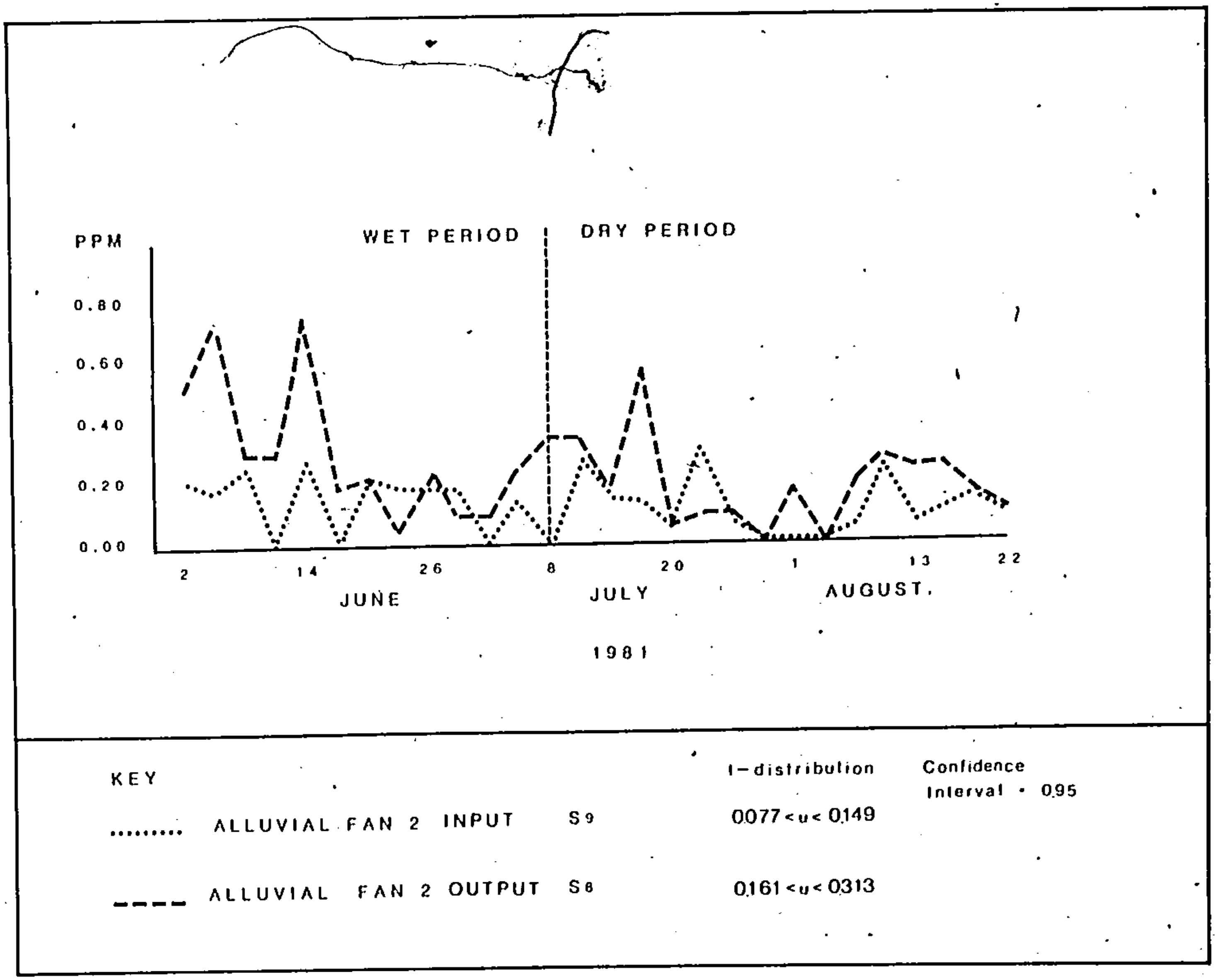


Figure 4.11 Variation of Fe concentration for alluvial fan 2, input and output.

passage through the landform, include ferrous iron released during weathering and the decay of organic matter (Cleaves et al., 1970; Leonard et al., 1979; Reid et al., 1981).

4.3.3 Landform solute differences

The spatial variation in the levels of solute concentration between these type-sites is presented in Table 4.7. The talus output exhibited the highest results for 11 of the 17 tests. The rock glacier stream was commonly the second most concentrated and rated second for 10 of 17. The alluvial fan outputs displayed chemistries which were generally more dilute than the talus and rock glacier. The total scores derived from the classification supported this observation (a low score represented a higher stream concentration). The talus and rock glacier rated first and second highest in stream concentration with total scores of 29 and 49 respectively. The alluvial fan total scores followed with 3 at 54, 2 at 57 and 1 at 62.

The temporal variation of specific conductance for the outputs of the landforms are graphed in Figure 4.12. The comparison illustrates and tests (t distribution) this spatial variation which existed between the streams which drained the landforms surrounding the headwater basin. Specific conductance can be used as a general indicator of the concentration of total dissolved solids (TDS) (Hem, 1970). Since electrical conductivity adequately

Table 4.7

The spatial variation of solute concentration between the type-sites. Rating of overall seasonal mean values of landform outputs.

			Hydrochemical Analysis (ppm)															
			Hardness			Solutes												
Landform Site	SEC	pH	Total	Ca	Mg	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3	Total Score
Talus S_{13}	1	3	1	1	4	1	1	1	1	3	1	3	1	3	2	1	1	29
Rock Glacier S_4	2	4	2	2	4	2	3	2	2	4	2	2	5	2	4	2	5	49
Alluvial Fan 3 S_{10}	4	2	4	4	1	4	2	3	4	2	4	5	4	5	1	3	2	54
Alluvial Fan 2 S_8	5	1	5	5	2	5	4	5	3	1	3	1	2	4	3	5	3	57
Alluvial Fan 1 S_1	3	5	3	3	3	3	5	3	5	5	5	4	2	1	5	4	3	62

Note: The rating of 1 to 5 corresponds to the number of landform sites whereby 1 is the highest concentration and 5 the lowest. pH rated by degree of acidity. SEC measured in microsiemens.

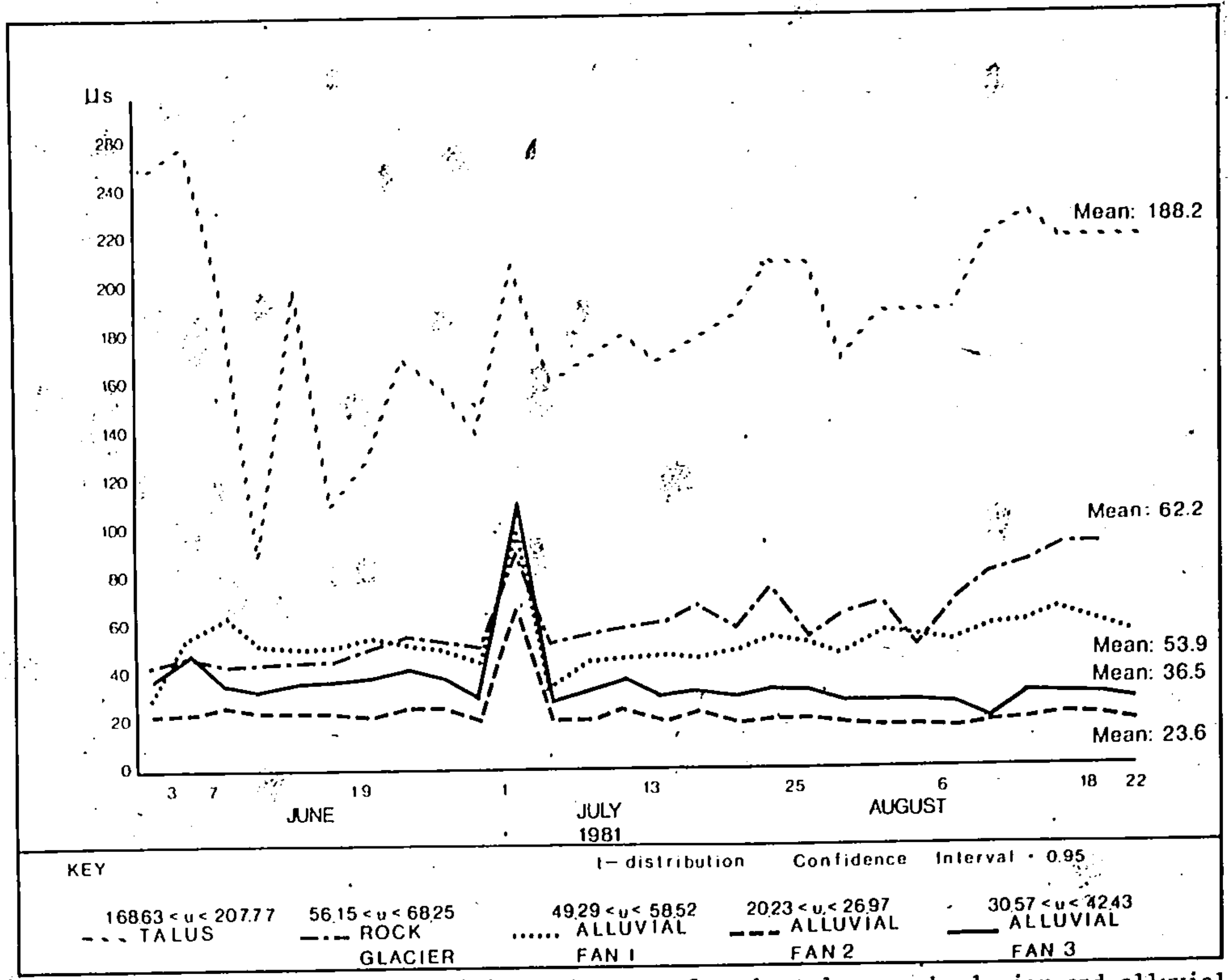


Figure 4.12 Temporal variation of specific conductance for the talus, rock glacier and alluvial fan outputs. The high readings of July 2nd registered for all thirteen samples (S_1 to S_{13}). Damage to the conductivity probe may have caused this peak and a new probe was used on July 5th through to August 22nd.

provided an index of stream solute concentration the values were not converted into TDS using TDS = AC where A is a constant (Hem, 1970).

The talus stream registered considerably higher conductivities than the other outputs. This is attributed to a landform influence on stream concentration. Snowmelt and precipitation percolated vertically through the large sized surface layer of the form, freely washing the rock debris. Residence time however increased as percolation encountered the finer sized fractions which increase with depth. Horizontal movement exposed the water to additional mineral assemblages and a greater solute content was acquired. The conductivity results of the talus suggest that, due to this increase of inhomogeneity and decrease of porosity with depth, throughflow resided in the form for a longer period of time than was the case for the rock glacier and alluvial fans. It is postulated that more active weathering rates operated in this landform due to its younger unconsolidated composition and longer water/rock contact time. Hence, the operation of such geochemical processes as dissolution and ion exchange had more time to operate (Gorham, 1961). While dissolution began immediately with water and rock contact, ion exchange processes would have been limited to particles of colloidal size (Freeze and Cherry, 1979; Krauskopf, 1967) through to the sand size (Kennedy, 1965).

The rock glacier output displayed the second highest conductivities of the streams. Like the talus, no surface runoff was observed on the landform. The results imply that the drainage did not follow a distinct water course through the landform but occurred as a slow percolation flow. This seepage of water through the rock mass allowed for the pick-up of trace elements. No dye tracing was performed on the talus or rock glacier because these landforms were characterized by no specific input flow and no distinct water course throughflows. Johnson (1978; 1981) has investigated throughflow times for rock glaciers and has recorded long residence times for this talus-derived type. The suggestion that water flow through the landform was slow is supported by the observed gradual decrease of particle size with depth. This characteristic has been documented for both rock glaciers and taluses by a number of researchers (e.g., Barsch, 1977; Johnson, 1978; 1981; Sosedov, 1974). In addition, certain amounts of percolation may have been held in the form longer due to freezing onto existing interstitial ice (dependent on the location of the 0°C isotherm within the form). This delay of throughflow, which would have been greatest during the spring, has been discussed by Johnson (1978) and Sosedov (1974).

The conductivities of the alluvial fan outputs were slightly less than that of the rock glacier stream and considerably more dilute than that of the talus.

These surface and nearsurface streams of the alluvial fans had less opportunity to pick up solutes. The dye tracing indicated that drainage travel times did not exceed 2h (longest residence time was 115 min over a stream course of 450m). The steeper upper sections of the fans were characterized by surface flows which had limited contact with the unconsolidated mantle. This drainage on the lower sections, however, developed braided nearsurface characteristics and experienced an increase in rock/soil contact. It is inferred that solute acquisition was greater in this zone which was less steep and composed of smaller sized sediments.

Although the fan drainage chemistries were very similar, the total scores of Table 4.7 imply that water from alluvial fan 1 was slightly more dilute than water from 2 and 3. While this trend did not show in the conductivity results (alluvial fan 1 was greater than 2 and 3), it did occur in 7 of the other 16 tests. This observation may be explained by the following geomorphic differences between the forms:

(1) Alluvial fan 1 was steeper than the other fans. Greater slope angles were measured for this fan for all sections of the longitudinal transects (Table 4.1).

(2) At the base section of the forms where slope angles were the least (1 = 12°,

2 = 3°, 3 = 3°), particle size analysis (Table 4.2) indicated higher silt fractions for the larger fans (1 = 1 per cent, 2 = 35 per cent, 3 = 49 per cent).

These differences influenced the degree of stream concentration by affecting the residence time of water passage. The residence time measurements obtained for the three fans (Section 4.2.3) support this claim.

4.3.4 Hydrological influence

Comparison of stream solute levels between the wet and dry periods of 1981 indicate that the hydrological regime affected the solute levels. Higher concentrations and increased variability were recorded for the majority of tests during the time when snowmelt and precipitation events dominated (June 2 to July 8). Tables 4.8 and 4.9 illustrate that solute concentration and variance decreased with the lower discharge associated with the drier period. The Cl concentrations of Figure 4.13 illustrate this general trend of decreasing solute concentration and variability which occurred during the study period. Three processes appear to have been responsible for the higher solute levels during the wet interval: (a) accumulated ions in the snowpack were released during spring thaw; (b) soluble materials held in the unconsolidated deposits during the winter were flushed out by the heavy rains

Table 4.8

Hydrological influence on stream solute concentration. Comparison of wet and dry period mean values.

		Hydrochemical Analysis (ppm)															
			Hardness			Solutes											
Landform Site	SEC	pH	Total	Ca	Mg	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus																	
Input (S_3)*	I	I	I	I	–	I	X	X	X	X	X	X	X	X	X	X	X
Output (S_{13})	I	X	I	I	X	X	X	X	X	X	I	X	X	X	I	I	X
Rock Glacier																	
Input (S_3)*	I	I	I	I	–	I	X	X	X	X	X	X	X	X	X	X	X
Output (S_4)	I	X	I	I	X	X	X	X	X	X	I	X	X	X	X	I	X
Alluvial Fan 3																	
Input (S_{11})	I	X	X	X	X	X	X	X	X	X	I	X	X	X	I	I	X
Output (S_{10})	X	X	X	X	X	X	X	X	X	X	I	X	X	X	X	X	X
Alluvial Fan 2																	
Input (S_9)	I	X	X	X	X	X	X	X	X	X	X	X	X	X	I	X	X
Output (S_8)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	X
Alluvial Fan 1																	
Input (S_2)	I	X	I	I	X	X	X	X	X	X	X	X	X	X	I	X	X
Output (S_1)	I	X	I	I	X	X	X	X	X	X	X	X	X	X	X	I	X

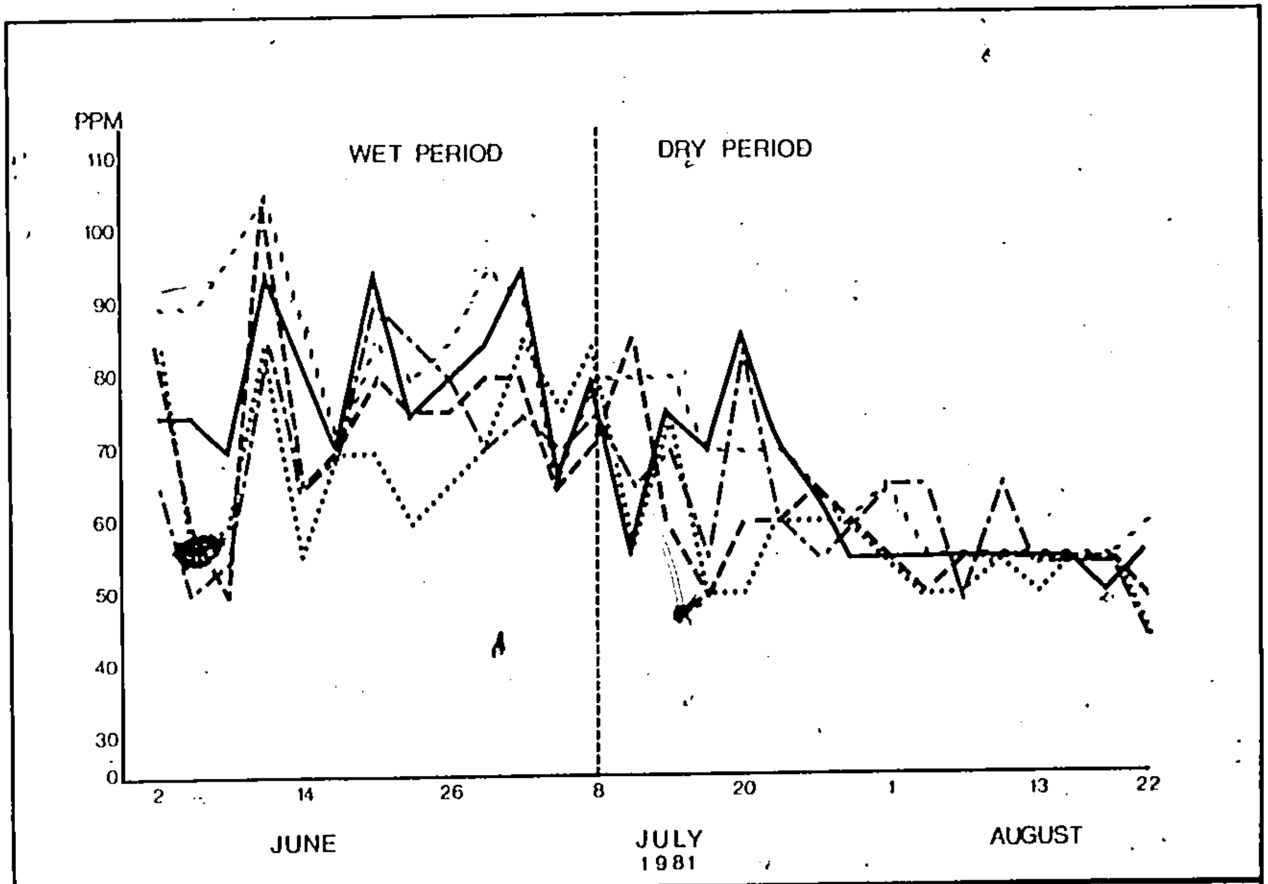
Note: (I) indicates increased concentration with less discharge, (X) indicates decreased concentration with less discharge. pH rated by degree of acidity. SEC measured in microsiemens. (*) Comparison of snow and rain analysis.

Figure 4.9

Hydrological influence on stream solute concentration. Comparison of wet and dry period standard deviations.

	Hydrochemical Analysis (ppm)																
			Hardness			Solutes											
Landform Site	SEC	pH	Total	Ca	Mg	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus																	
Input (S_3)*	X	X	I	I	–	X	X	X	X	X	X	X	X	X	X	X	X
Output (S_{13})	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	X	X
Rock Glacier																	
Input (S_3)*	X	X	I	I	–	X	X	X	X	X	X	X	X	X	X	X	X
Output (S_4)	I	X	X	I	X	X	X	X	X	X	X	X	X	X	X	I	X
Alluvial Fan 3																	
Input (S_{11})	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	X	X
Output (S_{10})	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	I	X
Alluvial Fan 2																	
Input (S_9)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	I	X
Output (S_8)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	I	X
Alluvial Fan 1																	
Input (S_2)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Output (S_1)	X	I	X	X	X	X	X	X	X	X	X	I	X	X	X	X	X

Note: (I) indicates increased variance with less discharge, (X) indicates decreased variance with less discharge. pH rated by degree of acidity. SEC measured in microsiemens. (*) Comparison of snow and rain analysis.



KEY	LANDFORM OUTPUTS		Mean	Standard Deviation	Mean	Standard Deviation
. . . .	TALUS	S13	85.8	10.6	63.3	9.0
—·—·—	ROCK GLACIER	S4	71.9	11.6	61.8	8.7
....	ALLUVIAL FAN 1	S1	70.8	11.5	55.0	7.1
— — —	ALLUVIAL FAN 2	S8	73.8	13.4	58.0	8.6
———	ALLUVIAL FAN 3	S10	80.4	10.1	59.7	9.7
			Wet Period		Dry Period	

Figure 4.13 General decrease of Cl concentration and variability for the landform stream outputs.

of June; and (c) the source area for the streams changed during the dry spell. The variability in solute concentrations is attributed to the operation of dilution processes.

During the wet spell, snowmelt contributed to streamflow. By July 8 no snow remained on either of the north or south facing ridges which bank the headwater basin. As shown in Table 4.8 the aliquot from snow samples displayed generally greater concentrations than the bulk precipitation collections. This suggests that the contribution of dissolved solids made by snowmelt to the watercourses partially caused the higher wet period values. Subsequently, dissolved ions which accumulated in the snowpack during the winter were released during this spring thaw (Section 2.4).

The heavy spring rains also promoted the high concentrations since they caused a thorough flushing of the unconsolidated deposits. Soluble material which accumulated in the landform surface and nearsurface layers during the fall of 1980 was held through the winter and flushed out by the June 1981 rainstorms. Although September 1980 was wet (7 days of rain), October and November only experienced 2 days of rainfall (Environment Canada, 1980). Weathered, leached and decayed organic materials were redissolved or washed out of the unconsolidated mantle as newly infiltrated water displaced the older water. This process, where stored water is displaced by fresh rainwater, has been discussed by Hewlett and Hibbert (1967) as subsurface translatory flow. Water stored in the pore spaces of the landforms during the winter had longer time to reach an equilibrium concentration of solutes and, therefore, when flushed into the streams, contributed to the higher spring dissolved ion levels. High stream solute concentrations in the spring, caused by snowmelt and/or flushing processes, have been recorded by several researchers (e.g., Church, 1974; Feller and Kimmins, 1979; Leonard et al., 1979; Schreier et al., 1980; Zeman, 1973).

The third hydrological process which may have influenced the high solute values of the wet period is the possibility of changing source areas for the streams (Cleaves et al., 1970; Toler, 1965; Walling and Webb, 1980). During the spring, runoff (snowmelt and precipitation) from the high plateaus of the Ruby Range contributed to streamflow. This stream source was highly mineralized since it travelled a long distance and was in contact with rock and soil material for a long period of time prior to reaching the headwater landforms. In contrast, during the dry warmer period, runoff from the plateau areas was reduced and streamflow consisted of inputs from local sources (i.e., melted seasonal ground ice and direct precipitation). These stream sources had a dilute solute concentration due to limited contact with weathered products and contributed to lower stream dissolved ion levels. The discharge behavior exhibited by the alluvial fan 1 stream supports this inference. At the apex of the fan (input site S_2), the flow reduced and ran dry on August 16. However, at the base of the form (output site S_1), the flow remained constant throughout the study period. It follows that during the dry period the input site (S_2) commonly displayed higher concentrations than the output from the alluvial fan (S_1). Subsequently, limited evidence of a landform influence for this stream was recorded during this time (Table 4.6).

The high variability of stream solute levels during the wet period suggests that dilution processes also operated. The lower solute values can be explained by the following dilution processes: (a) streams were diluted by the contribution of precipitation which possessed a low concentration of ionic species; (b) increased surface runoff and rapid throughflow resulted in shorter residence time and reduced contact with the lithologic debris. The Mg concentrations for the alluvial fan 3 stream shown in Figure 4.10 is a good example of the high variability which occurred during the wet period. Standard deviations for the input and output sites were 10.6 and 13.2, compared to 5.3 and 5.6 respectively for the drier spell. It is postulated that the high values are associated to flushing effects, while the lower ones are attributed to dilution.

CHAPTER 5

CONCLUSIONS

5.1 Summary

The objective of this thesis was to investigate the influence of geomorphology on alpine stream hydrochemistry. The investigation was accomplished by testing the hypothesis that different landforms affected the hydrology and hydrochemistry of the streams which ran over and through the forms in different ways.

A water balance study was conducted between June 3 and August 21, 1981, to obtain the general hydrological picture of the headwater lake. Hydrological parameters were monitored to provide an indication of flushing and dilution processes which occurred to the streams which route the landforms. Through the application of a water balance equation, the lake water budget components were determined and the following observations were made:

(1) Residuals suggested that the headwater lake was partially fed by lateral inflow and groundwater inflow, and characterized by a subsurface outflow;

(2) precipitation had the strongest affect on the seasonal regime of the lake;

(3) measured catchment response indicated lags between the main surface inflow,

surface outflow and storage fluctuation;

(4) a positive relation existed between lake storage and subsurface outflow.

The contribution made by runoff from the landforms surrounding the lake was not isolated in the water balance equation. This lateral inflow was one of the ungauged parameters and was assumed to follow the general hydrological regime trend. The results during the study period illustrated that the regime could be divided into a wet and dry period. Snowmelt and precipitation between June 2 and July 8 caused the increased stream discharges and high lake storage of the wet term. Reduced stream flows and a decrease of lake storage, due to limited precipitation events between July 9 and August 22, distinguished the drier term.

Between June 2 and August 22, 1981, hydrochemical analysis was used to gauge the landform effect on stream solute concentration. Five streams were monitored which drain the different landform types. The spatial and temporal ionic concentration behavior of the streams was used as an indicator of landform influence on solute dynamics. The following solute trends were recorded as evidence that the landforms did affect the stream hydrochemistry:

(1) An increase of concentration was observed between input and output sites of the

landforms; and

(2) stream outputs from the landforms exhibited significant differences in concentration.

This downstream increase of stream ionic concentration is attributed to the acquisition of solutes as the streams passed over and through the landforms. The differences between the stream output concentrations suggested that the landforms exhibited different degrees of influence, controlled by drainage residence time.

A third solute trend of higher concentrations and increased solute variability occurred during the wet period suggesting that the hydrological regime also influenced the stream solute levels. Spring flushing of accumulated ions in the snowpack and in the unconsolidated deposits, and the possibility of changing source areas may have caused the higher solute levels. Solute dilution associated with increased discharge resulted in the lower concentrations. The operation of these processes during the wet period contributed to its higher solute values and increased solute variability.

5.2 Discussion

Although water chemistry studies have focused on the various factors which contribute to solute concentration, limited research has tested if landforms located within the same drainage basin affect stream ionic concentrations. The influence of contrasted terrain on solute levels for large study areas has been documented. For example, Walling and Webb (1980) have explained the solute spatial variations in the Middle and Upper Exe basin, Great Britain, by contrasts in relief and variations in the underlying geology (watershed area: 601 km^2). Foggin and Forcier (1977) have suggested that the solute concentrations for fifty headwater streams in Western Montana are controlled by basin parent material composition and morphometric character. However, few studies have uncovered landform influences on stream chemistry for small basins. Burt (1979) studied the variation of solute concentrations of soil and stream water during throughflow events at Bicknoller Combe, Somerset, England. Working within a study area of 10,000 m^2, his results displayed different stream chemistries associated with the base of a hillslope hollow and the adjacent spur zones. Burt has suggested that hydrological and solutional process differences between the slope types account for the development of the two distinct solute environments.

Apart from studies like the Bicknoller Combe example, limited research has been conducted which considers such questions as (a) Do landforms exhibit a control on solute dynamics? (b) Do different landforms in the same drainage basin affect stream solute concentration? These two questions have been addressed in this thesis for the headwater basin of the Gladstone Creek Region, southwest Yukon Territory. The results imply that landforms should be considered when assessing the solute dynamics of small alpine streams. This landform variable joins the group of factors (e.g., geology, hydrology, biota, etc.) which interact to determine stream ionic concentration. Additional research is required before we can attempt to evaluate the extent to which each of these affect solute concentration. At present, our knowledge remains at the identification stage due to difficulties in isolating, monitoring and rating these various factors (Garrels and Mackenzie, 1967; Gorham, 1961; Wilson, 1979).

APPENDIX A

HYDROLOGICAL RESULTS

Table A.1

Stage/discharge, main surface inflow.

Date 1981	Time P.T.	Stage Above Datum: Low Point in Stream Bed (m)	Discharge (m³/sec)
June 3	1245	.293	1.21
7	1030	.283	1.03
9	2100	.283	0.90
12	1000	.314	1.41
15	1215	.399	3.89
18	1000	.414	4.23
22	1030	.527	8.77
23	1615	.482	5.61
27	1300	.378	3.31
July 1	1045	.344	1.89
4	2200	.369	2.30
6	2130	.378	3.21
9	1100	.393	3.94
13	1030	.387	3.13
16	2245	.369	2.58
19	2200	.350	1.79
21	1245	.387	2.24
25	1200	.347	1.84
27	1230	.378	3.32
31	2145	.414	3.83
August 3	800	.393	3.20
6	1715	.393	2.54
9	1245	.357	2.03
12	2130	.341	1.68
14	1315	.323	1.47
17	1015	.293	1.27
21	1015	.293	0.98

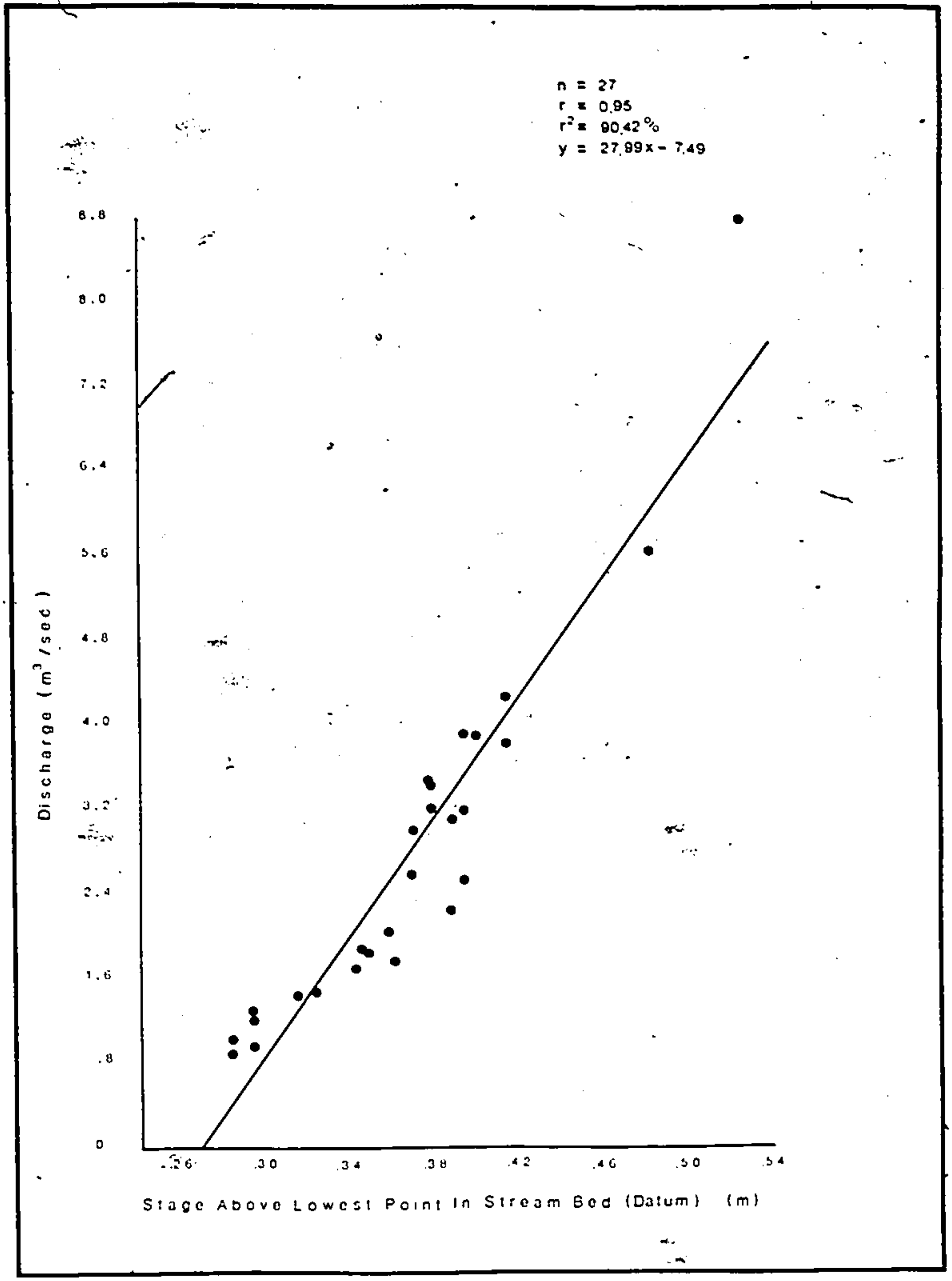


Figure A.1 Stage/discharge line, main surface inflow.

Table A.2

Stage/discharge, surface outflow.

Date 1981	Time P.T.	Stage Above Datum: Low Point in Stream Bed (m)	Discharge (m^3/sec)
June 3	1215	.597	3.25
7	1000	.399	1.66
9	2030	.396	1.55
12	930	.427	1.80
15	1145	.558	2.75
18	930	.658	3.98
22	1000	.725	4.51
23	1545	.838	5.64
27	1230	.753	4.74
July 1	1015	.664	3.54
4	2130	.570	2.60
6	2100	.607	3.12
9	1030	.661	4.11
13	1000	.655	3.75
16	2230	.607	3.02
19	2145	.512	2.18
21	1230	.582	2.35
25	1145	.515	2.21
27	1200	.549	2.54
31	2130	.607	3.09
August 3	730	.588	2.93
6	1700	.558	2.56
9	1230	.503	2.26
12	2115	.457	1.74
14	1300	.448	1.90
17	1000	.414	1.49
21	1000	.375	1.24

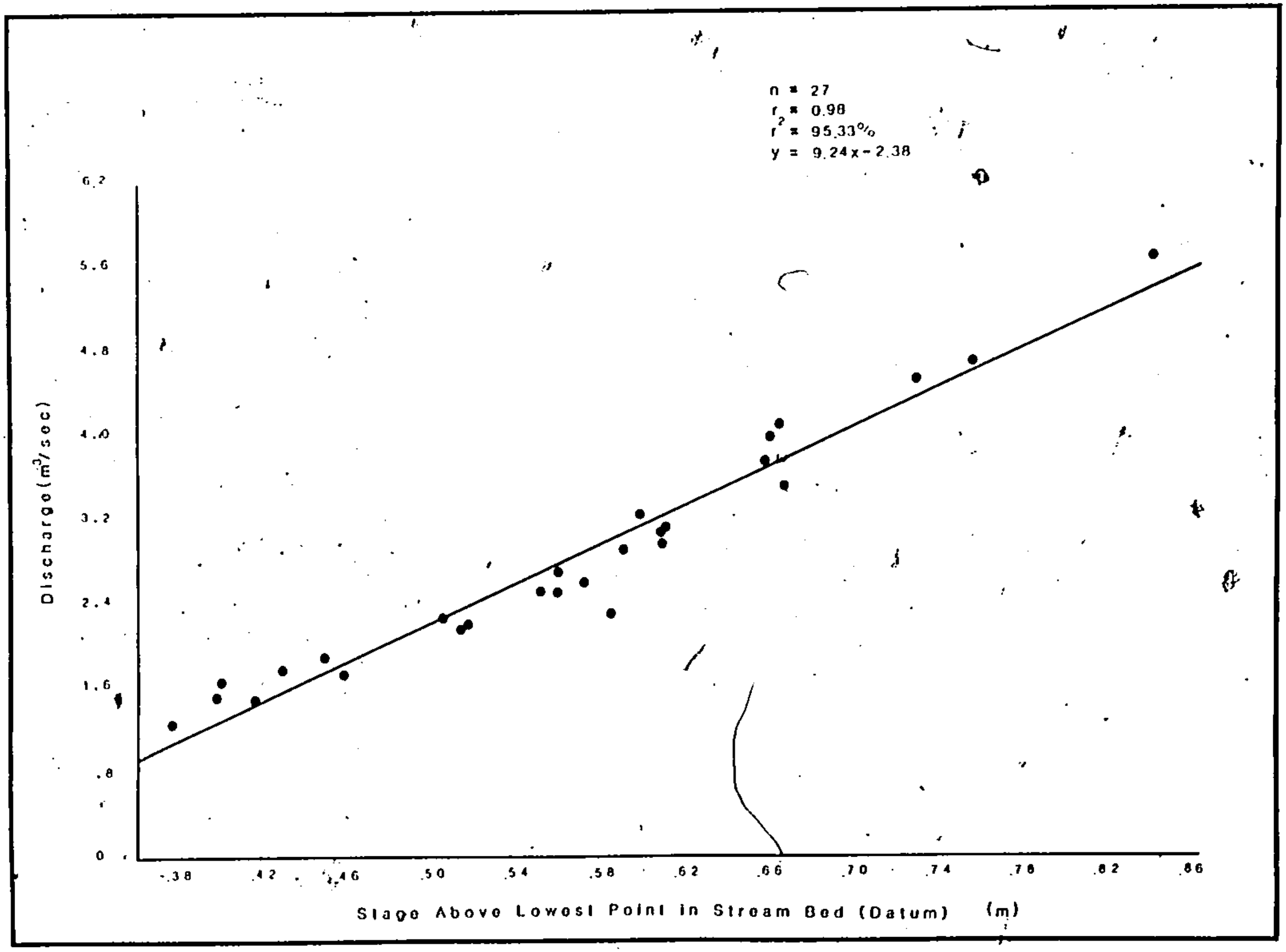


Figure A.2 Stage/discharge line, surface outflow.

Table A.3

Calculation of Parameter Ic, June 3 – August 21, 1981.

Date 1981	Is (m^3)	P (m^3)	E (m^3)	Os (m^3)	Δs (m^3)	Ic=Il+Iss-Oss (m^3)
June 3	68 000			273 000	-30 300	174 700
4	54 000			208 000	-18 200	135 800
5	39 000	16 900		161 000	- 6 100	99 000
6	42 000	5 400		142 000	-12 100	82 500
7	76 000	26 600		118 000	6 100	21 500
8	151 000	0		134 000	- 3 000	-20 000
9	49 000	0		124 000	- 3 000	72 000
10	30 000	0		112 000	-12 100	69 900
11	42 000	2 400		106 000	12 100	73 700
12	126 000	0		106 000	12 100	- 7 900
13	177 000	0		134 000	18 200	-24 800
14	250 000	10 300		174 000	48 400	-37 900
15	327 000	600		237 000	42 400	-48 200
16	332 000	13 900		269 000	12 100	-64 800
17	339 000	21 200		296 000	42 400	-21 800
18	356 000	3 100		320 000	0	-39 100
19	347 000	10 300	600	321 000	-12 100	-47 800
20	330 000	1 800	900	317 000	0	-13 900
21	327 000	13 300	200	308 000	24 200	- 7 900
22	581 000	8 500	200	372 000	90 700	-126 600
23	533 000	8 500	1100	453 000	24 200	-63 200
24	429 000	0	1000	465 000	-12 100	24 900
25	363 000	600	400	447 000	-36 300	47 500
26	304 000	3 000	1100	427 000	-18 200	102 900
27	284 000	0	1000	402 000	-36 300	82 700
28	260 000	0	500	385 000	-18 200	107 300
29	206 000	0	300	364 000	-36 300	122 000
30	194 000	0	1200	341 000	-12 100	136 100
July 1	185 000	0	700	314 000	-24 200	105 500
2	165 000	0	2300	277 000	-12 100	102 200
3	148 000	4 800	600	252 000	-24 200	75 600
4	194 000	12 700	200	249 000	12 100	54 600
5	247 000	1 800	500	257 000	12 100	20 800
6	267 000	0	600	273 000	30 300	36 900
7	296 000		700	296 000	30 300	31 000
8	296 000		700	314 000	18 200	36 900
9	296 000		1300	321 000	0	26 300
10	296 000		900	321 000	0	25 900
11	305 000		800	325 000	0	20 800
12	303 000		500	329 000	-36 300	- 9 800

Table A.3

(Continued)

Date 1981	Is (m³)	P (m³)	E (m³)	Os (m³)	Δs (m³)	Ic=Il+Iss-Oss (m³)
July 13	284 000		700	316 000	0	32 700
14	272 000		700	304 000	-12 100	20 600
15	267 000		1300	294 000	- 6 100	22 200
16	247 000		1100	292 000	-12 100	34 000
17	247 000		1000	269 000	-12 100	12 800
18	238 000		800	240 000	-18 200	-15 400
19	214 000		800	222 000	0	8 800
20	296 000		400	226 000	18 200	-51 400
21	298 000		500	256 000	0	-41 500
22	267 000		300	256 000	-18 200	-28 900
23	238 000		900	241 000	0	3 900
24	214 000		900	220 000	-12 100	- 5 200
25	197 000		1200	202 000	0	6 200
26	201 000		100	202 000	12 100	13 200
27	247 000		700	226 000	0	-20 300
28	211 000		1100	237 000	0	27 100
29	199 000		500	240 000	0	41 500
30	206 000		400	233 000	30 300	57 700
31	342 000		400	268 000	12 100	-63 500
August 1	327 000		600	288 000	0	-38 400
2	318 000		700	289 000	0	-28 300
3	305 000		800	269 000	- 6 100	-41 300
4	296 000		200	257 000	0	-38 800
5	315 000		800	261 000	- 6 100	-59 300
6	303 000		1000	253 000	-30 300	-79 300
7	279 000		1000	237 000	0	-41 000
8	243 000		800	224 000	- 6 100	-24 300
9	211 000		1200	208 000	- 6 100	- 7 900
10	199 000		1000	188 000	- 3 000	-13 000
11	197 000		700	170 000	- 3 000	-29 300
12	175 000		500	160 000	- 6 100	-20 600
13	126 000		1100	150 000	- 6 100	19 000
14	122 000		700	136 000	-12 100	2 600
15	93 000		1500	120 000	-18 200	10 300
16	64 000		200	110 000	0	46 200
17	54 000		100	120 000	- 6 100	60 000
18	54 000		500	124 000	- 6 100	64 400
19	54 000		800	114 000	0	60 800
20	54 000			106 000	3 000	55 000
21	49 000			100 000	- 6 100	44 900

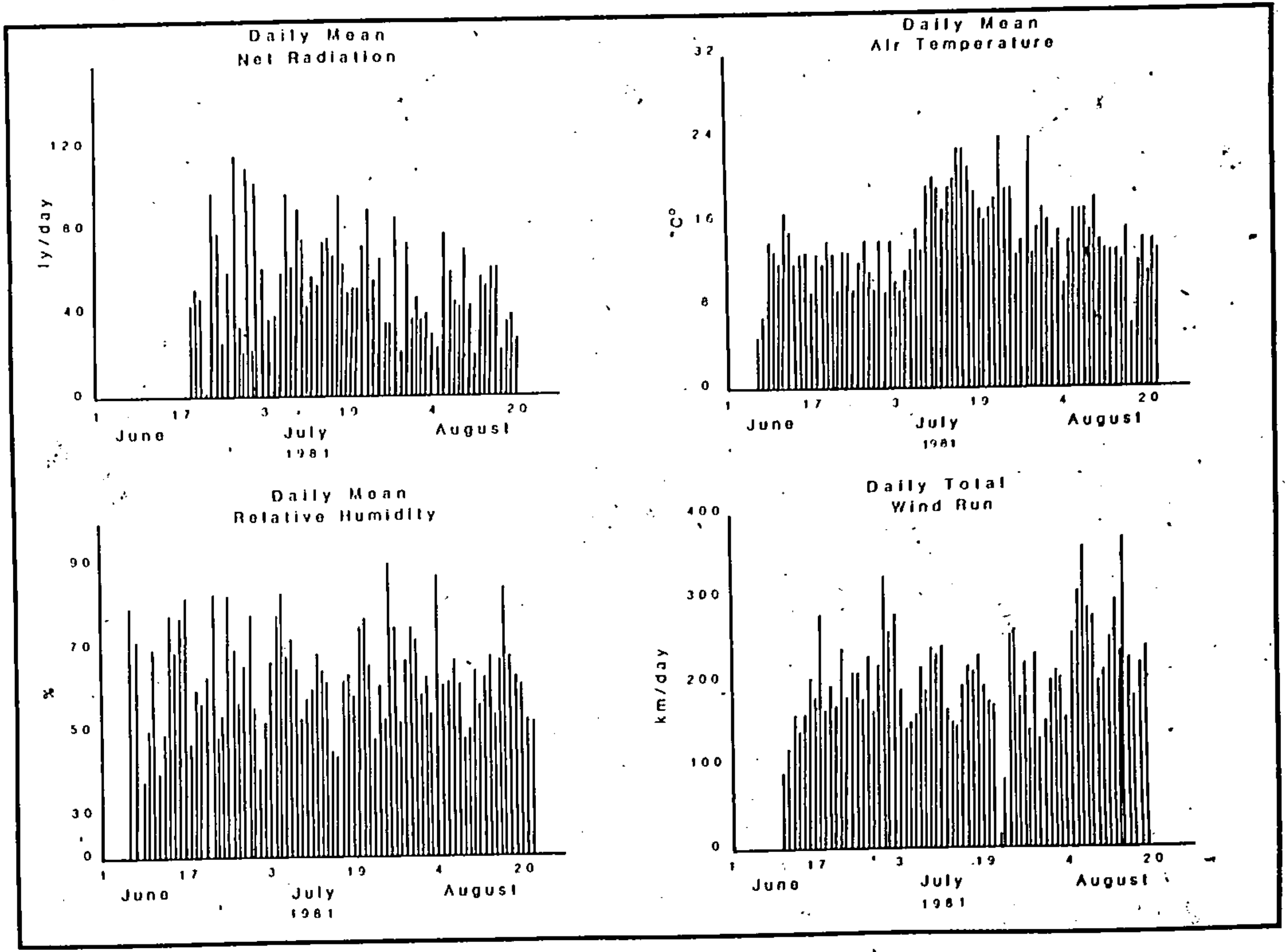


Figure A.3 Variation of daily meteorological observations for the headwater lake. Source: D. Lagarec, University of Ottawa.

APPENDIX B

HYDROCHEMICAL ANALYSIS

Table B.1

Descriptive statistics of hydrochemical results for the wet period, June 2-July 8, 1981.

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus	$\overline{x}$	12.6	6.92	0	0	0	.535	69.6	.087	.408	.306	.485	.095	.041	.565	.381	10.1	.022
Input (S_3)	s-d	15.0	.596	0	0	0	.621	12.7	.036	.278	.120	.384	.171	.025	.691	.287	3.36	.032
Output (S_{13})	$\overline{x}$	175.4	6.46	94.9	78.5	16.5	1.09	85.8	.121	.598	.257	.736	.152	.054	.568	5.73	69.6	.029
	s-d	54.7	.489	14.8	12.8	12.9	.846	10.6	.031	.389	.195	.413	.236	.059	.646	1.08	35.1	.040
Rock Glacier	$\overline{x}$	12.6	6.92	0	0	0	.535	69.6	.087	.408	.306	.485	.095	.041	.565	.381	10.1	.022
Input (S_3)	s-d	15.0	.596	0	0	0	.621	12.7	.036	.278	.120	.384	.171	.025	.691	.287	3.36	.032
Output (S_4)	$\overline{x}$	52.6	6.42	37.7	21.2	16.5	.556	71.9	.105	.445	.235	.517	.137	.034	.550	.448	11.5	.017
	s-d	12.3	.517	14.5	4.36	12.7	.193	11.6	.040	.192	.117	.262	.191	.031	.639	1.05	4.56	.026
Alluvial Fan 3	$\overline{x}$	29.5	6.75	30.6	10.8	19.8	.570	76.9	.094	.432	.185	.468	.072	.039	.504	6.39	10.4	.023
Input (S_{11})	s-d	17.8	.565	10.4	2.24	10.6	.262	8.55	.024	.274	.153	.367	.098	.025	.608	1.90	5.46	.033
Output (S_{10})	$\overline{x}$	43.0	6.50	37.5	11.7	25.8	.467	80.4	.079	.379	.295	.458	.102	.043	.525	6.87	14.1	.020
	s-d	20.7	.508	13.4	4.54	13.2	.291	10.1	.033	.230	.193	.322	.087	.027	.624	1.41	4.83	.031
Alluvial Fan 2	$\overline{x}$	22.7	6.70	38.3	11.8	26.5	.597	76.9	.104	.472	.134	.458	.146	.039	.529	5.88	11.2	.011
Input (S_9)	s-d	18.5	.626	19.5	3.21	19.5	.259	12.2	.038	.199	.092	.354	.103	.029	.657	1.24	3.97	.021
Output (S_8)	$\overline{x}$	27.1	6.37	38.8	11.8	26.9	.607	73.8	.069	.448	.314	.452	.244	.043	.515	6.40	9.16	.020
	s-d	11.9	.527	15.9	3.11	14.7	.602	13.4	.032	.268	.226	.240	.274	.035	.660	1.77	4.80	.024

Table B.1

(Continued)

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Alluvial Fan 1 Input (S_2)	$\overline{x}$	32.6	6.41	32.8	11.7	21.1	.706	74.6	.089	.414	.166	.392	.072	.038	.578	3.44	10.2	.015
	s-d	16.2	.572	10.8	5.09	10.4	.577	12.3	.038	.283	.142	.220	.145	.032	.647	3.53	3.82	.030
Output (S_1)	$\overline{x}$	52.8	6.27	35.1	17.2	18.8	.552	70.8	.092	.359	.171	.333	.086	.043	.821	4.98	9.86	.018
	s-d	16.7	.501	12.3	5.86	10.2	.232	11.5	.046	.339	.140	.231	.092	.026	1.34	4.69	3.74	.067

Table B.2

Descriptive statistics of hydrochemical results for the dry period, July 9-August 22, 1981.

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus Input (S_3)	$\bar{x}$	16.2	6.35	1.67	1.67	0	.800	47.5	.040	.187	.080	.325	.048	.013	.158	.205	6.03	0
	s-d	8.66	.394	4.08	4.08	0	.295	11.7	.020	.070	.096	.158	.044	.021	.102	.119	3.22	0
Output (S_{13})	$\bar{x}$	199.3	7.19	96.7	86.4	10.3	.565	63.3	.069	.365	.152	.556	.031	.039	.147	6.04	75.2	.009
	s-d	20.2	.139	9.64	7.86	7.13	.299	9.00	.013	.197	.102	.133	.058	.030	.116	2.31	11.5	.023
Rock Glacier Input (S_3)	$\bar{x}$	16.2	6.35	1.67	1.67	0	.800	47.5	.040	.187	.080	.325	.048	.013	.158	.205	6.03	0
	s-d	8.66	.394	4.08	4.08	0	.295	11.7	.020	.070	.096	.158	.044	.021	.102	.119	3.22	0
Output (S_4)	$\bar{x}$	70.9	7.45	41.6	32.9	8.71	.389	61.8	.059	.316	.181	.485	.049	.029	.154	4.46	13.9	.003
	s-d	13.3	.511	5.45	5.01	5.24	.188	8.68	.013	.179	.104	.107	.041	.022	.129	.943	7.65	.007
Alluvial Fan 3 Input (S_{11})	$\bar{x}$	37.5	7.23	20.5	10.1	10.4	.427	58.0	.049	.265	.108	.463	.025	.030	.187	9.00	11.3	.004
	s-d	6.78	.180	6.39	2.07	5.30	.202	8.19	.019	.165	.071	.124	.043	.023	.161	2.89	4.42	.011
Output (S_{10})	$\bar{x}$	30.8	6.75	24.5	10.7	13.9	.441	59.7	.062	.333	.189	.458	.031	.033	.163	6.68	10.9	.013
	s-d	3.69	.256	6.65	2.09	5.63	.151	9.72	.017	.184	.112	.108	.041	.022	.164	2.00	4.99	.029
Alluvial Fan 2 Input (S_9)	$\bar{x}$	30.7	7.27	27.3	11.5	15.8	.411	57.0	.046	.271	.095	.463	.046	.028	.167	6.43	10.3	.003
	s-d	6.68	.294	8.02	2.20	7.43	.207	4.55	.022	.153	.091	.167	.053	.025	.138	2.20	4.37	.010
Output (S_8)	$\bar{x}$	20.7	6.78	20.9	10.1	10.8	.313	58.0	.049	.295	.170	.505	.049	.038	.143	4.63	11.4	.003
	s-d	2.19	.332	5.39	1.77	4.59	.146	8.62	.019	.171	.141	.144	.067	.017	.112	1.09	4.99	.007

Table B.2

(Continued)

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Alluvial Fan 1	$\overline{x}$	57.9	7.45	35.9	23.4	12.5	.292	55.4	.055	.291	.088	.500	.052	.018	.215	3.63	9.01	.006
Input (S_2)	s-d	9.44	.279	6.35	3.50	8.00	.101	9.00	.011	.128	.085	.121	.043	.024	.281	1.08	3.61	.017
Output (S_1)	$\overline{x}$	54.9	7.68	36.5	24.4	12.7	.378	55.0	.052	.271	.072	.430	.057	.037	.150	2.89	11.0	.005
	s-d	5.93	.728	6.26	3.56	7.20	.226	7.07	.021	.143	.068	.092	.104	.024	.130	.892	3.59	.012

Table B.3

Descriptive statistics of hydrochemical results for the overall period, June 2-August 22, 1981.

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Talus	$\bar{x}$	13.7	6.74	.526	.526	0	.618	62.6	.072	.338	.235	.434	.081	.032	.437	.325	8.80	.015
Input (S_3)	s-d	13.2	.596	2.29	2.29	0	.545	16.0	.039	.253	.154	.333	.143	.027	.599	.257	3.76	.028
Output (S_{13})	$\bar{x}$	188.2	6.85	95.9	82.7	13.1	.806	73.8	.093	.473	.201	.640	.087	.046	.342	5.90	72.6	.019
	s-d	41.1	.504	12.1	11.0	10.5	.659	14.9	.035	.318	.158	.305	.174	.045	.488	1.82	25.0	.033
Rock Glacier	$\bar{x}$	13.7	6.74	.526	.526	0	.618	62.6	.072	.338	.235	.434	.081	.032	.437	.325	8.80	.015
Input (S_3)	s-d	13.2	.596	2.29	2.29	0	.545	16.0	.039	.253	.154	.333	.143	.027	.599	.257	3.76	.028
Output (S_4)	$\bar{x}$	62.2	6.96	39.7	27.3	12.4	.469	66.7	.081	.378	.207	.500	.091	.031	.344	4.47	12.7	.010
	s-d	15.6	.726	10.8	7.51	10.2	.205	11.3	.037	.193	.112	.194	.140	.027	.487	.978	6.35	.020
Alluvial Fan 3	$\bar{x}$	33.8	7.01	25.2	10.4	14.8	.494	66.8	.070	.343	.144	.465	.047	.034	.334	7.79	10.9	.013
Input (S_{11})	s-d	13.5	.469	9.79	2.13	9.37	.239	12.6	.031	.234	.121	.261	.076	.024	.452	2.78	4.86	.025
Output (S_{10})	$\bar{x}$	36.5	6.63	30.6	11.1	19.4	.453	69.3	.070	.355	.237	.458	.064	.038	.331	6.77	12.4	.016
	s-d	15.3	.406	12.1	3.42	11.4	.223	14.3	.027	.204	.161	.228	.074	.024	.470	1.72	5.08	.029
Alluvial Fan 2	$\bar{x}$	27.0	7.00	32.5	11.6	20.8	.497	66.3	.073	.364	.113	.461	.092	.033	.335	6.17	10.7	.006
Input (S_9)	s-d	13.8	.552	15.3	2.67	15.0	.247	13.4	.042	.200	.094	.265	.093	.027	.486	1.81	4.13	.016
Output (S_8)	$\bar{x}$	23.6	6.59	29.2	10.9	18.3	.450	65.4	.059	.366	.237	.480	.140	.040	.316	5.45	10.4	.011
	s-d	8.69	.473	14.5	2.58	13.2	.441	13.5	.027	.230	.196	.192	.213	.026	.485	1.68	4.94	.019

Table B.3

(Continued)

Landform Site	Statistic	SEC	pH	Total Hardness	Ca Hardness	Mg Hardness	NH_4	Cl	Cr	Cu	Fe	Ni	NO_3	NO_2	PO_4	SiO_2	SO_4	SO_3
Alluvial Fan 1 Input (S_2)	$\overline{x}$	45.3	6.93	34.3	17.5	16.8	.499	65.0	.072	.352	.127	.446	.062	.028	.396	3.53	9.61	.011
	s-d	18.3	.692	8.81	7.34	10.1	.458	14.4	.032	.224	.122	.183	.105	.029	.522	2.56	3.69	.024
Output (S_1)	$\overline{x}$	53.9	7.03	35.8	21.1	15.5	.459	62.3	.070	.312	.118	.385	.071	.040	.461	3.86	10.5	.011
	s-d	11.9	.949	9.36	5.93	9.09	.241	12.2	.040	.252	.117	.175	.098	.025	.963	3.36	3.64	.046

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ABSTRACT

This thesis investigated the influence of geomorphology on stream hydrochemistry for the headwater lake basin of Gladstone Creek, Yukon Territory (61°24'N/138°24'W). Landforms affected the hydrochemistry and hydrology of the surface and subsurface streams in different ways. Between June 2 and August 22, 1981, the spatial and temporal solute behavior of the streams indicated that (1) an increase of stream ionic concentration occurred with the surface and subsurface drainage, (2) landform types exhibited different degrees of influence on stream ionic concentration, and (3) higher solute concentrations occurred during the snowmelt and precipitation period. Hydrological parameters were monitored to provide an indication of flushing and dilution processes through the application of a water balance equation. The water balance record illustrated that the regime could be divided into a wet and dry period. It was determined that landforms exert some control on solute dynamics and that different landforms in the same drainage basin have variable effects on solute concentration. The results imply that detailed landform descriptions should be performed when assessing the solute dynamics of small alpine basins.

RÉSUMÉ

L'objet de la présente thèse était d'examiner l'influence de la géomorphologie sur l'hydrochimie des cours d'eau issus du bassin lacustre supérieur du Gladstone Creek, dans les Territoires du Yukon (61°24'N/138°24'O). Le relief affecte l'hydrochimie et l'hydrologie des eaux de surface et souterraines de diverses façons. Entre le 2 juin et le 22 août 1981, le mouvement spatial et temporel des éléments dissous dans l'eau indiquait: (1) qu'un drainage en surface ou souterrain entraîne une hausse de la concentration ionique de l'eau; (2) que le relief influence de façon variable la concentration ionique; et (3) que la concentration du soluté est plus élevée au moment de la fonte des neiges et par temps de pluie. On a surveillé les paramètres hydrologiques afin d'avoir une idée des mécanismes d'élimination et de dilution par l'application d'une équation sur le bilan hydrique. Le bilan hydrique indique qu'il est possible de séparer le régime fluvial en périodes humide et sèche. Le relief a un certain effet sur la dynamique des substances dissoutes et la présence de lits différents dans le même bassin entraîne une variation de la concentration du soluté.

Les résultats impliquent qu'on devrait procéder à une description détaillée du relief au moment d'évaluer la dynamique des substances dissoutes dans les petits bassins alpins.