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THE ROLE OF THE SNOWPACK AND SNOWMELT RUNOFF IN THE NUTRIENT BUDGET OF A SUBARCTIC ECOSYSTEM

by

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ABSTRACT

This study examines the impact of snowmelt runoff on nutrient transfer from the terrestrial to the aquatic (lake) portion of a subarctic catchment 6 km WSW from Schefferville, Québec.

Statistically significant differences in snow chemistry were recorded among the tundra, woodland and forest snowpacks. Significant overland scouring of nutrients from the organic horizons were recorded in the tundra, woodland and forest. A calculation designed to generate, on a daily basis, 70% of the meltwater from the terrestrial catchment to the lake indicates overland flow is a predominant route of meltwater during the spring. Deuterium/hydrogen measurements aided in determining mixing of snowmelt and lake water. The data indicate snowmelt water is undistinguishable from lake water at depths greater than 1.0 m.

It is concluded that snowmelt runoff is an important event for nutrient transfer from terrestrial to aquatic systems in this environment.

RÉSUMÉ

Cette étude examine l'impact de l'ecoulement de la fonte de neige sur le déplacement nutritif de la portion terrestrielle à la portion aquatique d'un bassin hydrographique 6 km ouest sud ouest de Schefferville Québec.

Des différences statistiquement importantes en la chimie de la neige sont enregistrées dans la neige tombée de la tundra, de la région boisée et de la forêt. Un écoulement important ainsi qu'une chasse d'eau substantielle d'éléments nutritifs de l'horizon organique fut enregistrée dans la toundra, la région boisée et la forêt. Un calcul journalier désigné à engendrer 70% de l'eau de fonte de la terre au lac indique que l'écoulement est une route prédominante pour l'eau de fonte durant le printemps. Les données indiquent que l'eau de fonte est indistinguable de l'eau du lac à des profondeurs plus grandes que 1.0 mètre.

Il est conclu que l'écoulement de la neige fondue est un événement important dans le déplacement des éléments nutritifs de la terre aux systèmes aquatiques dans cet environnement.

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CONTRIBUTION TO ORIGINAL KNOWLEDGE

To my knowledge this is the first study examining the impact of snowmelt runoff on nutrient transfer from subarctic terrestrial to aquatic systems during springmelt.

Specific contributions within the study include; 1) an evaluation of snowpack chemistry in a subarctic catchment, 2) physical factors influencing the runoff process at springmelt within the snowpack, 3) the impact of snowmelt runoff on nutrient transfer from terrestrial to aquatic portions of a subarctic catchment, and 4) the physical mixing of snowmelt water with lake water.

Contrary to reports in the literature the vegetation in the study catchment had minimal impact upon the snowpack nutrient mass. Though statistical differences occur among the tundra, woodland and forest snowpacks, the ecological significance of these differences is probably minimal.

The heterogeneity of the snowpack due primarily to differences in the density of the stratigraphic layers resulted in downslope diversion of meltwater to water bodies. Though this volume may be minimal the timing of this diversion flow is critical in terms of snowpack elution for it is during the early melt when the greatest amount of exsolving of nutrients occurs. Diversion of this early meltwater will reduce the physical and chemical interaction with the organic horizons at the base of the snowpack. Diversion by well formed ice layers is reported, but not by snow stratigraphic density differences. There has not been any research reporting the internal flow pattern of meltwater within a subarctic snowpack. Snowmelt runoff plots established within the tundra, woodland and forest plant communities enabled the recording of the chemical interaction of snowmelt water and the organic horizons above the frozen mineral soil. To the author's knowledge this method has not been used to record this interaction in the arctic, subarctic or temperate regions. Very significant scouring of nutrients was recorded in the three plant communities during springmelt.

Though deuterium/hydrogen has been used as an effective tracer of groundwater contribution to stream flow, it has not been used as a tracer of snow meltwater mixing in arctic, subarctic or temperate lakes. Substantial retention of terrestrial source nutrients within the lake was recorded during the springmelt. Mass balances of this nature have not been examined in subarctic lakes.

This study has demonstrated that in terms of nutrient mass transfer from terrestrial to aquatic portions of ecosystems during the springmelt, the subarctic is substantially different than the temperate region.

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CHAPTER 1

INTRODUCTION

1.1 Thesis Outline

The introductory chapter defines the hydrological differences between temperate and subarctic ecosystems as they relate to springmelt runoff. In this chapter, the simple point is made that little is known about the transfer or retention of nutrients in subarctic systems during snowmelt. By comparison much is known about the interactions of meltwater and the terrestrial catchments in temperate zones - mainly as a result of recent interest in the ecological impacts of acidic snowmelt runoff. In chapter 1, hypotheses are presented regarding the transfer and retention of nutrients within subarctic ecosystems during springmelt.

The second chapter examines the study area near Schefferville, Québec. As well, the field methodology is discussed and the laboratory procedures used for water analyses are listed.

Chapter 3 presents the snowpack hydrological data. The spatial and temporal variation of snowpack stratigraphic layers is examined statistically, both within and between plant communities. The water equivalence survey at peak snowyear is presented along with the occurrence and spatial distribution of concrete frost. A calculation designed to generate snowmelt runoff water downslope is described and utilized to predict the daily flux of water to the lake.

Chapter 4 examines the spatial pattern of nutrient concentration within the snowpack and the daily flux of nutrient mass from each runoff plot. Diversion meltwater flow within the woodland and forest snowpack are discussed as they relate to nutrient discharge from the snowpack. The daily pattern of scoured nutrient mass and concentration in the woodland and forest snowpacks are discussed. The significance of this scouring is postulated.

In chapter 5, mass balances are constructed for the runoff plots and for the entire catchment. The yearly mass balance for total phosphorus (TP) is calculated to determine the relative importance of the spring melt contribution to the lake. Comparisons are drawn between the temperate and subarctic regions.

Chapter 6 examines the degree of mixing of snowmelt water and Elizabeth Lake. Two approaches are used: 1) the stable isotope ratio differences in deuterium and hydrogen and 2) predicted littoral zone lake temperatures given solar radiation and calculated volumes and known temperatures of snowmelt water entering the lake on a daily basis.

The final chapter summarizes the results, presents the conclusions and makes suggestions for future study.

1.2 Hydrological aspects of snowmelt runoff in temperate and subarctic regions

Much of the current interest in snowpack and snowmelt hydrology studies has stemmed directly from the research and resulting literature dealing with the routing and impact of environmental contaminants--principally acidic precipitation--in and on land and lake ecosystems (for example Rennie, 1978; Drablos and Tollan, 1980; Hutchinson and Havas, 1980; Harvey et al., 1981; Overrein et al., 1981; Bobée et al., 1982 and D'Itri, 1982). These studies have examined the snowmelt process in temperate regions where, as a rule, snowmelt water infiltrates the soil mantle during melt periods. Overland flow during snowmelt occurs rarely in temperate regions; where it does, it is restricted to: 1) areas where high water tables result in partial area or saturated overland flow (Dunne et al., 1975) or 2) areas where the infiltration capacity of the soil is exceeded by the snowmelt runoff intensity. This latter point is termed Horton overland flow, the definition of which will include soils affected by concrete frost (defined by Trimble et al., 1957) and areas where midwinter thaws and subsequent freezing temperatures have resulted in the formation of an impervious ice cover over the ground cover thus facilitating full or partial overland flow during springmelt. Price and Hendrie (1983) report limited occurrences of this latter example at Perch Lake, Ontario.

Bobée et al. (1982) report widespread overland flow in the temperate region of Québec during the 1980 springmelt. They attribute this to an unusually thin snowpack formation and the assumed (unmeasured) occurrence of concrete frost. Concrete frost formation in southern Québec is thought unusual as sufficient snow falls (Hydrological Atlas of Canada

1978) to form a snowpack capable of insulating the ground beneath. Naiman (1982) reports that snowmelt in the Moisie River watershed, Québec, percolates into the soils. Reports of Horton overland flow in temperate regions all indicate the process is of minimal importance during snowmelt periods (Wright, 1976; Likens et al. 1977; Siegel, 1981; Price and Hendrie, 1983; Verry, Pers. Comm. 1984).

The pattern of snowmelt runoff in temperate regions contrasts with snowmelt in the subarctic where concrete frost is more common and infiltration of snowmelt water is reported to be reduced to insignificant proportions of the total snowpack water equivalence (Price, 1975; Fitzgibbon, 1977). Three other major factors differentiate the snowmelt process in the subarctic from that occurring in the temperate regions to the south: an absence of above freezing temperatures and rainfall during the snowyear and a large proportion, approximately 50%, of the annual precipitation is snowfall. In the temperate region rainfall is common during the springmelt and thaw events occur prior to springmelt (Hendrie, 1984; Scheider et al., 1984; Semkin et al., 1984).

1.3 The hypothesized impact of mineral soil impermeability on snowmelt runoff chemistry.

It is hypothesized that the physical differences governing snowmelt runoff pathways in temperate and subarctic terrestrial ecosystems will be reflected in the snowmelt runoff chemistry. For example, retention of nutrients recorded on the terrestrial portions of temperate systems, particularly phosphorus (P), will not apply in the subarctic. Models concerning nutrient dynamics in catchments derived from data collected in temperate systems should be evaluated in light of the physical differences that occur before application to a subarctic ecosystem is made. Chapin et al. (1978:190) state that "the functioning of natural (subarctic) systems will not be understood until the factors regulating movement of limiting elements through these systems are elucidated".

1.4 Atmospheric contribution of P and N to aquatic and terrestrial systems in the temperate and subarctic regions.

In the temperate climatic region it is reported that the atmospheric contribution of P and N (the principal biologically important nutrients) is the primary external source of these nutrients to terrestrial and aquatic systems (Schindler et al., 1976; Likens et al., 1977; Scheider et al., 1979; Semkin et al., 1984). It is assumed from reviewing the literature (Dugdale and Dugdale, 1961; Haag, 1974; Chapin et al., 1978; Moore, 1980) that the atmospheric inputs of P and N in more northern regions including the subarctic are very significant as they represent the only major incoming source of these biologically important nutrients. Exceptions to this for P may be found where sedimentary bedrock dominates watersheds. Dillon and Kirchner (1975) report total phosphorus (TP) export figures of approximately 0.11 kg ha^{-1} yr^{-1} for forested watersheds underlain by sedimentary rock; these figures can exceed the reported bulk atmospheric deposition of TP especially in more northern regions. Table 1-1 lists annual bulk atmospheric TP loading for temperate and subarctic sites.

In the subarctic, the low mean annual temperatures equate to low productivity in ecosystems, both terrestrial and aquatic. As the growing season is reduced, decomposition rates are lower (Moore, 1981, 1984; Douce and Crossley, 1982) and the mass of biologically important

Table 1-1. Annual total atmospheric deposition for selected sites in the temperate and subarctic climatic zones. ($Kg \cdot ha^{-1} \cdot yr^{-1}$).

	TP	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NO_3^{-}
Subarctic (Québec)[1]	.052	2.57	.60	3.34	1.49	.14
Subarctic (Sweden)[2]	.055	nd	nd	nd	nd	nd
Subarctic (Alaska)[3]	.012	nd	nd	nd	nd	nd
Temperate (northwest Ontario)[4]	.327	3.80	.90	1.60	1.10	1.71
Temperate (central Ontario)[5]	.208	9.90	3.80	1.27	.94	nd
Temperate (Minnesota)[6]	.137	2.75	.43	.72	.74	nd
Temperate (New Hampshire)[7]	.306	2.20	.60	1.60	.90	nd
Temperate (southern British Columbia)[8]	.250	3.70	3.0	11.0	2.50	nd
Temperate (central Ontario)[9]	.41	6.75	1.02	4.02	1.59	3.47
Temperate (northern Ontario)[10]	.09	1.12	.84	nd	8.09	nd

[1]Moore (1980)
[2]Likens *et al.* (1977)
[3]Chapin *et al.* (1978)
[4]Schindler *et al.* (1976)
[5]Schindler and Nighswander (1970)
[6]Wright (1976)
[7]Likens *et al.* (1978)
[8]Scrivner (1975)
[9]Scheider *et al.* (1980)
[10]Jeffries and Semkin (1983)

and available nutrients is limited. Moore (1980) states that between 20 and 60% of the macronutrients in the organic portion of the eastern subarctic terrestrial ecosystem are held within the soil organic matter. The slow decomposition rates result in very oligotrophic systems.

The contribution of the snowpack to the nutrient budget of subarctic ecosystems represents a substantial potential source of nutrients. Due to the reported impermeability of the mineral soil the large potential source of nutrients may bypass the terrestrial portion of the catchment and enter streams, lakes or bogs. The land's loss may prove the aquatic system's gain. This of course will be a function, in the case of lakes, of the degree of mixing ongoing within the lake during the melt period. If, as recorded by Bergmann (1982) in an arctic lake near Baker Lake, N.W.T., the meltwater discharges across the lake surface without significant mixing, approximately 50% of the annual atmospheric contribution of nutrients will be essentially lost to the ecosystem. If the mixing of meltwater with the lake is pronounced, the addition of biologically important total dissolved phosphorus (TDP) and NO_3^- would increase the primary productivity of the aquatic system. In the temperate zone, Schindler and Nighswander (1970: 2021) report that "the major rejuvenation of yearly nutrient concentrations in Clear Lake, central Ontario appeared to occur during the period of snowmelt in the spring". Jeffries et al., (1979) report that mixing of springmelt water may extend to several metres in depth in Canadian Shield lakes in the temperate region. The controlling factors are the intensity of melt, topography of the terrestrial catchment, bathymetry of the aquatic system receiving the water, the volume of water contained in the snowpack, the depth of overburden and soil into which the meltwater percolates and the water content and water level of the soil and groundwater respectively.

1.5 Transfer of P and N from terrestrial to aquatic systems in temperate and subarctic regions.

Determination of the potential differences in the transfer of P and N, from land to aquatic systems between temperate and subarctic regions at spring melt is difficult because within the temperate ecosystems there appears to be contrasting results for both P and N. The impact of accumulated winter precipitation on the nutrient budgets of temperate systems is not well investigated, or at least not well reported, as annual rather than seasonal budgets are usually considered. This is especially true for P. Due to the great interest in the acid shock of snowmelt runoff to aquatic systems in the spring (Gunn and Keller, 1984 and others), NO_3^-, as a dissociated by-product of HNO_3^- has been the subject of more intensive reported investigation (Schofield, 1977; Glover et al., 1980).

Potential retention of P by soils is very high as it can be absorbed by microorganisms, plants and adsorbed by soil colloids. Its bonding affinity to soil colloids is reportedly very strong especially at low pH (Johnson and Cole, 1977); in addition P can precipitate with Al, Fe, Ca^{2+} and other cations (Bear, 1967; Hesse, 1971) and thus become immobilized in the soil. Gorham and McFee (1980) state that the formation of secondary minerals effectively reduces the leaching of P to aquatic systems. The data gathered during springmelt at two sites in the temperate region of the Canadian Shield tends to confirm the terrestrial portion of the catchment's high affinity for P (Schindler et al., 1976; Wright, 1976). Likens et al. (1977) report that during the springmelt, the P input to the system exceeds that recorded in stream runoff in the White Mountains of New Hampshire.

Leonard et al. (1979), Lewis and Grant (1980), Verry and Timmons (1982) and Bjärnborg (1983) all report substantial flushing of P during the springmelt. With exception of the work of Verry and Timmons (1982), the research listed examined spring runoff in mountainous areas where the slopes of the catchment are steep, soil not well formed and the melt is very intense. Bjärnborg (1983) attributes the elevated P levels in streams in northern Sweden during the spring to the erosion of soil particles into streamwater. Verry and Timmons (1982) state that springmelt flow is restricted to the O horizon in the upper portion of a catchment in the Marcell Experimental Forest in northern Minnesota. It is suspected that infiltration into the A and B horizons occurs as Verry (Pers. Comm., 1984) states that infiltration of snowmelt water into the soil occurs in this region as overland flow is restricted geographically to very small areas.

Studies examining NO_3^- mass balance during springmelt on terrestrial catchments in the temperate region are limited in number. Though annual mass balances are well reported and indicate without exception the net retention of atmospheric source NO_3^- by the land (for example, Schindler et al., 1976; Wright, 1983) the pattern during the melt period is not as clear cut as that reported above for P. From the available literature coniferous forests or forests with a significant coverage of coniferous trees appear to have adopted strategies for retaining NO_3^- during spring melt. Of the nine studies reporting net retention of snowpack and spring precipitation source NO_3^-, seven occur in terrestrial catchments with either coniferous trees or a dominant coniferous/ subdominant deciduous tree forest (Leonard et al., 1979; Martin, 1979; Skartvist and Gjessing, 1979; Glover et al., 1980; Cadle et al., 1983; Christophersen et al., 1983).

In certain streams flowing into Harp Lake a largely deciduous forested catchment in central Ontario, Jeffries et al. (1981) report decreasing NO_3^- concentrations through the springmelt period. Verry and Timmons (1982) report net NO_3^- retention in a deciduous forested catchment in northern Minnesota. Storgama, a small Norwegian catchment with mixed coniferous/deciduous vegetation does not retain any of the snowpack-source NO_3^- infiltrating the ground surface (Christophersen et al., 1983).

Net loss of NO_3^- during springmelt occurs in only two reported studies. Hornbeck and Likens (1974) examined springmelt in a deciduous forest at Hubbard Brook Experimental Forest in New Hampshire and report net flushing of NO_3^- out of the terrestrial portion of the catchment above that determined in the snowpack.

The pattern of NO_3^- movement during spring in the Hubbard Brook Experimental Forest (Likens et al., 1977) suggests that the flushing of NO_3^- from the hardwood deciduous catchment eases in the late spring when the vascular plants begin to grow. The observation is essentially the same as that reported for a hardwood-deciduous at Turkey Lakes Watershed in northern Ontario by Foster (1984) and Semkin et al. (1984). Gunn and Keller (1984) state that in a northern Ontario coniferous-deciduous (subdominant) forested watershed the nitrate originating from the snowpack is initially flushed through the system, that discharging during the latter portion of the melt is retained within the terrestrial catchment due to biological utilization.

In tundra sites in Norway, Seip et al. (1980) report that the NO_3^- from snowpack melt is initially retained by the tundra then, during the latter portion of the melt the remaining snowpack-source NO_3^- is flushed out of the system.

The strategy which enables the reported coniferous forested sites to retain snowpack-source NO_3^- during the melt period may be attributable to microorganisms in the organic horizons of the soil profile. Moore (1983, 1984) reports microorganism activity in the organic horizons of subarctic podzols during the snowyear as significant decomposition of first year litter occurs. It is possible that in the nutrient limited conditions of temperate coniferous forests, soil microorganisms may absorb snowpack source NO_3^- as it infiltrates into the soil. Since NO_3^- has a poor adsorbing capacity to soil colloids and can be displaced with ease by PO_4^{3-} and SO_4^{2-} (Johnson and Cole, 1977), the latter reported to be the dominant anion in winter precipitation (Scheider et al., 1980), the only other means of retention within the soil other than organic uptake is specific adsorption to Fe and Al (see Johnson and Cole, 1977: 14).

1.6 Conceptual model of P and N transfer from terrestrial to aquatic portions of a subarctic ecosystem during springmelt.

The potential interactions of snowpack-source P and N with the terrestrial catchment in the temperate region provide the basis of a conceptual model of nutrient transfer during springmelt in the subarctic where it is reported infiltration of meltwater into mineral soil on slopes is very minimal. Effective sealing off of the soils to infiltration may affect the transfer of P more so than N because of the differential bonding potential of PO_4^{3-} and NO_3^- to soil colloids. Relatively speaking the mass of snowpack source P being retained within the N-limited subarctic terrestrial system (see Moore, 1980) may be relatively less than the N retention. The strategies adopted for retention of NO_3^- by more southerly temperate coniferous forest soils may be assumed to apply to subarctic soils low in available N. Though the N retention in the coniferous temperate forests reported above has been attributed here to microorganism activity in the organic layers of the soil the possibility of adsorption to Fe and Al in the B (illuvial) horizon exists (Johnson and Cole, 1977). A possible argument in favour of microbial absorption is that in a podzol soil in a hardwood forest at Turkey Lake Watershed in northern Ontario infiltration of meltwater through a well defined B horizon does not result in adsorption of NO_3^- during the spring melt period. NO_3^- mass reduction in discharge begins only when the vascular plants begin absorbing nutrients out of the soil in the late spring (Foster, 1984). The hardwood forests are not limited by low quantities of available-N as reported in the subarctic by Moore (1980). The flushing of NO_3^- out of the hardwood system in spring exceeds that available in the snowpack and is obviously not being absorbed by microorganisms at least in any significant quantity.

If the examples of the temperate system serve as a model for the subarctic system it is expected that NO_3^- may be effectively retained by the organisms present in the O, L, F and H layers and that much of the P will drain into aquatic systems receiving the meltwater.

In the temperate region, the percentage of atmospheric-source P and N reaching the lake surface from the terrestrial portions of catchments (on an annual basis) is very low. Scheider et al. (1979) report that in central Ontario, Harp Lake accounts for 12.6% of the total watershed area. The precipitation falling directly on the lake represents 20% of the annual input to the lake. Along similar lines of comparison, the precipitation falling directly on the lake contributes 44% of the TP and 67% of the NO_3^- the lake receives annually. Wright's (1976) data for Dogfish Lake, an undisturbed catchment in northern Minnesota indicates that annual precipitation input directly to the lake accounts for 82% of the TP received by the lake on an annual basis. The larger the ratio of the terrestrial portion of the catchment to the lake surface, the greater the proportional contribution of the land to the P load to the lake. Schindler and Nighswander (1970) and Schindler et al., (1976) report lake contribution values for P and N in central and northern Ontario to be 80 and 79 percent and 49 and 43 percent respectively. The ratio of land to lake area at the central and northern Ontario sites is 6.1:1 and 1.4:1, respectively.

In the subarctic, according to the conceptual model outlined above, the precipitation falling directly on the lake will contribute a significantly smaller portion of the lakes annual P load than to a temperate watershed with similar terrestrial watershed area - lake area ratio. If Lake 239 located at the Experimental Lakes Area in northwestern Ontario (Brunskill and Schindler 1971) was subjected to subarctic climatic conditions it would receive an additional 37 Kg of TP due to additional snow contribution, an increase of approximately 51% over current natural loading. Assuming an annual retention by the lake of 84% (Schindler et al., 1976) Lake 239 would increase in TP concentration by 6.30 ug L^{-1}. The current x TP concentration of Lake 239 is approximately 10 ug L^{-1}. An equation: $\log_{10}$ [chla] = 1.45 $\log_{10}$ [P] - 1.14, developed by Dillon and Rigler (1975) to predict summer chlorophyll a concentrations from TP concentrations at spring overturn is employed to determine the increase in productivity due to the additional snowpack source TP. The predicted increase in chlorophyll a concentration in Lake 239 would be from approximately 2.04 mg m^{-3} chl.a to 4.15 mg m^{-3} chla; greater than 100% increase in productivity.

Although the bulk atmospheric P deposition in the subarctic is less than most reported sites in the temperate region (Table 1-1), the subarctic lakes will receive a proportionally greater mass of P than temperate systems. A comparison with temperate areas such as Hubbard Brook Experimental Forest where the bulk atmospheric deposition of P is less than the reported subarctic values (Table 1-1) shows that if the subarctic and temperate catchments had an equivalent land:lake ratio, the subarctic lake would receive a higher loading of P due principally to the addition of snowwater from the terrestrial snowpack.

The impact of snowpack source NO_3^- on lake productivity is thought not to be as pronounced as the impact of snowpack-source P. This is primarily because in the subarctic N-limited terrestrial ecosystem it is assumed the N retention factors operating in many of the reported studies noted above in temperate coniferous forests are operating to more or less the same degree of efficiency during spring melt. For this conceptual model it is thus assumed that the snowpack source NO_3^- will be retained by the terrestrial system. With spring melt retention of NO_3^- by the subarctic terrestrial system, water bodies would receive a greater proportion of NO_3^- from direct precipitation than would temperate lake systems. This is primarily because the snowpack in the subarctic represents a greater percentage of the year's annual precipitation than does the snowpack in the temperate regions. According to this conceptual model which forms the structural basis for hypotheses concerning nutrient transfer during spring, subarctic lakes will receive proportionally greater P mass than N mass from the terrestrial portion of the catchments. Rigler (Pers. Comm. 1981), Diamond (Pers. Comm. 1982) and Smith et al. (1983) report that primary production in certain lakes in the subarctic portion of the Labrador geosyncline near Schefferville Québec is limited by nitrogen and not phosphorus as is reported for most temperate region lakes (Schindler et al., 1973; Vollenweider, 1975). The conceptual model outlined above whereby the loading of P to a subarctic lake is proportionately greater than N may in part explain the observations noted by Smith et al. (1983).

1.7 Scouring of available nutrients at the base of the snowpack.

There are two components which can be considered as potential nutrient sources to surface water bodies during spring melt in the subarctic. The first is the nutrient mass available within the snow; a partial product of the atmospheric deposition and leaching of organic material deposited on the snowpack during the snowyear. The second potential source of nutrients is the O, L, F and H horizons over and through which the meltwater is flowing. Temperatures (-5.0 to 0.0°C) recorded at the base of a subarctic snowpack in Alaska (Whitney, 1976) strongly suggests that decomposition by microorganisms could proceed through a substantial portion of the winter. Cessation of plant activity through the winter months suggests that available-form nutrients produced during this period of decomposition could be absorbed by vegetation, adsorbed by soil colloids or flushed out of the system at springmelt. Since commencement of this study, decomposition of organic matter has been documented beneath the annual snowpack in the temperate (McBrayer and Cromack, 1980), subarctic (Moore, 1984) and arctic (Douce and Crossley, 1982) regions. Moore (1984) reports that in the Schefferville region of the subarctic, significant amounts of decomposition occur during the winter months. In another study, Moore (1983) demonstrates that a significant amount of this decomposition occurs just prior to snowfall accumulation in late fall, at a time when plant activities are minimal and flushing is minimal because precipitation falls as snow.

It is thought that during the springmelt period dissolved nutrients accumulated from the period of intensive decomposition referred to by Moore (1983) plus decomposition occurring through the snowyear at the base of the snowpack are flushed out of the system by the springmelt. The nutrient mass scoured at this time a product of physical and chemical interaction at the base of the snowpack.

1.8 Implications of impermeable soils for the chemistry of snowmelt runoff.

It has been reported that the pH of rain and snow falling in the subarctic is mildly acidic, pH 4.0-6.0, (Drake and Moore, 1980; Daoust, 1982). During springmelt the initial fraction of the meltwater discharging from the snowpack will, according to the literature contain a disproportionate fraction of the snowpack-source hydrogen ion (Johannes et al., 1980). Because the subarctic soils are frozen during the melt period and would remain so except in areas where ponding of water occurs, the acidic meltwater would reach downslope water bodies with very little if any interaction with the mineral soil. Unless significant ponding occurs or very high buffering within the surface vegetation and litter occurs, a large portion of the H^+ ion in the meltwater runoff will reach sensitive water bodies.

A large proportion of the eastern subarctic--approximately 80% (Holmes, 1965)--is composed of Precambrian granite. The remaining 20% consists of the Labrador geosyncline a trough of sedimentary deposits. It follows that a very significant portion of the eastern subarctic has little buffering capacity to neutralize the atmospheric acid load. Modellors concerned with predicting the effective buffering capacities of Precambrian shield subarctic systems would have to account for the lack of infiltration of acidic snowmelt water into the mineral soil of these sensitive subarctic ecosystems. As snowfall comprises approximately 50% of the annual precipitation in the eastern and 45% in the western subarctic, a significant percentage of the annual precipitation will essentially bypass the largest component of the ecosystem which can effectively buffer the acidic snowmelt runoff. Implications for downslope aquatic systems which are not well buffered, for example in the Canadian Shield, are primarily a reduction in the time it takes to reduce the whole lake pH. This will, in turn, be a partial product of the degree to which the snowmelt water mixes with the lake water.

In temperate catchments, the degree of mixing is a product of several physical and climatic factors such as basin morphometry, lake volume, volume of snowwater on the catchment and intensity of the melt. Jeffries et al. (1979) report differences in the mixing depth of snow-melt water in lakes in south central Ontario. The differences are qualitatively attributed to the factors described above.

Several studies undertaken in the temperate (Groterud, 1972; Henriksen and Wright, 1977; Hultberg, 1977; Stigebrandt, 1978 and Hendrey et al., 1980) and Arctic regions (Schindler et al., 1974 and Bergmann, 1982) have indicated that the meltwater entering lakes by streams discharge across the lake surface in a relatively thin sheet. Interaction of meltwater with the lake sediments is thought not to be significant.

1.9 Implications of meltwater terrestrial subsurface and overland flow on lake mixing.

A literature search reveals studies of lake mixing in subarctic lakes are almost non-existant. La Perrier (1981) was the only exception; the geographical location of this study area-northern Alaska--makes it more arctic in nature. In this area snowfall is low, unlike a large portion of the subarctic where snowfall water equivalence is very significant. La Perrier's monthly sampling interval permitted only a general examination of mixing through the year.

In temperate watersheds much of the water running directly from the land to the lake does so via subsurface flow, as such, the meltwater may enter the lake through the sediments in the littoral zone. Measurements of the hydraulic conductivity of this flow at the Experimental Lakes

Area in northwestern Ontario is approximately 4.0 x 10^{-5} cm sec^{-1} (Beaty, Pers. Comm. 1982). This value was recorded the day after a 2.5 cm rain storm. Measurements during snowmelt runoff were not taken.

Saturation overland flow produces flow velocities (during snowmelt) between .11 and .28 cm sec^{-1} (Dunne and Leopold, 1978). Price (1975) reports overland flow rates during springmelt to reach a maximum of .82 cm sec^{-1} in the eastern Canadian subarctic. It is thought that the flow velocities of meltwater overland runoff in the subarctic will approximate those reported above for saturation overland flow by Dunne and Leopold. Application of the mean value of .20 cm sec^{-1} to the velocity of snowmelt water enables the formulation of hypothesis regarding the degree of mixing ongoing at spring melt in subarctic lakes.

Wetzel (1975) reports that "...in lakes, velocities of only a few mm sec^{-1} can induce turbulent flow". This can lead to mixing between two layers of differing densities. During the winter months, surface temperatures in subarctic lakes will be less than 4°C. The energy required to disturb any density differential in very frigid waters is very small. Wetzel (1975) reports "the amount of work required to mix layered water masses between 29°C and 30°C is 40 times that required for the same masses between 4° and 5°C. It follows that the formation of stratigraphically distinct layers of snowmelt water and lake water where overland flow enters a lake is not guaranteed, especially as the inflowing water falls in the range of crating necessarily apply to temperate lakes in the range creating turbulent flow. What may be true for subarctic lakes need not necessarily apply to temperate lakes at least where direct runoff into the lake is concerned.

The hydraulic conductivity of the Quaternary deposits overlying the bedrock in the Canadian Shield ranges between 2.10^{-3} $cm.sec^{-1}$ to 7.10^{-5} $cm.sec^{-1}$ (Newbury and Beaty, 1980 and Craig, Pers. Comm. 1983). The low hydraulic conductivities reported for littoral zone seepage and subsurface flow (which eventually contributes to the downslope water body) are, according to Wetzel (1975) insufficient to create turbulent flow and concomitant mixing with lake water. Hence mixing of snowmelt water and lake water may be physically impossible in temperate regions if the direct inflow to lakes is by subsurface flow and seepage in the shallow littoral zone.

Overland saturated flow directly into lakes during springmelt is unreported in the literature. The literature examining the occurrence and mechanisms prompting overland saturated flow are primarily concerned with areas draining into first and second order streams (for example Dunne et al., 1975 and Pierson, 1983). Newbury (Pers. Comm. 1983) has observed overland flow thought due to saturated conditions on a Canadian Shield catchment in northwestern Ontario. Although the observations were not qualified by measurement, the topography of this particular area suggests the groundwater table would be in position to displace and redirect subsurface flow. Observations on three spring melts at the Turkey Lakes Research Watershed in northern Ontario indicate overland saturated flow is not a common event where direct input into the lakes from land is concerned (Craig and Semkin, Pers. Comm. 1984). The velocities reported above for overland saturated flow would be sufficient to promote mixing in the shallow littoral zone of lakes during springmelt; the frequency and occurrence of this process contributing directly to lakes in the temperate region is unknown.

The degree of lake mixing during springmelt in the temperate zones is reported to be small (Hendrey et al., 1980). The potential for snowmelt water mixing to greater than a few cm in depth with lake water in the subarctic appears to be high. Implications of different mixing regimes between subarctic and temperate lakes for nutrient budgets will be discussed.

If the meltwater mixes in the littoral zone of subarctic lakes a high proportion of the incoming nutrients will be retained within the lake. The processes thought responsible for this retention are adsorption of nutrients to littoral sediments and biological uptake by plankton.

Most of the lake nutrient models have been formulated from temperate lake data (for example, Dillon and Rigler, 1974). Application of these models to subarctic lakes should be evaluated in light of the differences between the two systems. Mixing of snowmelt and lake water in the littoral zone of subarctic lakes will not be apparent in samples taken from sampling sites located at the deepest portion of the lake or in the lakes discharging stream, as is the practice in temperate lakes.

1.10 Purpose

The purpose of this research is to examine the role of the snowpack and snowmelt runoff in the nutrient budget of subarctic tundra, woodland, forest and lake ecosystems during the springmelt period. The hypotheses established to provide a framework for this research are discussed below.

1.11 Hypotheses

1.11.1 Impact of plant community upon snowpack nutrient mass

Terrestrial and aquatic systems in northern latitudes are normally oligotrophic (Schindler et al., 1974; Haag, 1978; Bliss, 1978; Moore, 1981). Though nutrient concentrations in precipitation falling in the subarctic are reported to be lower than most reported temperate sites, the atmospheric contribution of available form or dissolved nutrients (<.45 um) in precipitation is speculated to be proportionately more important to the subarctic systems. Decomposition is very slow and biologically important available P and N is lowered in the subarctic terrestrial systems (Haag, 1978; Moore, 1981). Lakes in the eastern subarctic near Schefferville, Québec rank among the most oligotrophic lakes reported in the literature (Rigler, Pers. Comm., 1981).

As the winter snowpack comprises a very significant portion of the annual precipitation it represents a substantial contribution to these oligotrophic subarctic systems.

Additional nutrient input to the snowpack by organic matter is reported in the temperate regions (e.g., Pearson and Taylor, 1982) and in a study conducted by Manuel (1983) near Schefferville, Québec.

The dominant plant communities in the subarctic are lichen-heath tundra; open spruce-lichen woodland and closed spruce-moss forest (Hare, 1955). It is hypothesized that the nutrient concentrations in the snowpack will reflect the plant community. Assuming that the atmospheric nutrient contribution to each plant community is equal, the differences between plant community snowpacks can be attributable to organic deposition during the snowyear. The recorded differences are hypothesized to be significantly different due primarily to the increasing density of spruce (*Picea* spp.) trees, the species with the greatest above snow surface biomass and therefore potentially the greatest contributor of litter to the snowpack during the snowyear. Accordingly, the ascending order of snowpack nutrient enrichment due to organic matter contribution is postulated to be lichen-heath tundra   open spruce lichen woodland   closed spruce moss forest.

1.11.2 Fate of snowpack-source nutrients during spring melt runoff

The conceptual model outlined above for snowpack-source P and N transfer during spring melt (section 1.6) provides the structure for hypotheses regarding the potential transfer of these biologcally important nutrients during runoff.

It is hypothesized that on slopes in the subarctic, snowpack source P will not be retained by the terrestrial portion of the catchment but will be transferred into downslope water bodies. This is primarily because the snowmelt water is isolated from the mineral soil where adsorption is reported to be very high (Johnson and Cole, 1977; Schindler et al., 1976). During the snowmelt process it is hypothesized that NO_3^- will be retained by the terrestrial catchment; very little if any of the snowpack-source NO_3^- will reach bodies of water into which the snowmelt water is draining. Microbial absorption of N within the humus layer is speculated to be very high as northern subarctic terrestrial systems are N limited (Moore, 1980). It is hypothesized that on slopes the snowpack-source Ca^{2+}, Mg^{2+}, Na^+ and K^+ will not be retained within the organic material above the frozen mineral soil during springmelt. This is primarily because of low biological activity and the fact that these nutrients are more readily available than P or N and as such are not considered limiting to production in the subarctic.

1.11.3 Interaction of snowmelt water and the organic layers at the base of the terrestrial snowpack.

McBrayer and Cromack (1980) report that the critical air temperature for decomposer activity is not known but is well below 0°C. Temperature recorded at the base of a thick snowpack in the Alaskan subarctic (Whitney, 1976) indicate a temperature range amenable to decomposition (0 to -5°C). More recently, Moore (1983) reports snowpack temperatures at the snowpack base in the Schefferville region to range between +0.1°C and -3°C. It is hypothesized that a portion of the dissolved nutrient accumulation resulting from: 1) the intensive period of decomposition in the subarctic just prior to the initiation of the annual accumulation of snow, reported by Moore (1983) and 2) the decomposition occurring beneath the snowpack (Moore 1984), will be physically flushed out of the organic horizons above the frozen mineral soil during the melt period. This of course will occur only on slopes. Where ponding of water occurs, the mineral soil will thaw much faster and infiltration and nutrient retention within the soil or subsurface water will occur.

In accordance with the discussion and hypothesis on the fate of snowpack source NO_3^- it is assumed that the NO_3^- released during decomposition is retained by the N-limited system and is not physically flushed from the terrestrial portion of the catchment. It is assumed that P, Ca^{2+}, Mg^{2+}, K^+ and Na^+ released during decomposition will be flushed out of the system.

A portion of the P, Ca^{2+}, Mg^{2+}, K^+ and Na^+ scouring will be directly a result of the physical scouring by meltwater runoff; a portion will result from ion exchange. Phosphate will chemically exchange with SO_4^{2-}, NO_3^- and Cl^- on organic colloids. If this exchange reaction occurs within the L, F and H horizons of the subarctic soil strata during snowmelt runoff, some retention of the P mass may occur. The retention will decrease as meltwater contact time with the organic material decreases. The exchange efficiency will thus be a function of the melt intensity and the slope angle along which the meltwater flows. The greater these factors become the lower the anion exchange efficiency. It is hypothesized that because portions of the organic layers will be frozen during the early period of the spring melt, the retention of available PO^{3-}_4 within the organic layers will be reduced and the total P mass discharging from the terrestrial portion of a subarctic catchment will be greater than the mass determined in the snowpack. Cation exchange occurring at the base of the snowpack will increase the cation mass discharging from the terrestrial portion of the system. Thus the discharging cation mass will exceed the sum of the snowpack source cation mass plus that physically scoured from the system. Though complete separation of the physically scoured mass from the mass resulting from cation exchange is impossible under field conditions, it is possible to hypothesize about the pattern of cation discharge and the causal mechanisms of this discharge.

1.11.4 Temporal pattern of snowmelt runoff/nutrient discharge within the terrestrial portions of subarctic catchments.

Hypotheses regarding the temporal pattern of nutrient discharge within the plant communities focus on the reported exsolving pattern of ions from snowpacks (Seip, 1980) and the frozen nature of the organic layers above the frozen mineral soil.

It is assumed the exsolving of ions from the snowpack will be proportionally greater during the initial portion of the melt. The degree to which physical and chemical scouring of nutrients occurs in the organic and surface mineral horizons is contingent upon the frozen nature of these layers. On slopes it is assumed the mineral soil is essentially impermeable to meltwater infiltration. The frozen nature of the organic horizons just prior to springmelt will vary from year to year, dependent upon the degree of saturation just prior to the initiation of the annual snowpack. Ambient air temperatures and the rate of snowpack accumulation are important. Snow is an efficient insulator; its efficiency generally increasing with depth (Granberg, 1982). If the organic layers were unfrozen, the greatest scouring of nutrient mass would be expected during the initial portion of the melt as the greatest proportion of snowpack source ions will exsolve and percolate into the O, L, F, H layers at this time. Cation and anion exchange would be greatest at this time. A frozen organic substrate would curtail the ion exchange as the number of exchange sites would be restricted at this time.

It is hypothesized that the scoured nutrient mass discharging from the terrestrial portion of subarctic catchments will be proportionally greater during the initial part of the snowmelt runoff, reflecting the disproportionate exsolving of snowpack source ions at this time. The degree of disproportionately will be a function of the quality of the organic layers above the frozen mineral soil.

1.11.5 Snowmelt-lake water interaction.

The potential for snowmelt water-lake mixing appears high in the subarctic as overland flow rates reported above are in the range needed to disrupt lake water stratification especially at low water temperatures. It is hypothesized that in the subarctic significant mixing of snowmelt water with lake water occurs. Because of the oligotrphic nature of these lakes (Rigler, Pers. Comm. 1981) it is hypothesized that much of the biologically important nutrients, N and P will be retained within the aquatic system.

1.12 Study area selection

The study area chosen was the Schefferville region of the eastern subarctic. The Schefferville region is typical of the eastern subarctic, climatically and botanically and excellent logistical support is available at the McGill Subarctic Research Station in Schefferville.

This area receives approximately 49% of its annual precipitation as snow (Barr and Wright, 1981), typical of the eastern subarctic (Canada, 1978). The soil is reportedly frozen through the duration of the springmelt (Price, 1975). Examination of the Hydrological Atlas of Canada reveals that snow depths and seasonal temperatures recorded at Schefferville are typical of the eastern subarctic. The frozen, relatively impermeable soils recorded during springmelt by Price (1975) are probably typical of much of the eastern subarctic as few differences exist among the climatic factors (snow depth, seasonal temperatures, autumn rainfall) primarily responsible for the frozen condition of the soils.

The plant communities inhabiting the Schefferville region are representative of those found in the eastern subarctic (Hare, 1955; Harper, 1964; Hustich, 1965).

The presence of the McGill Subarctic Research Station was a primary factor in the selection of a study area as it has provided facilities for researchers on subarctic processes for over 25 years. The studies produced from the McGill Station are immeasurably helpful in understanding hydrological processes and nutrient cycling in the subarctic. A limnological project based at the McGill Station under the direction of the late Dr. Frank Rigler was an added reason for conducting the study in this area.

CHAPTER 2

METHODOLOGY

2.1 Introduction

This chapter describes the study site, pre-fieldwork analysis, the initial basin survey during the winter prior to the field season and basin instrumentation. The sampling strategy for the snowpack, snowmelt runoff, and lake and stream discharge measurements are included. Stream, lake and snow sample treatment and chemical analysis are described.

2.2 Study area

2.2.1 Introduction

The Schefferville region was chosen for several basic reasons. The region is distinctly subarctic in terms of its climate (Hare, 1950), snow hydrology (Price, 1975), soil (Moore, 1980) and vegetation (Hustich, 1965). A wealth of environmental and ecological information collected by various researchers on the immediate region is available. In particular, concurrent studies included terrestrial nutrient dynamics focusing principally on litter decomposition and soil nutrient cycling and nutrient dynamics in lakes.

2.2.2 The physical environment

Schefferville, Québec is located on the Labrador geosyncline at 54°54'N, 66°57'W at 503 m.a.s.l. (Figure 2-1). The geosyncline comprises approximately 20% of the eastern subarctic land area, and contains carbonaceous rocks with high concentrations of Ca^{2+}, Mg^{2+} and P.

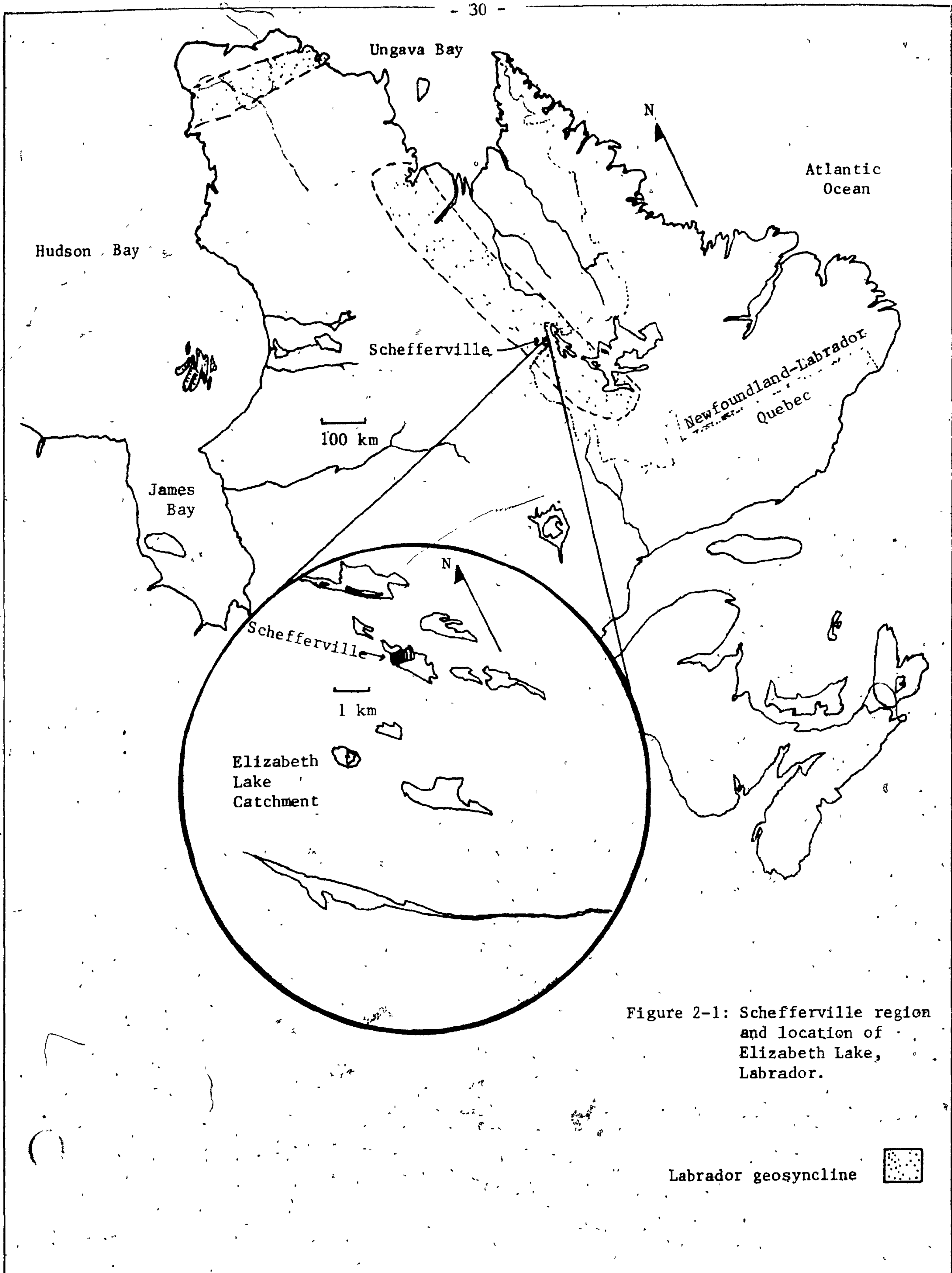

Figure 2-1: Schefferville region and location of Elizabeth Lake, Labrador.

Dillon and Kirchner (1975) report high export of P in drainage waters of sedimentary basins in the temperate zone. The notable outcrops of dolomite in the Schefferville area (Geological Survey of Canada, 1961) imply that the aquatic systems bordering on this rock type have elevated P concentrations. Elizabeth Lake, a small lake within 6 km of Schefferville is one such example. Chénard (1981) reports total phosphorus (TP) concentrations in excess of 8 $\mu g\ L^{-1}$ for this lake. The very oligotrophic lakes within this region such as Dolly Lake have TP concentrations at the limit of detectability, .01 $\mu g\ L^{-1}$ (Rigler, Pers. Comm. 1980). The granitic bedrock of the Canadian Shield is nutrient poor (Dillon and Kirchner 1975) and as such the nutrient concentrations in lakes on the eastern subarctic shield are uniformly low (Orth, Pers. Comm. 1980).

The climate of the Schefferville region is characterized by long cold winters and short cool, wet summers. The mean annual temperature recorded at the McGill Station between 1955 and 1979 (inclusive) is -4.5°C with an annual average of 771 mm of precipitation (Barr and Wright, 1981). Snowfall, comprising approximately 48% of the annual precipitation has been recorded in all months of the year; much of the rainfall is recorded from late May through to early September.

The ridge-valley-ridge topography, of the Labrador trough striking northwest-southeast, has an appreciable influence on vegetation distribution, snow accumulation and indirectly on the soil climate during the snow year.

The ridges, composed of more resistant rock, such as chert-breccia, are essentially devoid of vegetation greater than .25 m above ground surface. The snowpack on the exposed ridges is generally less than .5 m; only weakly able to insulate the ground beneath it. In the valleys snowpack accumulation ranges between 1.0 and 3.0 m. Although the snowpack in the valleys is sufficiently thick to insulate the ground against the formation of permafrost, the soil surface is reported to freeze and remain so through the springmelt period (Price, 1975). This feature is of utmost importance as it is one major factor which distinguishes subarctic ecosystems from temperate ecosystems where meltwater frequently infiltrates the unfrozen soil.

The major plant communities of the Schefferville region are lichen-heath tundra (hereafter referred to as tundra), open spruce-lichen woodland (hereafter referred to as woodland) and closed spruce-moss forest (hereafter referred to as forest). The terminology employed to describe the plant communities follows that of Hare (1959) who describes their widespread occurrence throughout the Labrador-Ungava Peninsula. The typical coenocline (Whittaker, 1975) is tundra occupying the elevated ridges, woodland growing in the midslope area, the forest occupying the well drained portions of the valley floor and in poorly drained portions of valley floors and nutrient poor fens. The pattern of growth is not so much successional as it is environmental.

The pedogenic processes operating in the Schefferville area, in order of importance are 1) podzolization, 2) gleying, 3) organic matter decomposition, 4) leaching and 5) weathering (Nicholson 1973). Moore (1978) describes in detail processes affecting soil pedogenesis in the subarctic. The soil is frozen during most of the snowyear (Price 1975), temperatures at the base of snowpacks have been recorded in subarctic Alaska to range between 0°C and -5°C (Whitney, 1976) and in the eastern Canadian subarctic to range between +0.1°C to -3°C (Moore 1983). This temperature range is sufficient for decomposition of organic material by microorganisms (Hendriksson et al., 1982), as shown by Moore (1983, 1984).

2.2.3 Selection of the Elizabeth Lake Catchment

The following criteria were established in the selection of the study site:

i) the catchment had to contain a selection of plant communities typical of this portion of the subarctic: lichen-heath tundra, open spruce-lichen woodland and closed spruce-moss forest.

ii) the catchment had to be reasonably close to the McGill Station in Schefferville such that transportation was not a logistical problem during the winter and spring when numerous water samples needed to be shipped to the lab for cold storage.

iii) contamination of the catchment should be minimal, either by direct human contact (e.g. snowmobiles) or by atmospheric pollution caused by the iron ore mines near the town of Schefferville.

iv) though not imperative, a catchment which had or was the focus of research, either limnological, hydrological or terrestrial would provide the added bonus of background information.

The only catchment which met all of the site selection requirements was that of Elizabeth Lake located approximately 6 km southwest of the Schefferville townsite (Figure 2-1).

The topography of the Elizabeth Lake catchment typifies the ridge-valley-ridge sequence well noted in the Labrador geosyncline. Elizabeth Lake is located on a dolomite deposit. The ridges containing the catchment are composed of more resistant chert-breccia. The coenocline typical of this region exists in the Elizabeth Lake catchment: tundra occupies the upper ridges, the distribution of forest closely follows the shape of the dolomite outcrop and the woodland dominates the lower parts of the valley slopes and portions of the valley floor.

Although the Wishart mine is located approximately 1 km southwest of Elizabeth Lake it was no longer operational and the tailings were snow covered through the snowyear. Although contamination of the Elizabeth Lake snowpack from this source cannot be entirely discounted, the prevailing northwesterly wind would reduce the probability.

Access to the Elizabeth Lake catchment was restricted by the Iron Ore Company of Canada (IOCC), eliminating disruption of the natural terrestrial snowpack by snowmobiles.

The Elizabeth Lake catchment was the site of an extensive snow survey during the 1978-79 snowyear (Adams and Barr, 1980). This survey provided information on the depth, density and water equivalence of the snowpack within each plant community and on the lake ice cover.

A limnological project conducted by the late Frank Rigler had collected several years data on Elizabeth Lake TP concentrations. An initial survey of intermittent streams by the limnology project provided valuable information on the terrestrial contribution of TP to the lake during the ice free year. Regular sampling of the single discharging stream from the lake provided baseline information on the lakes hydrology and TP mass flux from the lake. A Foxboro diaphragm recorder installed in 1978 provided continuous recording of the lake level.

By comparison with other subarctic lakes regularly sampled in the Schefferville area, Elizabeth lake is meso-eutrophic (as defined by

Wetzel, 1975) with average concentrations of epilimnetic TP of 12 ug L^{-1} (Rigler, unpublished data, 1980). This is thought to be a function of the dolomite deposit in the catchment. Although the eutrophic nature of the lake will not affect the significance of the results dealing with the interaction between snow meltwater and the terrestrial portion of the catchment, the significance of spring nutrient loading to the lake will be affected.

2.3 Initial surveys

As it was initially hypothesized that vegetation will significantly alter the chemistry of snowmelt runoff, a detailed map of plant community distribution was prepared. Black and white panchromatic aerial photography (1:2400) provided by the Iron Ore Company of Canada was used to map plant communities within the Elizabeth Lake basin. According to Heller et al., (1964) this photographic scale is more than adequate for plant community identification.

A preliminary survey of potential field sites in December 1978 included a cursory examination of snowpack depth distribution within the various plant communities. As snowpack accumulation and melt are partially a product of the environment in which the snowpack is located, slope angle, aspect and exposure to the prevailing northwesterly wind were noted. Further qualification of snowpack physical qualities and distribution just prior to peak snow year on the Elizabeth Lake catchment was determined from data reported in Adams and Barr (1980).

By comparing the aerial photography, a contour map of the same scale (provided by IOCC) and observations from the initial field survey, a preliminary basin boundary and drainage map was produced. This map designates areas of primary (draining directly into the lake) and secondary (areas contributing to elevated ponds which may reach the lake via groundwater, if at all) drainage.

During spring 1979, the Elizabeth Lake basin was examined on foot to provide ground truthing for the vegetation and drainage baseline maps. The panchromatic photography provided by IOCC was taken in 1958, but as growth is very slow, few corrections were necessary and individual trees and other suitable benchmarks could be identified. More recent photography (1970, 1:50,000) was of too small a scale for useful plant community interpretation or drainage delineation.

One of the major considerations for plant community division was the effect of the vegetation structure on the physical structure of the snowpack. It was hypothesized that the snowpack structure would have implications for the melt pattern and the chemical interaction between the meltwater and the base of the snowpack. The roughness factor created by vegetation and its effects on snowpack composition in the Schefferville area have been documented by Granberg (1971).

An added reason for the delineation of the catchment into plant communities is the effect of vegetation on solar radiation and therefore on the melt pattern during the springmelt.

Within the Elizabeth Lake catchment, 12 plots, each 400 m^2, were examined for species composition using the Braun-Blanquet method of plant species association. Four plots were located within each of the three recognized plant associations. Species dominance in each plot (tree, shrub, herb, ground) was of particular interest; subdominant species were also noted. The plots were established in a representative position within each assemblage so that the transition areas along the borders were excluded. The criteria of Mueller-Dombois and Ellenberg (1974:46) were met in each plot: namely, the sample stand was large enough to contain all species belonging to the plant community, the habitat was uniform within the stand area and the plant cover was as homogeneous as possible. As the detailed vegetation survey was not of great importance to this study only species significance and sociability were noted (Table 2-1).

The analysis reveals that the 3 vegetation units determined initially by observation for Braun-Blanquet analysis can be defined as three separate plant associations.

Plant community analysis revealed a difference in shrub and ground vegetation species in portions of the woodland plant community (appendix A). The woodland community has two principal components in the shrub-ground vegetation which essentially differentiates the plant community into two subgroups. The two subgroups are: 1) the woodland which is associated with a considerable growth of the shrubs *Betula glandulosa* and *Ledum groenlandicum*, and 2) the woodland in which the shrub growth is very sparse. The dominant ground species associated with the two subgroups are 1) lichen and moss species in roughly a 70-30 % coverage ratio in the plots with considerable shrub growth and 2) lichen dominant (90% ground cover) in the plots with little shrub growth.

From both a structural and compositional viewpoint the plant communities found on the Elizabeth Lake catchment are similar to those found elsewhere in the eastern subarctic (Hustich, 1954; Harper, 1964; Hustich, 1965; Crum and Kallio, 1966; Makinen and Kallio, 1980).

Table 2.1. Species significance scale showing cover-abundance for each numerical rank.

Ranking	Species significance Qualitative value	Cover-abundance (%)
1	Rare occurrence	Negligible
2	Seldom occurring	up to 5
3	Common occurrence	6 - 10
4	Occurring often	11 - 20
5	Occurring very often	21 - 35
6	Abundant cover	36 - 50
7	More abundant	51 - 75
8	Very abundant	up to 95
9	Most abundant	96 - 100

	Sociability Index
1	Growing singly
2	Grouped or tufted
3	Growing in small patches or cushions
4	Growing in small colonies, extensive patches, or forming carpet
5	Forming pure populations

Sociability is an evaluation of dispersion of a species within a sample plot.

2.4 Snowmelt runoff enclosures

Runoff enclosures were constructed in the three plant communities to collect and monitor snowmelt and its chemical composition.

Preliminary examination of the snowpack and data provided by Adams and Roulet (Pers. Comm. 1979), coupled with the Elizabeth Lake catchment drainage map, resulted in a rough estimate of the potential snowpack water volume which could drain into Elizabeth Lake during snowmelt. Using Price's (1976) estimate of 5.0 cm maximum melt day^{-1} [1], a rough calculation was made of discharge which could be expected from each plant community for a given surface area per unit of time (assuming concrete frost prevented any significant infiltration).

Based on these estimates of snowmelt runoff, rectangular enclosures measuring 3.0 m in width by 30.0 m in upslope length (Figure 2-2) were constructed in each of the three plant communities during the late summer and early fall of 1979. The locations are shown in Figure 2-3. The decision to construct two plots in the woodland and two in the forest and one in the tundra was based on the variation of ground vegetation within the two treed plant communities and the lack of variation within the tundra.

A second reason for the number and distribution of runoff plots related to the accumulation of organic matter beneath the living vegetation. The mor[2] accumulation in the tundra was insignificant compared with that beneath the lichen in the woodland and much less than that

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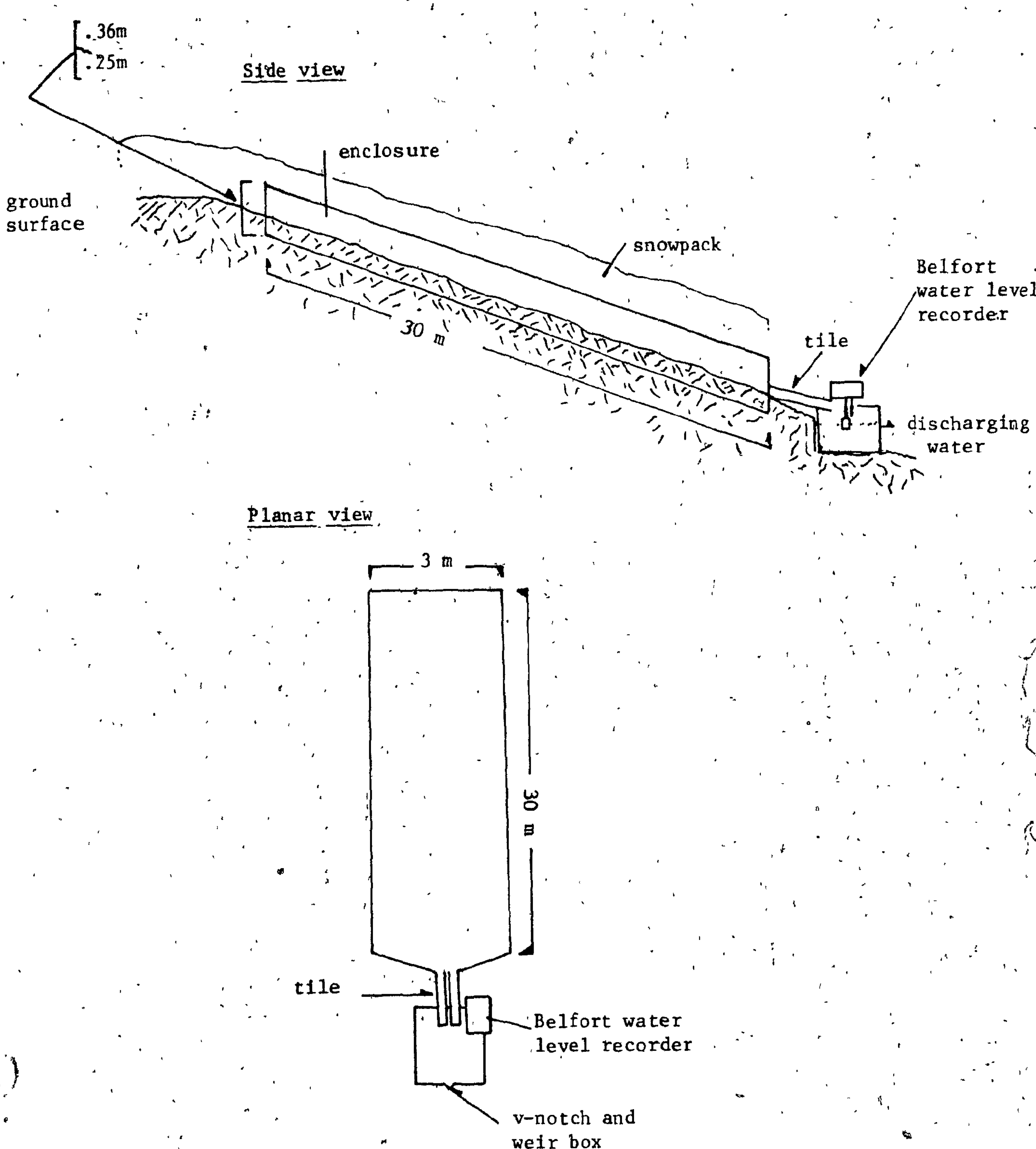
[1] Price's (1976) estimate was for a forest community. An additional 2.5 cm day^{-1} were added for the tundra and open spruce plant community.

[2] Mor is defined as humus consisting of organic mater distinct from the mineral soil beneath.

Figure 2-2: Schematic illustration of snowmelt runoff enclosure



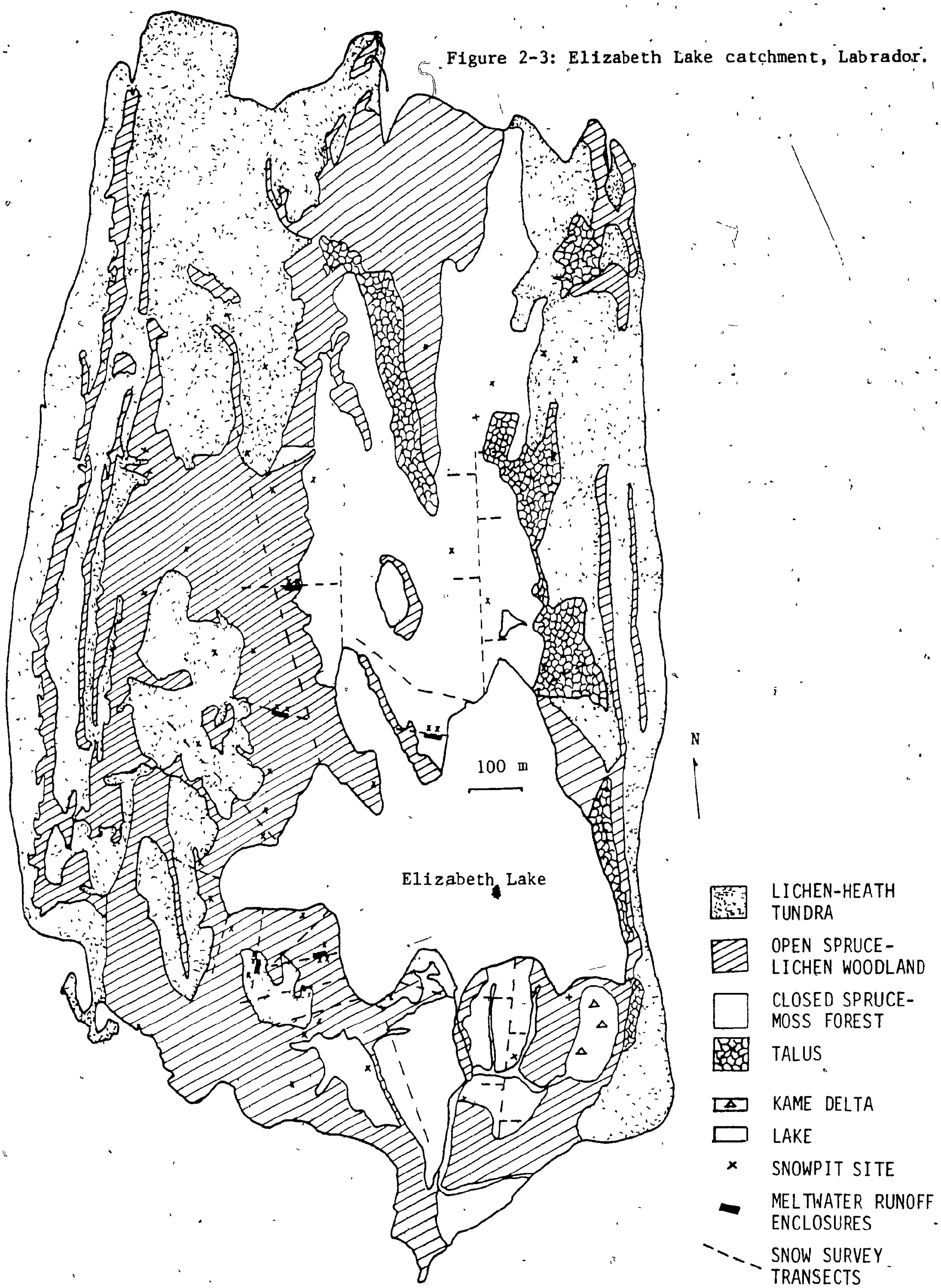


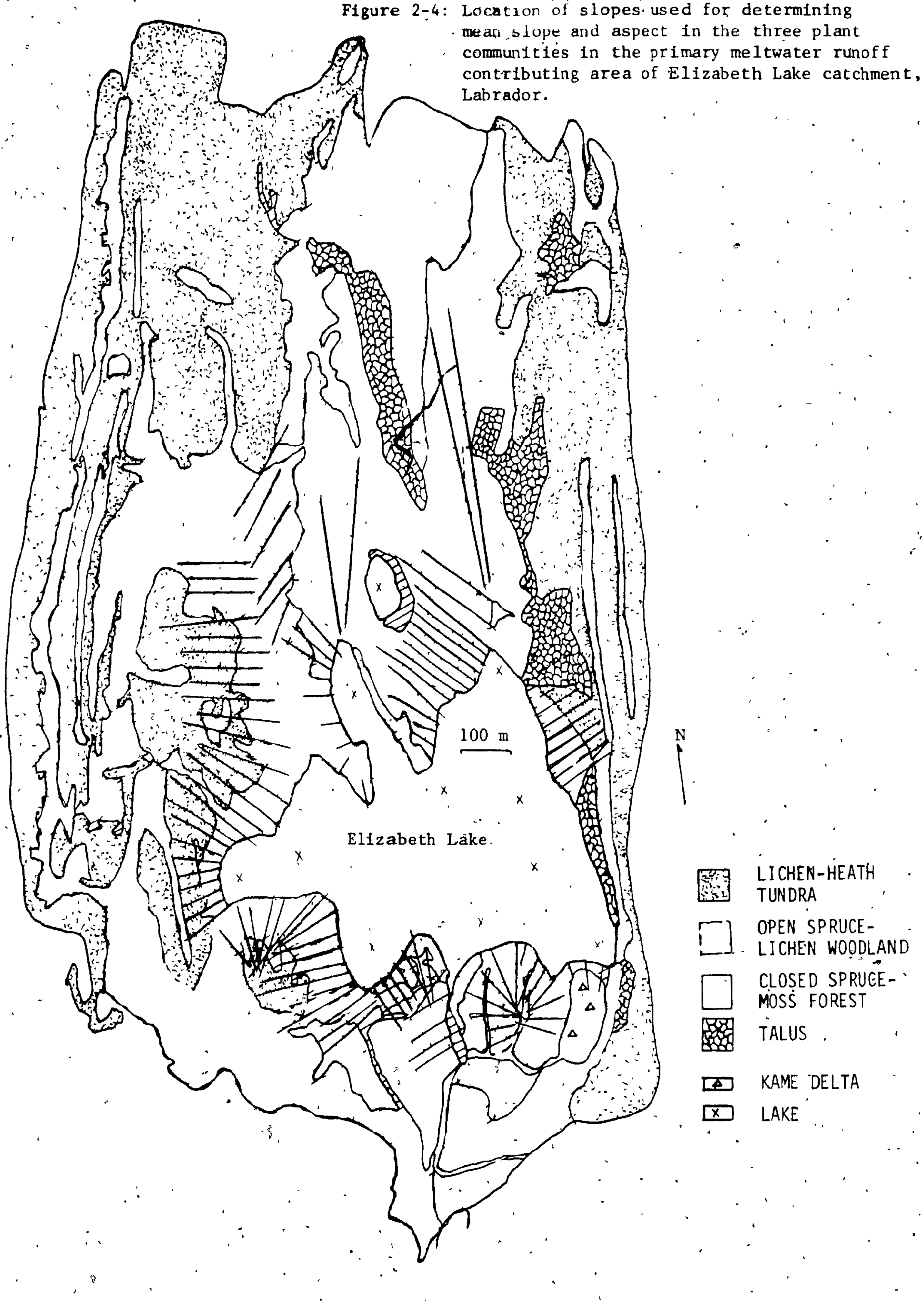
Figure 2-3: Elizabeth Lake catchment, Labrador.

beneath the moss in the forest. As the ground vegetation and mor would be the principal organic components with which the meltwater would interact with it was thought this physical and chemical interaction would be more significant in the forested plant communities. This consideration aided in the decision to locate two runoff plots in each of the woodland and forest and one in the tundra.

Site selection for the runoff plots was based on similarity of plant composition, slope angle and aspect within the particular plant community at large. The similarity between the plant species within the runoff plots and corresponding plant communities has been noted above. The slope was measured at 137 locations within the primary meltwater runoff contributing area. Measurements were taken approximately each 25 m on hillsides within this area. The only exceptions were the talus slopes and cliffs, where measurements were not taken. As the primary reason behind this exercise was to determine how representative the meltwater runoff plot sites were within the plant community in question it was not necessary to include the portions of the primary runoff contributing area comprised of rock. Figure 2-4 illustrates the locations of the slopes selected for measurement.

In the forest, 37 measured slopes have a mean slope of 8.63°, s (standard deviation) = 2.97; sx (standard error of the mean) = .49). The slope of the runoff plots in the forest are 9.5° and 12.5°, somewhat greater than the mean value. The mean determined value for the forest is somewhat misleading as it is based on 19 samples taken from the north basin which represents 82% of the forest within the catchment and 18 samples taken from the south basin forest which represents only 18% of

Figure 2-4: Location of slopes used for determining mean slope and aspect in the three plant communities in the primary meltwater runoff contributing area of Elizabeth Lake catchment, Labrador.



the total catchment forest. The discrepancy between sample numbers and area is due to topography. In the north basin, the mean slope is 10.8° (s = 2.26; $s\bar{x}$ .52); the two forest runoff plot sites slopes fall within 1 S of the mean. The woodland sites on the primary contributing area have a mean slope of 13.3° (s = 9.04; $s\bar{x}$=1.04; n = 76). The two runoff plots have slopes of 9.8° and 19.5°, both within one standard deviation of the mean. The tundra has a mean slope of 16.1° (s = 4.75; $s\bar{x}$=.20; n = 24); the tundra runoff plot has a slope of 13.5°, within one standard deviation of the mean.

Within the primary contributing area, plant communities occupy sites with different slopes and aspects. The hourly exposure of direct sunlight on the plant communities was calculated in order to determine how representative the aspect of the runoff plot slope is of the plant community it represents. Only one day during the melt period was used to determine the hourly exposure of direct sunlight on slopes of different aspect within the catchment. The 15 May was chosen as it was approximately halfway through the melt period. The hours of sunrise and sunset were 0345 and 2000 hours, respectively (U.S. Navy 1960). The altitude of the sun at different times was derived from the following equation:

$$\mathrm{Sin}\,\alpha = \mathrm{Sin}\,\delta \cdot \mathrm{Sin}\,\phi + \mathrm{Cos}\,\delta \cdot \mathrm{Cos}\,\phi \cdot \mathrm{Cos}\,\tau$$

where: α = angle between the direction of radiation and the horizontal surface

δ = the suns declination

ϕ = the latitude

τ = the sun's angle hour (Raudkivi, 1979)

Direct sunlight is defined as that striking a slope between 45° and a line perpendicular to the slope. Areas with very similar aspects in the plant communities were defined from the map; each area assigned an aspect and mean slope gradient. At hourly intervals between 0500 and 1700 hours measurements were taken for 6 forest sites, 8 woodland sites and 6 tundra sites. In the forest the runoff plot slope received 7.0 hours of direct radiation; the mean value for the plant community is 7.83 hours ($s = .69$, $s\bar{x} = .28$, $n = 6$). Although the runoff plot received less direct radiation than most of the forest areas it is thought because of the relatively dense growth of white spruce that the difference exhibited between the runoff plot and the rest of the plant community may be negligible in terms of its direct impact on the intensity of snowmelt.

The woodland runoff plot slope received 8.0 hours of direct radiation somewhat less than the mean value ($\bar{x} = 8.62$, $s = 1.93$, $s\bar{x} = .68$, $n = 8$) but within one standard deviation of the mean. The tundra runoff plot received 7.0 hours of direct radiation; the mean value is 7.16 hours ($s = 3.62$, $s\bar{x} = 1.48$, $n = 6$).

2.4.1 Construction of runoff enclosures

The plywood sides of the runoff plot enclosures were entrenched 25 to 30 cm below the ground surface; approximately 30 cm of the plywood protruded above the ground surface. This was sufficient to contain and isolate the saturated flow within the runoff plot from that outside the enclosure. To reduce channelling of snowmelt water along the inside wall of the enclosures, the fence was constructed such that it ran flush to the ground surface along the inner perimeter of the plot. To reduce heat absorption by the plywood during the melt period, the walls of the enclosure were covered with white 6 mil plastic. The outer walls were shored up with rock and soil and braced with wood where necessary. After construction of the runoff plots was completed, each site and the slope from lakeshore to top of the slope were surveyed using a theodolite and standard surveying techniques (Bouchard and Moffat, 1972).

The enclosures were constructed such that at the downslope end of the plot meltwater would be channelled through two, 12 cm diameter ABS plastic tiles which in turn drained into the V-notch weirbox. Each weirbox was equipped with a Belfort 5-FW-1 continuous water level recorder fitted with manually wound 24-hour clocks. The water level recorder was housed in a plywood box mounted over the weirbox.

2.5 The field season

A report on moisture migration from moss to the snowpack in the interior of Alaska (Santeford, 1978) states that between 25 and 30% of the winter snowpack water equivalence is derived from moss via vapour transport flux. Occurrence of this process would alter snowpack and snowmelt runoff chemistry. As a major purpose of this research focuses on understanding the physical and chemical interaction between meltwater runoff and the organic strata of the base of the snowpack it was imperative to determine if the moisture migration as reported in subarctic Alaska occurred at the study site and, if so, its significance to the water equivalence of the snowpack.

Ground vegetation (moss and/or lichen), mor and soil samples were taken from 35 sites on the basin during early November 1979 and again at peak snowyear at the end of March 1980.

With the exception of 2 sites located within 5 m of each of the five runoff plots, the 35 remaining sites were selected in a stratified, random fashion. The number of sites within each plant community is a function of the percentage of the total basin area which each community occupies. The two sampling dates were critical periods in the snow-year. The November sampling was initiated immediately following the first major snow storm which remained on the ground. Up to this time, minor amounts of snow had fallen and melted, contributing to the vegetation and soil moisture content. The second sampling date was as close to peak snow year as possible, without interfering with the snowpack chemistry and water equivalence sampling.

To determine percent moisture content, samples taken on both sampling dates were weighed, and reweighed after being oven-dried for 24 hours at 105°C.

A second purpose of this sampling schedule was to evaluate the distribution of concrete frost formation in the surface soil.

It is reported that during spring melt in the eastern subarctic, the soil remains frozen and, as such, infiltration of meltwater is negligible (Price, 1975; Fitzgibbon, 1977). The impermeability of the soil during this period of the year is reportedly due to the formation of concrete frost. As ground frost of this nature impedes water movement through the soil, its spatial distribution in the catchment within each plant community is of primary interest. It was hypothesized that soil moisture content would be significantly higher in the areas with concrete frost than in those areas--specifically on the upper portions of steep slopes--where the frozen soil had a freeze-dried texture (observed during the spring of 1979). The "freeze-dried" soil crumbles when compressed, the "concrete" frozen soil requires substantial force from an axe to chip portions from the ground. Price and Hendrie (1983) define concrete and honeycomb frost. The former a result of rapid freezing in very wet soil; the latter a product of the soil being relatively dry on freezing. The frost formation on porous, well drained, organic rich soil tends to be honeycomb. The March sampling date was suitable for determining the maximum distribution of concrete frost.

2.5.1 Snowpack temperatures

In order to record the temperature at the snowpack base and approximately one half way up from the ground surface, precalibrated Fenwall thermisters were installed in the snowpack beside each runoff plot 2 weeks before the melt began in the tundra. Three sites were chosen at each plot, one at the downslope end, one at the upslope end, the third site equidistant between the others. A Digital multimeter was used to read the resistance on each thermister which was later converted to the correct temperature. The primary purpose of measuring snowpack temperature was to determine when the snowpack was approaching 0°C and if freezing temperatures would occur in the snowpack and at the base during the melt period. Temperature readings were taken each day from installation until snowmelt began, after which readings were taken up to three times a day.

2.5.2 Snowpack sampling

Surveys were conducted at peak snowyear to assess the water equivalence, physical structure and chemical composition of the snowpack.

2.5.2.1 Water equivalence survey

Water equivalence measurements were taken in the portions of the basin which flow directly into the lake during spring melt. A Mount Rose snow tube was used to collect samples taken at 5 m intervals along 21 transects, most of which extended in a straight line from the shoreline to the border of the catchment; a total of 360 samples were taken (Figure 2-3).

The shortcomings of estimating water equivalence with Mt. Rose snow tubes are reported in Price (1975) and Granberg (1980). A common reported error is 7% overestimation of actual water equivalence (Granberg, Pers. Comm. 1981). The Mt. Rose snow tube used in this study was calibrated and found to overestimate the snowpack volume by between 5 and 8%. The tube was calibrated initially and at the end of daily sampling periods by weighing samples taken in the tube, then depositing the contents in a plastic bag. The sample was later melted and the volume measured in a graduated cylinder. The appropriate correction factors were applied to each set of samples.

2.5.2.2 Snowpack stratigraphy and chemical composition

At peak snowyear, in early April 1980, 50 snowpits were dug at various sites throughout the catchment (Figure 2-3). Selection of 40 of the sites was done using the stratified random selection procedure mentioned above for choosing soil pit sites. The remaining 10 pits were dug near the base and upper end of each runoff plot, care being taken not to disturb the snowpack within the enclosures. The snow pits were dug within 5 m of the plots.

The physical structure of the snowpack was determined by employing a 'snow-kit' designed by the National Research Council; the methodology involved being described by Adams and Barr (1974). Depth, density, water equivalence (depth x density), temperature and dominant grain size were noted for each layer. For chemical analysis, snow samples were taken from layers large enough to sample (greater than 5.0 cm in thickness) and placed in clear plastic bags. Snow was scooped into the sample bag by hand which was encased in a clear, clean plastic bag. Separate bags were used to sample each layer in a snowpit. A maximum of 5 samples were taken from each pit.

The chemical data derived from the snowpits were used to determine the chemical composition of the snowpack. Composite chemical concentrations were found for each snowpit by computing weighted means. To determine the ionic mass for P, N, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} in the snowpack the average snowpit nutrient concentration was determined for each plant community and multiplied by the plant community water equivalence determined from the Mount Rose snow tube survey. The chemical composition of the snowpack within the runoff plots was determined in a similar manner except only the snowpits located beside the plots were used to determine the chemical concentration. The 12 sites sampled within each runoff plot using the Mount Rose snow tube were used to determine runoff plot water equivalence; combined with the snowpit nutrient concentrations, the mass of each nutrient present in the runoff plots was calculated.

A second purpose behind the sampling strategy of the snowpack was to identify horizontal and vertical chemical variation within the snowpack. Statistically significant variation among plant community snowpacks will indicate enrichment due not to atmospheric sources but sources within the catchment. Statistical tests performed to determine nutrient concentration variation among sites within the same plant community were useful as a measure of confidence in the mean values used to determine the mean nutrient snowpack concentration for each plant community. This would prove very useful in the later work examining the nutrient mass balance within the different plant communities during springmelt. Of particular interest was how representative the chemistry of the runoff plots (extrapolated from nearby snowpits) were of the plant community snowpack they were representing.

Analysis of variance was performed to determine the variation among sites within the same plant community snowpack. The t-statistic was employed to determine if significant differences existed between plant community snowpacks. As there was some consistency of stratigraphic layering within the snowpacks of the forest and woodland, samples from the same layers (presumably resulting from the same storms) could be taken and stratigraphic layers could be compared among different snowpits for both physical features and chemistry.

While intracommunity comparisons for woodland and forest snowpacks are possible, intercommunity comparisons of stratigraphic layers within the snowpack become difficult. The greater the difference in roughness factor created by the vegetation, the more dissimilar the physical structure of the snowpack. As the roughness factors of forest and woodland are superficially similar at most sites, comparisons were possible between stratigraphic layers.

2.5.3 Spring melt

The melt period lasted almost 7 weeks on the Elizabeth Lake basin from approximately 21 April to 11 June 1980. As the melt period was characterized by alternating cold and warm periods, the sampling schedule reflected the weather. During peak melt at each runoff plot several samples were taken each day. During periods of very low flow, only one sample was taken per day.

At the runoff plots, water samples were taken at the discharging end of the plastic tile, at which time the flow rate was noted using stop watch and a plastic 500 mL graduated cylinder and recorded on the water level recording chart.

Samples were collected in 1 L plastic bottles which were prewashed in a 5% solution of conc. HCL and rinsed well in distilled water. Prior to collecting the sample, the bottles were rinsed twice with sample water. To allow for expansion when later frozen, the bottles were filled with 750 mL of sample. A strip of parafilm was placed over the open mouth and the cap screwed on slowly in order to prevent perforation of the parafilm strip. The samples were stored in freezers at -15°C at the McGill Station.

Temperatures of the snowmelt water were recorded when samples were taken using a calibrated YSI probe.

2.5.3.1 Snowpack diversion layer sampling

A homogeneous snowpack such as described in the Price et al., (1977) model for snowmelt in the subarctic near Schefferville was not found in the Elizabeth Lake basin. Instead, stratigraphic layers displayed a wide range of densities. This heterogeneity resulted in a destructive metamorphosis process in the snowpack of the open and closed spruce plant communities. Although this will be discussed at some length later in the thesis, a short description is necessary in order to explain the sampling procedure employed.

The melting pattern for a homogeneous snowpack described by Price (1975) is obeyed within the surface stratigraphic layer, if the layer beneath it has a significantly greater density. When the hydraulic head increases (i.e., the saturated layer increases in depth), the water in the saturated layer flows slowly downslope. When the dense snow layer beneath the saturation layer has deteriorated due, in part, to increasing ambient temperatures and to the heat from the meltwater in the saturation layer, meltwater will begin to percolate into the denser secondary layer. The process continues down through the snowpack, depending on the densities and porosities of the different layers composing the pack. Sampling of this meltwater accumulating in the primary layer was accomplished by inserting a glass funnel (pre-acid washed and well rinsed with distilled water) into the base of the saturated layer and simultaneously directing the trickle of water into a sample bottle.

The saturated layer was tapped in this fashion until approximately 300 mL of sample was collected.

2.5.3.2 Lake sampling

Elizabeth Lake was sampled five times, once prior to the melt period on 15 April 1980 and four times during the melt: 6 May 1980, 18 May 1980, 2 June 1980 and 7 June 1980. The last sampling was the day before the candled black ice cover was broken up by strong winds.

Eight sites on the lake were chosen for sampling, selected subjectively such that interaction between snowmelt runoff and the lake water could be best examined (Figure 2-3). The major basins of the lake were represented as well as some sites closer to shore.

It was hypothesized that during the spring melt, the assumption of horizontal continuity of chemical concentrations at common depths in a lake in this portion of the subarctic is invalid. The common practice of sampling a lake at one location usually at the deepest spot — justifiably used by limnologists during stable periods of a dimictic lake's annual cycle — was abandoned in favour of a sampling procedure better oriented to the spatial interaction between snowmelt water and lake water.

Lake water was collected with a 2 L Van Dorn water sampler from each site at the black ice lake water interface, 0.5 m, 1.0 m, 2.0 m and at 1 m intervals until either the bottom or 10 m was reached. Below this depth, samples were taken at 12 m, 16 m and 22 m.

Samples for nutrient analysis were stored in 1 L plastic bottles, and frozen at -15°C shortly after collection.

Water temperatures were taken at each site using a precalibrated YSI telethermometer (model T 2475). Readings were taken at the black ice—lake water interface and at 2.0 cm intervals to a depth of 0.5 m, then at 1.0 m and every 1 m thereafter to the sediment-lake water interface.

2.5.3.2.1 Transect lake survey

To evaluate the interaction between meltwater and lakewater in the littoral zone, a series of four holes were dug through the ice in an offshore transect from the forest plot during peak runoff (1, 2, 3 June). The sites were located 3, 7, 20 and 30 m from shore. The depths at each site from the hydrostatic water level to the sediment surface were 0.85 m, 1.85 m, 3.80 m and 5.0 m respectively. The sites are shown in Figure 2-3. Lake sampling sites G and H could be tied into this transect to illustrate chemical variation in the lake from a shallow site.

2.5.3.2.2 Deuterium/hydrogen sampling

Samples for deuterium/hydrogen (D/H) analysis were collected from the top 2.0 m of lake water using a straight 2.50 m x 10 cm (diameter) copper pipe attached to a pine board measuring 30 cm x 5 cm x 2.43 m. To take a sample the top end of the tube was sealed creating an airlock. The sampler was then lowered through the ice hole to the desired depth, the airlock then removed and the sampler filled with water from depth. The top end of the sampler was then resealed, the sampler withdrawn from the lake and the contents emptied into 20 ml glass scintillation vials with plastic seals to prevent evaporation. From depths greater than 2.0 m, samples for D/H analysis were taken with the Van Dorn water sampler. Samples were stored at room temperature until analysis.

On each sampling date water for D/H and major cation analysis was extracted from each site. Conductivity of each sample was read and pH of selected samples was taken. Samples were taken from the black ice-lake water interface, .05 m, .10 m, .25 m and down in increments of .25 m until either the sediment or the 2.0 m depth was reached. The copper pipe described above was used to gather sample for D/H and major cation analysis. Below 2.0 m at the 20 and 30 m offshore sites, samples were taken at 1.0 m intervals to the lake sediment using a Van Dorn sampler.

2.5.7.3 Surface inflows and outflows during snowmelt

During snowmelt, one perennial, two intermittent and numerous ephemeral streams drain into Elizabeth Lake. The lake is drained on the surface by a single perennial outflow. Groundwater movement was not investigated; Rigler (Pers. Comm. 1980) reported that water balances calculated for Elizabeth Lake during the summer months indicates groundwater flow does exist but represents a very small portion of the annual hydrological budget. Calculation of the residual term in the hydrological budget can be done in the summer with error recognizable in the evapotranspiration and evaporation terms of the hydrological equation; during snowmelt however, the error involved in estimation of the daily influx to the lake of snowmelt water may offset or negate any attempt to estimate groundwater contribution to the water balance of Elizabeth Lake.

Stream discharge from Elizabeth Lake was measured on 14 occasions during the springmelt: 1, 2, 3, 10, 14, 19, 20, 24, 30, 31 May and 3, 4, 5, 7 June 1980. Measurements supplied by Rigler and Barr (unpublished data 1979-1980) indicate pre-melt discharge levels, for comparison with snowmelt runoff levels. Discharge was measured along a portion of the stream which had well defined banks, using a dye dilution technique described by Church and Kellerhals (1974). Prior to adding the dye to the stream, four samples were taken, one for chemical analysis and three for background optical density readings. Stream temperature was taken using a precalibrated thermister. The sampling station was located approximately 15 m downstream from the dye source, to ensure that the dye was well mixed in the stream. Samples downstream were collected in prewashed 200 ml plastic bottles every 45 seconds. Optical densities of all samples were determined in the laboratory in Schefferville using a Bausch and Lomb 100 spectrophotometer at 566.5 nm. The following equation was used to determine the discharge:

$$\text{Stream discharge} = \frac{\text{Dye optical density x pump rate}}{\text{stream optical density}} = m^3.min^{-1}$$

where: Stream optical density = optical density of dyed stream water - optical density of background sample.

2.5.3.3.1 Inflowing meltwater to Elizabeth Lake

The Elizabeth Lake terrestrial catchment was divided into two areas of snowmelt water discharge: 1) the primary contributing area, where the meltwater reaches the lake directly by overland flow or via streamflow and 2) the secondary drainage areas where the meltwater is ponded and reaches the lake only by groundwater seepage. The hydraulic conductivity of the bedrock is not known but is assumed to be slow enough that the water would not contribute significantly to the lake during the study period.

The methods involved in calculating the inflow from the one perennial and two intermittent streams is discussed in detail in Chapter 3. A calculation derived from the hydrological data of the meltwater runoff plots is also presented to account for the daily contribution of overland flow directly to the lake.

2.6 Laboratory analysis

All water samples were stored in freezers at -15°C in Schefferville until such time as the analysis could begin. When phosphorus (P) analysis began the samples were thawed, aliquots of 200 ml and two, 22 ml samples were taken for nitrogen (N), major cation analysis and conductivity, respectively. The N samples were refrozen in prewashed 250 ml nalgene bottles. A drop of HCl was added to each plastic scintillation vial containing the sample for major cation analysis and refrigerated at 4°C until analysis could be performed.

Snow samples were melted at room temperature (approximately 20°C) in the plastic bags in which they were sampled and funneled into prewashed 1 L plastic sample bottles, from which aliquots were drawn for N, major cation and conductivity analysis. The remaining sample was used for P analysis.

2.6.1 Phosphorus analysis

It has been recognized that freezing would likely increase the phosphorus (P) concentrations in samples from the upper few metres of the lake as the planktonic organisms would rupture upon freezing. This recognition was born out in the two samples taken to check this. On 7 May the samples taken from the surface and 4 m at site E (Figure 2-2) were split into two sample bottles. One bottle from each depth was frozen at -15° and the other was refrigerated at 4°C. Within 24 hours the samples were analyzed for TP (total phosphorus) and TDP (total dissolved phosphorus). The TDP of the frozen sample increased by 5% for the surface sample and approximately 2% in the 4 m sample. Triplicate subsamples were extracted from each sample to determine replicability of the method of analysis as it was assumed P concentration in each subsample would be equal.

Similar tests on samples taken at earlier dates were not done because phosphorus analysis could not be conducted until after 7 June. Samples could have been stored in the refrigerator at 4°C from other sampling dates and analyzed at a later date, however, it was felt that the incubation time in the refrigerator would have had 'unnatural' effects on the sample and the P concentrations would have been unrepresentative.

Table 2-2. Increase in total dissolved phosphorus* concentrations due to freezing lake water samples.

		$\bar{x}$ TP	$\bar{x}$ TDP
surface	refrigerated	6.60	2.12
	frozen	6.56	2.20
4 m	refrigerated	16.03	7.59
	frozen	15.93	7.74

*All values in $\mu g\ L^{-1}$

Phosphorus analysis on all water and snow samples was conducted at the McGill Subarctic Research Station. All snow, meltwater, streamwater and selected lake samples for P analysis were split into two. Half of the sample was filtered through prewashed .45 μm millipore filters for TDP analysis. The remaining unfiltered portion was used for TP analysis. De-ionized water was filtered through prewashed millipore filters to determine potential P contamination resulting from this source. Golterman (1970) recommends this method for initially reducing the contamination caused by the membrane filter and secondly determining a correction factor which can be applied to other samples. Three filters per run were tested; there was little variation from the P concentration of the blanks. The error in the P analysis never exceeded 2%; this figure is based on triplicate standard results.

The persulfate digestion technique follows the method of Strickland and Parsons (1974), further modified by Rigler (Prepas and Rigler 1982). Phosphorus was analyzed on a Bausch and Lomb 100 spectrophotometer at 885 nm using a 10 cm path length glass cell.

2.6.2 Major cation analysis

All major cation analyses were conducted on unfiltered samples in Montreal. A Perkin Elmer atomic absorption spectrophotometer was used to determine specific concentrations of Ca^{2+}, Mg^{2+}, K^+ and Na^+. The procedure is outlined in Perkin Elmer (1976).

2.6.3 Ammonia analysis

Analysis of ammonia follows the manual method found in Stainton et al. (1977). Unfiltered samples were read on a Bausch and Lomb 70 spectrophotometer at 640 nm.

2.6.4 Nitrate and Nitrite analysis

For NO_3-N and NO_2-N analysis, the manual method described by Stainton et al. (1977) was followed. The reduction efficiency of the cupric sulphate treated cadmium columns was frequently checked using the standards. Efficiency of the columns never fell below 98% during the period of analysis. A Bausch and Lomb 70 spectrophotometer at 543 nm was used to determine absorbance of the treated samples using a 1.0 cm cuvette.

2.6.5 Conductivity

Conductivity on all water samples collected in the field was measured at the McGill Subarctic Research Station. Samples were slowly warmed to 25°C in a water bath before reading. The meter, a Markson electromark analyzer was zeroed with distilled, de-ionized water at 25°C.

2.6.6 pH

pH measurements were mostly made at the McGill Subarctic Research Station as soon as possible after sampling. When transportation of samples back to the lab was impossible pH measurements were read in a cabin at Elizabeth Lake. A Fisher (model 210) pH meter was used, with 4.01 and 6.0 pH buffers. While the measurement was taken, the sample was continuously stirred with magnetic stirrer. The temperature of the sample when measured for pH was that (or would soon be in the case of snow) of the environment. The temperature of snowmelt water was 2°C when the pH was read.

2.6.7 Deuterium/Hydrogen analysis

Analysis of D/H samples was done at Lamont-Doherty Geological Observatory, Palisades, New York. Water samples were converted quantitatively to hydrogen gas using a uranium furnace at 700°C. The ratio of DH to H_2 was measured on a 3 inch Nuclide mass spectrometer with dual collectors. Samples are reported relative to SMOW (Standard mean ocean water, Copenhagen) in per mil as follows:

$$0/00 = \frac{(D/H)\ \text{sample} - (D/H)\ \text{SMOW}}{(D/H)\ \text{SMOW}} \times 1000$$

CHAPTER 3

SNOWMELT RUNOFF HYDROLOGY

3.1 Introduction

This chapter will examine the hydrological components of the study, such as the formation of the snowpack, the physical characteristics of the snowpack at peak snowyear, the effect of snow stratigraphy on snowmelt runoff and predicted impacts of the diversion of substantial quantities of snowmelt runoff downslope prior to reaching the snowpack base. As well, this chapter examines the areal distribution of concrete frost and "freeze-dried" frozen soil; the occurrence of "concrete" frozen soil is associated with extremely low rates of meltwater infiltration.

By assessing the hydrological input to the lake during springmelt it is possible to calculate nutrient mass balances and thus assess the importance of snowmelt runoff in the nutrient cycling of the terrestrial and aquatic components of the catchment.

This chapter also defines the four subbasins within the Elizabeth Lake basin wherein discharging springmelt water is either measured or calculated. The means of measuring the discharge from these four areas is discussed. A hydrological calculation incorporating the daily runoff is formulated to compute the daily addition of snowmelt water runoff to the lake from the large portion of the terrestrial catchment draining directly into the lake via overland flow. The end result of this chapter is a hydrological budget on a day to day basis of water movement in the entire Elizabeth Lake catchment.

3.2 The snowpack

The mean monthly snowfall for the snowyears 1955-56 to 1979-80 recorded at the McGill Station at Schefferville is illustrated in Figure 3-1. The snowfall for the 1979-80 snowyear is included for comparison. With the exception of January and May the monthly recorded snowfall is within one standard deviation of the mean value. During January and May, the recorded snowfall significantly exceeded the mean monthly recorded values.

Snow surveys were carried out at peak snowyear such that both an accurate estimate of the snowpack water equivalence and snowpack chemistry could be made prior to the onset of spring melt. Accuracy in these estimates before the snowpack becomes ripe is important for later formulating accurate and meaningful hydrological and chemical mass balances between 1) the snowpack and the resulting terrestrial runoff and 2) between the snowmelt water draining into the lake and lake discharge.

Peak snowyear is defined as the time in the year when the maximum amount of snowfall has accumulated. According to the weather records and snow cover data recorded by the McGill Subarctic Research Station in Schefferville, peak snow year occurs between early and mid-April. Recorded temperature differences between Elizabeth Lake and the McGill Station in Schefferville indicate a cooler climate at the study site. Table 3-1 illustrates the differences in recorded temperature between the Elizabeth Lake basin and the McGill Station. It should be noted that the thermometer used at Elizabeth Lake was not a maximum-minimum thermometer and was not housed in a Stephenson screen, but rather hung in the shade on the branch of a spruce tree approximately 2.0 m above

Figure 3-1: Snowfall recorded at the McGill Subarctic Research Station for the snowyears: 1955-56 to 1979-80 (inclusive)
Legend: ┼ mean value; I 1 standard deviation
o recorded value for 1979-80 snowyear

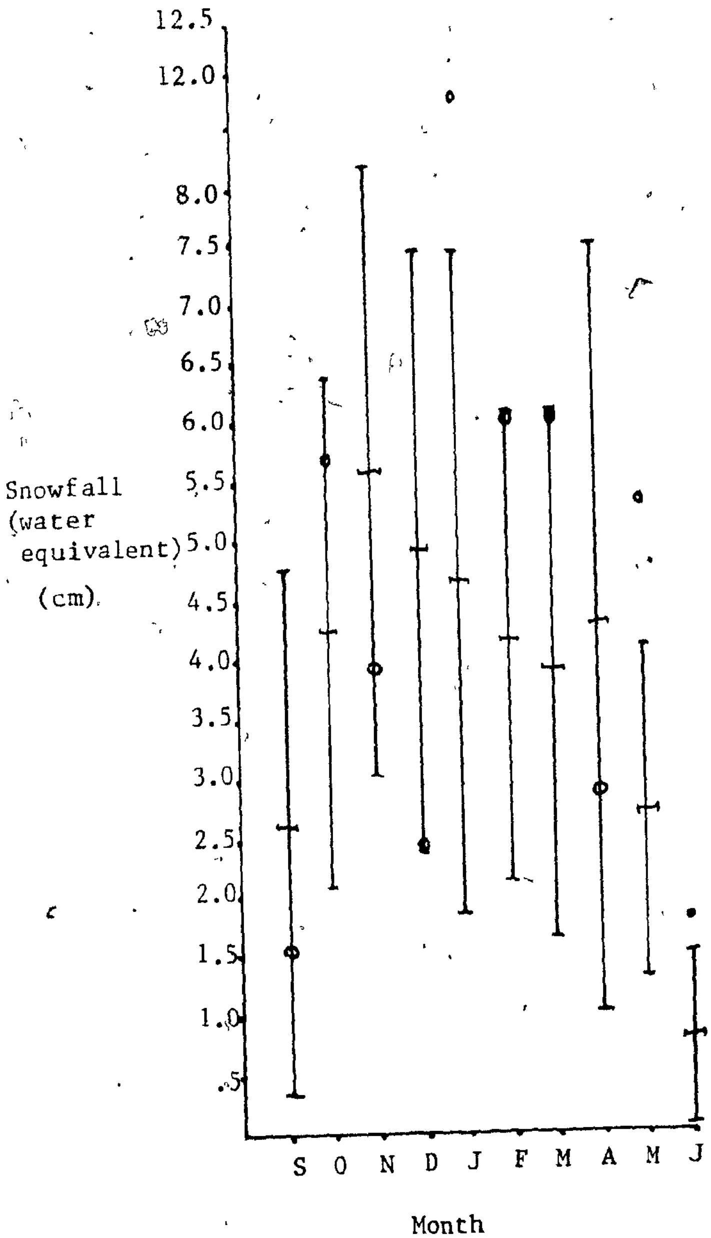


Table 3-1. Maximum daily temperatures recorded at Schefferville and Elizabeth Lake.

	Daily maximum	
	Schefferville	Elizabeth Lake
February		
10	-16.4 °C	-17.8 °C
11	-16.6 °C	-18.9 °C
12	-15.0 °C	-14.5 °C
13	-17.0 °C	-19.2 °C
14	-12.8 °C	-14.5 °C
15	-16.8 °C	-16.5 °C
17	-18.2 °C	-21.0 °C
18	-14.0 °C	-17.5 °C
19	-11.5 °C	-14.3 °C
March		
1	-20.8 °C	-23.8 °C
3	-17.4 °C	-19.9 °C
4	-14.6 °C	-14.3 °C
5	-19.6 °C	-22.0 °C
8	-23.2 °C	-26.1 °C
10	-13.0 °C	-17.1 °C
11	-1.9 °C	-5.0 °C
May		
1	8.4 °C	6.2 °C
2	13.7 °C	10.1 °C
3	2.1 °C	2.0 °C

the snowpack surface. What was assumed to be the daily maximum temperature was recorded shortly after the sun was at its zenith. These recorded temperatures indicate that the Elizabeth Lake site is cooler by approximately 2°C. The more elevated location of Elizabeth Lake (693.5 m.a.s.l. as opposed to the McGill Station's 503.0 m.a.s.l.) may partially explain the cooler climate as the dry adiabatic lapse rate is 1°C per 100 m. Observation of the latter stages of the 1979 spring melt both at Schefferville and Elizabeth Lake help confirm this. Portions of the snowpack at Elizabeth Lake in exposed sites remained weeks after the Schefferville snowpack melted.

It was therefore decided the optimum date for peak snowyear surveys of the snowpack on Elizabeth Lake would be in the latter part of the recorded range, just prior to mid-April.

3.2.1 Snowpack surveys

Two separate snowpack surveys were conducted between 4 and 10 April 1980. The first (4-8 April) involved evaluating the depth, density, water equivalence, ice crystal size and temperatures of the different stratigraphic layers comprising the snowpack. At this time samples were taken from designated stratigraphic layers for chemical analysis. The second survey (9,10 April) was undertaken to evaluate, as accurately as possible, the water equivalence of the snowpack on the terrestrial portion of the catchment. This was accomplished by taking integrated snowpack samples from the surface to the base of the snowpack using a Mount Rose Snow Tube. These surveys aided in determining how representative the runoff plot snowpack was in relation to the snowpack of the plant community in which each was located.

3.2.1.1 Snowpack water equivalence

3.2.1.1.1 Contribution of water to the snowpack from ground vegetation, mor and soil

A recent study of the transfer of water from moss to the overlying snowpack via vapour transport is discussed by Santeford (1978). It is reported that in the Alaskan interior this process is responsible for between 25 and 30% of the snowpack's water equivalence at peak snowyear (15 April). The calculated contribution is approximately 3 cm of standing water. The consequences for hydrological calculations were discussed by the author. There are several points worth mentioning. During spring melt the dehydrated moss layer will reabsorb as much water as was lost by vapour transport flux into the snowpack. Hence, stream response to the onset of melt will be delayed until the water deficit of the moss is satisfied. This has not only repercussions in terms of formulating water budgets, but is potentially important for those studying the chemical interaction of snowpack meltwater with the underlying vegetation and soil.

Santeford (1978) mentions the problem of depending upon snow course data for an accurate estimate of atmospheric-derived snowpack water equivalence in plant communities where bryophytes constitute a significant portion of the ground cover, and there exists a sufficient temperature gradient from the ground to the snow surface to promote vapour flux.

For these reasons the water content of ground vegetation, mor and upper soil were measured at 35 selected sites on the Elizabeth Lake catchment.

The results of this survey are presented in appendix B. A t-test (Freund, 1972) was employed to determine if the water content change in ground vegetation, mor and soil from November to March was statistically significant. The differences in ground vegetation and mor water content in the three plant communities are all statistically significant at the 99% confidence interval. Soil water content changes registered in this period of time are statistically insignificant.

In all three plant communities, the water content of the ground vegetation and underlying mor decreased from the initial sampling to the second. This decrease, on average, for both organic layers is remarkably consistent. For ground vegetation there is a loss of 10.4, 11.4 and 10.3% of the water content in the tundra, woodland and forest respectively. Very similar losses are recorded from the mor; in the same order of plant community association these losses were 10.4, 10.9 and 11.1%.

Calculations of the amount of water potentially contributed from the ground vegetation and mor to the snowpack during the winter period from November to March were made by dividing the differences of the means of the triplicate samples taken in November and March by the volume of water present in the original (November) samples. In this manner, the percentage of water lost from the original samples can be calculated. As there is considerable variation in water content in ground vegetation and mor within short distances, as shown by the range of the triplicate sample values, using both November and March water content (L m^{-2}) is important for a more realistic estimate of total water flux into the snowpack. To determine the volume of water which migrates into the snowpack using the March water content (expressed as volume) it is assumed the volume of water remaining in the ground vegetation and mor is equal to the percentage of the original water volume remaining after vapour flux. If, for example, the change in water content of ground vegetation in the woodland is 10.0% and the March water content was 20.0 L m^{-2}, this volume is equal to 90% of the original sample. A simple calculation determines the initial water content.

If it is assumed that all of the water lost from the ground vegetation and mor migrates upwards into the snowpack by vapour transport as described by Santeford (1978), the total volume added to the snowpack would be as follows (the first value based on the November water volumes; the second based on the March volumes); tundra: approximately .05-.07 cm, woodland: approximately .05-.08 cm, forest: approximately .05-.06 cm. These figures represent extremely small fractions of the total water equivalences found in the snowpack in the respective plant communities; tundra: approximately 0.42%, woodland: approximately 0.13% and forest: approximately 0.14%. These values are significantly different from the values reported by Santeford (1978). Underestimations of the water content of ground vegetation and mor are possible and should not be discounted, however the difference between the Alaskan data (3.00 cm vapour flux from ground surface) and the Elizabeth Lake data (.06 cm) suggests that the physical and climatic differences between the black spruce-moss plant community of the Alaskan interior and the plant communities of the Labrador interior are responsible. Black spruce communities usually inhabit poorly drained sites. This, accompanied by the fact that this portion of Alaska has high precipitation just prior to the formation of the annual snowpack, means that the bryophytes inhabiting these sites may have a higher water content than Elizabeth Lake ground vegetation where slopes less than 8.0% are rare. The Labrador snowpack is much deeper than the snowpack reported at the Alaskan site (Santeford, 1978); this increased insulation may also account for a decreased vapour flux into the Labrador snowpack.

3.2.1.1.2 Water equivalence snow survey

A comprehensive snow survey of the Elizabeth Lake terrestrial snowpack was undertaken on 9 and 10 April 1980.

Table 3-2 illustrates the estimate of standing water on the terrestrial catchment at peak snowyear within each plant community. The talus slopes and disturbed (roads) areas are included as well. At peak snow year the mean snow depth (water equivalent) on the terrestrial portion of the Elizabeth Lake catchment was 34.2 cm.

The runoff enclosures were sampled for standing water at peak snowyear. At 5.0 m intervals, duplicate Mt. Rose snow tube samples were taken. In Table 3-3 the depth, density and water equivalence of the runoff enclosures are compared with the snowpack results of the plant community they represent. T-tests were performed on the snowpack characteristics of the runoff plots and the corresponding plant community data to determine if significant differences exist. In all cases there were no significant differences (at the 95% C.I.); therefore it is assumed that the plots are representative of the snowpack within the corresponding plant community.

Table 3-2. Estimate of standing water at peak snowyear for each plant community on the terrestrial catchment.

Plant community	Water equivalence ($m^3 \times 10^3$)	%
Forest	125.1	23.7
Woodland	283.9	53.8
Tundra	82.4	15.6
Bog	2.4	0.5
Talus	16.1	3.0
Disturbed	18.2	3.4
Total	528.1	100

Table 3-3. Comparison of snow characteristics for runoff plots and average of plant community.

		Community			Runoff plot		
		x		n	x		n
forest:	water equivalence (cm)	46.86	13.01	105	40.82	6.53	12
	density (g/cm^3)	0.25	0.02	105	0.27	0.003	12
	depth (cm)	187	--	105	150	--	12
woodland:	water equivalence (cm)	49.98	21.86	160	37.19	8.5	12
	density (g/cm^3)	0.29	0.06	160	0.28	0.09	12
	depth (cm)	170.5	--	160	147.8	--	12
tundra:	water equivalence (cm)	15.26	13.03	39	11.03	3.48	12
	density (g/cm^3)	--	--	39	--	--	12
	depth (cm)	--	--	39	--	--	12

3.2.1.2 Snow stratigraphy

Figure 3-2 illustrates examples of snowpack stratigraphy in the three plant communities. Though variation does exist within the stratigraphic pattern of each plant community snowpack these three examples are representative of such stratigraphy. In the woodland, forest and tundra snowpacks, a total of 45 snowpits were excavated: 29 in the woodland, 10 in the forest and 6 in the tundra.

A student t-test (Freund 1972) was used to determine if there are significant differences in depth, density and water equivalence in the tundra, forest and woodland snowpacks as represented by the snowpit sites. Although the statistics listed in Table 3-3 show differences between woodland and forest for snowpack depth and water equivalence, these differences are not considered significant at the 95% confidence interval (CI) t-statistic. Snow depth was the only parameter significantly different between the woodland and forest, at only the .10 level.

The tundra snowpack showed significant differences between the forest (less depth and water equivalence at 99% CI, less density at 95% CI) and the woodland (less depth and water equivalence at 99% CI and 98% CI levels respectively and less dense at 90% CI level).

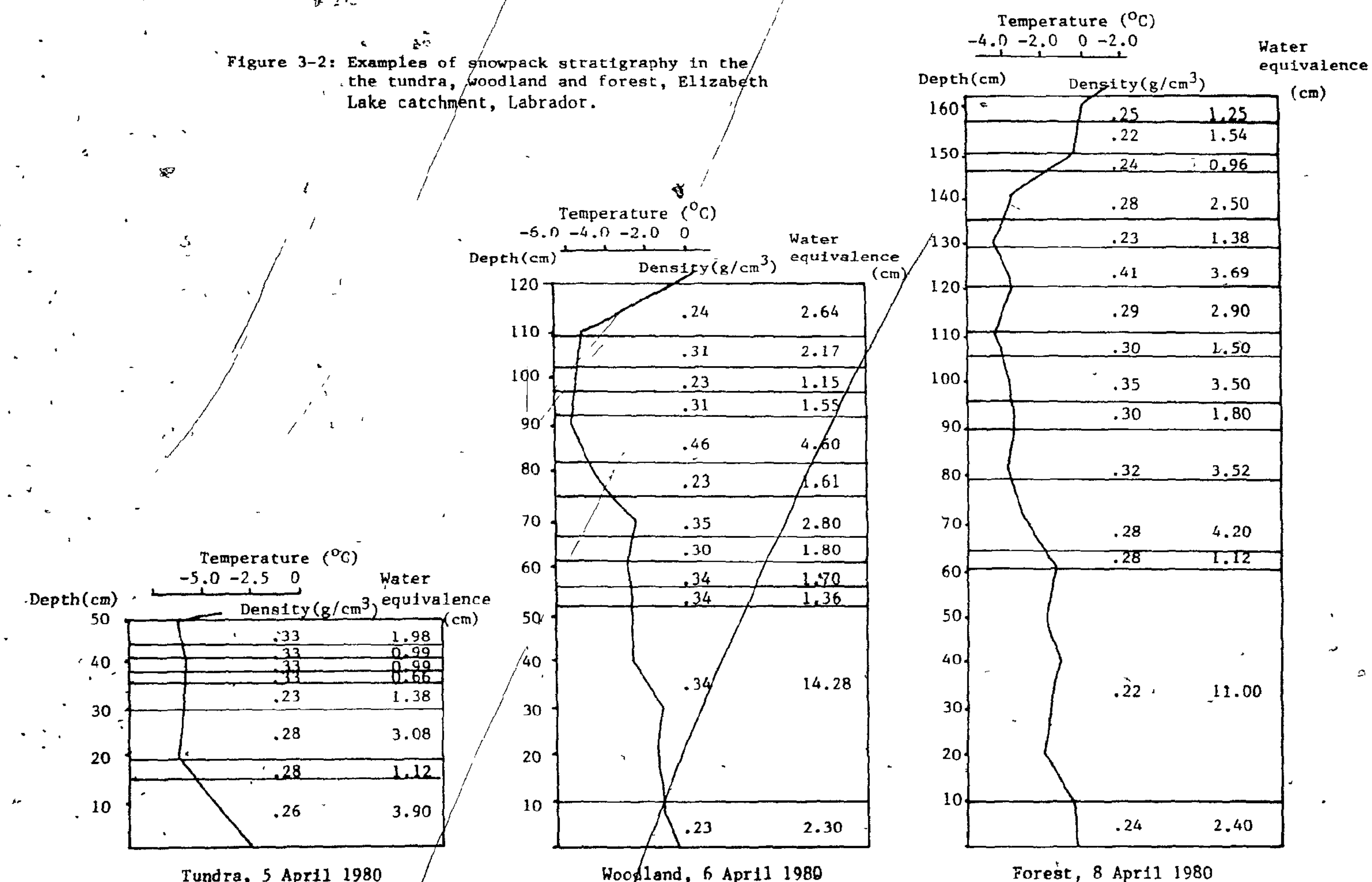


Figure 3-2: Examples of snowpack stratigraphy in the the tundra, woodland and forest, Elizabeth Lake catchment, Labrador.

3.2.1.2.1 Snowpack stratigraphy and implications for snow meltwater chemistry.

During the first few days of snowmelt in the woodland and forest plant communities in the Elizabeth Lake basin the density differences existing among the stratigraphic layers played a significant role in determining the route of snowmelt water downslope. Vertical unsaturated melt occurs in the upper layers of the snowpack until a more dense layer is met and the resistance created by this denser layer results in accumulation of meltwater above the denser layer. Once the vertical flow has been impeded, downslope flow (horizontal saturated flow) occurs.

Although the downslope flow rate within this saturated layer could not be measured in situ, the thickness of the saturated layer at certain intervals along the slope was measured along a 100 m 12° slope in the forest community. Measurements were taken at different intervals during the time period when this process was evident. The downslope depth of the saturated layer was significantly greater (8-12 cm) than the up-slope depth measurement (1-2 cm near the top) thus indicating downslope movement. It is estimated from the runoff enclosures in both the woodland and forest plots that the volume of water discharging from the snowpack during this period of time (1-10 May) is 5.8% of the total volume of snowpack water. During this time, a saturated layer did not exist at the base of the pack and it was assumed that all of the water discharging from the pack originated from the upper part where vertical flow was diverted by a denser snow layer. Although this volume has little hydrological significance it can have major chemical significance.

Until 14 May most of the meltwater was diverted downslope by layers of relatively dense snow. In the forest between 10 and 14 May a snow-melt pattern very similar to that described by Colbeck (1977) develops. The free water begins to percolate through the previous (apparently) impervious snowlayers. The free water continues to percolate vertically until an as yet undisturbed dense snowlayer impedes infiltration. Once again the flow is diverted downslope. This process appeared to dominate the snowmelt runoff pattern in the close spruce until 14 May when a noticeable saturated layer began forming at base of the snowpack indicating vertical flow through the pack was dominating over horizontal displacement by dense stratigraphic layers.

From the 2 to 12 May, dense snowlayers in the woodland snowpack caused a runoff pattern similar to that described in the forest between 1 and 14 May. As in the forest, this runoff pattern is assumed to include the entire plant community. Spot checks at different locations within the woodland confirmed this. The stratigraphy data confirm the widespread occurrence of dense snow layers in the woodland snowpack. This melt pattern described above for the woodland and forest snowpacks was observed only at a few sites in the tundra, thus it is assumed to be relatively insignificant especially since most of the tundra snowpack melted in the space of a week.

Researchers have previously described the subarctic snowpack in the Schefferville region as homogeneous (Price 1975; Fitzgibbon 1977). In such a snowpack, snowmelt runoff occurs in principally two directions; vertically (as unsaturated flow) and "horizontally" along the slope of the ground (as saturated flow). A model designed to predict snowmelt runoff from sub-basins in the Schefferville region by Price (1975) implements the assumptions of vertical unsaturated flow and horizontal saturated flow. Aside from a few minor deviations from the actual hydrograph of snowmelt water discharging from gauged sub-basins, Price's predicted hydrograph reflected the actual hydrograph quite accurately. Although this model is quite useful for hydrograph prediction, the assumption of homogeneity within the snowpack may be misleading to those interested in evaluating the chemical interaction between the melting snow and the terrestrial portion of the catchment, over which it is flowing. The importance of this lateral flow will be examined in Chapter 4.

3.3 Snowmelt runoff plots

Three of the five runoff plots, one in each of the plant communities, performed as expected. One woodland plot began discharging late in the melt period. The volume of recorded runoff amounted to less than 10% of the expected volume. Runoff was not recorded in one of the forest plots. As sublimation of a significant portion of the snowpack would not have been possible (later in this section) it is strongly suspected that the unaccounted for water infiltrated into the ground. Though this is probably true for the forest runoff plot, it is questionable for the woodland runoff plot, as the plot began discharging meltwater late in the melt period. Explanations for the pattern of discharge in the woodland plant community runoff plot are difficult. One explanation attributes this to the partial area overland flow process. If the soil was frozen in honeycomb fashion as described by Price and

Hendrie (1983) or porous concrete as reported by Stoeckeler and Weitzmann (1960) meltwater would easily infiltrate the soil. Raising of the water table to a point on the slope within the runoff plot prior to the disappearance of the snowpack would result in partial area overland flow. A second explanation may attribute the late discharge in the woodland plot to Hortonian flow. The discharge corresponds to peak discharge in the woodland runoff plot which recorded meltwater discharge throughout the melt period. It is possible that the infiltration capacity at this time of peak discharge was exceeded and discharge through the weirbox occurred. This explanation seems more plausible than that of saturated overland flow as the base of the runoff plot in question is located approximately 4 metres above the valley floor. It is thought the water required to fill void spaces within this mass of soil and till would be in excess of the water stored in the snowpack, especially considering that the water would be discharging, albeit at a slower rate than the input rate, downslope. As well, seepage from the ground downslope of the runoff plot did not occur during the melt period. This would be expected if partial area overland flow was occurring.

Excavation of snowpits in close proximity to the two runoff plots which failed to produce discharge or substantial discharge revealed what appeared to be impervious concrete frost. At these sites overland flow was evident. Straub (1950) reported the occurrence of cracks in concrete frost caused by periods of intense freezing. The cracks increase infiltration rates in the spring (Straub, 1950). As the ground surface outside of, but close to the runoff plots had the appearance of impervious concrete frost, it is assumed the ground surface within the plot was frozen in similar manner. It is thought that infiltration during the melt period is a product of thermal cracking of the concrete frost.

An additional factor which should be considered is that the two plots which essentially failed to produce runoff were the last to be constructed. Construction was completed a week prior to the initiation of the annual snowpack. At this time the surface of the soil had begun to freeze. It is possible that the trench within which the enclosure walls were placed drained a portion of the plots as the texture of the soils made it impossible to seal the inside wall of the enclosure fence as effectively as was the case with the three enclosures which were constructed during late summer.

The question arises, how representative of the basin were the plots that functioned as expected? Field observations attested to the fact that overland flow was very widespread. Section 3.4.5 examines the relationship between the daily input to the lake and the corresponding discharge plus daily change in lake storage. Had infiltration of meltwater been widespread, the relationship would not have been as close as it is. Assuming that infiltration had been widespread there would have been a significant hysteresis as the hydraulic conductivity of the subsurface flow would be reduced from that of the overland flow. In Canadian Shield soil-unconsolidated till, the hydraulic conductivity of upper subsurface sediment is approximately 3×10^{-3} cm sec^{-1} (Beaty, Pers. Comm. 1983; Craig, Pers. Comm. 1984). If the hydraulic conductivity in the upper soil-till is even an order of magnitude greater than the reported Canadian Shield values, the infiltrated meltwater would travel approximately 26 m day^{-1}. As the average measured slope length within the primary meltwater runoff contributing area is approximately 125 m, a maximum delay of several days (4.8) would occur between infiltration and seepage into the lake. The hydraulic conductivity gauged within the runoff plots averages approximately 6 m hr^{-1} (section 3.4.4) or 144 m day^{-1}; till conductivity = 2.6 m day^{-1}. A hysteresis would be evident and attributable to the hydraulic conductivity of overland flow. If significant infiltration had occurred, the hysteresis would be significantly more pronoucned then it was.

The discussion below will refer only to the runoff plots which performed as expected.

The efficiency of the plots was calculated by comparing the estimated water equivalence of the plots with the volume of water discharging during the melt period. The snow which fell after 10 April until each plot was drained of snowmelt water was extrapolated from the Nipher gauge data recorded at the McGill Station in Schefferville. This equated to an additional water equivalence of 1.53 cm to the tundra, 5.49 cm to the woodland and 5.63 cm to the forest plot.

Sampling of the runoff plots was abandoned once the discharge was reduced to a trickle and approximately 90% of the ground cover was bare of snow. Periods of discharge measurement were 26 April - 3 May in the tundra, 2 May-6 June in the woodland and 2 May - 11 June in the forest. The calculated volumes of snow (water equivalent), additional precipitation falling after the peak snowyear measurements, and corresponding plot discharges are noted in Table 3-4. The efficiencies are listed in

Table 3-4: Snowmelt runoff plot water equivalence data illustrating the total estimated water equivalence in the plots at peak snowyear and accounting for the additional precipitation after peak snowyear.

	Tundra	Woodland	Forest
total water equivalence (m^3)	11.03	37.19	40.82
estimated water equivalence of plot at peak snowyear (m^3)	8.13	25.52	30.34
ratio for water equivalence values[1]	1.00	2.45	1.89
precipitation added to plot after peak snowyear* (m^3)	1.80	6.28	6.40
total discharge from plot (m^3)	8.83	29.88	35.44
discharge as a percent of plot water equivalence at peak snow year	108.61	117.08	116.81
discharge as a percent of plot water equivalence with nipher data added	88.92	93.96	96.46

*this was derived from the nipher gauge data at the McGill Subarctic Research Station.

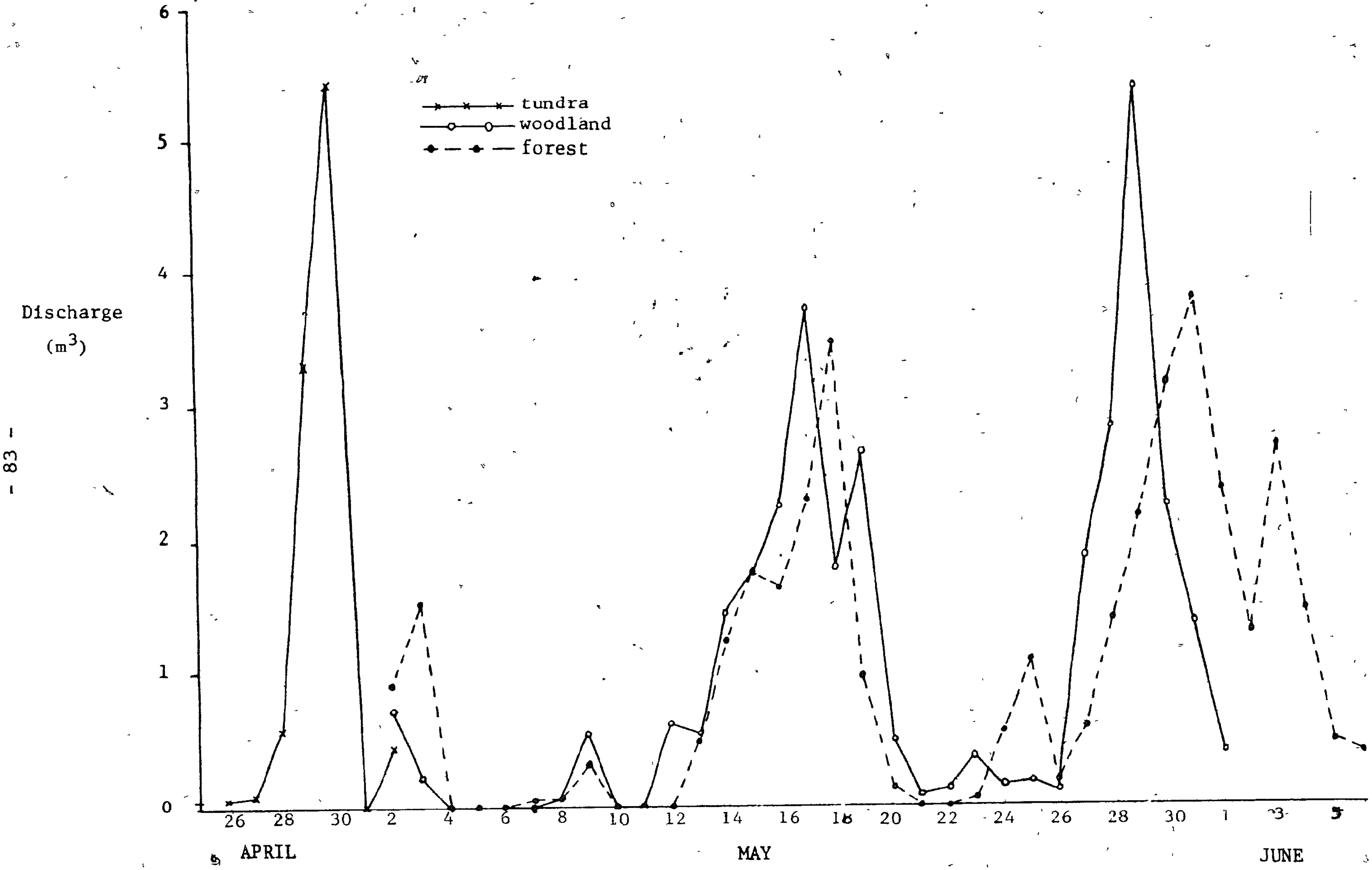
[1]There were 12 sampling points within each runoff plot for evaluation of snow water equivalence.

two ways; the first is the percentage the discharge represents of the calculated volume on 10 April, the second is the percentage derived from the calculated volume plus the extrapolated Nipher gauge data. The discrepancies between the calculated water content of the plots and the spring discharges can be attributable to several factors, some or all of which may be important. There is error attached to the initial estimation of water equivalence within the runoff plots. Extrapolation from the Nipher gauge data recorded in Schefferville to the Elizabeth Lake basin is undoubtedly a source of error.

Although much effort was spent shoring up the walls of the runoff plots, leakage cannot be discounted. Minor leakage along the downslope end of the woodland plot was observed only near the end of the melt period. Loss at this time was kept to a minimum as the structure was reinforced and leakage stopped. Sublimation can be eliminated because it requires between 2826 and 2847 KJ kg^{-1} of water (Raudkivi, 1979) and the radiant input to the Elizabeth Lake snowpack is but a fraction of this. Evaporation will account for some loss, but because of the low daily temperatures would not amount to any significant volume.

The seasonal discharge hydrograph for the three runoff plots are shown in Figure 3-3. From observation, the hydrograph for the tundra plot reflected the way in which a very large portion of the tundra snowpack melted. Price (1975) reported a very short, intense tundra melt in the Schefferville region. Both the woodland and forest melt patterns are very similar to one another: bimodal hydrographs, the peaks centred on 18 May and 31 May.

Figure 3-3: Meltwater runoff plot discharge for tundra, woodland and forest.



Although the melt period extends in the woodland from 2 May to 5 June, approximately 85% of the snowmelt water discharges during these 2 intense periods of melt extending 11 days in total. Similarly, the forest plot melt lasting from 2 May to 11 June discharges 74% of its snowmelt water within a 12 day period.

Daily melt hydrographs show a distinct pattern. During the initial melt period, peak discharge occurs between 4 and 7 hours after the maximum daily temperature. This delay is reduced as the melt progresses because the meltwater channels within the snowpack are clearly defined, grow significantly larger with time and the increasingly warm ambient temperature result in periods of 24 hour melt.

3.4 The spring melt and contributing areas

3.4.1 Introduction

This section will identify the four hydrologic areas contributing snowmelt water to Elizabeth Lake during the melt period. The method by which discharge was calculated/measured is examined. For the large area contributing meltwater directly to the lake via overland flow, a calculation is employed to generate meltwater flow into the lake. This equation is based on the daily hydrographs produced in each of the runoff plots. The relationship between measured lake discharge and lake stage is discussed.

3.4.2 The hydrologic sub-basins

The Elizabeth Lake basin can be divided into 3 hydrologic sub-basins, and a primary contributing area (Figure 3-4). The subbasins labelled East tundra and Pond area drain into Elizabeth Lake by intermittent streams. The Valley area, a glacial melt water channel, drains into the lake via a stream which flows year round. During the winter months, groundwater maintains the discharge of this stream. The discharge of these streams was measured using the dye dilution technique described in Chapter 2. Elizabeth Lake has one outflow stream, the discharge of which was monitored frequently during the spring melt. Table 3-5 lists the measured snowpack water equivalence of plant communities, bog, talus and disturbed areas within each hydrologic area.

3.4.2.1 Valley area

The Valley consists of two areas: the 'upper valley' and the small area closest to the lake, designated 'near valley'. The separation is important because the 'near' area began contributing water to the lake on 3 May while the 'upper' area collected runoff water at the base of the valley until the end of May.

The snowpack at the base of the upper valley behaves in much the same manner as a sponge. The snowpack reached its saturation capacity on 31 May when it began to discharge into the lake. Snowmelt runoff from the upper valley area continued to discharge into the lake after 14 June, when the study was concluded. However, by this date the upper valley had contributed approximately 95% of its calculated snow volume (water equivalent).

Figure 3-4: Hydrological areas and bands of flow used to calculate daily input of meltwater to Elizabeth Lake, Labrador.

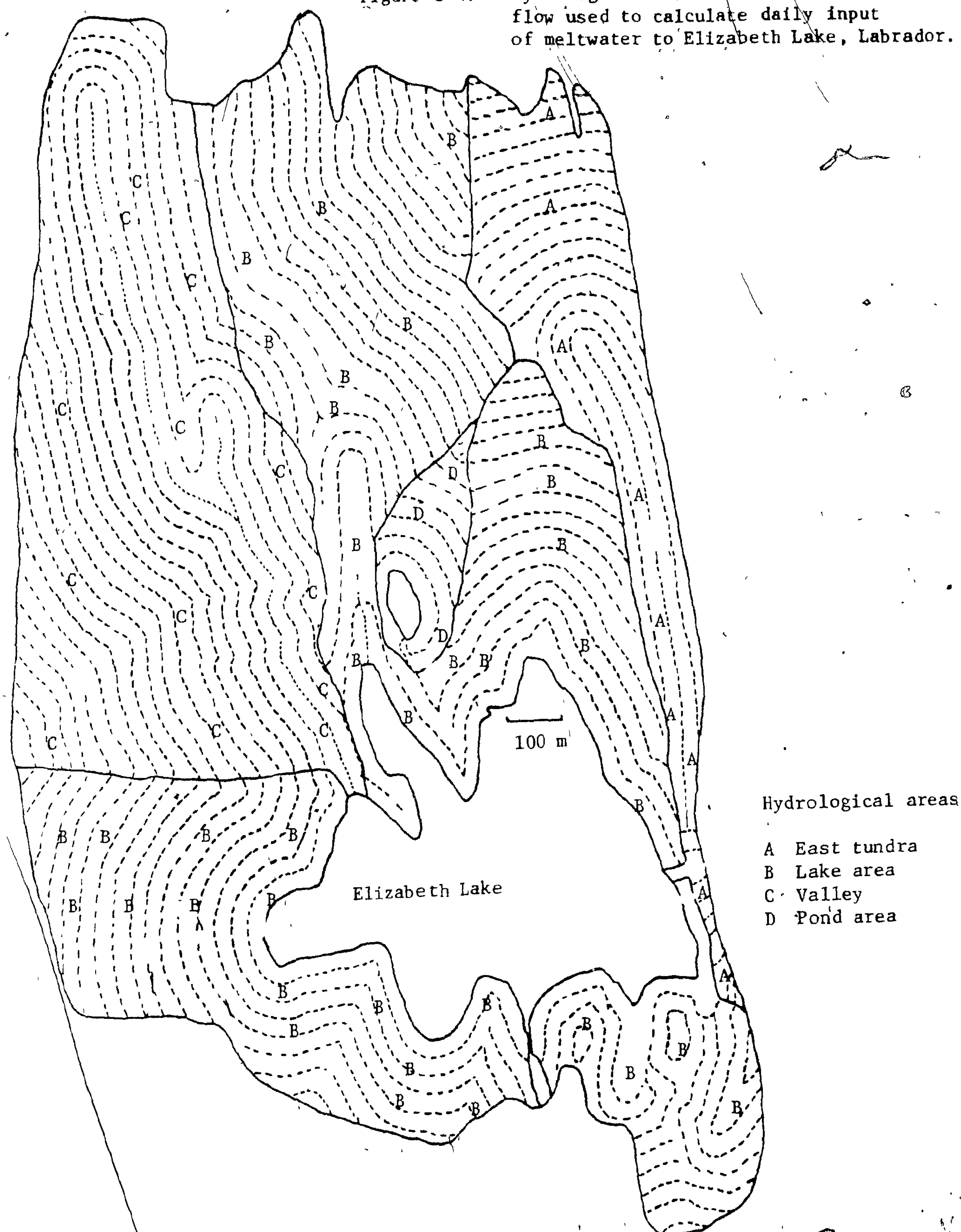


Table 3-5. Areas and snowpack water equivalence of plant communities within hydrologic areas.

Plant communities	Hydrologic areas									
	Lake		Valley		East tundra		Pond		Total	
	area	water equiv.	area	water equiv.	area	water equiv.	area	water equiv.	area (%)	water equiv.
forest	23.62	109.23	.38	1.77	.28	1.27	2.78	12.85	27.06 (17.43)	125.12 (23.68)
woodland	36.67	178.67	19.15	93.31	2.78	10.26	.34	1.65	58.94 (37.97)	283.89 (53.72)
tundra	14.02	20.45	29.02	42.34	13.44	19.61	--	--	56.48 (36.38)	82.40 (15.60)
bog	.32	1.58	.18	0.86	--	--	--	--	.50 (0.32)	2.44 (0.50)
talus	5.92	11.52	.85	1.66	.73	1.43	.78	1.53	8.28 (5.33)	16.14 (3.05)
disturbed	3.97	18.23	--	--	--	--	--	--	3.97 (2.56)	18.23 (3.45)
total	84.52	339.69	49.58	139.94	17.23	32.57	3.90	16.03	155.23 (100)	528.22 (100.00)
%	54.45	64.31	31.94	26.49	11.10	6.17	2.51	3.03	100%	

water equivalence in $m^3 \times 10^3$
area in $m^2 \times 10^3$

By 2 June the snowpack in the near valley has essentially disappeared. The discharge for the stream draining the valley is shown in Figure 3-5. Much of the discharge from 2-30 May was estimated from a calculation to be discussed in section 3.4.4. Actual discharge measurements using dye dilution are indicated in Figure 3-5. All but four of the daily discharge figures listed for 31 May-14 June are derived from dye dilution. The discharge during those four days was estimated from a metre stick placed upright in the stream in late May. The depth was compared to depth read when the stream was gauged using dye dilution. The error involved in these estimations may be as much as 25-50%. The total snowpack (water equivalence) of the valley area represents 26.49% of the Elizabeth Lake terrestrial snowpack.

3.4.2.2 The East tundra

This area began contributing meltwater to Elizabeth Lake on 18 May. Dye dilution was used to estimate the discharge (Figure 3-6) for the dates shown. The discharge on the remaining dates was estimated from a relationship derived between the known discharge values and the daily mean temperature. This relationship ($y = 36.23x + 157.08$, $r = .90$, $n = 9$) is significant at the 99% confidence interval.

The discharge from this area was similar to the upper valley. Topographically, this area is a small, elongated valley, containing a comparatively thick snowpack which held much of the meltwater draining from the sides of the valley until the 18 May, when the area began contributing snowmelt water to the Elizabeth Lake. The streambed, until the

Figure 3-5: Hydrograph of stream which drains Valley area of Elizabeth Lake, springmelt, 1980.

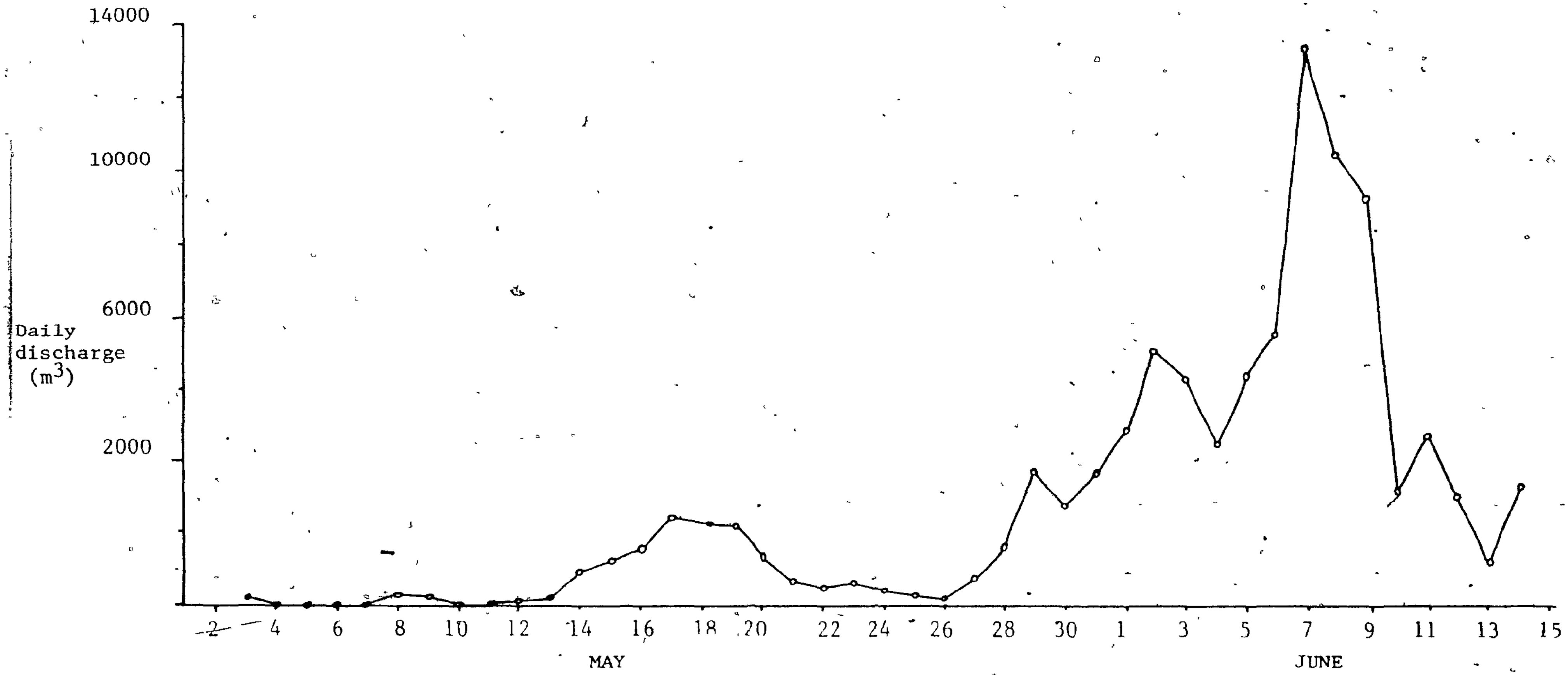
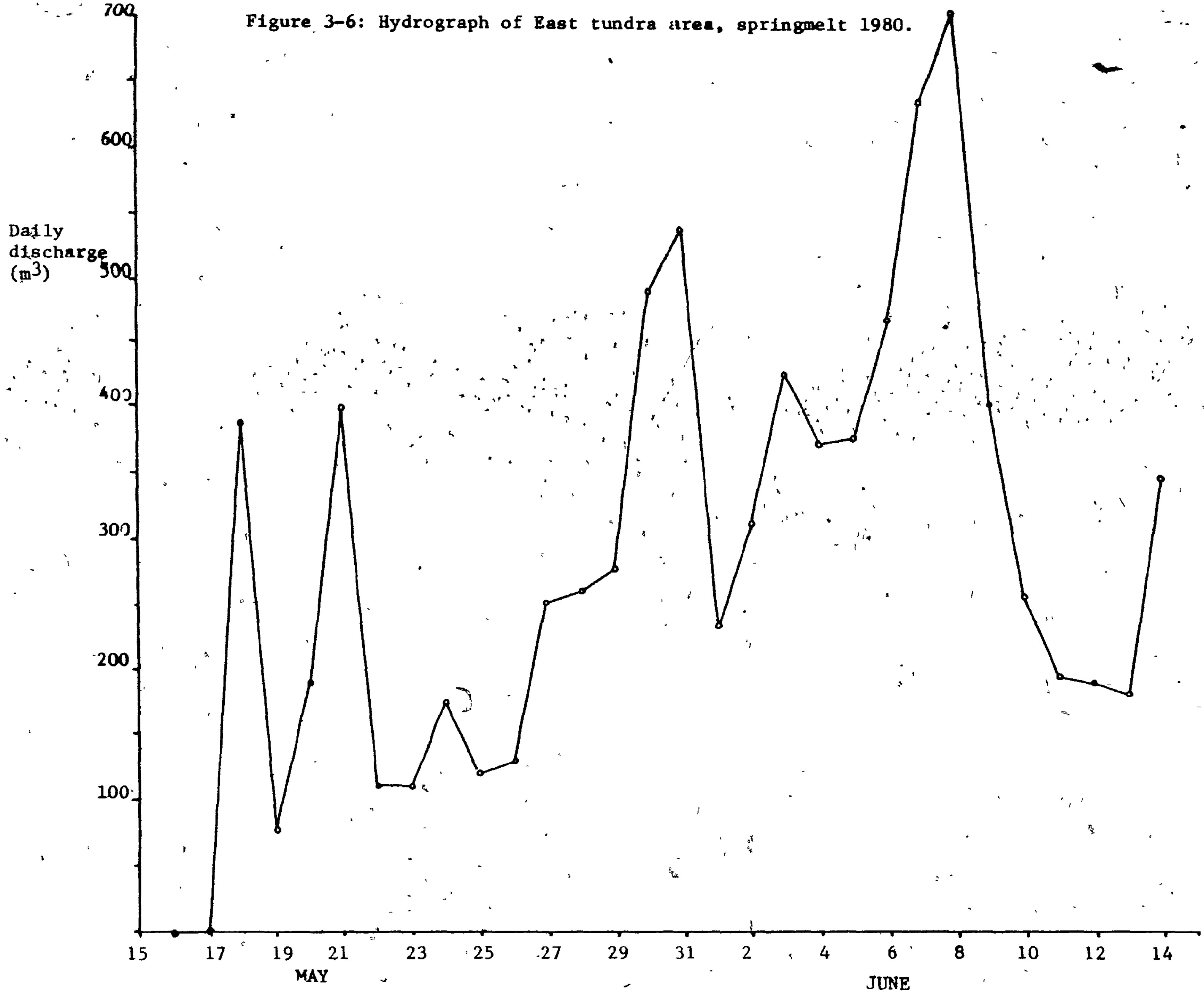


Figure 3-6: Hydrograph of East tundra area, springmelt 1980.



very end of May, consisted of a thick layer of white ice, similar in appearance to aufeis. This area contributed 6.17% of the terrestrial snowpack water to Elizabeth Lake during the spring of 1980.

3.4.2.3 Pond area

The Pond area is essentially a separate basin within the Elizabeth Lake catchment. It drains into a small pond, approximately .46 ha in area. Though the pond surface (at low winter water level) is approximately 11 m above that of Elizabeth Lake, groundwater seepage into the larger lake through the dolomite bedrock appears to be negligible. The bathymetry of this pond is unknown. The water levels of this pond dropped approximately .3 m during the winter months (mid November to mid April). This equals a groundwater discharge of approximately 8.6 m^3 day^{-1}. This factor would undoubtedly be an underestimate as groundwater or subsurface water would be draining into the pond as well.

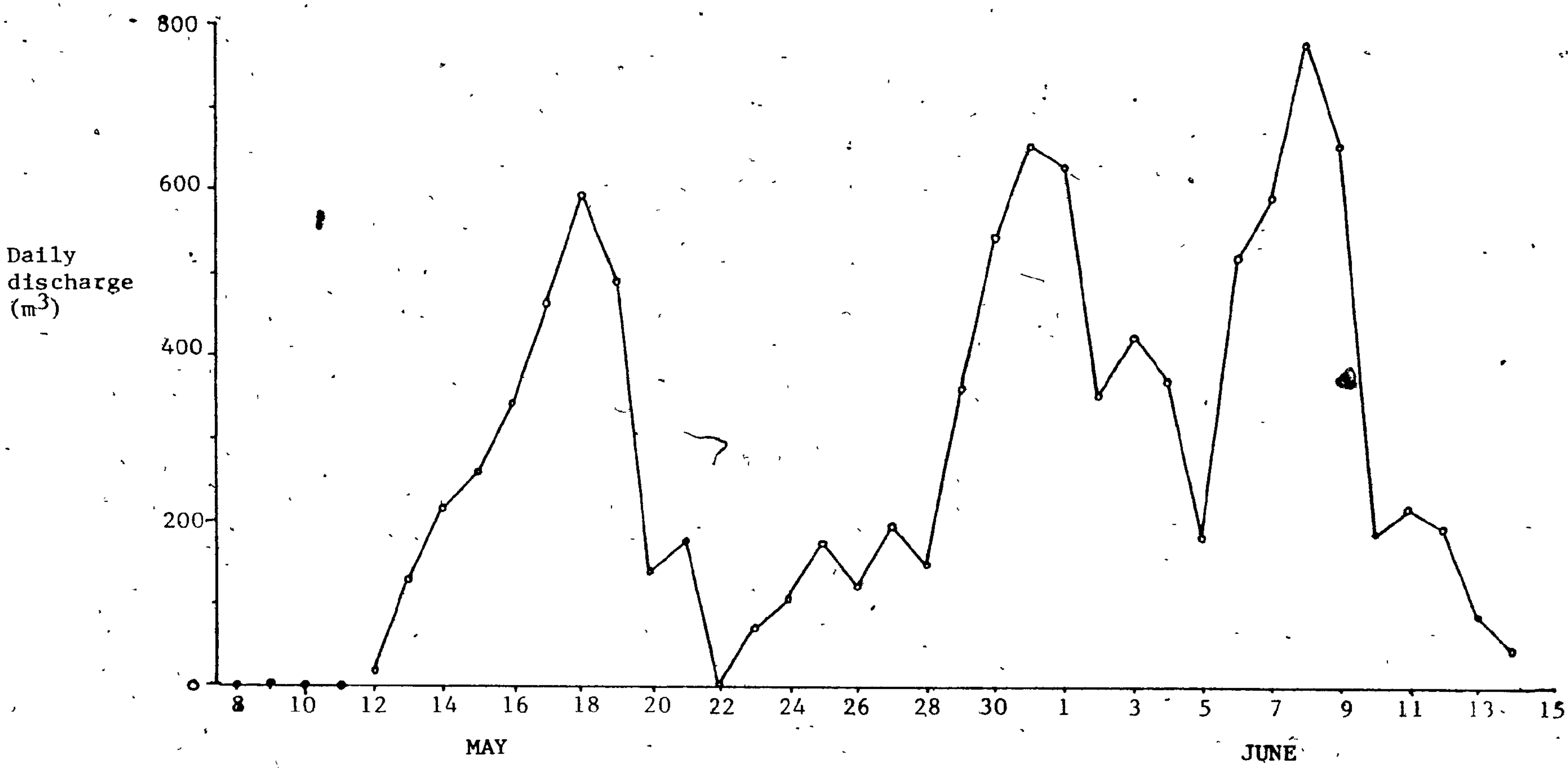
The difference in elevation between the lip of the discharging channel of the pond and the pond surface was .45 m on 15 April. Melt water was observed flowing onto the ice surface on 2 May. On 12 May the pond surface raised above the lip of the discharge channel and drainage into Elizabeth Lake began.

As the pond area contributes approximately 3% of the terrestrial snowpack water to Elizabeth Lake, time could not be spent doing dye dilutions each day the stream was discharging. In all, dye dilution was performed on 10 days out of a possible 37. A meter stick wired to a concrete slab was placed in the stream near the pond. Each day the stream stage was recorded. It was hoped that since the volume of the snowpack (water equivalent) draining into the pond was known (approximately 16,000 m^3), the volume of water needed to raise the pond to the tip of the streambed was known (approximately 2060 m^3) and the total volume of stream discharge on dye dilution measurement dates (later measurements recorded 4200 m^3) was known that it would be possible to deduce from the record of stream stage the approximate discharge for each day. In order to use the stage record, the readings would be totalled and this sum would equal 100% of the unmeasured remaining snowmelt water (approximately 9740 m^3). Each days measurement would represent a certain percentage of the 'total stage' which when multiplied by 9740 m^3 to derive that day's discharge. This is admittedly, a crude approximation, but within an acceptable error considering this basin only contains 3.0% of the Elizabeth Lake terrestrial snowpack. Regression analysis comparing the stream stage with the discharge data for the 10 dates when the dye dilution measurements were taken, yields a strong correlation (r = .97 at the 99% confidence interval). The equation describing this relationship, (Log y = .15 x + 1.99), was used to calculate the runoff for the dates when dye dilution measurements were not made. The resulting hydrograph is shown in Figure 3-7.

3.4.2.4 The primary contributing area

The primary contributing area labeled 'Lake area' is so named because it contributes snowmelt water directly to the lake without passing first through well defined stream beds. It comprises 54.7% of the terrestrial catchment and contributes 64.3% of the terrestrial source snowmelt water to the lake during the melt. A calculation

Figure 3-7: Hydrograph of Pond area discharge, springmelt 1980.



designed to generate daily snowmelt runoff into the lake from the primary contributing area is presented in section 3.4.4.

3.4.3 Elizabeth Lake outflow

The daily record of discharge in the outflow is presented in Figure 3-8. A significant (at the 99% confidence interval) relationship between lake stage and the measured discharge ($\log y = .0637x - 3.0968$; $r = 0.90$, $n = 14$) enables daily calculation of discharge from the lake stage (Figure 3-9). The dates of actual measurement are indicated in Figure 3-9.

Early in the melt, dye dilution measurements in the stream under-represent the actual discharge because the stream discharges through the snowpack in many channels. The snowpack disrupted the flow of discharging lake water such that the runoff was following not only the stream bed but also adjacent areas as well. This made it difficult to make sure the dye was well mixed. The snowpack acting as a temporary dam, diverted some of the water. The equation above was derived from measurements taken after an appreciable amount of snow was melted at the site where dye dilutions were run. It was then apparent that the dye was mixing with all of the discharging water.

3.4.4 Daily calculation of meltwater runoff into the lake from the primary contributing area

After the initial melt period in the woodland and forest when a small, albeit chemically important, volume of meltwater is diverted downslope by dense snowpack layers, the melt pattern resembles that described by Price (1975) and Colbeck (1977). A significant portion of the

Figure 3-8: Elizabeth Lake discharge, springmelt 1980.

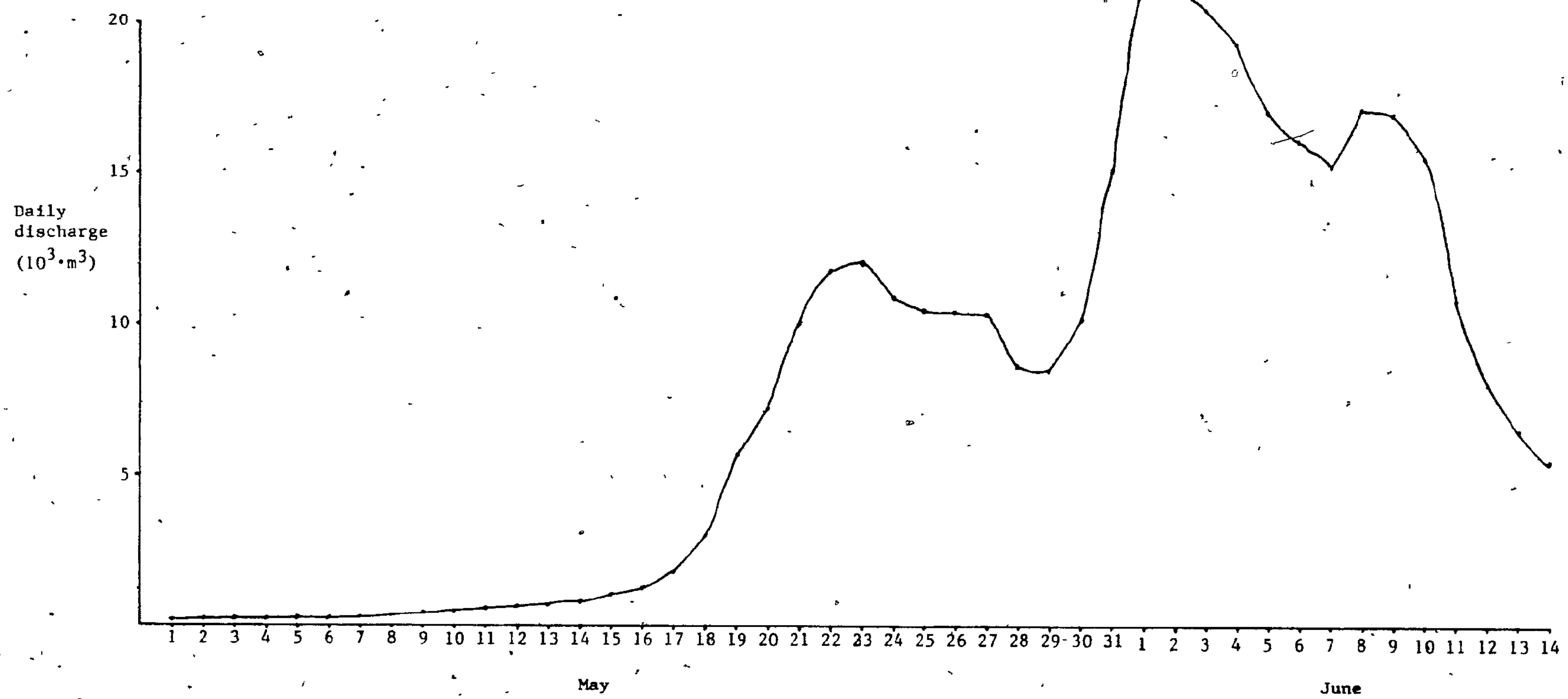
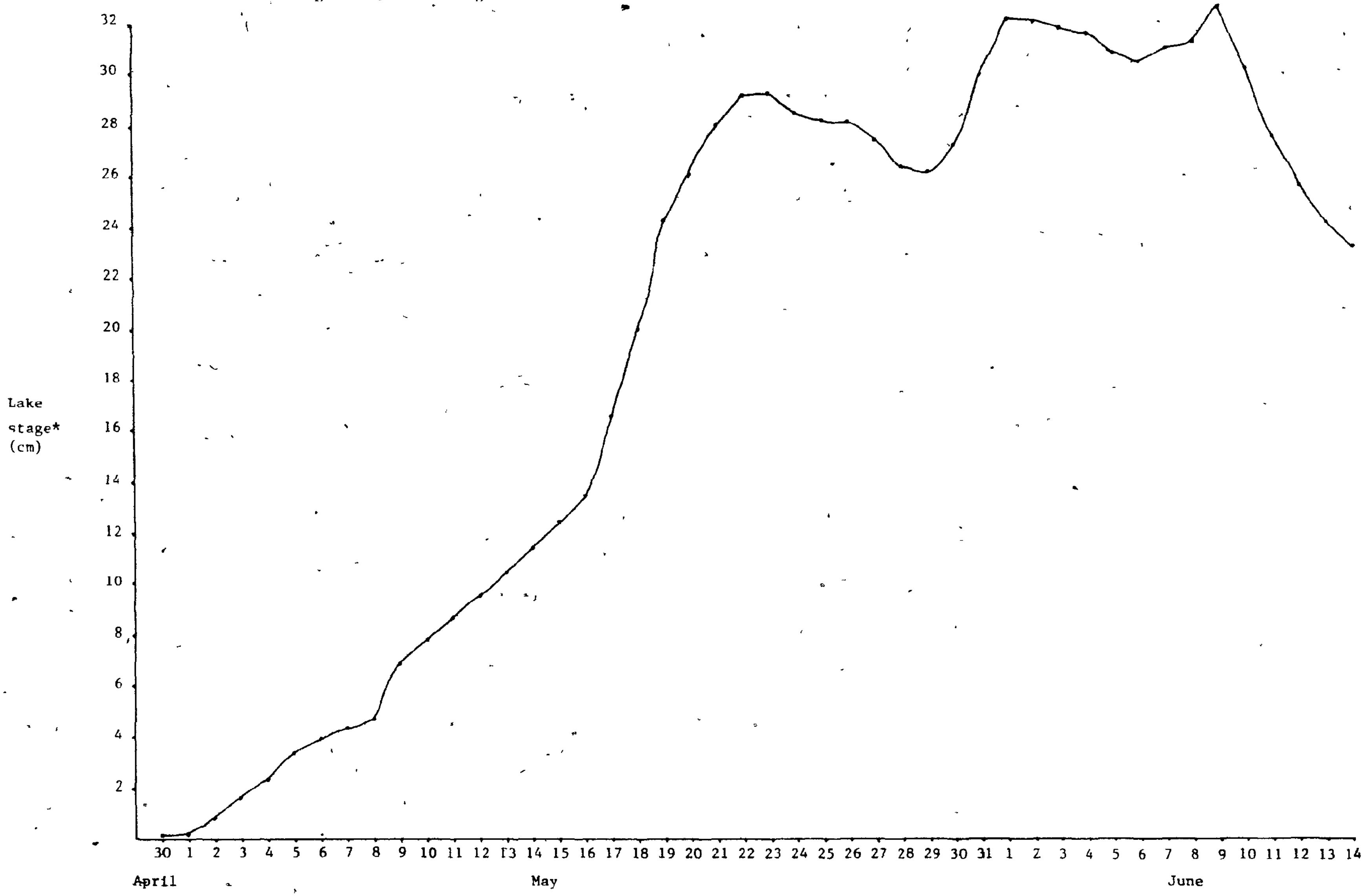


Figure 3-9: Lake stage



*lake stage is expressed in cm above winter baseline stage snowpack meltwater flows initially in more or less a vertical direction until flow is impeded by frozen soil; flow is then directed horizontally downslope.

A calculation to determine the daily flux of meltwater from the primary contributing area into the lake was derived by extrapolating the characteristics of the runoff plot hydrographs to the entire snowpack within each plant community.

Discharge from the snowpack in the primary contributing area was calculated in the following manner: from the shoreline to the top of the subbasin the land area was separated into bands 30 m wide, the same length as the upslope sections of the runoff plots. The calculation consists of two components 1) flow generated within each band and 2) flow entering each band from upslope. The plant community snowpack water equivalence within each band is estimated by multiplying the area the plant community occupies by its mean water equivalence.

The daily runoff generated within each band from each plant community is equal to the percentage of snowpack melted that day in the appropriate runoff plot. The distance downslope that this volume of water flows is derived from the daily hydrograph. It is assumed that when peak flow is reached the entire 30 m runoff plot is contributing meltwater to the weirbox at the downslope end of the plot. The time necessary to reach this peak each day is divided by the length of the slope, i.e. 30 m. The downslope snowmelt runoff velocity within each plant community is thereby calculated for each day (Table 3-6). If water originating from a tundra snowpack flows into an woodland snowpack, its runoff velocity would change in accordance with the flow rate

Table 3-6. Snowmelt runoff velocity determined within the woodland and forest runoff plots.

	Velocity (cm.sec^{-1})	
	woodland	forest
May 2	0.10	0.09
3	--	0.09
4	--	--
5	--	--
6	--	--
7	--	0.09
8	0.10	0.09
9	0.16	0.10
10	--	--
11	--	--
12	0.17	--
13	0.13	0.10
14	0.11	0.10
15	0.12	0.14
16	0.12	0.14
17	0.12	0.15
18	0.14	0.15
19	0.13	0.15
20	0.17	0.17
21	0.19	--
22	0.19	--
23	0.21	0.17
24	0.19	0.17
25	0.21	0.17
26	0.24	0.19
27	0.27	0.21
28	0.14	0.17
29	0.19	0.19
30	0.17	0.17
31	0.24	0.17
June 1	--	0.21
2	--	0.19
3	--	0.19
4	--	0.21
5	--	--
6	--	--
7	--	--

calculated for the woodland that day. At the beginning of each daily melt period, water at the base of the snowpack originating from the previous day's melt assumes the runoff velocity calculated for the new day's melt. In this manner, the daily flux of snowmelt water from the primary contributing area into the lake is calculated. The calculation continues until the runoff plots cease discharging water. At this time it is assumed that all of the snowpack in that particular community has melted.

The basic assumption in this calculation is that the measured daily runoff from the runoff plots is representative of the particular plant community at large. This assumption is really an overall assumption which consists of a number of identifiable subsets: namely slope, aspect, similarity of vegetation and snowpack. The similarity between the runoff snowpacks and the plant community snowpacks in which they are located has been discussed earlier in chapter 2.

3.4.4.1 Justification of the hydrological calculation

Incorporation of an existing model to predict the daily inflow of meltwater to Elizabeth Lake, was not possible for a variety of reasons. The primary purpose of this work is to examine nutrient fluxes during snowmelt not to construct a generally applicable model of snowmelt generation and runoff or to calibrate existing models.

To calibrate an existing model such as that of Price (1975) to the snowmelt conditions with the various environments in the Elizabeth Lake basin would have required a significant amount of time.

The incorporation of the Stanford watershed model to climates dissimilar to that which the model was originally intended has been the sole purpose of large scale projects in eastern Canada (e.g., Llamas _et al_., 1978) and Ohio (Ricca, 1972). Llamas _et_ _al_. (1978) expanded the importance of snowmelt runoff to accommodate Canadian conditions, but this could not be applied to subarctic conditions as the Canadian version accounted for infiltration of meltwater into the soil.

If it can be assumed that a runoff plot is representative of a particular plant community snowpack then the exchange of heat between the air and the snowpack should be essentially similar at the runoff plot and other sites within the specific plant community. As it is the complex interactions of heat and the snowpack which produce meltwater runoff, the runoff recorded per m^2 of runoff plot should be similar to that in other portions of the snowpack in the plant community of concern.

The structure of the runoff plot enclosure may impede the movement of air with the plot snowpack. This could in effect slow the melt process to a small degree. There was however no observable difference in the melt pattern of the snowpack within or outside the runoff plots however.

3.4.5 Comparison of calculated and measured input with the actual discharge

Figure 3-10 illustrates the daily input to the lake from all sources. This includes the calculated input from the primary contributing and near valley area, the input from the upper valley, pond and east tundra areas, and the lake snow and white ice cover. In order to test the validity of calculated and measured daily input a comparison was drawn with the actual measured storage and discharge (Fig. 3-10).

A cumulative plot of daily calculated plus measured input and daily lake discharge plus storage is illustrated in Figure 3-11. The calculated plus measured input is consistently greater than the discharge plus storage. These differences are most pronounced between 14 May and 9 June 1980.

The calculated input from 1 May to 15 June is 462,100 m^3, a 7.75% overestimate of the actual discharge of 426,300 m^3. This overestimation is understandable because, at least in the primary contributing area, the calculation used to determine the daily flux of meltwater into the lake assumes that the snowpacks in the forest and woodland disappear on the 11 June and 6 June respectively. In fact, some patches of snow remained in both plant communities after the calculated date of disappearance. No estimate was made of the remaining snow. There is general temporal concordance between input and lake peaks, as shown in Figure 3-10.

The variation apparent between the daily meltwater flowing into the lake and the sum of daily discharge plus daily change in storage illustrated in Figure 3-10 is due not just to potential error in the overland flow calculation but in part to the error in total stream inflow measurements, as dye dilution was not conducted each day of the melt.

Figure 3-10 Predicted + measured input to lake and storage + discharge.

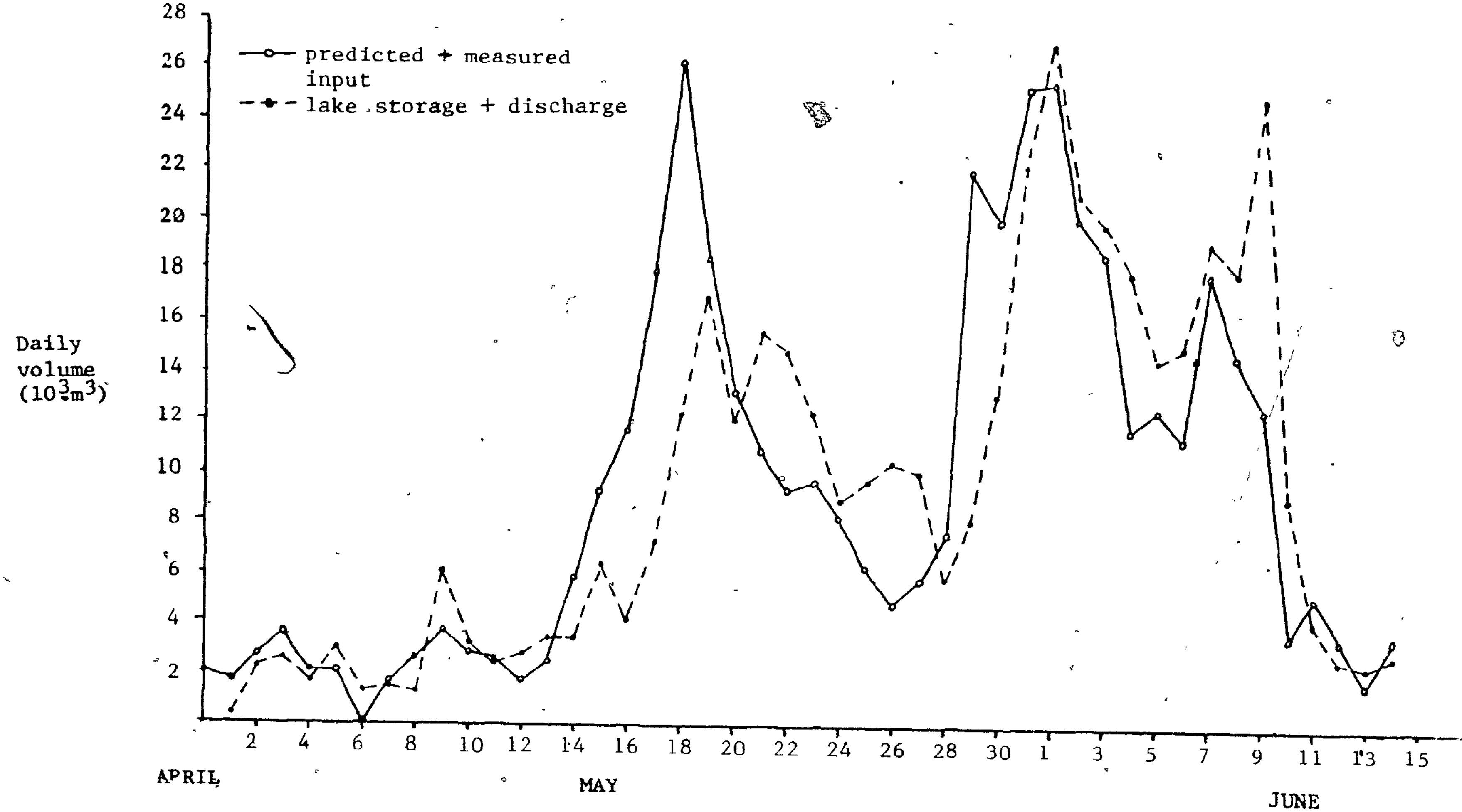
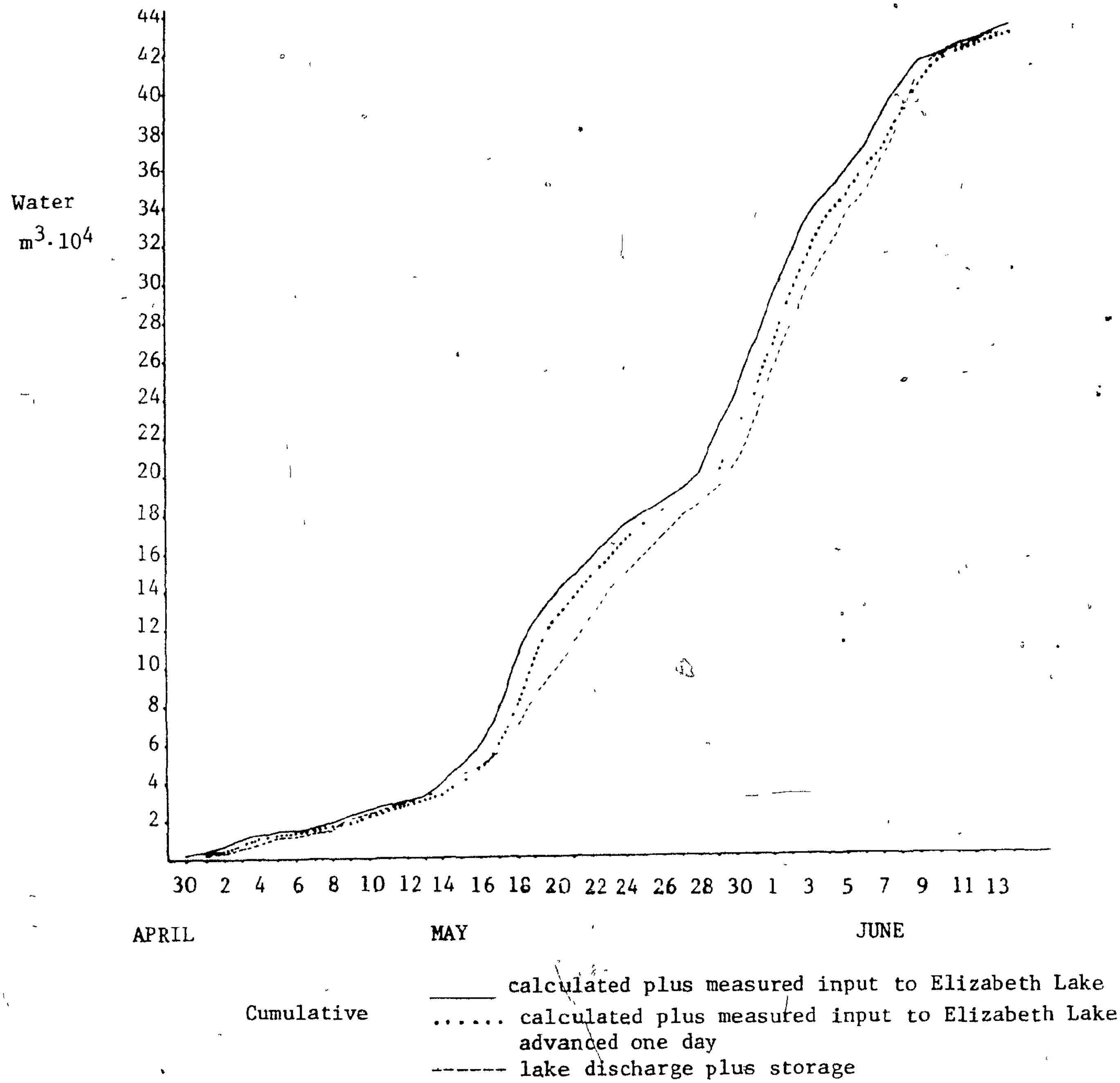


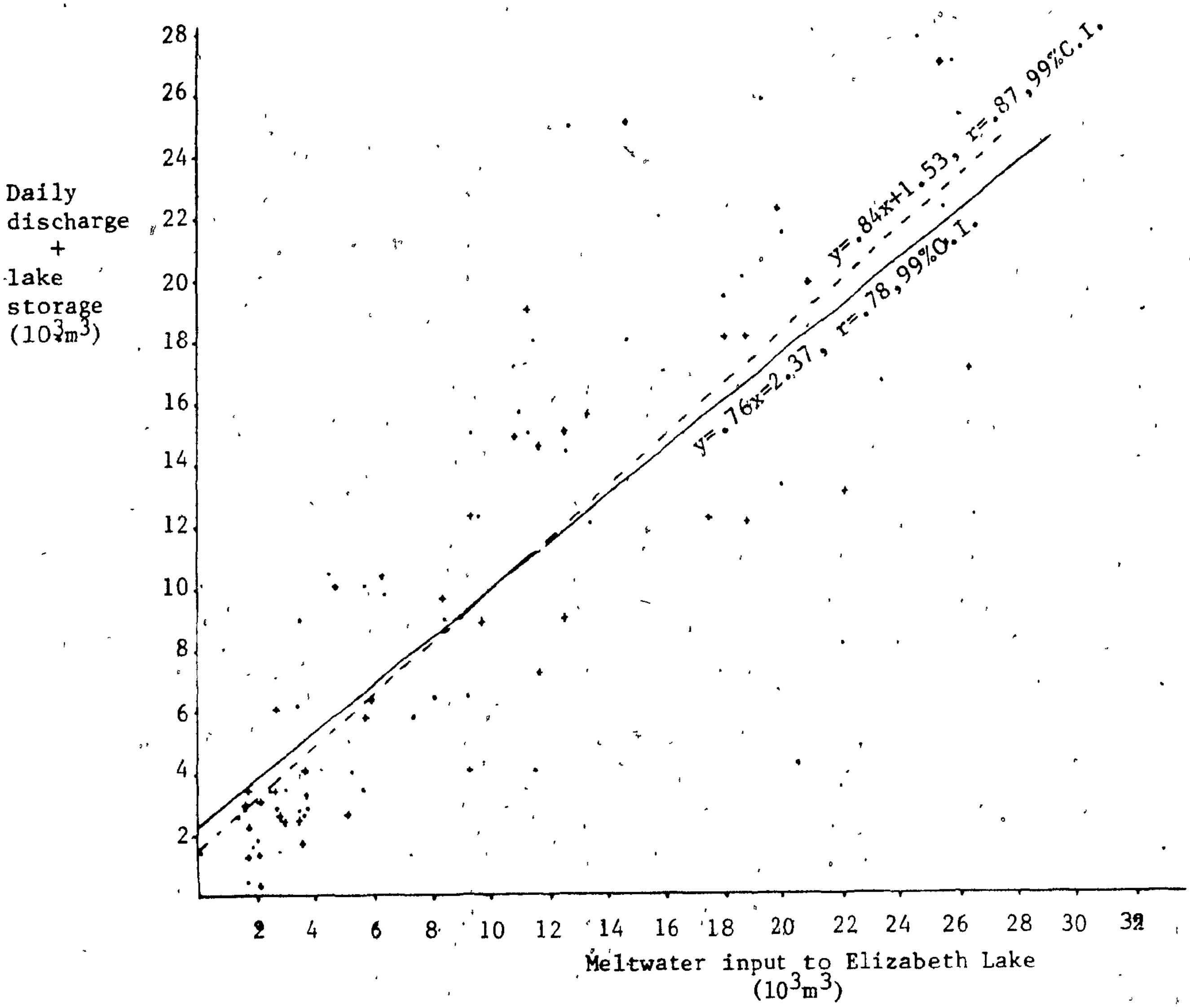
Figure 3-11: Comparison of cumulative daily measured input plus calculated input and cumulative lake discharge plus storage.



A linear regression compares the daily lake discharge plus daily change in lake storage and calculated input to the lake (Fig. 3-12). An equation describing the relationship has a correlation coefficient of .78, significant at the 99% confidence interval (n = 45).

As the discharge response to the daily input will likely be delayed as the flow continues over a 24 hour period the equation above describing 'same day' input and response is not accurately describing the intended relationship. Assuming that a delay of one day occurs between the input of meltwater to Elizabeth Lake and corresponding stream discharge a new relationship involving a one day delay is formulated. The new equation, Figure 3-12 has a correlation coefficient of .87, significant at the 99% confidence interval (n = 44). Though both equations describe a significant relationship, in the latter, the input accounts for 76% of the variation exhibited in the outflow; in the former equation the input accounts for 61% of the discharge variation. Likely the input-response time delay is somewhat less than a 24 hour period. As the data are formulated only for daily readings and not the daily hydrograph, the true input-response time delay remains unknown. In Figure 3-11 a one day advance of the input data lessens the differences between the cumulative daily calculated plus measured inputs to Elizabeth Lake and the cumulative daily discharge plus storage. During portions of the early and latter melt, the input exceeds the lake discharge plus storage though not by very significant margins. Generally speaking there is good agreement between the cumulative input and cumulative output.

Figure 3-12: Relationship between daily lake discharge plus daily change in lake storage and calculated overland flow and measured stream input to Elizabeth Lake, springmelt 1980.



Legend
.... = ______ .. same day input/output relationship

+ + + = \- - - + + one day delayed input/output relationship

CHAPTER 4

TERRESTRIAL AND WHOLE CATCHMENT NUTRIENT MASS BALANCE

4.1 Introduction

This chapter examines certain aspects of nutrient transfer during the springmelt attributable to meltwater runoff. This involves an accurate assessment of the nutrient masses within the tundra, woodland and forest snowpacks and the impact of physical processes such as diversion flow which will affect the transfer of snowpack-source nutrients to downslope water bodies prior to interaction with organic horizons at the base of the snowpack.

Total nutrient mass balances are examined within the tundra, woodland and forest snowpack runoff plots in order to determine whether snowpack-source nutrients are retained by or nutrients scoured from the organic horizons and mineral soil surfaces at the base of the snowpack.

The elution pattern of nutrients from the woodland and forest snowpacks were recorded. This made possible the calculation of daily nutrient mass balance within the respective meltwater runoff plots.

Daily nutrient mass transfer from the terrestrial to the aquatic portion of the Elizabeth Lake catchment was accomplished by adding the daily nutrient mass values determined for the inflowing perennial and intermittent streams to the daily contribution from the portion of the terrestrial catchment contributing nutrients directly by overland flow. The calculation for the daily overland flow contribution is a product of the hydrological calculation discussed in Chapter 3 (section 3.4.4) and the daily total nutrient export from the woodland and forest runoff plots.

The daily nutrient mass balance for Elizabeth Lake is presented for the 1980 springmelt. The springmelt export of nutrients from these sub-arctic ecosystems are compared to results from temperate study sites.

The relative importance of the springmelt contribution of TP, Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} to the lake in relation to the ice-free season contribution are examined.

4.2 Snow Chemistry

The purpose of investigating the chemical content of the snowpack is threefold: 1) to determine the potential snowpack nutrient load within each plant community at springmelt, 2) to determine the representativeness of the snowmelt runoff plot snowpack to the plant community snowpack within which it is located, and 3) to determine the chemical variation within and among plant community snowpacks.

4.2.1 Snowpack chemical composition

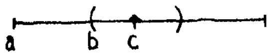
The chemical composition of the tundra, woodland and forest snowpacks determined from samples extracted at peak snowyear is illustrated in Figures 4-1 and 4-2. Beneath each histogram the mean sample value and sample range within 1 s is shown. The range of confidence (99%) in the error of each mean:

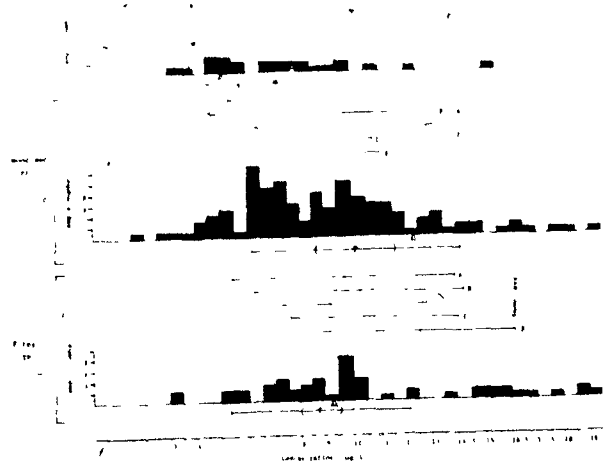
$$E = z^{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad \text{or} \quad t^{\alpha/2} \frac{s}{\sqrt{n}} \qquad \text{(Freund, 1972)}$$

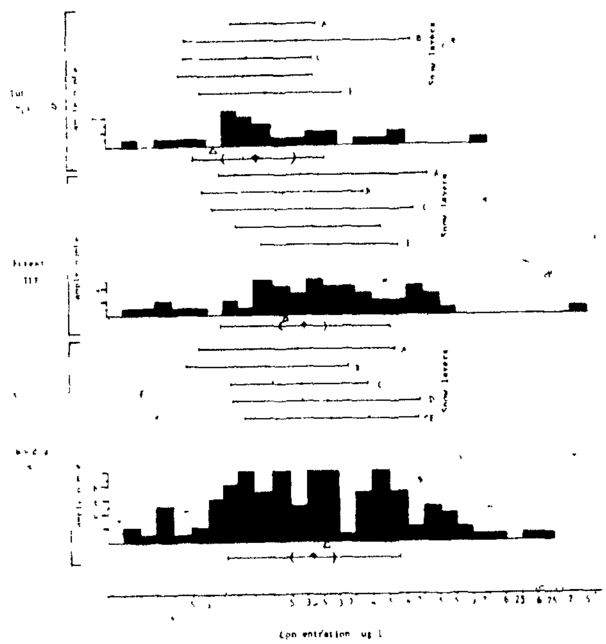
is shown for each nutrient within the three plant community snowpacks. The mean nutrient concentration of each stratigraphic section (described in Chapter 3) and the range of values within 1 s of the mean are included above the histograms.

Table 4-1 lists the total mass for each nutrient measured in the three snowpacks. The calculation consists of three components: 1) the area (m^2) of each of the three plant communities; 2) the mean snowpack water equivalence of each plant community and 3) the total snowpack mass for each ion at peak snowyear. The calculation is described below:

Figure 4-1: Concentration of TP TDP and NO_3^- in the tundra woodland and forest snowpacks. The mean concentration for the snowmelt runoff plot within each plant community snowpack is shown (Δ).
Legend: a: 1 standard deviation; b: standard error of the mean; c: mean value.







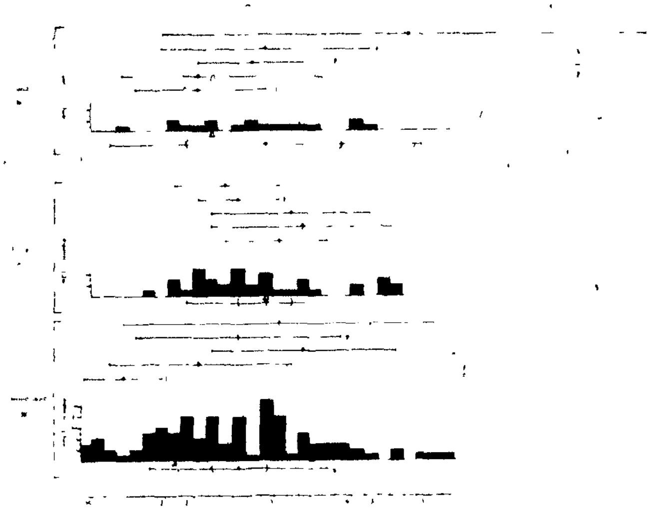


Figure 4-2: Concentration of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} in the tundra, woodland, and forest snowpacks. The mean concentration for the snowmelt runoff plot within each plant community is shown (△). Legend as in Figure 4-1.

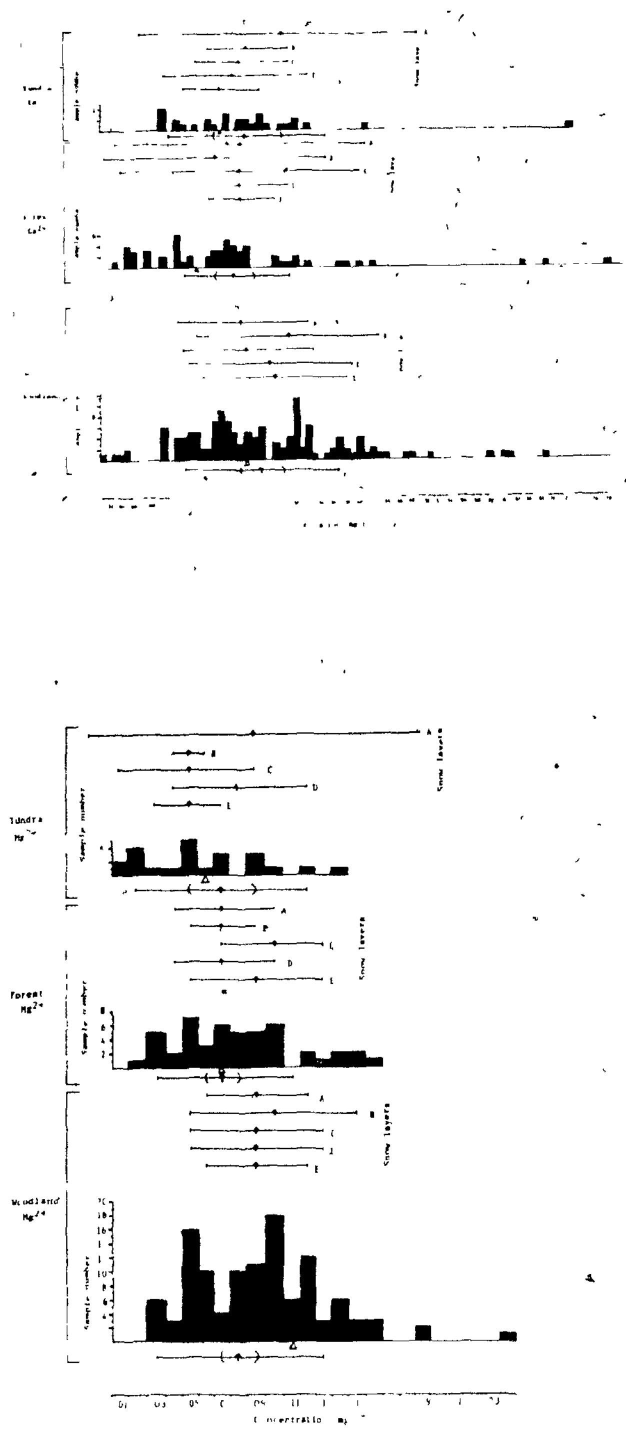
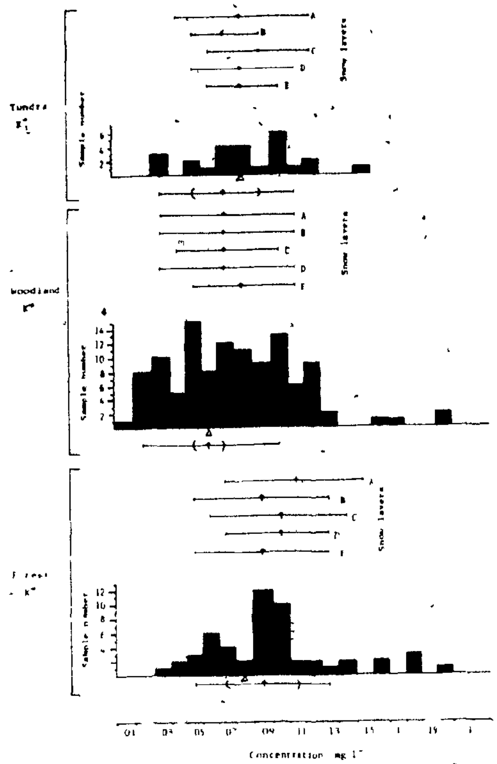


Figure 4-2:
continued.



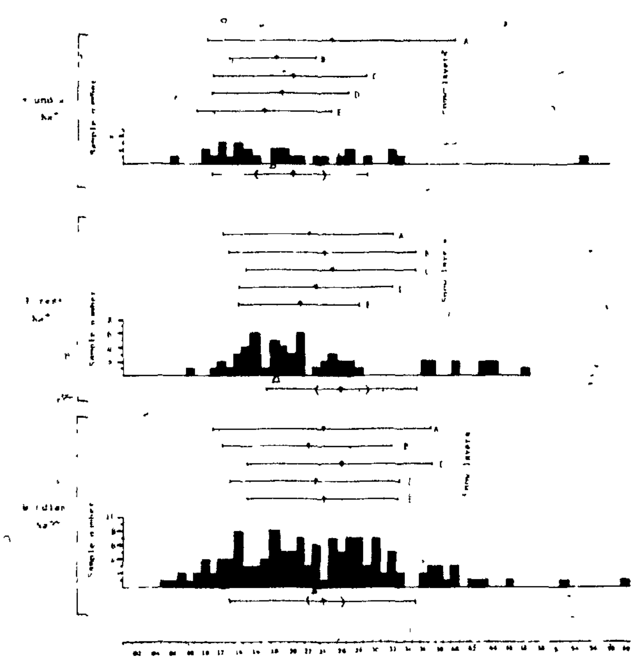


Table 4-1. Snowpack nutrient mass, Elizabeth Lake catchment, Labrador.

			Tundra	Woodland	Forest	Total
snowpack volume (water equivalent, m^3)			96337	274060	131325	
volume ratio			1	2.84	1.36	
Mass (Kg)	Ca^{2+}	(actual)	22.16 ± 7.34[2]	68.52 ± 10.19	27.58 ± 8.12	118.26
		(equilibrated)[1]	22.16	24.09	20.23	
	Mg^{2+}	(a)	9.63 ± 3.76	21.92 ± 3.35	9.19 ± 2.79	40.74
		(e)	9.63	7.70	6.74	
	K^{+}	(a)	6.74 ± 2.56	16.44 ± 3.10	11.82 ± 2.72	35.00
		(e)	6.74	5.78	8.62	
	Na^{+}	(a)	19.27 ± 6.17	65.77 ± 7.96	34.14 ± 6.84	119.18
		(e)	19.27	23.12	25.04	
	TP	(a)	.71 ± .22	2.48 ± .30	1.36 ± .26	4.55
		(e)	.71	.87	1.00	
	TDP	(a)	.23 ± .08	.85 ± .11	.42 ± .10	1.50
		(e)	.23	.30	.31	
	NO_3	(a)	22.16 ± 8.01	57.55 ± 7.46	30.20 ± 7.62	109.91
		(e)	22.16	20.23	22.15	

[1] The mass values of the woodland and forest snowpacks have been equilibrated to the water equivalence of the tundra snowpack such that a more realistic comparison can be illustrated.

[2] The expected range of snowpack specific ion mass (resulting from the product of the mean snowpack water equivalence and mean ionic concentratin) is determined by employing a modification of the following equation:

Expected range within which 68% of the data will fall $= \sqrt{[\bar{x}^2 \cdot (S_4)^2] + [\bar{y}^2 \cdot (S_x)^2]}$

The modification involves replacing S with the 99% confidence limit (a) of the mean (described above) calculated for each ion being examined. Thus, the expected range of ion mass determined from the projected product of the two means =

$$\sqrt{[\bar{x}^2 \cdot (CL_y)^2] + [\bar{y} \cdot (CL_x)^2]}$$

$$\text{Snowpack mass} = A_o \cdot S_{we} \cdot \bar{x}N$$

where A_o : area of specific plant community (m^2)
S_{we}: $\bar{x}$ snow water equivalence in specific plant community (m)
$\bar{x}N$: $\bar{x}$ ion concentration in specific plant community mg m^{-3}

The calculated range for the total ionic mass within the snowpack of each plant community is listed in Table 4-1. It can be asserted with a probability of .99 that the determined mean is within the stated range of the true mean.

4.2.2 Snowpack stratigraphy

Snowpack stratigraphy was investigated to aid in determining chemical differences and similarities within each plant community snowpack. The reported diversion of snowmelt water by ice layers (Colbeck, 1977) formed along stratigraphic boundaries within the snowpack necessitates evaluation of snowpack chemistry by stratigraphy such that if a diversion similar to that reported by Colbeck occurs, a reasonably accurate evaluation of the ionic loss can be made. Sampling of the snowpack stratigraphy at different sites within each plant community provides the statistics for such an assessment.

Due to the large number of stratigraphic layers within the snowpacks (as many as 17) the strata were separated into 5 groups. A composite sample was taken from each group for chemical analysis. The division of strata within each plant community snowpack was done such that chemical comparisons of a particular group could be drawn among different snowpits. This was only possible where stratigraphic similarity existed.

The strata within the forest snowpack at different sites was quite comparable, presumably because of reduced wind disturbance. At the woodland sites, the open nature of the woodland enables the wind to play a more prominent role in disrupting the natural stratigraphy of the snowpack. Topographic differences in the exposed tundra produced a large range of snow depth. This results in a large variation in physical stratigraphy; thin, densely compacted strata on the exposed sites and more pronounced stratigraphy in the hollows where the snowpack may measure in excess of 2 m. Segmenting the strata into five groups enabled a comparison of the strata among sites on a temporal basis. For example the first stratigraphic group at the base of the tundra snowpack would be comparable at each site as it is that initially deposited. Likewise the uppermost stratigraphic group among all sites represents the most recent deposition of snow. The three remaining fractions between the initial and most recent groups would be comparable among the sites on a similar temporal basis.

4.2.3 Variation in snow chemistry among plant communities

It was hypothesized that the snowpacks would have very similar nutrient concentrations barring influence from the plant community. The means and ranges (+1s) displayed in Figures 4-1 and 4-2 indicate that the tundra snowpack has lower TDP, TP and NO_3^- concentrations than the woodland and forest plant community snowpacks. Difference of means tests (after Freund, 1972) were conducted to compare the nutrient concentrations between plant community snowpacks. The results are illustrated in Table 4-2. Statistically the tundra snowpack [TP] is significantly less than both the woodland and forest. The differences apparent

Table 4-2. Nutrient concentrations in snowpack stratigraphic sections and mean snowpack concentrations for all plant communities.

		A	B	C	D	E	$\bar{x}$
Ca^{2+} mg L^{-1}	Tundra	.28	.23	.22	.21	.23	.23
	Forest	.22	*.18	.22	.22	.22	.21
	Woodland	.22	.30	.23	.26	.27	.25
Mg^{2+} mg L^{-1}	Tundra	.09	.10	.11	.11	.09	.10
	Forest	.07	.05	.08	.06	.08	.07
	Woodland	.08	.09	.07	.07	.08	.08
Na^{+} mg L^{-1}	Tundra	.25	.18	.20	.19	.17	.20
	Forest	.37	.22	.25	.23	.21	.26
	Woodland	.24	.22	.26	.23	.24	.24
K^{+} mg L^{-1}	Tundra	.07	.06	.07	.07	.07	.07
	Forest	.10	.08	.09	.09	.07	.09
	Woodland	.06	.06	.06	.05	.07	.06
TP g L^{-1}	Tundra	7.83	8.94	6.35	6.50	7.50	7.42
	Forest	9.62	10.29	9.06	10.80	12.10	10.36
	Woodland	9.55	9.04	10.03	8.32	8.50	9.05
TDP g L^{-1}	Tundra	2.45	3.02	2.11	2.10	2.46	2.53
	Forest	3.34	2.84	3.23	3.20	3.49	3.21
	Woodland	2.96	2.56	3.07	3.45	3.51	3.11
NO_3^{-} mg L^{-1}	Tundra	.34	.23	.22	.18	.18	.23
	Forest	.20	.21	.25	.26	.24	.23
	Woodland	.22	.22	.24	.20	.17	.21

* the brackets ([) indicate statistically significant differences (95% confidence level)

in Figures 4-1 and 4-2 for [NO_3^-] are not statistically significant. Other statistically significant differences not apparent in Figures 4-1 and 4-2 include [Ca^+] and [K^+] between woodland and forest and [Na^+] between the tundra and forest snowpacks. [Na^+] is significantly lower in the tundra than in the forest; the difference in [Na^+] noted between tundra and woodland snowpacks is not statistically significant.

4.2.3.1 Stratigraphic variation in chemical concentration among plant communities

The mean and range (+1s) of the measured ions within each stratigraphic section of the snowpack are illustrated in Figures 4-1 and 4-2. Patterns indicating increasing or decreasing concentration with depth are evident for NO_3^- in the three plant community snowpacks; decreasing in the tundra and woodland and increasing in the forest. In the forest snowpack, [TP] increases from the top to bottom of the snowpack; [TP] pattern is not evident among the stratigraphic sections within the tundra or woodland snowpacks. The cation concentration distribution through the snowpacks does not follow any distinctive pattern. Specific concentrations of measured ions within the 5 stratigraphic sections of each plant community snowpack are listed in Table 4-2, statistically significant differences determined by the t statistic (after Freund, 1972) are noted.

4.1.3.2 Discussion on statistically significant differences in ionic concentrations noted among the snowpacks.

Na^+ and TP concentrations differ significantly between tundra and forest snowpacks. For TP this difference is most apparent in the lower

Table 4-3. Nutrient analysis, water equivalence and depth of snowpack of snowpits and runoff plots.

	Tundra			Woodland			Forest		
	Snowpits A	Snowpits B	Runoff plot	Snowpits A	Snowpits B	Runoff plot	Snowpits A	Snowpits B	Runoff plot
TP ($\mu g\ L^{-1}$)	5.97	5.02	5.49	9.46	8.14	8.80	11.20	13.54	12.37
TDP ($\mu g\ L^{-1}$)	1.14	2.24	1.69	2.52	3.20	2.86	3.00	3.24	3.12
NO_3^- ($mg\ L^{-1}$)	0.22	0.17	0.20	0.19	0.13	0.16	0.21	0.24	0.19
Ca^{2+} ($mg\ L^{-1}$)	0.18	0.19	0.19	0.22	0.27	0.25	0.17	0.14	0.16
Mg^{2+} ($mg\ L^{-1}$)	0.10	0.09	0.09	0.07	0.09	0.08	0.06	0.07	0.07
K^+ ($mg\ L^{-1}$)	0.07	0.08	0.08	0.06	0.05	0.06	0.09	0.07	0.08
Na^+ ($mg\ L^{-1}$)	0.17	0.19	0.18	0.24	0.21	0.23	0.18	0.19	0.18
water equivalence (cm)	21.42	13.96	11.03	40.02	37.21	37.18	43.97	37.43	40.82
depth (cm)	76.00	54.00	56.70	135.00	110.00	112.33	162.00	177.00	162.33
density (g/cm^3)	0.22	0.14	0.19	0.30	0.34	0.32	0.27	0.25	0.26

stratigraphic layers (Table 4-2) where the concentrations in the forest snow are between 4 and 5 ug L^{-1} higher than those recorded in the tundra. [Na^+] differences are noted between the composite samples and not between particular stratigraphic groups. The increased concentration of Na^+ in the forest may be related directly to the efficiency of coniferous trees to trap dry fallout (Overrein et al., 1981). The significant differences determined for [TP] between the woodland and forest plant community snowpacks may be attributable to increased organic deposition in the forest (see Werren, 1978) due to the increased amount of above snowpack biomass (i.e., standing trees). The increased [TP] in the forest snowpack above that determined for the tundra and woodland snowpacks is most pronounced in the lower stratigraphic layers. It is thought this difference is due chiefly to deposition of dry fallout in the early winter. Other possible sources include organic matter deposition from the trees, shrub layer litterfall and upward migration of litter-source P during the early snowyear when the upper soil and ground vegetation are still not completely frozen.

It is thought that dry fallout might be more pronounced during the initial portion of the snowyear as later in the winter much of the source area for dry fallout material would be under snowcover. Hammer (1984) reports that dry fallout in northern latitudes comprises a small proportion of the total atmospheric load during the winter months.

The stratigraphic variation in chemical properties in the forest snowpack cannot be solely related to greater accumulations of litter. Further, indication of increased organic matter in the lower portions of the snowpack should be apparent by examining the [K^+]. It is widely reported, most recently by Jones (1984) that $[K^+]$ in snowpacks is proportional to the organic content of the snowpack. In the Elizabeth Lake catchment snowpack data, there is very little vertical variation in $[K^+]$ within the three plant community snowpacks. This is indirect evidence that the vertical distribution of deposited organic matter is much the same throughout the snowpack within each plant community.

A possible source of P to the lower portions of the snowpack is upward movement of litter source P during the early snowyear when the upper soil and ground vegetation are still not completely frozen. A moisture gradient exists between a very dry, cold snowpack and a saturated, relatively warm litter-ground vegetation-mor strata at the base of the shallow snowpack. This process was observed during the 1983-84 snowyear in a northern Ontario Canadian Shield deciduous forest (English and Jeffries, unpublished data 1984). The affected snowpack portion, clearly distinct due to discolouration by what was thought to be organic acids had greater [TDP] than the upper unaffected portion of the snowpack. This would indicate the dissolved fraction of the total detectable P would be affected by this process. Since the [TDP] in both the woodland and forest snowpack are similar, attribution of this process to increased [TP] in the lower forest snowpack is dismissed.

4.2.3.3 Differentiation of snowpack ionic mass load by equilibration

Equilibration of the calculated total ion mass within the tundra, woodland and forest snowpack are shown in Table 4-1. The equilibrated expressions enables comparison of individual plant community contribution to snowpack chemistry. The statistical significance of these differences was not found as only one number for each snowpack is determined.

Proportionally more K^+, Na^+ and TP mass is found in the forest snowpack. The differences are attributable to the increased above snowpack biomass contributing litter to the snowpack and effectively trapping dry fallout which is later deposited in the snowpack beneath. Overrein et al. (1981); Abrahamsen et al. (1976), Horntvedt et al. (1980) and Foster et al. (1983) discuss the chemical modification of precipitation by coniferous trees. Their results demonstrate that NO_3^- and NH_4^+ are adsorbed by coniferous tree crowns and most other ions are enriched in throughfall. This is in part due to the scouring of dry deposition from the foliage during rainfall events.

Though the reports of canopy drip resulting from snow melting on trees were not found it is thought that since dry deposition, which is thought to play a major role in determining the chemistry of canopy drip, occurs in winter, then the meltwater would be similarly enriched.

The increased K^+ and Na^+ mass in the forest snowpack may in part be due to enrichment from the meltwater dripping from the spruce crowns during the late winter when the adsorption of solar radiation by the spruce trees and subsequent (observed) melt of snow in the boughs occurs. The concentration of K^+ and Na^+ in the surface (A) portion of the forest snowpack are elevated above the concentrations determined for the surface snow in the tundra and woodland (Table 4-2).

The equilibrated TDP mass is proportionately equal in the forest and woodland; both of these values well elevated above the tundra equilibrated TDP mass. The equilibrated NO_3^- mass within the tundra and forest are essentially equal; the woodland snowpack NO_3^- equilibrated mass is slightly less. The equilibrated Ca^{2+} and Mg^{2+} mass are noticeably higher in the woodland and tundra snowpacks respectively. The exact reasons for this are unknown, though in the tundra it is thought that the open patches of ground on the ridge tops may be contributing dust, thus the elevated concentrations of Mg^{2+}. The equilibrated Ca^{2+} increase in the woodland may be organic in source as the colonies of Labrador tea and dwarf birch in the woodland are more numerous and greater in density than in the tundra or forest.

4.2.4 Evaluation of snowmelt runoff plot ionic mass

Direct sampling of the runoff plots for nutrient analysis was not practical because disturbing the snow in the plots would disrupt the natural melt pattern of the snowpack. Instead, 2 snowpits were dug within 10 m of the plots, one near the upper portion of the plot, one at the lower end; nutrient analysis were performed on the samples taken at these sites (Table 4-3). It was assumed that if there are chemical differences between the runoff plot sites and these snowpit sites it should be insignificant. Physically the sites are very similar: differences in slope angle and aspect are indistinguishable and the vegetation composition is much the same. As demonstrated below in Table 4-3 there is no significant difference between the water equivalence and depth of the snow runoff plots and the nearby snowpits for the woodland and forest. The water equivalence of the tundra runoff plot is less than the mean of the two sampled sites by 6.66 cm. This difference, though large, is not reflected in the ionic concentration. As shown in Table 4-3 the variation in ionic concentration at the two tundra sites is small. The [TDP] variation is the largest shown.

Assessment of the nutrient mass within the runoff plots involved determining the weighted mean concentrations for each stratigraphic section. Student t tests revealed no significant difference (95% confidence level) between the nutrient concentrations in the 2 snowpits. The mean nutrient concentration of the two snowpits sampled near the runoff plots is that used to determine the nutrient mass of the runoff plots. The runoff plot snowpack nutrient mass was simply calculated by multiplying the extrapolated mean nutrient concentration by the measured (chapter 3) water equivalence volume (Table 4-4).

As the runoff plots were the sole means of measuring the interaction between melting snow and the soil surface and ground cover it was important to determine how representative the runoff plot snow chemistry was in relation to that determined at other snowpit sites within the same plant community. This analysis would give some measure of confidence that the results determined at springmelt at this site could be considered representative of the snowmelt interaction at other sites within the appropriate plant community.

Student t tests were employed to determine if the runoff plot snowpack chemical concentrations are statistically comparable with the other snowpit site data. The results are illustrated in Table 4-5. In each case where significant differences are registered, the runoff plot concentration is less than the value derived for the plant community snowpack at large. The only exception is TP in the forest snowpack where the concentration in the runoff plot is approximately 2 $\mu g\ L^{-1}$ greater than the mean value for the forest snowpack at large.

Table 4-6 compares the equilibrated total masses between the runoff plots and the plant community snowpacks they represent. Generally speaking there is good agreement specifically for the cations and NO_3^- among the three plant community snowpacks. The TDP mass in the runoff

Table 4-4. Runoff plot snowpack nutrient mass.

		Tundra	Woodland	Forest
TP (mg)	(actual)	54.5	279.7	454.4
	(equilibrated)	" (1.00)[1]	83.0 (1.52)	122.8 (2.25)
TDP (mg)	(a)	16.8	90.9	114.6
	(e)	" (1.00)	26.9 (1.61)	31.0 (1.84)
NO_3^- (g)	(a)	2.0	5.1	7.0
	(e)	" (1,33)	1.5 (1.00)	1.9 (1.27)
Ca^{2+} (g)	(a)	1.9	7.9	5.9
	(e)	" (1.20)	2.3 (1.47)	1.5 (1.00)
Mg^{2+} (g)	(a)	.9	2.5	2.6
	(e)	" (1.29)	.7 (1.00)	.7 (1.00)
K^+ (g)	(a)	.8	1.9	2,9
	(e)	" (1.00)	2.2 (1.22)	1.8 (1.00)
Na^+ (g)	(a)	1.8	7.3	6.6
	(e)	" (1.00)	2.2 (1.22)	1,8 (1.00)
water equivalence (m^3)		9.93	33.46	36.74

[1] The figures in brackets for each nutrient represent the ratio of the equilibrated values among the three plant communities.

Table 4-5. Assumed runoff plot and plant community nutrient concentrations.

	Tundra			Woodland			Forest		
	Runoff plot conc.	Plant community conc.	Significance	Runoff plot conc.	Plant community conc.	Significance	Runoff plot conc.	Plant community conc.	Significance
TP (g/l)	5.43	7.44	x	8.80	10.03	x	12.37	10.41	x
TDP (g/l)	1.75	2.58	x	2.86	2.87		3.12	3.22	x
NO_3^- (mg/l)	0.20	0.23		0.16	0.19	x	0.19	0.23	x
Ca^{2+} (mg/l)	0.19	0.23	x	0.25	0.23		0.16	0.21	x
Mg^+ (mg/l)	0.07	0.08		0.08	0.08		0.07	0.07	
K^+ (mg/l)	0.08	0.07		0.06	0.06		0.08	0.08	
Na^+ (mg/l)	0.18	0.20		0.23	0.24		0.18	0.26	x

x = significant difference between values at 95% confidence interval.

Table 4-6. Equilibrated ionic mass for the snowmelt runoff plots and respective snowpacks.

	Tundra		Woodland		Forest	
	Plot mg, (mg.m^{-2})	Total snowpack mg, (mg.m^{-2})	Plot mg, (mg.m^{-2})	Total snowpack mg, (mg.m^{-2})	Plot mg, (mg.m^{-2})	Total snowpack mg, (mg.m^{-2})
TP	54.5 (.61)	73.2 (.81)	279.7 (3.27)	287.7 (3.36)	454.4 (5.05)	380.5 (4.23)
TDP	16.8 (.19)	23.7 (.26)	90.9 (1.06)	98.6 (1.15)	114.6 (1.27)	117.5 (1.31)
	g, (mg.m^{-2})	g, (mg.m^{-2})	g, (mg.m^{-2})	g, (mg.m^{-2})	g, (mg.m^{-2})	g, (mg.m^{-2})
Ca^{2+}	1.9 (21.10)	2.2 (24.40)	7.9 (92.40)	7.9 (92.40)	5.9 (65.60)	7.7 (85.60)
Mg^{2+}	.9 (10.00)	1.0 (11.10)	2.5 (29.20)	2.5 (29.20)	2.6 (28.90)	2.6 (28.90)
K^{+}	.8 (8.90)	.7 (7.80)	1.9 (22.20)	1.9 (22.20)	2.9 (32.20)	3.3 (36.70)
Na^{+}	1.8 (20.00)	1.9 (21.10)	7.3 (85.40)	7.6 (88.90)	6.6 (73.30)	9.5 (105.60)
NO_3^{-}	2.0 (22.22)	2.3 (25.6)	5.1 (59.6)	6.7 (78.4)	7.0 (77.80)	8.4 (93.30)

plots is consistently less than the corresponding plant community snowpacks. The differences found for TP mass are the most significant ionic mass differences determined, most pronounced in the tundra, where the plot value is .20 mg m^{-2} less than the snowpack and in the forest where the plot has .82 mg m^{-2} more TP than the snowpack.

4.3 Diversion flow

As discussed in chapter 3 diversion flow due to density differences of stratigraphic layers within the snowpack occurs in the early period of the springmelt along slopes in the woodland and forest plant communities.

4.3.1 Woodland runoff plot

Within the woodland snowpits excavated very near the open spruce runoff plot during the initial melt period, the diversion layer comprised the uppermost 10.4% (water equivalent) of the snowpack. This value was extrapolated to the snowpack in the runoff plot, as excavation of the snowpack within the runoff enclosure to determine the actual extent of the diversion layer would have disturbed the natural melt pattern.

Construction of the runoff plot is such that discharge originating from the upper snowpack layers cannot be separated from baseline flow resulting from water seeping vertically through the snowpack to the ground level. The snowpack within the runoff plot near the weir was sculpted at the initiation of melt such that the meltwater draining downslope in the upper snowpack in the manner described above was channeled into the draining tile of the runoff plot. The physical structure of the snowpits used to determine the diversion layer are shown in Figure 4-3.

During the woodland snow melt period the diversion layer began forming on 2 May and had deteriorated completely by 12 May when a saturated layer was first visible at the base of the snowpack. In the runoff plot it was estimated that 3309 L of snowpack water comprised the diversion layer. During the 2, 3, 8 and 9 May, 1555 L were discharged from the plot; approximately 47% of the water equivalence of the diversion layer. A review of the literature suggests that 50-80% of the ionic masses in the snowpack are removed during the initial 30% of snowmelt runoff. This could allow a prediction of the range of nutrient masses flushed out during diversion flow. In order to predict this mass flux, the assumption of chemical homogeneity of the snowpack has to be accepted. Although nutrient concentration differences do occur among certain stratigraphic layers in the snowpack, the actual values are so small that the significance is more statistical than ecological. It can be assumed for the sake of this discussion that chemical homogeneity exists from the top to the bottom of the snowpack.

Based on this assumption, 10.4% of the snowpack volume will contain 10.4% of the snowpack nutrient mass. During diversion flow approximately 47% of the water equivalence of the affected portion of the snowpack discharged. It would therefore be expected that mass flux from the diversion layer prior to its deterioration would be in the upper range or in excess of the 50 to 80% ion loss often measured and reported for the initial 30% of snowmelt runoff. The predicted values of mass flux during this time will range between 5.2 and 8.3% of the total snowpack

Figure 4-3: Physical structure of woodland snowpack snowpits used for determining the water equivalence of the diversion layer within the woodland runoff plot.

Snow layer	Density (g·cm^{3-})	Water equivalence(cm)
A	.12	0.60
	.19	1.90
	.20	1.20
B	.37	4.81
C	.29	2.32
	.26	2.34
	.32	3.20
D	.28	1.12
	.30	1.20
	.27	2.43
	.28	1.68
E	.31	7.44
	.25	3.00

Depth (cm): 120, 110, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10

Snow layer	Density (g cm^{3-})	Water equivalence(cm)
A	.16	1.12
	.20	1.60
	.24	1.20
B	.36	5.76
C	.30	2.70
	.27	1.35
	.24	1.20
	.29	2.03
D	.32	2.88
	.26	2.60
	.29	3.77
	.26	0.78
	.25	1.75
E	.29	10.73
	.25	1.00

Depth (cm): 140, 130, 120, 110, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10 ion content. On 2, 3, 8, 9 May 1980 the woodland snowpack diversion layer was sampled in close proximity to the woodland runoff plot in the fashion described in section 2.5.6. The daily mass flux out of the diversion layer within the runoff plot was determined by multiplying the ionic concentration determined using the funnel method by the daily plot runoff. The actual discharging mass for each nutrient and the predicted mass flux are noted in Table 4-7. The actual mass discharge from the diversion layer ranges between approximately 62% and 88% of the original mass, in accordance with the reported exsolving rates in the literature. From the diversion layer, the discharging mass of the ions, with the exception of TDP, ranged between 5% and 8% of the respective total snowpack ion masses (Table 4-7). This was due not to total dissolved phosphorus exsolving in the snowpack but rather a slight difference in TDP distribution through the snowpack at the snowpits used to determine the chemical load of the open spruce runoff plot. TDP mass in the discharging diversion layer accounted for only 4% of the total TDP mass in the snowpack. Although statistically significant differences between stratigraphic layers were not detectable among all of the sites for TDP, the uppermost sampling section (the diversion layer) of the snowpack at the two snowpits deemed representative of the nearby runoff plot had a lower TDP mass (1.13 $\mu g\ L^{-1}$) than the underlying snowpack (3.44 $\mu g\ L^{-1}$).

Table 4-7. The export of nutrient mass from the diversion layer within the woodland snowpack.

Date		Ca^{2+} mg	Mg^{2+} mg	K^{+} mg	Na^{+} mg	TDP mg	TP mg	NO_3^- mg
2 May 1980	Diversion	333	111	133	281	2.36	9.51	192
	Plot discharge	862	236	317	517	16.15	19.30	202
	Enrichment	529	125	184	236	13.79	9.79	10
3 May 1980	Diversion	107	36	43	91	.76	3.07	62
	Plot discharge	117	41	146	105	4.32	5.56	70
	Enrichment	10	5	103	14	3.56	2.49	8
8 May 1980	Diversion	13	5	4	12	.06	.35	7
	Plot discharge	14	6	25	21	1.04	1.86	11
	Enrichment	1	1	21	4	.98	1.51	4
9 May 1980	Diversion	87	34	12	80	.13	2.11	48
	Plot discharge	127	74	121	206	9.19	16.50	166
	Enrichment	40	40	109	126	9.06	14.39	118
% enrichment	2 May	160.0	113.3	139.0	83.6	584.0	103.0	5.2
	3 May	8.9	13.4	240.0	15.4	466.0	81.0	13.0
	8 May	8.4	29.6	558.0	85.1	1575.0	428.0	44.8
	9 May	56.1	117.7	900.0	158.5	7090.0	682.0	244.0
Total mass flux from diversion layer		540	186	192	464	3.31	15.04	309
Total mass in diversion layer		828	298	232	729	3.74	22.10	471
Total mass in runoff plot		7939	2539	2268	7314	91	280	5167
Proportion of mass exported from diversion layer (%)		65	62	83	64	88	68	66
The exported mass from the diversion layer as a % of the runoff plot snowpack mass		7	7	8	6	5	4	6

4.3.1.1 Daily and total nutrient mass budgets for the diversion layer of the woodland snowpack.

Table 4-7 lists the daily mass of nutrients fluxing out of the diversion layer and the corresponding daily flux of nutrients from the plot. Enrichment factors are listed for each ion. With the exception of NO_3^-, the percentage enrichment above the expected value follows a similar pattern, though the actual degree of enrichment among different ions is quite large. The results indicate that diversion flow seeps into the snowpack below the dense stratigraphic layer over which the saturated layer forms. The significant enrichment indicates that meltwater originating from the diversion layer was percolating into the lower stratigraphic layers most probably along the stems of shrubs and herbs and trunks of trees which extend into and in some cases through the diversion layer. This interaction likely explains the very significant increase in TDP and K^+ mass above that found in the diversion layer. It is widely reported that snow meltwater leaches high quantities of K^+ from organic matter in snowpacks. The leaching of organic matter may explain the increase in TDP mass as well, at least during this initial stage of melt.

The substantial enrichment noted in the runoff plot discharge on 9 May 1980 for most ions may indicate initial contact with the organic material at the base of the snowpack. A saturated layer at the base of the woodland snowpack was not noted on this date.

4.3.2 Forest runoff plot

At approximately the 30 cm depth (the depth varying slightly from site to site) in the snowpack, a layer of snow with a density of .35-.40 g cm^{-3} (the range of values from a sampling of 12 snowpits) impeded meltwater vertical flow, diverting the meltwater downslope. Observations in the snowpack adjacent to the snow runoff plot strongly suggest that between 1 May and 10 May 1983, much of the snowmelt water was diverted downslope by this dense layer of snow. During this period of time, approximately 5.8% of the total snow runoff plot water equivalence discharged into the weirbox, representing 17.4% of the total runoff plot water equivalence. Approximately 33.3% of the water contained within this upper strata discharged between 1 and 10 May.

It is expected as discussed above for the woodland snowpack, that between 50 and 80% of the ions measured in the upper 30 cm of the snowpack will be accounted for in the plot discharge during this period of time. Assuming uniformity of nutrient concentrations in the snowpack from the surface to the base, this range of discharging nutrients will account for between 8 and 14% of the total ion content of the snowpack. Table 4-8 demonstrates that only TP and NO_3^- mass discharging during this time period fall close to the expected discharge (15% and 16% respectively). Ca^{2+}, Mg^{2+}, Na^+, TDP and especially K^+ far exceed the expected mass discharge. In all cases, except TP, TDP and NO_3^-, the discharge mass far exceeds the total measured nutrient mass in the diversion layer. A plausible reason for this is that discussed for the woodland runoff plot, that is the downslope diversion of snowmelt water is not 100% efficient and a small portion of meltwater is channelled vertically to the snowpack base along branches of shrubs, and tree trunks. The enrichment factor shown (Table 4-8) is simply the percentage increase in the discharge of the actual measurement over the expected measurement. The expected measurement is assumed to be 65%

Table 4-8. The export of nutrient mass from the diversion layer within the forest runoff plot snowpack.

Date		Ca^{2+} mg	Mg^{2+} mg	K^+ mg	Na^+ mg	TDP mg	TP mg	NO_3^- mg
2 May 1980	Diversion	399	164	246	377	3.0	17.4	339
	Plot discharge	659	371	560	970	5.9	7.7	430
	Enrichment	260	207	314	593	2.9	9.7	91
3 May 1980	Diversion	227	109	139	274	1.7	10.6	246
	Plot discharge	560	90	569	620	5.4	7.9	410
	Enrichment	333	19	430	346	3.7	2.7	164
7 May 1980	Diversion	23	37	14	94	.1	1.9	89
	Plot discharge	116	46	24	214	1.1	2.7	213
	Enrichment	93	9	10	120	1.0	.8	124
% enrichment	2 May	65	127	128	157	97	56	27
	3 May	147	17	309	126	218	25	67
	7 May	404	24	71	128	10	238	139
Total mass flux from diversion layer		649	310	399	745	4.8	29.6	674
Total mass in diversion layer		975	460	451	1015	8	41	1150
Total mass in runoff plot		5900	2654	2875	6651	115	454	7002
Proportion of mass exported from diversion layer (%)		66	67	88	73	60	72	59
The exported mass from the diversion layer as a % of the runoff plot snowpack mass		11	12	14	11	4	7	10

(the mean reported exsolving figure for snowpacks) of the total measured ion mass within the top portion of the snowpack.

Although there is interaction at the downslope end of the forest runoff plot with snow below the diversion layer, as the meltwater seeps down along the sculpted face of the snowpack to the discharging tile, this would not account for the large increases in nutrient concentration recorded in the plot discharge (Table 4-8). Samples taken directly from the saturated runoff layer within the snowpack during the early melt yield concentrations for Ca^{2+}, Mg^{2+}, Na^+, K^+, TDP, TP and NO_3^- which are, on the average approximately 45% less than those samples taken from the discharging plot (Table 4-8). The differences between plot runoff and diversion layer exported mass listed in this Table clearly indicate enrichment during the 3 May runoff for all nutrients except Mg^{2+}. With reduced concentrations, the same pattern is evident on 7 May, with the exception of Ca^{2+}.

The nutrient concentrations measured directly from the saturation layer for 3 May are slightly elevated above the concentrations determined for the upper snowpack prior to melt. This would be expected if the exsolving process discussed by Seip (1980) and Johanneson and Henriksen (1978) occurs.

4.3.3 Implications of snowmelt water diversion for mass balance.

The occurrence and duration and hence significance of downslope snowmelt diversion is a product of snowpack stratigraphy at peak snow-year, the intensity of melt and the density and structure of vegetation in the snowpack.

The less pronounced the stratigraphic density differences within the subarctic snowpack, the greater the potential for interaction of meltwater and the underlying vegetation litter and soil surface. The relative importance of the diversion layer is a function of the volume of water diverted prior to interaction with the ground surface (Chapter 3). Many dense stratigraphic layers within the snowpack could divert a significant percentage of the snowpack's ionic composition into water bodies with little, if any, interaction with the vegetation, litter and soil at the base of the snowpack. Therefore, an increase in stratigraphic layers capable of diverting snowmelt will reduce the nutrient flux from land to water body as scour is reduced.

4.3.3.1 Diversion of meltwater by ice layers

Seip (1978) discusses the frequent occurrence of seasonal thaw and subsequent freezing in Norwegian snowpacks as being a significant factor in reducing the contact between meltwater and soil. Although the occurrence of ice layers in the snowpack in this region is rare (Price and Dunne, 1976; Manuel, 1983), formation of ice layers within the snowpack would increase the displacement of meltwater downslope. More probable than the formation of ice layers within the snowpack due to rainfall or thaw-refreeze periods during the snowyear is the formation of an ice layer on the ground surface by freezing rain in late fall. In the autumn of 1979 such a storm blanketed the Schefferville region with an ice layer up to .5 cm thick. Within a few days, an intense storm deposited approximately 25 cm of snow on the landscape. The ice layer persisted well into December, when it appeared to have melted - primarily, it is assumed, due to heat flow from the soil to the air column above the snowpack. A combination of climatic factors could result in the persistence of an ice layer at the base of the pack through the snowyear. This ice would reduce the contact of meltwater and ground surface at least during the initial portion of the discharge when the flux of hydrogen ions out of the snow column is highest.

4.4 Mass balance of the runoff plots

Nutrient mass balance calculations of the runoff plots enable an accurate evaluation of snowmelt runoff interaction with the ground vegetation, litter and soil surface at the base of the pack. In order to calculate the daily flux of nutrient mass from the runoff plot, the mean concentration of the discharge samples for each day was calculated and multiplied by the concomitant daily discharge. The number of samples taken daily was primarily a function of melt intensity. During very cool periods when discharge from the runoff plots was reduced to more or less a trickle only one sample was taken. Up to six samples were taken during periods of intense melt.

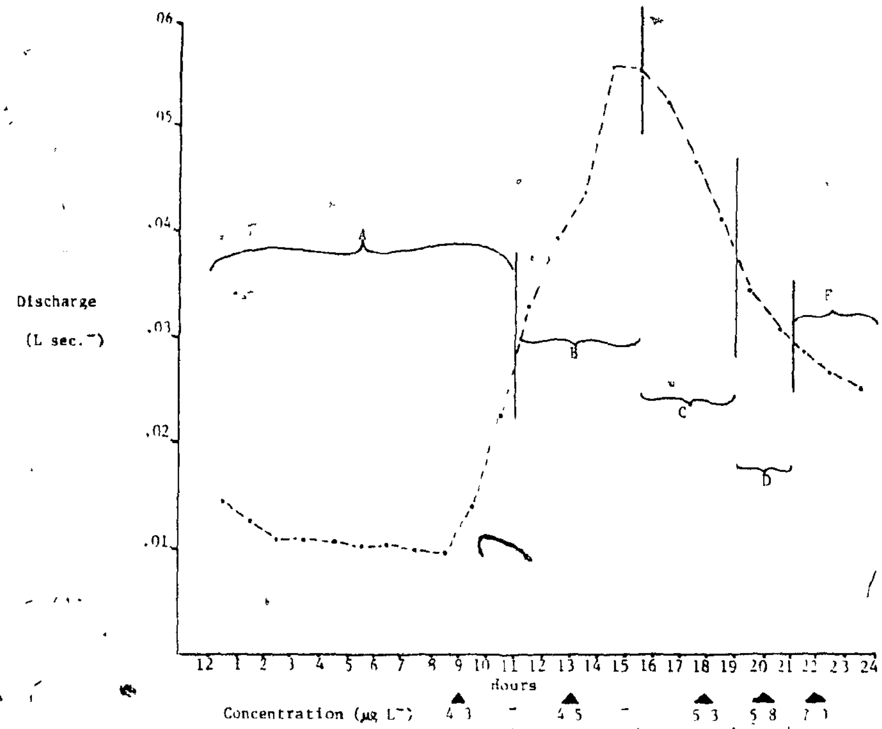
An alternative method of evaluating the mass flux from the plots involves calculating blocks of mass discharge during the 24 hour period. The number of blocks is a function of the number of samples taken during the day. The concentration for each sampling time would then be applied to a certain period of time on the hydrograph which would correspond to a specific melt water volume. The concentration times the designated volume would produce a block of mass discharged during that period of time.

The daily mass flux would simply be the sum of the block masses determined for each day. The problem with this calculation is that its accuracy may only be as good as the former method where the daily mean concentration is used. The inaccuracy is focused on the assumption of what volume corresponds to a particular measured concentration. The error involved here could be large. The potential for error is illustrated in Figure 4-4, which shows the hydrograph sampled in the forest meltwater runoff plot on 31 May 1980. In the initial hydrograph (a) the divisions pertaining to the sampled concentrations are chosen arbitrarily and the mass contributions to the outflow are calculated. The total mass of TP is 11,833 μg. The mass flux calculation using the mean concentration is 12,470 μg. In the second hydrograph (b) in Figure 4-4, the arbitrary boundaries are shifted by 1 hour. The resulting total mass flux of TP is now 12,083 μg. It is thus demonstrated that assigning the position of the arbitrary boundaries may result in substantial errors.

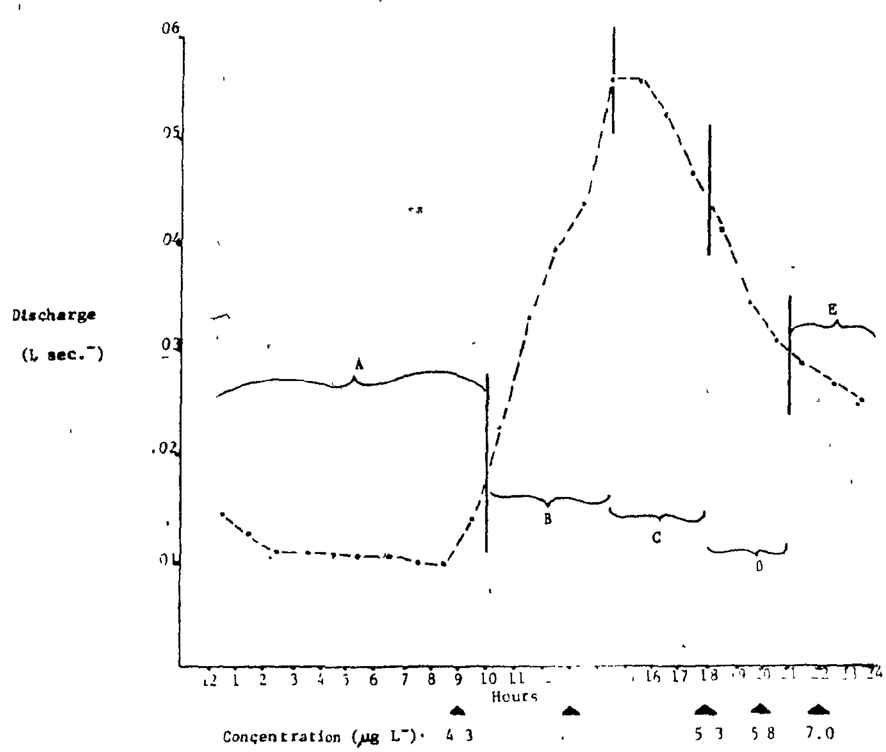
Scheider et al. (1979) examine various methods of accurately evaluating the P mass discharging in streams. They state that continuous measurement of discharge and occasional sampling for [P] determination produces an accurate estimate of the actual P mass discharge.

According to their work, the [P] determined at the midpoint of the time interval in question results in the most accurate estimation of the P mass discharging in streams. Application of this method to the data illustrated in Figure 4-4 results in an estimation of total mass discharge for this 24 hour period of 10,430 μg; somewhat less than the estimates given above. An alternative method discussed by Scheider et al. (1979) uses the mean [P] at the endpoints of the sampled time

Figure 4-4 Hydrograph illustrating change in calculated TP nutrient mass flux after a one hour shift in the arbitrary boundary. Forest melt water runoff plot, Elizabeth Lake, Labrador 31 May 1980



	A	B	C	D	E
Melt water volume (L)	486	713	599	233	287
Mass (µg)	2090	3209	3175	1351	2009
Total mass (µg)	11833				



	A	B	C	D	E
Melt water volume (L)	405	596	651	380	287
Mass (µg)	1742	2690	[illegible]	2204	2009
[illegible] (µg)	12083				

interval. Incorporation of this method with the example shown in Figure 4-4 results in a total mass discharge of 13,096 μg. It is assumed that a mean of several samples taken through the time period--in this case 24 hours (the method employed in this study)--would be more accurate than the two preferred methods listed by Scheider et al.

4.4.1 Tundra plot mass balance

About 95 percent of the snowpack in the tundra plant community in the Elizabeth Lake catchment melted between 26 April 1980 and 2 May 1980. The melt was interrupted on 1 May 1980 when ambient air temperatures dropped below freezing (-5.2°C, recorded in Schefferville). The remaining snow in the runoff plot melted and discharged on the following day. The daily flux of nutrients from the tundra plot is shown in Table 4-9 and illustrated in Figure 4-5.

On Table 4-9 there are two values listed for daily mass flux. The initial value is that calculated from the actual daily volume of water discharging from the plot. During the total melt period, there was an 11.3% discrepancy between the estimated volume of water in the snowpack (after the error of the sampling method for water equivalence determination was accounted for) and the measured volume of water discharging from the plot. During the short runoff period, leakage occurred at the discharging end of the runoff plot. As the soil was frozen (section 3.3) and evaporation was close to zero (section 3.3) it is assumed that most of the 11.3% discrepancy can be accounted for in the leakage. Thus the second number listed in brackets for total daily mass includes the 11.3%, assumed to discharge proportionally to the daily melt pattern.

Table 4-9. Daily flux of nutrients from the tundra plot.

	Ca^{2+} (mg)	Mg^{2+} (mg)	Na^{+} (mg)	K^{+} (mg)	TDP (mg)	TP (mg)	NO_3^- (mg)
April 26	38 (43)	18 (21)	36 (40)	17 (19)	2.80 (3.16)	3.74 (4.22)	27 (31)
27	22 (25)	27 (31)	73 (82)	73 (82)	1.96 (2.21)	3.00 (3.38)	29 (33)
28	281 (317)	112 (127)	320 (361)	135 (152)	7.62 (8.58)	18.20 (20.60)	124 (139)
29	1,060 (1,192)	595 (671)	2,310 (2,608)	992 (1,118)	26.80 (30.20)	44.60 (50.30)	1,060 (1,192)
30	1,580 (1,775)	869 (979)	2,120 (2,387)	1,520 (1,714)	34.40 (38.80)	59.80 (67.40)	543 (612)
May 1	--	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2	162 (183)	108 (124)	123 (158)	140 (158)	5.05 (5.69)	6.25 (7.04)	132 (148)
	3,140 (3,530)	1,730 (1,950)	4,980 (5,640)	2,880 (3,240)	78.70 (88.70)	136.00 (153.00)	1,910 (2,156)

Figure 4-5: Daily flux of nutrients from the tundra meltwater runoff plot.

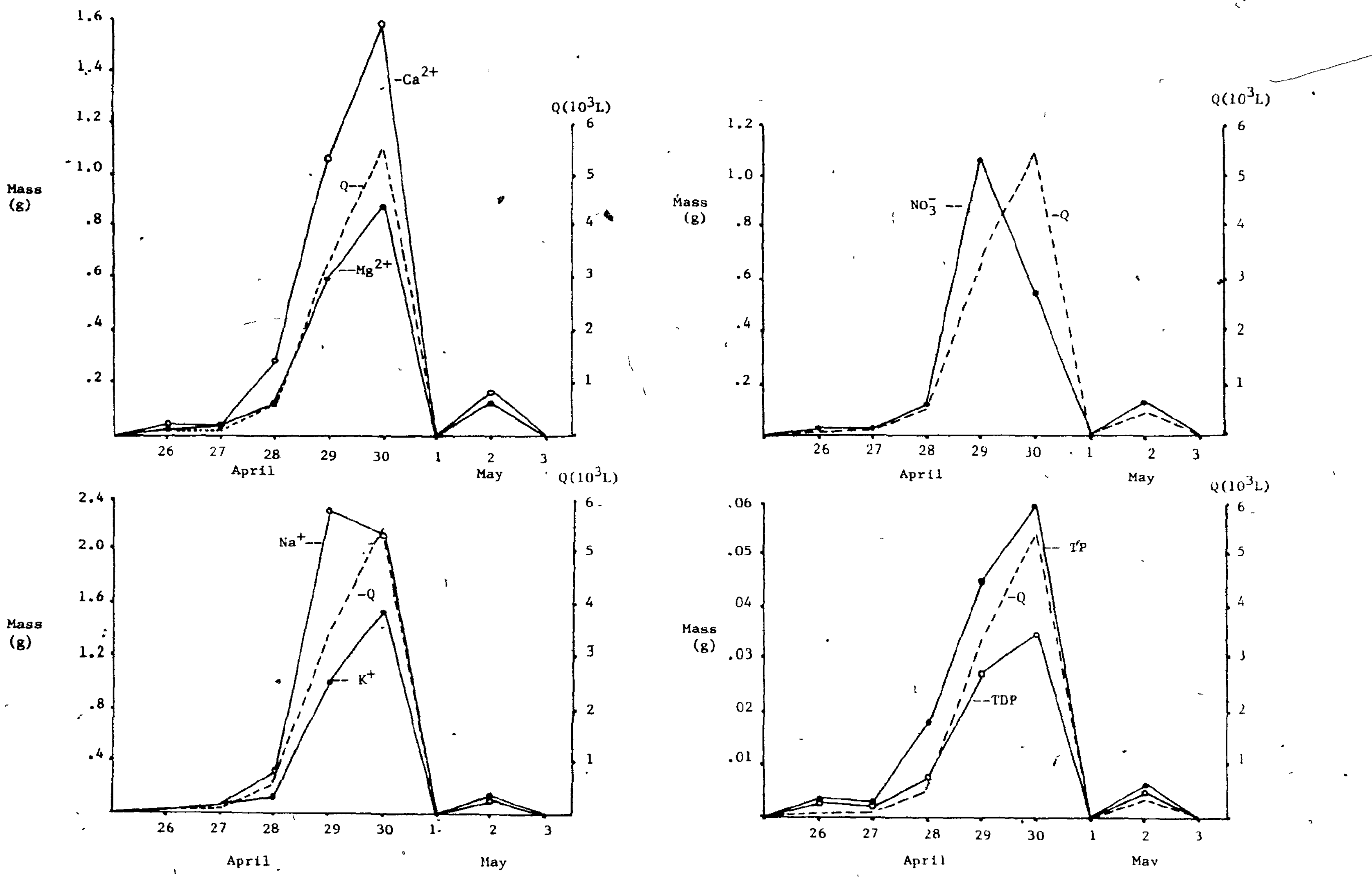


Figure 4-5 illustrates the relationship between daily plot discharge and nutrient flux. Generally speaking the mass flux appears to follow the discharge pattern. This is particularly true for Ca^{2+}, Mg^{2+}, K^{+}, TDP and TP. The maximum flux for Na^{+} and NO_3^{-} occurs one day prior to the maximum snowmelt runoff. For Na^{+} the mass discharging during peak runoff is still high. NO_3^{-} flux the day prior to peak runoff amounts to approximately 52% of the total NO_3^{-} mass discharging from the tundra plot. The day of peak meltwater discharge, approximately 28% of the measured NO_3^{-} mass discharges from the plot. This is most likely attributable to reduced NO_3^{-} available for scour by meltwater runoff.

The ionic mass discharging from the tundra plot on 2 May 1980 is thought to be a partial product of the diurnal freeze-thaw cycle common at this time of the year when the insulating capacity of the snowpack is much reduced. The Ca^{2+}, Mg^{2+}, and NO_3^{-} concentrations in the meltwater runoff of 2 May increased significantly after the freezing period of 1 May 1980. This indicates that the freeze and subsequent thaw may be important in releasing nutrients from organic matter at the base of the snowpack.

Linear regression between daily nutrient concentrations and discharge for the tundra runoff plot yielded no significant (95% CI) relationships. This is not surprising as the layers at the base of the snowpack with which the meltwater is interacting are composed of essentially three separate units; soil surface, mor and ground vegetation. Thaw along the slope within these units will be progressively greater the further downslope as the volume of meltwater flowing downslope at the snowpack base would increase. Discharge at anytime during the melt would reflect the sum product of thaw events along the slope. As such, a clear cut pattern may not develop as different units at the snowpack base will have different available-scourable nutrients.

The results of the mass balance for all nutrients in the tundra plot are presented in Table 4-10 employing the estimated snowpack mass and the measured discharge. With the exception of NO_3^- the calculated mass balances indicate substantial scouring of nutrients from the organic matter and soil surface at the base of the snowpack. Enrichment of meltwater is calculated in the following manner;

$$\frac{\text{Discharge mass} - \text{Snow mass}}{\text{Snow mass}} \times 100$$

Enrichment of the meltwater runoff from the tundra sampling plot is highest for TDP (353%); other nutrients also show substantial scouring: $K^+ > Na^+ > Mg^{2+} > TP > Ca^{2+}$ (Table 4-10). For NO_3^-, approximately 4% of the mass originally in the runoff plot snowpack is retained, presumably adsorbed by the vegetation and soil surface at the base of the snowpack.

4.4.2 Open spruce-lichen woodland runoff plot mass balance

4.4.2.1 Estimation of daily nutrient mass contribution from the snowpack

In order to determine the daily change in snowmelt runoff chemistry, that is whether retention of snowpack source nutrients or scour of nutrients from organic matter occurred, the daily contribution of nutrients from the snowpack to the base of the snow was ascertained. This was possible in the woodland and forest snowpacks due to the presence of diversion layers. Absence of a diversion layer in the

Table 4-10. Total nutrient mass discharge from meltwater runoff enclosures, original snowpack nutrient mass at peak snowyear and resulting enrichment of snowmelt water attributed to scouring of available form nutrients during overland flow.

	Total mass flux	Snowpack mass	Scoured mass	% Enrichment
Tundra				
TDP μg	$8.87 \cdot 10^{4}$	$1.96 \cdot 10^{4}$	$6.91 \cdot 10^{4}$	353
TP μg	$1.53 \cdot 10^{5}$	$.61 \cdot 10^{5}$	$.92 \cdot 10^{5}$	151
NO_3^- mg	$2.16 \cdot 10^{3}$	$2.24 \cdot 10^{3}$	$-.08 \cdot 10^{3}$	-4 retention
Ca^{2+} mg	$3.53 \cdot 10^{3}$	$2.13 \cdot 10^{3}$	$1.40 \cdot 10^{3}$	66
Mg^{2+} mg	$1.95 \cdot 10^{3}$	$.74 \cdot 10^{3}$	$1.21 \cdot 10^{3}$	164
Na^+ mg	$5.64 \cdot 10^{3}$	$2.01 \cdot 10^{3}$	$3.63 \cdot 10^{3}$	181
K^+ mg	$3.24 \cdot 10^{3}$	$.84 \cdot 10^{3}$	$2.40 \cdot 10^{3}$	286
Woodland				
TDP μg	$43.33 \cdot 10^{4}$	$9.10 \cdot 10^{4}$	$34.23 \cdot 10^{4}$	376
TP μg	$7.22 \cdot 10^{5}$	$2.79 \cdot 10^{5}$	$4.46 \cdot 10^{5}$	160
NO_3^- mg	$8.32 \cdot 10^{3}$	$5.09 \cdot 10^{3}$	$3.23 \cdot 10^{3}$	63
Ca^{2+} mg	$13.82 \cdot 10^{3}$	$7.95 \cdot 10^{3}$	$5.87 \cdot 10^{3}$	74
Mg^{2+} mg	$3.94 \cdot 10^{3}$	$2.54 \cdot 10^{3}$	$1.40 \cdot 10^{3}$	55
Na^+ mg	$10.19 \cdot 10^{3}$	$7.31 \cdot 10^{3}$	$2.58 \cdot 10^{3}$	35
K^+ mg	$9.19 \cdot 10^{3}$	$2.28 \cdot 10^{3}$	$6.91 \cdot 10^{3}$	303
Forest				
TDP μg	$29.91 \cdot 10^{4}$	$11.42 \cdot 10^{4}$	$18.50 \cdot 10^{4}$	162
TP μg	$7:16 \cdot 10^{5}$	$2.70 \cdot 10^{5}$	$4.45 \cdot 10^{5}$	165
NO_3^- mg	$11.40 \cdot 10^{3}$	$6.89 \cdot 10^{3}$	$4.51 \cdot 10^{3}$	65
Ca^{2+} mg	$20.37 \cdot 10^{3}$	$5.88 \cdot 10^{3}$	$14.49 \cdot 10^{3}$	246
Mg^{2+} mg	$7.99 \cdot 10^{3}$	$2.34 \cdot 10^{3}$	$5.65 \cdot 10^{3}$	241
Na^+ mg	$16.84 \cdot 10^{3}$	$6.19 \cdot 10^{3}$	$10.65 \cdot 10^{3}$	172
K^+ mg	$13.13 \cdot 10^{3}$	$2.89 \cdot 10^{3}$	$10.24 \cdot 10^{3}$	354

tundra snowpack eliminated the possibility of separating the daily snowpack nutrient contribution from the runoff plot discharging nutrient mass.

Estimation of the nutrient flux from the snowpack was based on samples taken from the upper portion of the snowpack defined above (section 4.3.1) as the diversion layer. The sampling method is discussed in Chapter 3. The nutrient flux pattern for the diversion layer was also used for the lower portion of the snowpack. The justification for this is that the lower portion is initially similar in chemistry (section 4.2) and snowpack structure (stratigraphy, density, water equivalence - Chapter 3) to the upper layer. Further it is assumed that the organic litter composition within the upper and lower snowpack should be similar as both portions of the snowpack are subject to similar organic matter deposition because the source, the surrounding vegetation, remains essentially the same through the snowyear.

The pattern of ion exsolving in the snowpack varies according to the nutrient. Basically, the pattern is as reported by Seip _et al._ (1980); that is, a significant portion of the ions are exsolved out of the snowpack during the initial 30% of the melt.

During the initial 30% of melt from the diversion layer, the following percentages of specific nutrient mass initially present therein are discharged: TDP (85%), K^{+} (77%), TP (58%), NO_3^{-} (56%), Ca^{2+} (55%), Na^{+} (53%), Mg^{2+} (51%). Flux of the remaining mass of nutrients during the final 70% of the melt runoff was determined by assuming that mass discharge would be discharged evenly on a weighted mean basis with meltwater discharge.

This method which assumes equal mass discharge per unit of snowmelt water discharge is basically inaccurate; however, because of the absence of data or a better method of simulation it will suffice. In the melt period the initial mass flux during the final 70% of water discharge will contain proportionally more mass than that discharging during the latter period. Data published by Johannessen and Henriksen (1978) resulting from field lysimeter and laboratory snowmelt studies show that during the latter 50% of the melt period, the curve describing the mass flux of nutrients follows the hydrograph, suggesting proportional mass flux with meltwater discharge. The water discharge recorded after the initial 30% and prior to the last 50% discharge of meltwater volume had more mass per unit discharge than that found during the last 50% of meltwater discharge, and significantly less than sampled in the initial 30% melt.

In terms of the total chemical mass balance for the runoff plots, any error resulting from the weighted mean calculation for mass discharge will be minimal as the displacement of mass should balance out.

In order to estimate the nutrient mass flux, the upper and lower snowpacks are each divided into two melt events; the initial 30% and the secondary 70%. For the two events in the upper snowpack, the volumes are calculated such that they can be used to estimate the flux of nutrients out of the snowpack on a daily basis. The hydrological discharge for the lower snowpack is evaluated in similar fashion for the same purpose.

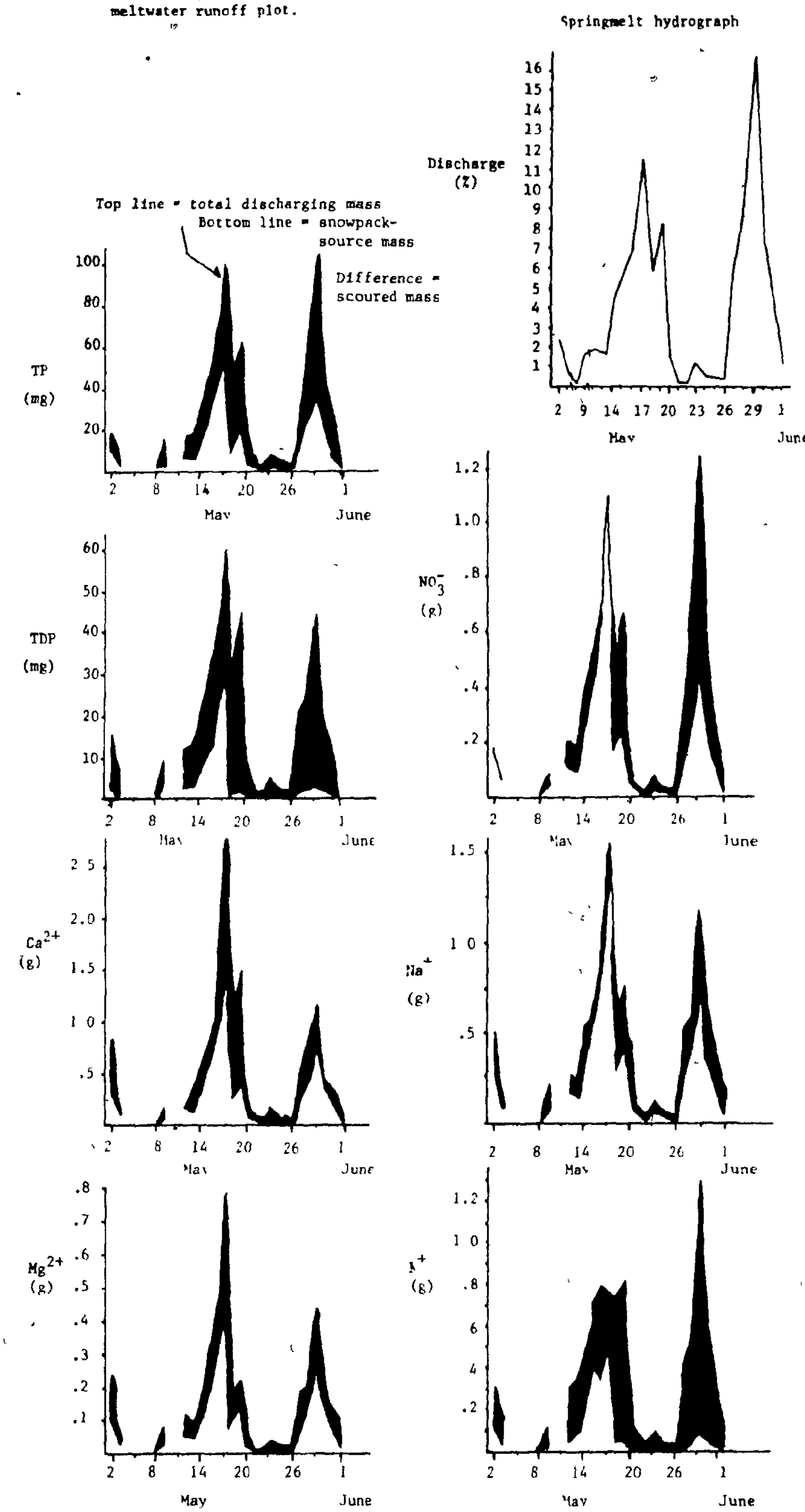
As a saturated layer was first observed at the base of the woodland snowpack on 12 May 1980 it was assumed that on this date the entire snowpack within the woodland runoff plot began contributing meltwater.

4.4.2.2 Nutrient input to and output from the woodland runoff plot

Figure 4-6 illustrates on a daily basis; a) the measured/calculated snowpack meltwater mass flux to the ground, b) the measured mass flux from the woodland plot and c) the difference between these two measurements which is assumed to be the mass of nutrients largely scoured from the base of the snowpack. The pattern of mass discharge from the woodland plot vaguely resembles the bimodal snowmelt runoff hydrograph. The daily values for each ion are listed in appendix C. The total mass balance for each ion is listed in Table 4-10.

For all measured ions, on all snowmelt days the mass flux exceeded the calculated snowpack contribution. Enrichment of mass in the plot outflow above that determined for the runoff plot snowpack, was greatest for TDP (376%) while Na^+ had the least enrichment (55%). The possibility of error in calculating the latter 70% of the snowmelt mass flux both within the diversion layer and the large underlying snowpack has been acknowledged. Implementation of data more attuned with the actual snowmelt runoff contributions at this time would likely result in decreased scour during the 18, 19 May (when the initial 20% of the final 70% of runoff from the larger snowpack occurs) and increased scour during the last few days of the melt. The scour of nutrients from the ground vegetation, mor and soil surface is examined in greater detail in Chapter 5.

Figure 4-6 Nutrient scour pattern during the 1980 springmelt in the woodland meltwater runoff plot.



4.4.3 Closed spruce-moss forest runoff plot mass balance

4.4.3.1 Estimation of daily nutrient mass contribution from the snowpack

During the melt period, the daily contribution of snowpack nutrient mass to the base of the snowpack was assessed in the same manner as described for the woodland runoff plot (section 4.4.2.1). A glass funnel was used to collect samples from the diversion layer of the forest runoff plot snowpack as described in Chapter 3.

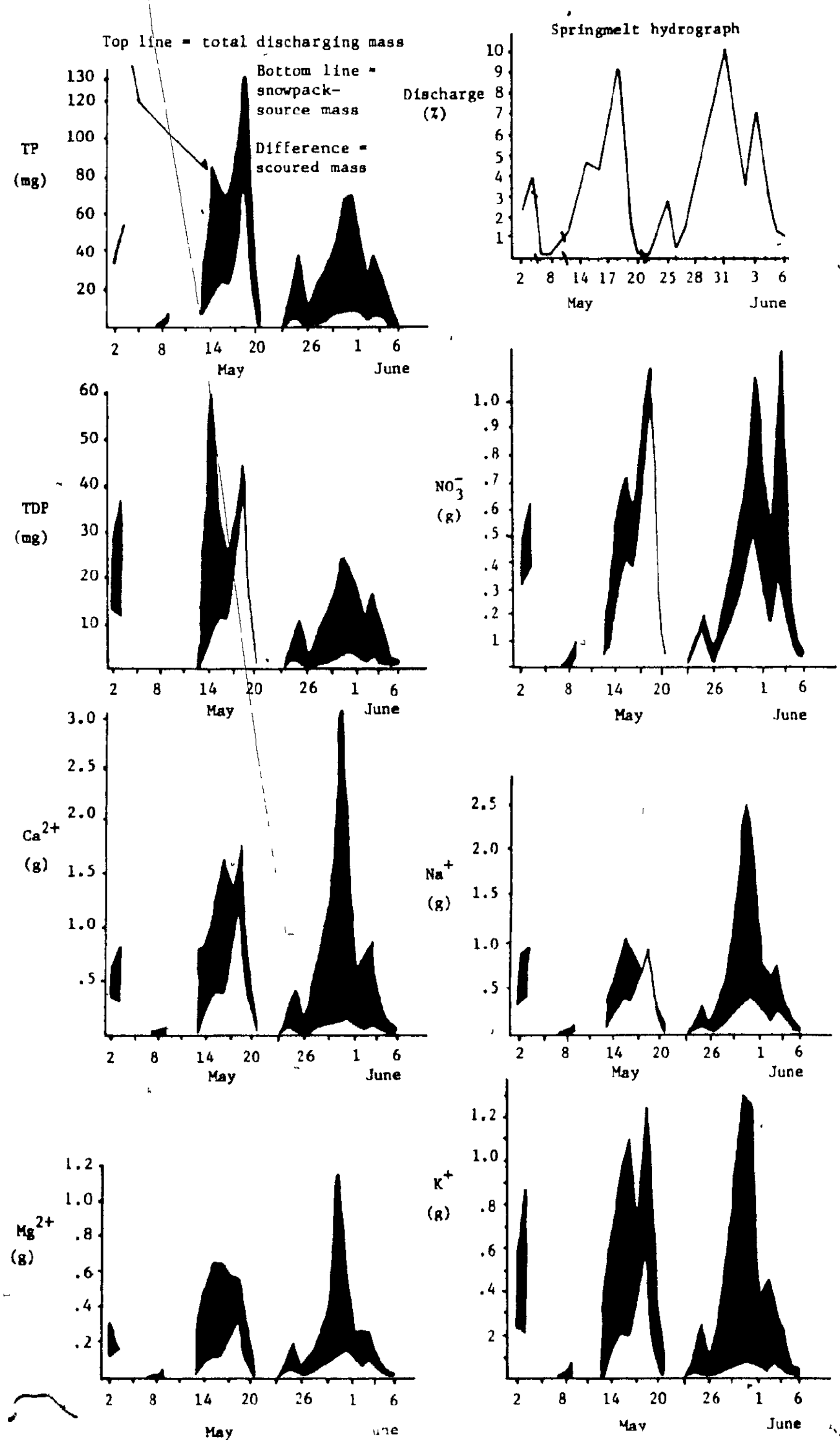
During the initial 30% of meltwater discharge from the diversion layer in the forest runoff plot, 50% of the NO_3^-, Na^+ and Mg^{2+}; 55% of the TP and 80% of the K^+, Ca^{2+} and TDP mass contained initially within the diversion layer discharged. The discharge of the balance of the nutrient mass with the remaining 70% of the meltwater within the diversion layer is determined in the same manner as described in section 4.4.2.1 for the woodland snowpack. This melt pattern determined for the diversion layer of the forest snowpack is applied to the larger portion of the snowpack underlying the diversion layer.

The initiation of melt for the lower snowpack was assumed to be 14 May, when the diversion layer had clearly broken down and a saturated layer formed at the base of the snowpack. For a four day period (14, 15, 16, 17 May) there is nutrient contribution from the upper pack and the lower pack. The division of melt for these days is assumed to be 50% from the upper and 50% from the lower pack. An error in this estimate of even 50% would not affect the nutrient flux significantly.

4.4.3.2 Nutrient input to and output from the forest runoff plot

Figure 4-7 illustrates on a daily basis; a) the measured/calculated snowpack meltwater nutrient mass flux to the base of the snowpack, b) the measured nutrient mass flux from the forest plot and c) the difference between these two measurements which is assumed to be the mass of nutrients largely scoured from the base of the snowpack. The daily values for each ion are listed in appendix D. The total mass budget for each ion is listed in Table 4-10. The calculated mass balance indicate significant scouring of all nutrients from the base of the snowpack. Enrichment is highest for K^+ (354%) and lowest for NO_3^- (65%). The scour of nutrients from the ground vegetation, mor and soil surface is examined in greater detail in Chapter 5.

Figure 4-7: Nutrient scour pattern during the 1980 springmelt in the forest meltwater runoff plot.



4.5 Conclusions

This chapter has defined and discussed the formation and daily flow patterns of discharge and nutrient mass within the diversion layers in the woodland and forest snowpacks. It is shown that the stratigraphy of the snowpack can play a role in diverting meltwater downslope prior to contact with the ground surface.

Whether this process occurs each spring is unknown, though diversion of meltwater downslope by ice layers in snowpacks in temperate areas has been reported (Colbeck, 1977; Seip, 1978), diversion of flow resulting from dense snow strata is unreported. The timing of the diversion has potentially significant repercussions on aquatic systems receiving the diverted water as it occurs during the initial period of the melt when a great proportion of the ionic content of the snowpack is exsolved. Bypassing of the ground layers - potentially capable of buffering the initial acidic meltwater runoff - ensures that the water bodies receiving this portion of the melt water receiving a high concentration of H^+. The significance of this process is a product of the stratigraphic density differences and the percentage of the snowpack water equivalence affected (i.e.; the depth of the diversion layer within the snowpack).

This chapter has examined the terrestrial nutrient mass balance during springmelt runoff. It has been established that significant masses of all nutrients examined, except NO_3^- in the tundra, are scoured from the organic layers at the base of the snowpack.

CHAPTER 5

NUTRIENT SCOUR PATTERN IN THE WOODLAND AND FOREST PLANT COMMUNITIES

5.1 Introduction

This chapter investigates the daily pattern of nutrient discharge from the woodland and forest runoff plots throughout the melt period. Emphasis is placed on the two peak periods of meltwater discharge to discern changes in pattern which may provide insight into the interaction of meltwater and the organic horizons and mineral soil surface at the snowpack base.

5.2 The daily pattern of scoured nutrient flux from the woodland and forest runoff plots.

It is of interest to determine whether the difference in snowmelt water between the first and second major discharge peaks in both runoff plots, is reflected in the chemistry of the meltwater discharging from the respective runoff plots. This question will be addressed further in this chapter.

The daily pattern of scoured nutrient flux was not determined for the tundra runoff plot as a diversion layer--from which the elution pattern of exsolved ions in the woodland and forest snowpack was determined--did not form during the melt period.

Based on the runoff plot data, significantly more Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and NO_3^{-} mass is scoured from the base of the forest snowpack than from the base of the woodland snowpack. Only greater masses of TP and TDP are scoured from the woodland site. Comparative masses are listed in Table 5-1. Due to the greater water equivalence of the forest runoff plot snowpack, the scoured nutrient masses are corrected such that comparisons can be made between the two sites. This correction simply expresses the nutrient flux which could be expected given equal volumes of discharging water from each site. The corrected values for the forest runoff plot are listed in brackets beside the actual values. A comparison of forest and woodland scoured nutrient mass flux is expressed in ratio form.

During the woodland and forest snowpack melt there are three distinct periods of scoured nutrient mass flux. These coincide with the initial peak of meltwater runoff which is defined above (chapter 3) as diversion flow and the two larger remaining periods of meltwater runoff

Table 5-1. Total scoured nutrient mass from forest and woodland meltwater runoff plots.

	Forest ($mg\ m^{-2}$)		Ratio[2]	Woodland ($mg\ m^{-2}$)
Ca^{2+}	161	(139)[1]	2.01:1	69
Mg^{2+}	63	(54)	3.38:1	16
K^+	114	(98)	1.21:1	81
Na^+	118	(102)	3.00:1	34
TP	5	(4)	1:1.25	5
TDP	2	(1)	1:4	4
NO_3^-	50	(43)	1.13:1	38
meltwater discharge (L)	36740	(31796)	1:1	31796

[1]The values listed in brackets represent the scoured ion mass from the forest equilibrated with respect to the water equivalence of the woodland runoff plot.

[2]The ratio expressed is that between the equilibrated forest values and the real woodland values.

(Figure 3-3). The exceptions to this pattern include TP and TDP for both the forest and woodland and NO_3^- in the woodland. For these cases there is no initial peak of scoured mass.

For the sake of comparative discussion of nutrient discharge from the woodland and forest snowmelt runoff plots, the initial peak is ignored as it contributes relatively insignificant proportions of the total scoured nutrient mass. The two large peaks of scoured nutrient discharge from the forest plot occur between 14 and 19 May (inclusive) and the 27 and 31 May (inclusive). The peaks at the forest site account for 30.7 and 49.6% of the total meltwater discharge respectively. The discharge recorded at the woodland runoff plot during each peak was essentially equal, 42.7% and 42.9% respectively.

The two major peaks are important for comparative reasons because the initial peaks in both the woodland and forest plots include the initial flush of meltwater from the larger portion of the respective snowpacks beneath the aforementioned diversion layer. This portion of the meltwater discharge from the snowpack contains disproportionately high fractions of the original ionic composition of the snowpack. The second peaks of meltwater discharge from the snowpacks to the ground surface are by comparison with the chemistry of the initial peaks rather dilute. For example, the flux of snowpack-source Ca^{2+} during the initial peak in the forest snowpack runoff represents approximately 69% of the total Ca^{2+} originally in the snowpack. The second peak discharges approximately 13% of the snowpack's original Ca^{2+} mass. This disproportional discharge of Ca^{2+} in the forest snowpack is representative of the pattern of the exsolving of other nutrients out of the woodland and forest snowpacks.

In the two plant community runoff plots the two peaks of discharge account for between 71 and 84% of the scoured nutrients in the woodland and between 56 and 84% in the forest. The percentages of nutrients scoured during each peak in both the woodland and forest runoff plots are listed in Table 5-2.

Comparison of the first and second peak meltwater discharge periods for woodland and forest is made possibly by equilibrating the values such that the total meltwater discharge for both initial and then both secondary peaks are equal. This allows a comparison of nutrient availability between the woodland and forest plot during the initial peaks and then during the second peaks. Table 5-3 below illustrates this comparison. During the initial and secondary peaks nutrient availability is much higher per unit of discharge in the forst meltwater runoff, this is especially so for Ca^{2+}, Mg^{2+} and Na^{+} during the second peak. The only exceptions to this are TDP and NO_3^- in the first peak and TP and TDP in the second where the scour, per unit of discharge is higher in the woodland plot.

The apparent differences in nutrient mass available for scour by meltwater in the woodland and forest plant communities are thought to be a product of the increased organic matter in the forest. Werren (1978) reports that in the Schefferville region the litter fall within the forest is significantly greater than that in the woodland. This would be expected as the standing biomass is observedly greater than that in the woodland. The greater mass of TDP available for scour in the woodland may be due to the notable (observed, not measured) accumulation of dwarf birch leaves on the lichen mat in the fall. Moore (1984) reports that in the subarctic approximately 63% of the first year litter decom-

Table 5-2. The percentage of total nutrient scour recorded during the first and second major meltwater runoff peaks in both forest and woodland runoff plots.

	Forest 1st Peak	2nd Peak	Woodland 1st Peak	2nd Peak
	%	%	%	%
Ca^{2+}	25.44 (.83)*	57.89 (1.17)*	59.84 (1.40)*	17.86 (.42)*
Mg^{2+}	38.75 (1.26)	45.38 (.92)	47.43 (1.11)	24.84 (.58)
K^{+}	32.34 (1.05)	48.21 (.97)	37.40 (.88)	43.00 (1.00)
Na^{+}	17.21 (.56)	61.38 (1.25)	31.90 (.75)	40.08 (.93)
TP	35.54 (1.16)	20.70 (.42)	35.63 (.84)	41.80 (.97)
TDP	35.02 (1.14)	38.71 (.78)	45.42 (1.06)	33.97 (.79)
NO_3^-	20.05 (.65)	63.87 (1.29)	32.20 (.75)	52.59 (1.22)
Q	30.72	49.56	42.66	42.98

* Scour efficiency is given in brackets. This is defined as the percentage of scour per percentage of discharge within each peak.

Table 5-3. A comparison of nutrient availability between the woodland and forest plot during the first and second major meltwater peaks.

	1st Peaks				2nd Peaks			
	Forest (mg m^{-2})	Ratio[2]	Woodland (mg m^{-2})		Forest (mg m^{-2})	Ratio	Woodland (mg m^{-2})	
Ca^{2+}	41.06	1.20:1	41.07	(34.17)[1]	93.2	7.6:1	12.26	(15.32)
Mg^{2+}	24.33	2.71:1	10.73	(8.97)	28.49	7.0:1	4.07	(5.09)
K^{+}	36.79	1.46:1	30.23	(25.15)	54.76	1.26:1	34.77	(43.44)
Na^{+}	20.36	2.28:1	10.78	(8.93)	73.23	4.35:1	13.48	(16.84)
TP	2.02	1.13:1	2.15	(1.79)	2.18	1:1.25	2.18	(2.72)
TDP	.72	1:2.10	1.82	(1.51)	.80	1:2.13	1.36	(1.70)
NO_3^-	10.05	1:1.01	12.17	(10.13)	31.99	1.29:1	19.88	(24.84)
Q (L)	11286	1:1	13564	(11286)	18208		13665	(18208)

1 Since the discharge of meltwater between the forest and woodland differs for the 1st and 2nd peaks, the woodland values were multiplied by a factor equilibrating the discharges.

2 The ratio expressed is that between the equilibrated woodland values and the real forest values.

position occurs between just prior to the formation of the annual snowpack and the end of the snowyear. Moore (1983) reports a substantial fraction of the decomposition which is reported at this time occurs in late autumn. Regardless of the timing of the decomposition, the byproducts of this process - available nutrients - would be subject to scour by meltwater during the spring melt.

The change in scoured nutrients per unit of discharge is evident between periods of peak discharge in both plant communities (Table 5-3). The only exceptions are TP, Na^+ and K^+ flux in the woodland runoff. This change for most nutrients indicates that the source of supply changes through the melt period.

For Ca^{2+}, K^+, and TP the pattern of scour differs significantly between the woodland and forest runoff plots. The woodland pattern shows a high scour of Ca^{2+} in the initial peak diminished significantly in the second peak. This is reversed in the forest plot. In terms of scour efficiency K^+ scour in the forest plot is somewhat greater during the first of the two major peaks of mass discharge; this pattern is reversed in the woodland plot. In the woodland plot runoff, TP mass scoured during the second peak is slightly greater than that recorded in the initial peak. In the forest runoff, the scour of TP is much more pronounced during the initial peak. Scour patterns between the two runoff plots for Na^+, Mg^{2+}, TDP and NO_3^- are the same. Certain assumptions can be drawn with regard to the pattern observed in Table 5-4.

A reduction in the supply of nutrients from the first major discharge peak to the second peak means either one of four things occurs, or a combination of all: 1) adsorption of nutrients by thawed soil at the base of the slope, 2) absorption of certain nutrients (P, N) by

Table 5-4. Nutrient scour during the first and second major meltwater runoff peaks in both forest and woodland runoff plots.

Forest

	1st peak scour (mg m^{-2})	Ratio	2nd peak scour (mg m^{-2})	
Ca^{2+}	41.06	1:1.41[2]	93.2	(57.77)[1]
Mg^{2+}	24.33	1.38:1	28.49	(17.66)
K^{+}	36.70	1.08:1	54.76	(33.94)
Na^{+}	20.36	1:2.23	73.23	(45.39)
TP	2.02	1.49:1	2.18	(1.35)
TDP	.72	1.44:1	.80	(.50)
NO_3^-	10.05	1:1.97	31.99	(19.83)

Woodland

	1st peak scour (mg m^{-2})	Ratio	2nd peak scour (mg m^{-2})	
Ca^{2+}	41.07	3.38:1[2]	12.26	(12.16)[1]
Mg^{2+}	10.73	2.66:1	4.07	(4.04)
K^{+}	30.23	1:1.14	34.77	(34.51)
Na^{+}	10.78	1:1.24	13.48	(13.38)
TP	2.15	1:1	2.18	(2.16)
TDP	1.82	1.35:1	1.36	(1.35)
NO_3^-	12.17	1:1.62	19.88	(19.73)

1 The figures in brackets represent the equilibrated scour values. The equilibration has been conducted in accordance with the volume of meltwater discharged during the initial peaks in the forest and woodland runoff plots respectively.

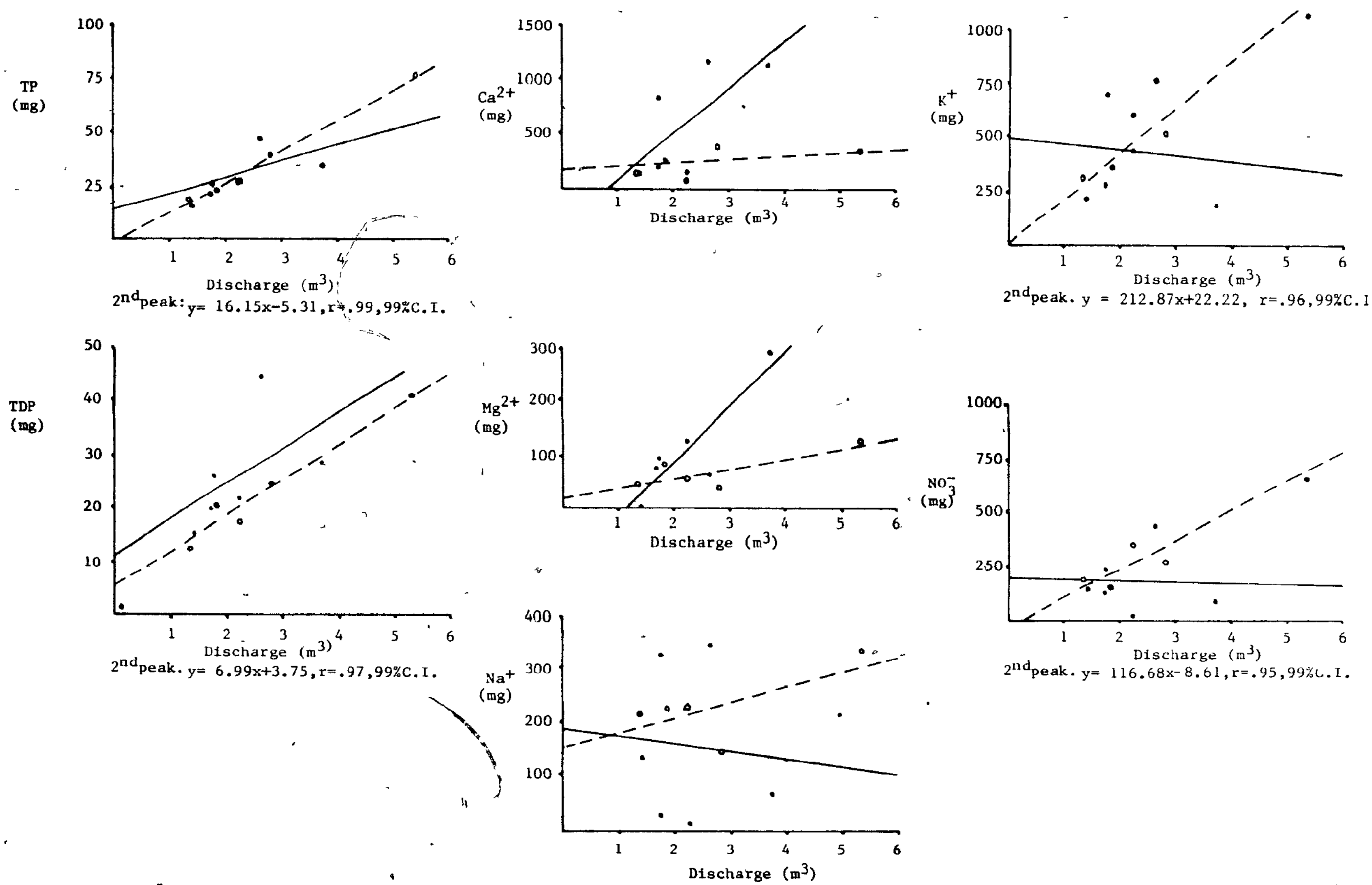
2 The ratio expressed is that between the equilibrated 2nd peak values and the actual 1st peak values.

shallow root systems or microbial organisms, 3) reduced supply of nutrients available for scour and 4) reduction of cation exchange as the ionic content in the snowpack is depleted significantly by the time the second major discharge is recorded. An increase in nutrient supply from the first to second peaks is attributable to continued thaw in the organic layers at the base of the snowpack and therefore increased supply of certain nutrients available for scour.

Deciphering the pattern of mass discharge is aided by considering the relationship between discharge and the amount of mass scoured from the meltwater plots during the two major peaks of snowmelt runoff (Figures 5-1 and 5-2). Linear regression analysis of the impact of discharge on mass output is statistically invalid if the results are used to predict mass flux as the mass used in the relationship is a direct product of the dependant variable - discharge. Though statistically invalid for predictive purposes, it is used here as a method of comparing the two periods of peak discharge within each runoff plot.

In the woodland runoff plot a pattern exists for K^+, TDP, TP and NO_3^- where, during the primary peak (14-19 May, inclusive) the water discharge-mass discharge relationship is non-existent except for Mg^{2+}, during the secondary peak for each of these nutrients and Ca^{2+} and Na^+ however the relationship is statistically significant (Figure 5-1). In other words during the initial peak, for the nutrients in question, a factor or factors other than quantity of melting snow plays a role in determining the mass of nutrients flushed out of the woodland plot. A similar pattern is evident for Na^+ discharge though the regression coefficient during the second peak is not significant. The pattern of Mg^{2+} is somewhat different than that described for the other nutrients. During

Figure 5-1. Linear relationships between mass and discharge for the 1st (——) and 2nd (– – –) peaks of intense nutrient scour, woodland meltwater runoff plot, Elizabeth Lake, Labrador. The significant relationships are listed below the figure for each nutrient.



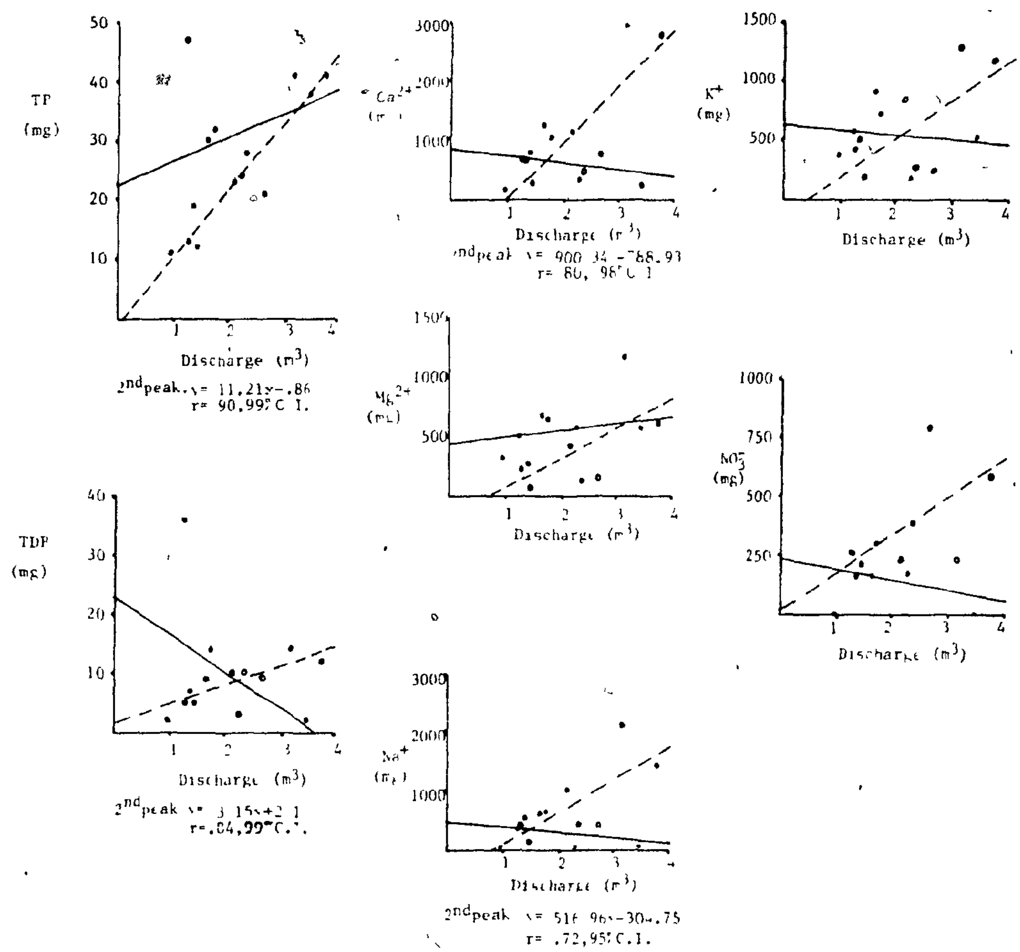
2nd peak: $y = 16.15x - 5.31$, $r = .99$, 99% C.I.

2nd peak. $y = 6.99x + 3.75$, $r = .97$, 99% C.I.

2nd peak. $y = 212.87x + 22.22$, $r = .96$, 99% C.I.

2nd peak. $y = 116.68x - 8.61$, $r = .95$, 99% C.I.

Figure 5-2 Linear relationships between mass and discharge for the 1st (——) and 2nd (- - -) peaks of intense nutrient scour, forest meltwater runoff plot, Elizabeth Lake, Labrador. The significant relationships are listed below the figure for each nutrient.



the initial peak, the mass-discharge relationship is stronger than in the latter peak.

The forest runoff data exhibits patterns which are somewhat different from that found in the woodland (Figure 5-2). The initial pattern identified for K^+, TDP, TP, NO_3^- and Na^+ in the woodland is evident for K^+, TP, NO_3^-, Na^+, Ca^{2+} and Mg^{2+} mass flux in the forest plot, though for the weak initial discharge peak relationships exhibited for NO_3^-, Na^+, Ca^{2+} and Mg^{2+}, the regression coefficient is negative. The second peak linear regressions are significant for only TP, TDP and Na^+.

The pattern in the woodland strongly suggests that the early scoured nutrient mass is a product of factors other than the discharge of water. These factors include availability of nutrients at the base of the pack and the release of a significant percentage of the snowpacks ion mass during the first discharge peak.

The pattern of mass discharge from the runoff plots is a result of a complicated set of interactions involving the exsolving of ions from the snowpack to the ground surface and the thawing of surface vegetation, mor and soil beneath the snowpack through the melt. The availability of nutrients for scour during the initial major runoff peak is limited as the organic strata beneath the snowpack is still partially frozen. The potential for cation exchange with the organic layers at this time, though high due to the chemistry of the meltwater, is negated somewhat as the number of potential exchange sites are restricted by the frozen state of the organic layers and soil at the base of the snowpack in both the woodland and forest plant communities. By the time the frost has disappeared in the organic strata, the soil surface has begun to thaw at the base of the slopes--and a greater number of sites for ion exchange are available--the meltwater discharging from the snowpacks is very dilute and the ion exchange potential generated by snowmelt water compared with the earlier peak, is very low.

Examination of the first major discharge peak of the forest runoff plot for scoured nutrient mass reveals, during 13-16 May inclusive, an intial high flux of nutrients, after which--despite increasing discharge of ion rich meltwater on 17 and 18 May, the mass of scoured nutrients is significantly reduced (Figure 4-7). This abrupt reduction in scoured nutrients is indicative of restricted supply and exchange sites due to frozen potential sources. After a further 20% of the forest snowpack meltwater discharged, a significant percentage of the total plot nutrient mass scour (for each nutrient) occurred during the second major peak of meltwater runoff.

In the woodland runoff plot, the same abrupt reduction of scoured nutrient mass recorded in the forest runoff plot is not evident (Figure 4-6). In the woodland site, with the exception of Ca^{2+}, Mg^{2+}, and TDP, the percentage of nutrient mass scoured per percentage of discharge is greater during the latter, more dilute portion of melt runoff than during the initial ion-rich 30% of the meltwater runoff (Table 5-2). At the forest site, TDP, Mg^{2+}, Na^{+} and NO_3^{-} have essentially the same discharge pattern as noted in the woodland runoff plot; the patterns for K^{+}, Ca^{2+} and TP are dissimilar. For Mg^{2+}, K^{+}, TDP and TP, scour per litre of meltwater discharge is greater in the initial 30% of the melt when the meltwater has a relatively high concentration of snowpack source ions. It seems apparent that in terms of total scoured nutrient mass discharging from the woodland and forest snowpacks, cation exchange plays a secondary role to the physical action of flowing water.

Comparative pH values of the snowpack water and corresponding plot discharge runoff water indicate that in both the woodland and forest snowpacks buffering by the ground layers and soil appear minimal during the initial exsolving of ions out of the snowpack.

Samples of meltwater taken during the initial 30% of the meltwater flow out of the diversion layer have pH's ranges from 3.80 to 4.05 in the woodland snowpack and 4.00-4.15 in the forest snowpack. Though the pH of the initial 30% of the meltwater runoff from the larger portion of the snowpack to the ground surface was not recorded it is assumed to approximate that measured in the diversion layer.

The pH of the meltwater discharging from the plots during the initial 30% of discharge from the larger portion of the snowpacks ranged between 4.1 and 4.30 in the woodland and between 4.15 and 4.40 the forest plot runoff. The slightly elevated pH's in the discharging meltwater reflect relatively low buffering by the organic matter at the base of the snowpack. This reinforces the statement above which attributes the frozen strata at this time to low potential for: 1) ion exchange and 2) flushing of available nutrients from the base of the snowpack.

5.3 Relationships between scoured nutrient concentration and meltwater discharge.

Calculating relationships between concentration (scoured nutrients only) and discharge for the forest and woodland runoff plots yields no significant relationships. This is not surprising as the layers at the base of the snowpack which the meltwater is flowing over and through are composed of essentially three separate components; ground vegetation, mor and mineral soil surface. The thaw along the slope within these units will be progressively greater the further downslope as the downslope portions will receive disproportionately more meltwater. Discharge at anytime during the melt would reflect the sum product of thaw events along the slope. As such, a clear cut pattern may not develop as different components at the snowpack base would have different quantities of available, scourable nutrients.

5.3.1 Relationships between scoured nutrient concentration and time

Though pattern is not apparent in relationships between meltwater and discharge and nutrient concentration, patterns do exist between concentration and time. Examination of scoured nutrient concentration on successive days of runoff reveals patterns of increasing and decreasing concentration of specific nutrients (Figures 5-3 and 5-4).

As notable scouring of nutrients occurs during the melt period it is of interest to this research to determine whether the scouring action has any impact on the nutrient status of the organic layers beneath the snowpack.

The pattern of concentration change in the forest runoff plot is notably different than that of the woodland runoff plot. In the forest runoff plot there is a progressive lowering of the concentrations of most scoured nutrients through the springmelt. The only exception is NO_3^-. For the woodland snowmelt data there is a lack of pattern through the entire melt period for Ca^{2+}, Mg^{2+}, Na^+, K^+ and NO_3^-. For TP and TDP however, a visible pattern exists wherein the concentrations of the

Figure 5-3: Daily scour concentration of nutrients from the base of the forest meltwater runoff plot, Elizabeth Lake, Labrador.

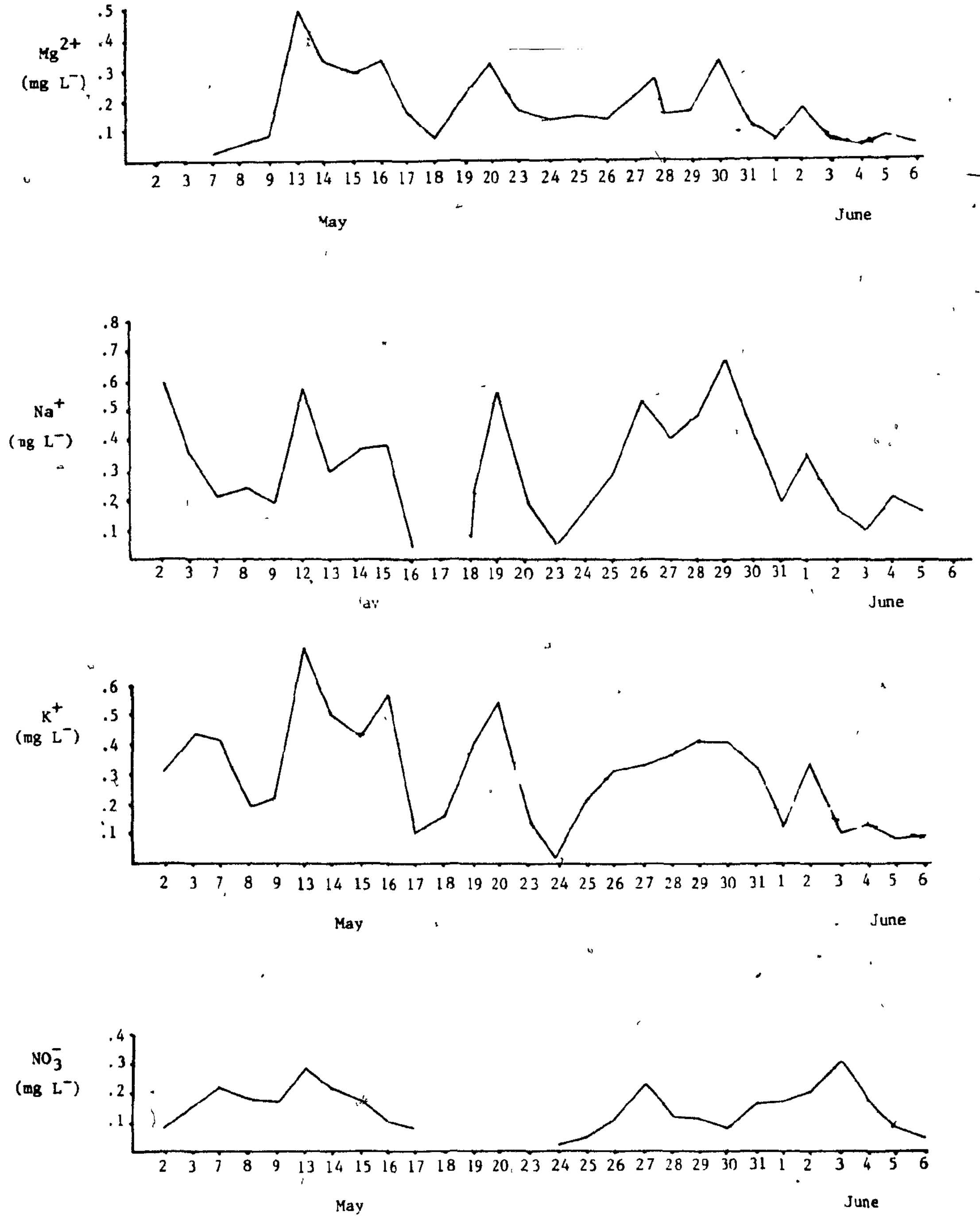


Figure 5-3 continued

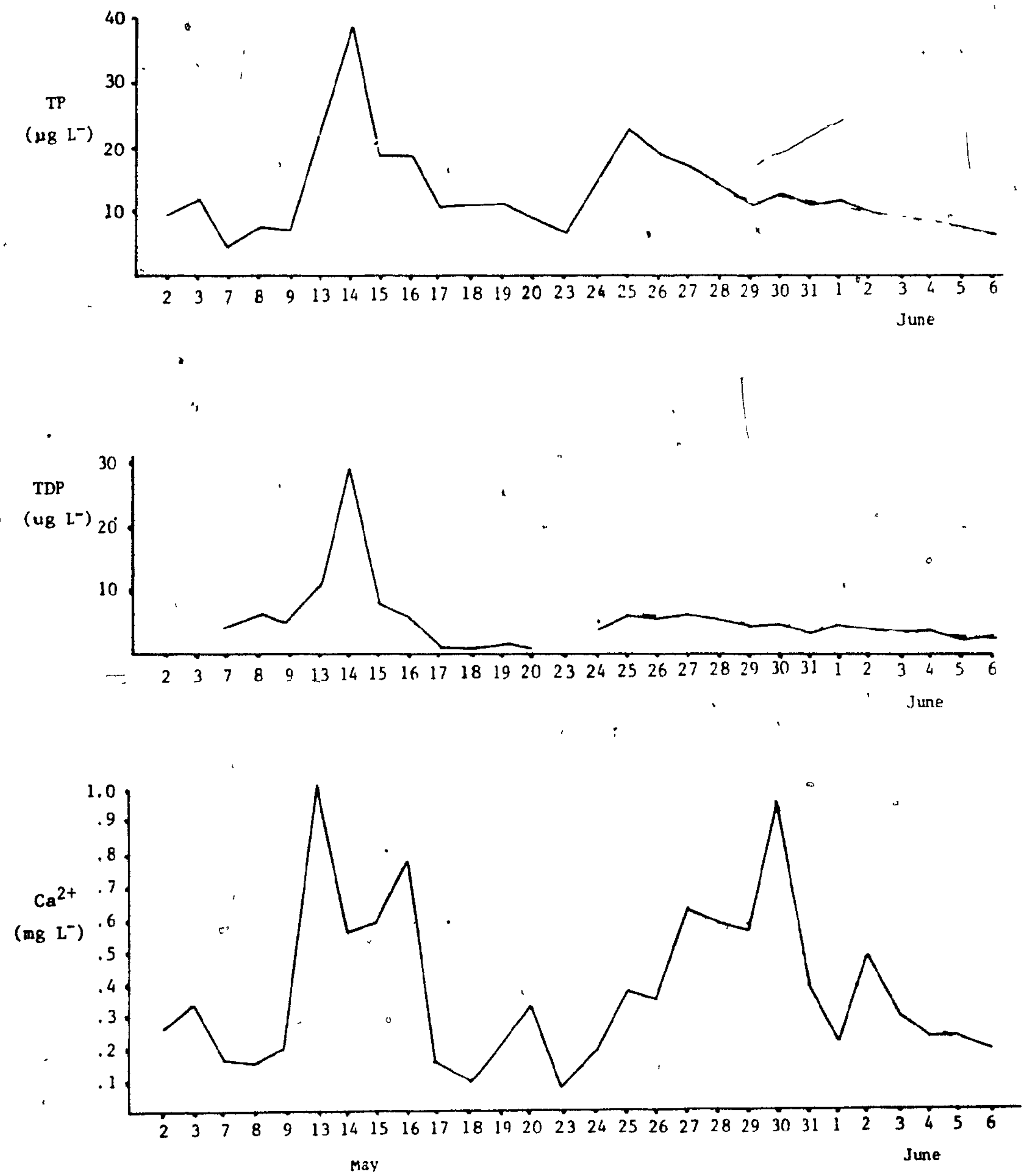


Figure 5-4: Daily scour concentration of nutrients from the base of the woodland meltwater runoff plot, Elizabeth Lake, Labrador.

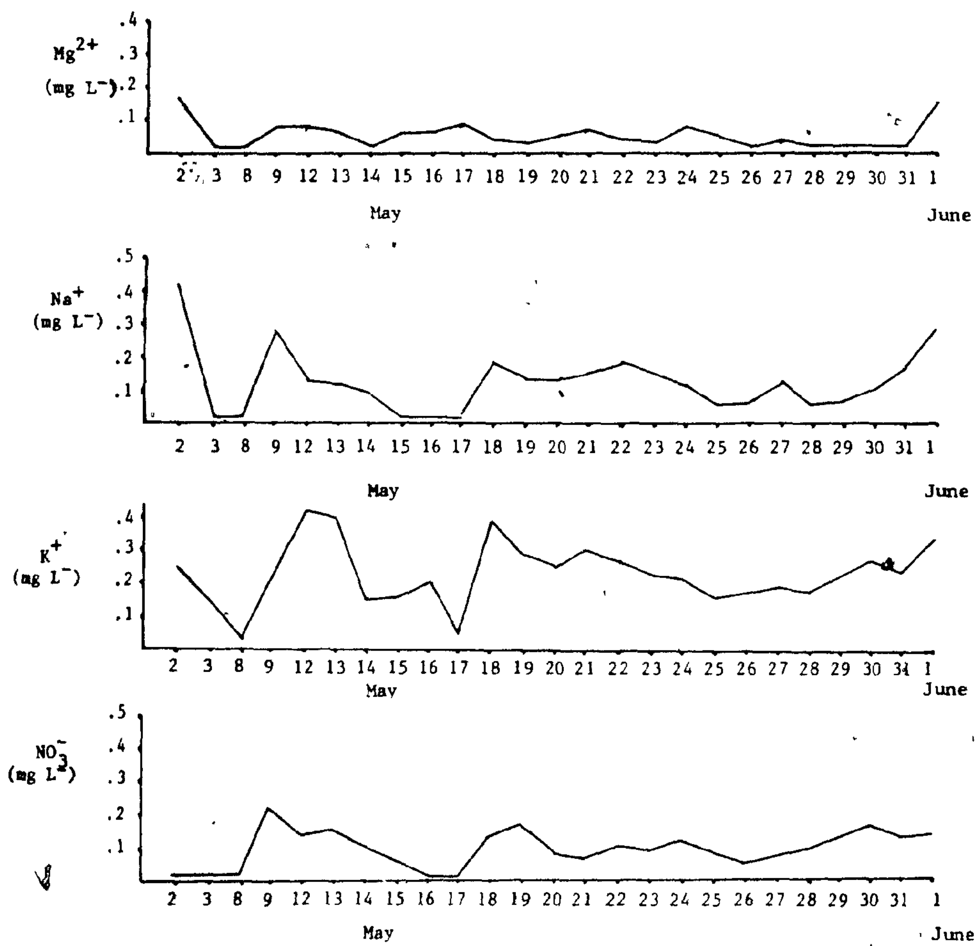
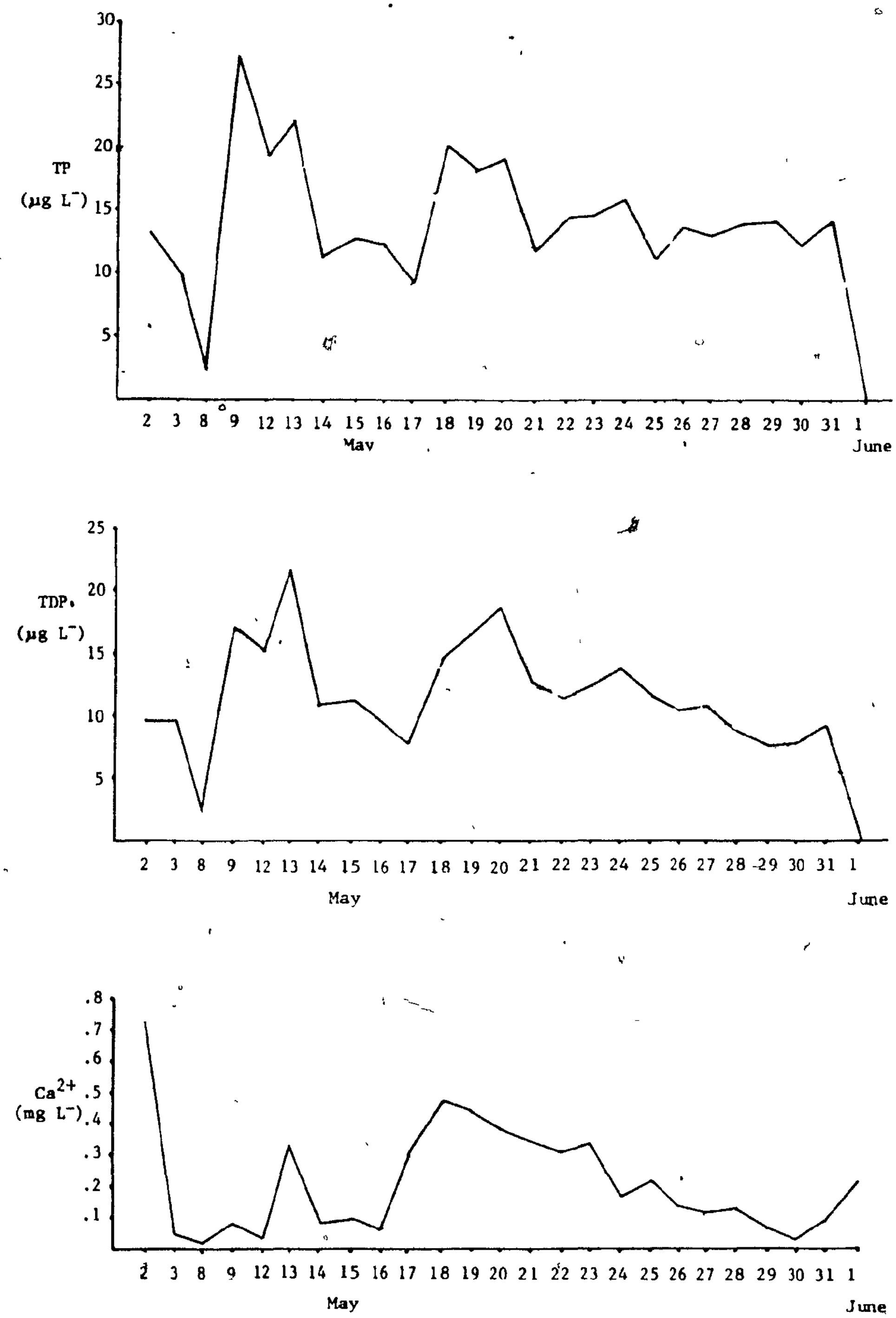


Figure 5-4 continued



nutrient gradually reduce with time. For periods of time shorter than the entire melt period patterns are evident. During the rising limb of the initial major meltwater runoff peak in the woodland snowpack (9-17 May inclusive), the pattern of concentration is, for all nutrients except Mg^{2+}, a mirror image of that portion of the hydrograph, reflecting progressive dilution. Although dilution during this time is evident for Ca^{2+}, the pattern is not as clear as the shown in the Na^+, K^+, TDP, TP and NO_3^- data. Similar patterns of dilution occur in the forest discharge data exist for Mg^{2+} and NO_3^- and to a lesser degree for TP and TDP. Ca^{2+}, K^+ and Na^+ display peaks of pronounced increases in concentration during the rising limb of the initial peak meltwater discharge period in the forest.

The loss of available nutrients from the base of the snowpack is best examined during the last portion of the melt rather than over the entire melt period for it is during this time when the organic layers are completely thawed. Theoretically at this stage of the melt period, the meltwater has the potential to scour the total mass of available nutrients in the organic layers. The time period used to determine whether the day to day loss in concentration continues when the organic layers have thawed is the last major meltwater discharge peak period.

During the initial part of this meltwater peak frozen sections of organic material were still present at the base of both plant community snowpacks. Field observations revealed that by the time maximum discharge occurred in this latter peak runoff period the frozen organic material had thawed more or less completely. On the upper portions of slope isolated frozen patches of mor were found at this time. From this point of complete thaw in the forest runoff plot, 33% of the snowpack remains to discharge into the organic layers; from this point in the woodland runoff plot approximately 30% of the woodland snowpack has yet to melt. A significant volume of water therefore remains to flush available nutrients from the recently thawed organic matter at the base of both plant community snowpacks.

The pattern of lowering concentrations is indicative of diminishing supplies of available form Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, TP and TDP at the base of the snowpack. The same can be said of TDP in the organic layers at the base of the woodland snowpack. Moore (1984) reports that a significant percentage of litter decomposition in the eastern subarctic occurs during the snowyear. McBroyer and Cromack (1980) report similar findings in the northern temperate regions. The results of this work in the subarctic indicate that on slopes, the snowmelt runoff scours significant masses of nutrients in relation to that initially available in the snowpacks and in relation to that available for scour in organic layers at the base of the forest snowpack to a limited degree in the woodland plant community. On the basis of the findings of Moore (1983, 1984), it is suggested that as significant amounts of decomposition occur in the litter in these organic layers during the snowyear that the available nutrients flushed out of the terrestrial system during spring melt represents a significant loss of nutrients potentially available to these terrestrial systems. This scouring would contribute to the oligotrophic nature of subarctic terrestrial systems. Though the daily pattern of scour is not known in the tundra, scour is recorded and the process of snowmelt runoff here contributes to the oligotrophic nature of the tundra.

5.4 Potential adsorption and absorption of scoured nutrients on thawed humus at the base of slopes

The gradual reduction in scoured nutrient concentrations discussed above may in part be a product of adsorption and absorption of available nutrients by the organic matter, fungus or microorganisms in the thawed organic layers at the base of the slopes.

Differential thaw of organic matter at the base of the snowpack occurs because the lower most portions of the slopes will receive proportionally more meltwater than the upper portions of the slope. Division of meltwater runoff plot snowpack water equivalence in equal sections indicates the very upper section receives 1/N m^3 of water at the base of the snowpack. The lower most section receives N m^3 of water. On any given melt date it is assumed that the same ratio exists. The larger volume of meltwater would speed up the thaw of ground vegetation, litter and upper layer of soil in the lower slope. The speed of thaw of a particular portion of the slope is directly proportional to its location on the slope.

Because the downslope organic matter will thaw first, it is feasible that the nutrients scoured from the thawing upper portions of the slope are adsorbed by organic matter, soil, or absorbed by microorganisms in the lower most slope areas. This could, to some degree explain the gradually lowering concentrations of various nutrients in the latter part of the melt period, especially in the forest runoff plot.

A consideration which may aid in explaining the pattern of mass flux from the woodland and forest concerns the preferential adsorption on humus and soil colloids of Mg^{2+} and Ca^{2+} over Na^{+} and K^{+}. Black (1967:185) states that "dilution of a soil water system containing monovalent and divalent cations displaces the equilibrium in such a direction that the adsorption of divalent ions increases whereas the adsorption of monovalent ions decreases". The humus, or decomposed litter beneath the lichen mat in the woodland and moss in the forest is reported by Hesse (1971) to adsorb relatively more Ca^{2+} and Mg^{2+} and relatively less K^{+} and Na^{+}. As the humus in the lower portions of the slope have thawed during the second major peak meltwater runoff period, conditions would be ideal for the retention of Ca^{2+} and Mg^{2+} scoured from upslope. In the woodland runoff plot, the ratio of equilibrated (with respect to meltwater discharge) scoured mass between the first and second major meltwater discharge peaks for Ca^{2+} is 3.38:1; Mg^{2+}, 2.66:1; Na^{+}, 1:1.24 and K, 1:1.14 (Table 5-4). The pattern, though not proof of preferential adsorption of the divalent cations in the humus is the type of pattern expected if this process is ongoing during the melt period. The decrease in scour of available Ca^{2+} and Mg^{2+} in the woodland runoff from the first to second major runoff peaks are thought indicative of decreased supply rather than adsorption to humic matter. The reason for this is that through the last peak there is no indication of lowering concentration. As more humus is thawed it is thought a greater proportion of the available nutrient would be adsorbed and consequently the concentration of these nutrients in the plot outflow would decrease.

In the forest runoff plot, the ratio of equilibrated scoured mass between the two major discharge peaks is Ca^{2+}, 1:1.41; Mg^{2+}, 1.38:1; Na^{+}, 1:2.21 and K^{+} 1.08:1 (Table 5-4). The pattern is dissimilar to that reported in the woodland runoff plot and is not indicative of the preferential adsorption of Ca^{2+} and Mg^{2+} reported by Hesse (1971). Whether Ca^{2+}, Mg^{2+} adsorption occurs downslope is unclear from this data. Though the Ca^{2+} concentration decreases through the second major discharge peak, the actual scoured mass per unit of discharge increases from the first to the second major peak.

In the forest plot, the pattern of decreasing Na^{+} concentration with time during the second major melt peak is thought to be a result of depleting Na^{+} availability rather than adsorption by thawing soil. Seip et al. (1980) state that Na^{+} adsorption to thawed podzol soil during snowmelt event is poor. The soil was observed to be frozen in early June. The NO_3^- date (see below) indicates that the soils began thawing on 4 June.

The TDP runoff data during the latter melt period in both woodland and forest is thought indicative of decreasing supply rather than adsorption by the soil because of the frozen soil.

NO_3^- mass flux scour from the forest plot slowly increases on a day to day basis from 24 May to 3 June (Figure 5-4). As NO_3^- is principally absorbed by plant roots, fungus and microorganisms in the soil and litter layer (Morrison, Pers. comm. 1983, Hendrikson et al. 1982) it is thought the increase is indicative of a much reduced capacity of these agents for absorption. Low temperature is reported to inhibit NO_3^- uptake by microorganisms in the litter (Hendrikson et al. 1982). Hendrikson et al. add that in the initial stages of decomposition organic matter acts as a nitrogen sink. Where litter is in advanced stage of decomposition, the organic matter will become a notable NO_3^- source. If these observations apply to the humus in the woodland and forest plant communities, continuing thaw of the mor at the snowpack base would yield NO_3^-. As it is reported that organisms in this freshly thawed matter inefficiently absorb NO_3^-, it is likely that the NO_3^- available would be scoured by meltwater runoff.

Noticeable decrease in NO_3^- scour occurs during 4, 5, 6, June in the forest runoff (Figure 5-4). This may be due to increased biological uptake of NO_3^- though the temperature remains low, saturated conditons still prevail and much of the soil remains frozen.

The increase in the NO_3^- mass in the second major meltwater runoff peak in both woodland and forest could be due to a) thawing of organic material and release of NO_3^- or b) nitrification. Brady (1974) states nitrification can begin at temperatures just above freezing but is severely hampered by saturated conditions (see also Hesse, 1971), such at those at the snowpack base during melt. Had soil thawed substantially NO_3^- mass reduction would likely be evident as the root systems of vegetation would readily absorb the nutrient.

5.5 Conclusions

In this chapter daily exsolving rates for ions out of the woodland and forest snowpacks were determined from patterns measured in the diversion layers. Examination of the differences between the daily exsolved values and corresponding nutrient mass flux from the runoff plots enabled an evaluation of the snowpack-ground chemical interactions through time.

Significant scouring of nutrients from the base of the snowpack occurs during the spring melt. Though the total mass balances are discussed in Chapter 4, the daily pattern of nutrient mass and concentration are examined in relation to discharge and the time of melt.

The frozen condition of the organic layers and soil during the initial major discharge peaks in both woodland and forest snowpacks indicates that potential sites for ion exchange will be unavailable at a time when a substantial proportion of the ions are exsolved from the snowpack. The lack of buffering during the initial portion of the melt will result in the displacement of additional H^+ to water bodies receiving the meltwater. This has repercussions on the nutrient budget as potentially exchangeable ions on the frozen ground vegetation or humus are not scoured out of the system.

In this chapter it is recognized that the scouring of nutrients by snowmelt water runoff is in part responsible for the oligotrophic status of eastern subarctic plant communities located on slopes. As decomposition during the late fall just prior to annual snowpack formation and during the snowyear is significant (Moore 1983) it is thought that the scoured nutrients are in part dissolved nutrients made available during this time. Thus it is assumed that this scouring represents a notable factor in maintaining the oligotrophic status of the terrestrial subarctic systems.

CHAPTER 6

SNOWMELT WATER - LAKE MIXING, DURING THE SPRINGMELT PERIOD.

6.1 Introduction

Chapter 4 examined the daily flux of nutrients from the terrestrial portion of the system to the lake, and the daily mass balance of nutrients entering and discharging from the lake. It was concluded that a substantial fraction of the P (TP and TDP), K^+, Na^+ and NO_3^- entering the lake during the springmelt period was retained within the lake.

This chapter will examine the interaction of snowmelt water and Elizabeth Lake water during the springmelt period.

Two methods are employed to determine the degree of mixing. The first method employs the natural isotopic ratio of deuterium/hydrogen as a tracer of snowmelt water in the lake. The second examines the temperature profiles taken during the sampling periods. A method is presented which determines the temperature of the lake water in the shallow littoral zone, given the calculated daily volume and temperature of incoming snowmelt water and the measured solar radiation input to the lake water.

6.2 The interaction of snowmelt and lake water using Deuterium/Hydrogen

During the melt period samples of snowmelt runoff water, lake water, ice and lake discharge water were taken and later analyzed for deuterium/hydrogen (D/H).

In order to use D/H as an efficient tracer of the snowmelt water entering the lake, sufficient differences in D/H values between the two water sources have to occur. Such is the case at this location; mean values recorded were: -144 0/00; lake water, -131 0/00; black ice, -112 0/00 and the outflowing stream -131 0/00. The error of the method was ± 2 0/00. Samples for snowmelt water were taken on various dates through the melt period both from inflowing streams to Elizabeth Lake and from the meltwater runoff plots. Lakewater from various depths was sampled on 1, 2, 3 June 1980, most intensively along a transect illustrated in Figure 6-1. The discharge was sampled on 24, 31 May and 4 June 1980. Black ice was sampled prior to and during candling.

The mean snowmelt runoff D/H value was -144 0/00 (range -140 0/00 to -145 0/00, n = 8). Lakewater showed little variation except in the nearshore areas; the mean value was -131 0/00 (range; -128 0/00 to -133 0/00, n = 16). The discharge matched the mean lake water values; 24 May: -130 0/00, 31 May: -131 0/00 and 4 June: -131 0/00. The black ice concentration prior to and during candling was -112 0/00 and -121 0/00 respectively.

The results of the intensive sampling along the transect illustrated in Figure 6-1 are shown in Figure 6-2. At the near shore site in .85 m of water, the sample taken at .75 m resembles the per mil values of snowmelt water; the sample concentration decreases to a value of -130 0/00, 20 cm below the water surface. The low values taken at the surface; -126 0/00 and -122 0/00 (sites G-3 and G-7 respectively, Figure 6-2) indicate the influence of the melting black ice. The D/H values at

Figure 6-1: Bathymetry map, Elizabeth Lake, Labrador (courtesy, Dr. F. Rigler). x = sampling sites (═══) = sampling transect for deuterium/hydrogen sample collection

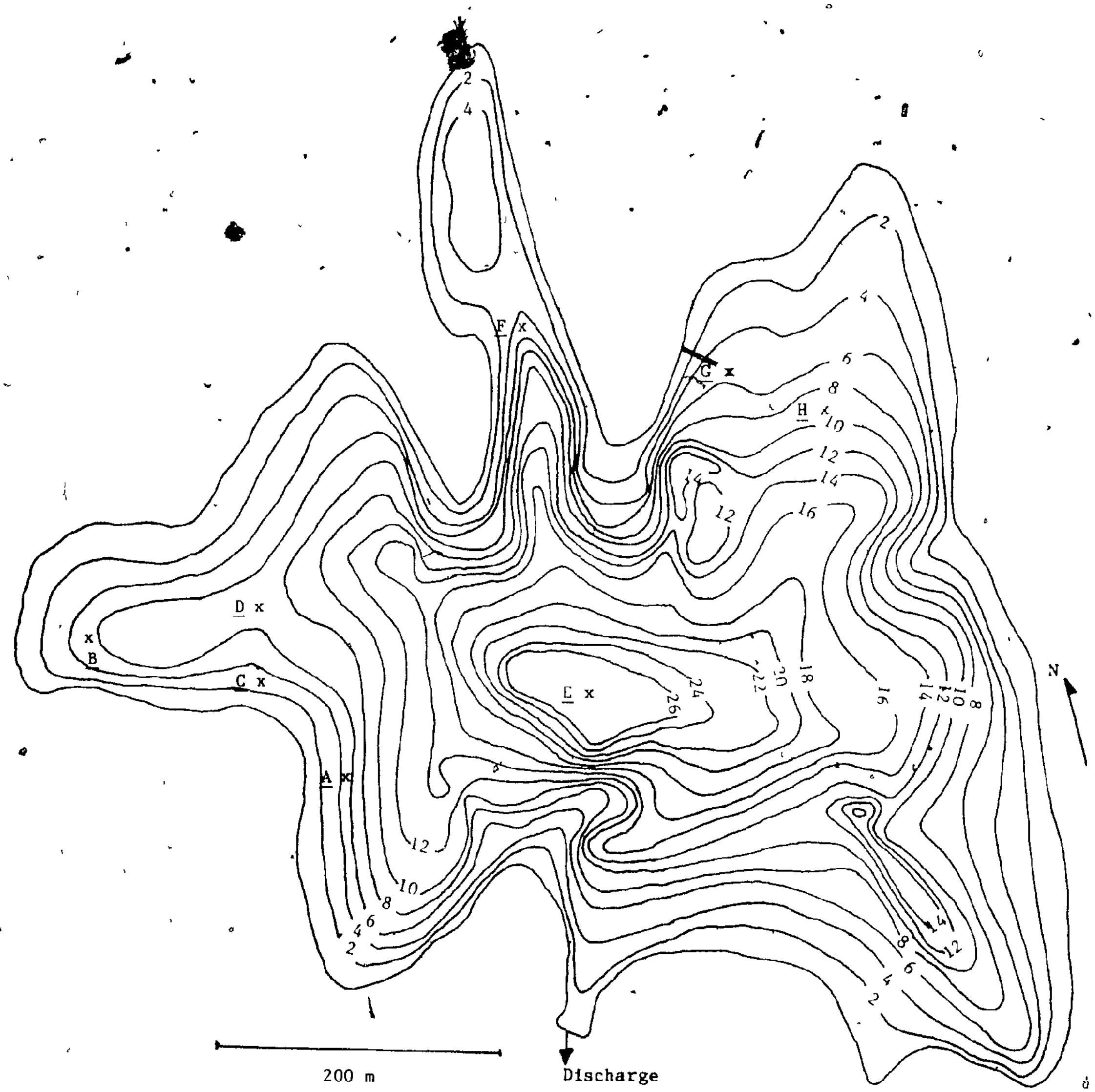
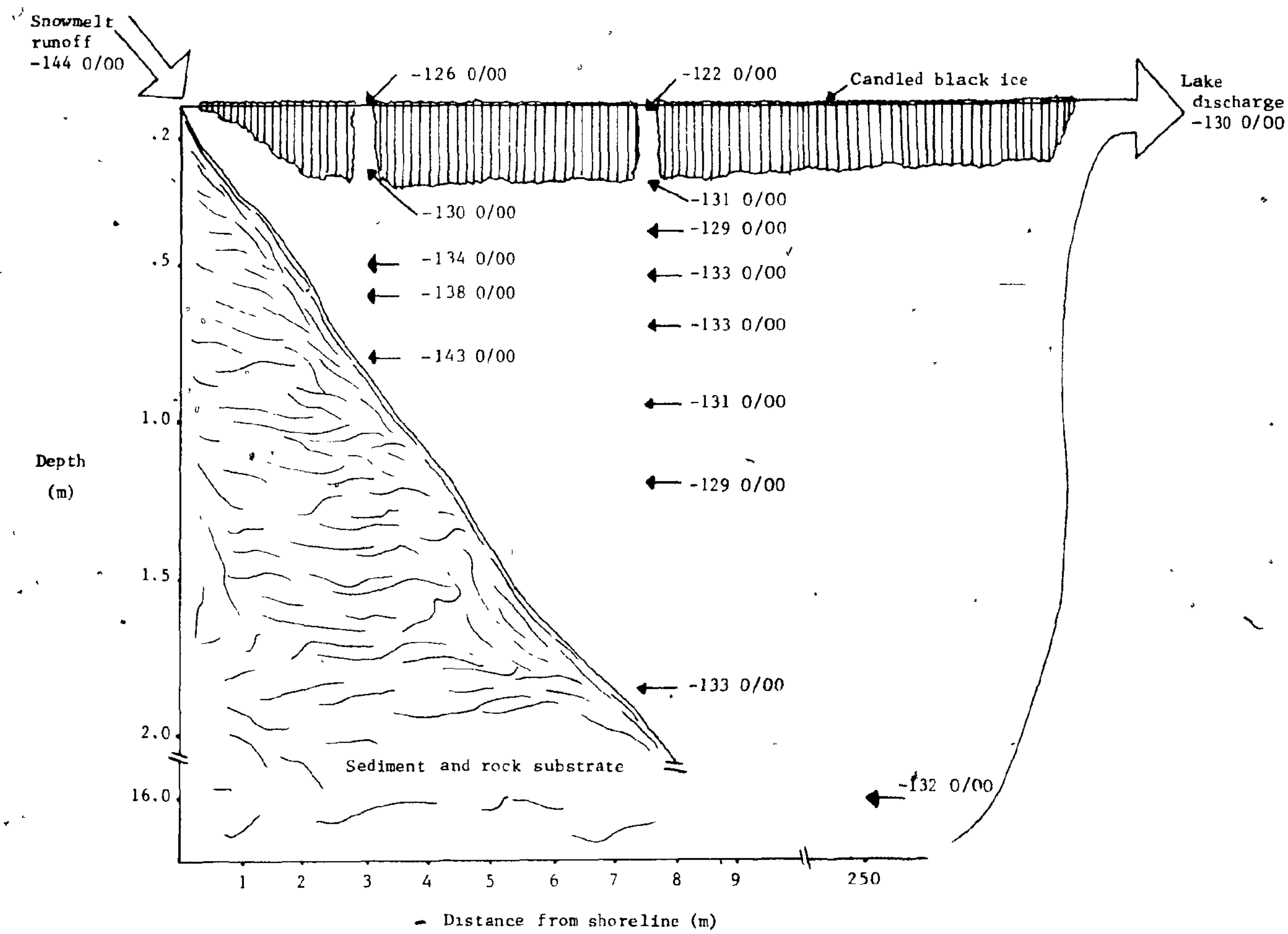


Figure 6-2: Distribution of deuterium/hydrogen values in the littoral zone sampling site, Elizabeth Lake, Labrador. 2 June 1980. Snow meltwater and lake discharge values are included.



the second site located a further 4 m offshore from G-3 in 1.85 m of water, indicate relative uniformity from the bottom to the top of the water column. It is probable the bottom water sampled at site G-3 is snowmelt water entering the lake; the progressive reduction of values the closer to the surface indicates mixing with the lake water. By the time the meltwater reaches site G-7 complete mixing with the lake water appears to have occurred. This data strongly indicates that the incoming meltwater is flowing along the sediment-lake interface for a short distance then mixing with the lake water. It is assumed that where overland flow is contributing directly to the lake (which applies to approximately 90% of the shoreline) the snowmelt water mixing with lakewater will occur in a similar manner as observed and described for this site.

Although a more intense sampling strategy along similar transects extending from the shoreline into the lake would produce a more conclusive deduction regarding snowmelt-lake water interactions, the results noted for this solitary transect are clearly indicative of an important springmelt process in the subarctic.

6.3 Temperature change in Elizabeth Lake, springmelt 1980.

Figure 6-3 illustrates the temperature profiles at the 8 sampled lake sites (Figure 6-1). The readings were taken from the surface down to a point just above the sediment water interface. The depth to sediment was taken from the hydrostatic water level, not the lake ice surface.

The temperature profiles indicate gradual heating of the lake water through the melt period by approximately 1 to 2°C. The depth of this

Figure 6-3: Temperature profiles at selected sites at Elizabeth Lake, Labrador, springmelt, 1980. Dates of temperature profiles: A, 6 May; B, 18 May; C, 2 June; D, 7 June.

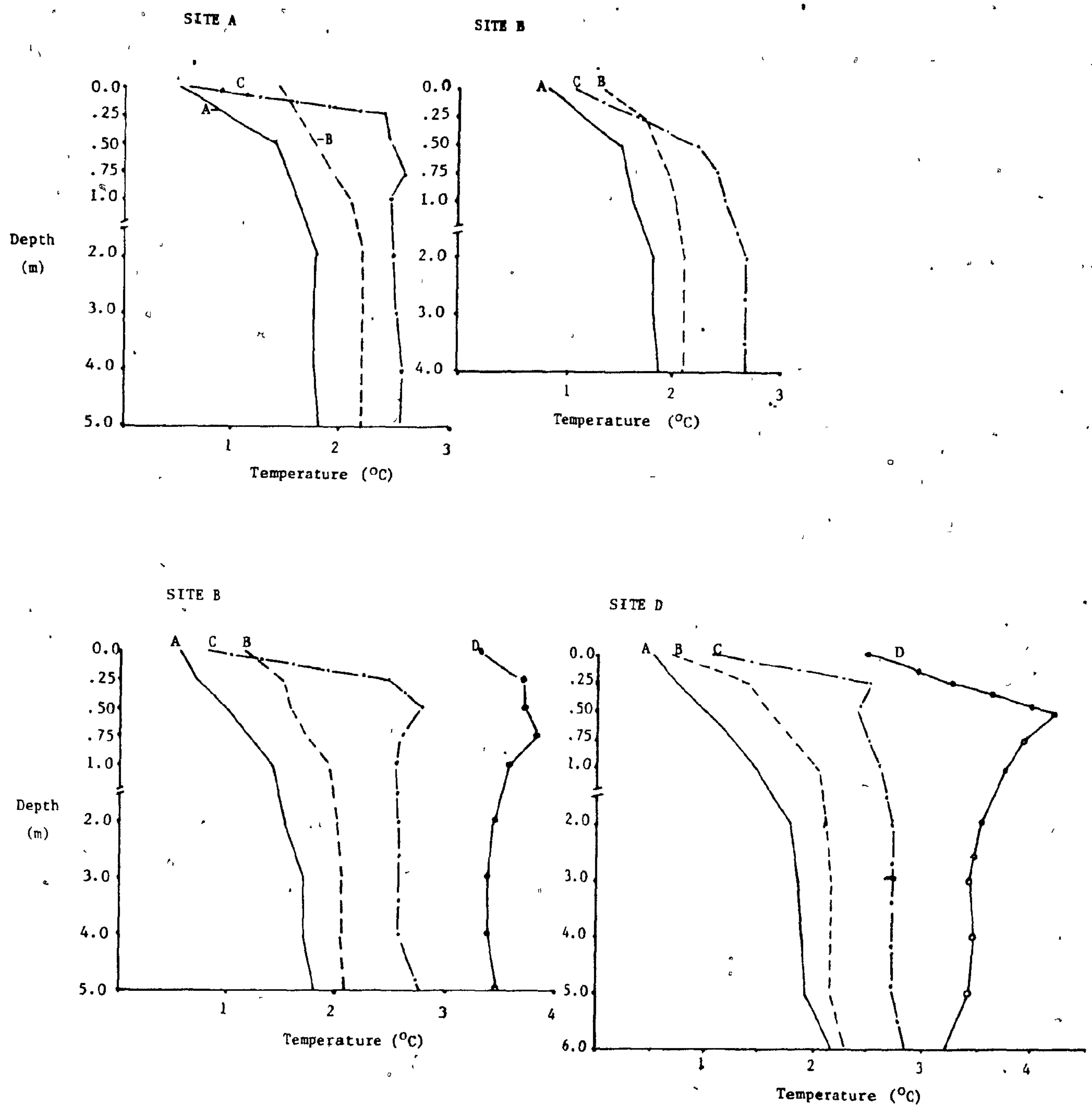
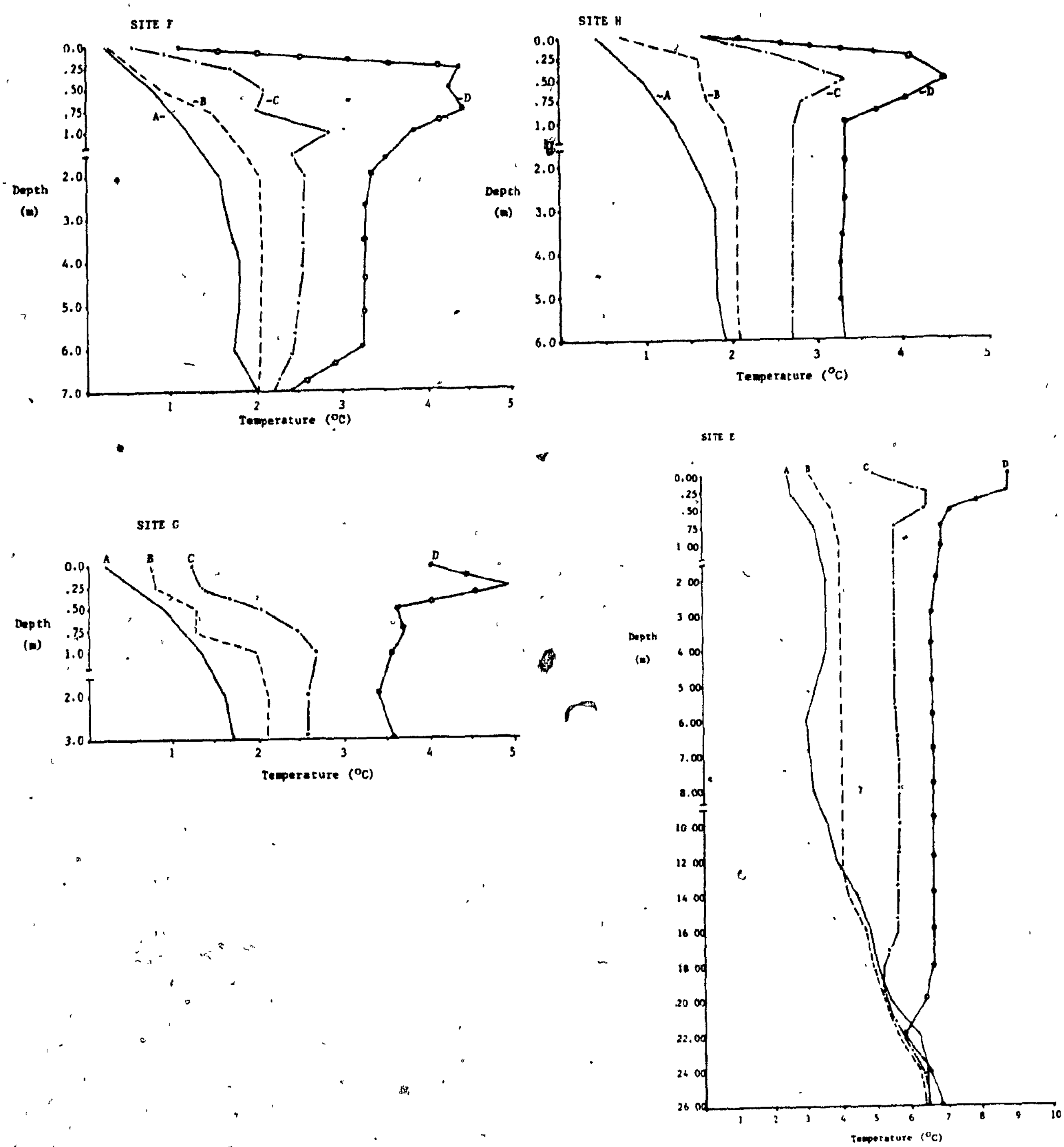


Figure 6-3 continued



heating extends to approximately 21 m. It is assumed that mixing of warmer upper water must occur to account for the increased temperatures below 6 m. Wetzel (1975) reports water at this depth receives less than 5% of the solar radiation penetrating the ice cover in an unproductive lake in northern Wisconsin.

To illustrate this point, the temperature increase from 6 May-7 June 1980 at the 10 m depth was 1.5°C[1]. To raise the temperature this amount, 1.5×10^2 cal cm^{-2} would be required. Wetzel reports the percentage of visible light transmission to 10 m in the unproductive lake reported above is approximately .10% of the light penetrating the ice cover. During the later stages of melt the percentage of light penetrating the ice cover at Elizabeth Lake was estimated to be 50%. The high albedo of the black ice at this date was due to extensive, advanced candling and 2 distinct bubble layers within the ice (Roulet, 1982). As well, light penetration along the C-axis of the black ice crystals was impossible due to the sun's angle at this time of the year. Roulet (1982) reports the turbidity of this lake at this time of year is 0.

The total radiation reaching the 10 m depth amounts to .05% of the total reaching the ice surface from 6 May to 7 June. The total available radiation is 8.35×10^7 cal m^{-2}; that reaching the 10 m depth is approximately 4.1×10^4 cal m^{-2}. If the water at the 10 m depth was essentially stagnant and retained all of the heat supplied by the penetrating radiation the net increase in temperature from 6 May to 7 June would be .04°C. If the assumed percentage solar radiation reaching the 10 m depth was underestimated by an order of magnitude, the increase in

[1] The accuracy of the YSI Telethermometer was determined by calibration to be ± .10°C. The readability of the scale on the instrument is advertized by the manufacturer to be approximately .03°C.

temperature would be only .41°C, far less than the 1.5°C recorded. The estimate of temperature increase due to solar radiation is likely an overestimate. For the above calculations it was assumed 50% of the solar radiation received at ice surface penetrates the ice cover. The presence of white ice in the earlier part of May coupled with a thicker ice sheet would assure this estimate of 50% is an overestimate.

Thus it appears that the heating of the water at 10 m and below is due principally from mixing from upper water. The uniformity of temperature from approximately 1.0 to 14.0 m recorded on 18 May and 1 June (the two periods of peak melt) seems to indicate mixing would occur as barriers to density differential are lacking.

6.3.1 Turbulence beneath the ice cover

From the latter peak of snowmelt runoff to the 7 May (just prior to ice-off) the temperatures recorded at the sites considerably removed from the shore lines (D, E, H) at the .25 m to .75 m depth were higher than those recorded at greater depths. For example at site E, the upper water, presumably heated by solar radiation, is denser than the underlying water. Measurements using YSI telethermometer on 2 and 7 June at sites D, E, F and H (Figure 6-1) indicate that instability due to radiation heating occurs in the surface waters. The temperature probe was held steady at the 1.0 m depth at Site F for 15 minutes on 2 June during which time the registered temperature ranged between 2.7 and 3.0°C. The barely perceptible but continuous movement of the needle on the recording dial of the telethermometer indicated turbulence assumed to be a product of solar radiation heating. Calculations of the incoming solar radiation for a 15 minute period during the sampling time show that even if the total amount of radiation reaching the ice surface penetrated, the resulting increase in water temperature would only amount to .09°C. The instability of the readings continued at 1.5 m, though the variation and speed of change significantly reduced. Barely perceptible movement of the temperature indicator was evident at 2 m; below this depth the needle on the instrument remained steady at one reading per depth sampled. The measured solar radiation is insufficient to account for the temperature increase (.30°C) recorded at 1.0 m. It is thought that the readings recorded represent some instability within the upper layers of the lake due in part to solar radiation. Wetzel (1975) notes the instability of ~~water~~ layers differentiated by temperatures within the range noted in Elizabeth lake at this time of year.

Meltwater draining from the surface of the ice into natural cracks, and other aberrations in the ice cover may play a role in the turbulence noted. Meltwater from this source can, although not always, pond on the ice surface. When this ponded water enters the lake its temperature is greater than that of the surface lake water as it has been heated directly and indirectly by incident radiation. The temperatures of two such ponds taken on 1 June were approximately 3.0°C. Adams and Allan (1984, unpublished data) report this is a major process promoting mixing between meltwater and lakewater in proglacial lakes on Axel Heiberg Island, N.W.T. Though ponded water could locally disrupt the temperature region of the surface water locally it is doubtful that it would have much effect on a large scale. The melting on the surface of the ice will be greater than at the lake water ice interface as the air temperatures are significantly greater during the melt period. The residence time of the meltwater on the ice surface was minimal as most of the meltwater from the upper ice cover did not pond, consequently the temperature of this water entering the lake would be close to 0°C. In certain locations along the ice surface much meltwater would converge on one ice hole and the volume (unmeasured) of water discharging into the lake at these sources would be sufficient to create turbulence in the surface layers below the ice cover. Wetzel (1975) notes that stratification of lake water at the cool temperatures recorded at springmelt can be disrupted with turbulence of only a few mm sec^{-1}. This turbulence would continue through most of the melt period. Though it is not known to what degree this process can affect the lake stability beneath the ice cover it should be acknowledged as it may disrupt the upper portion of the water column where samples are being extracted. This may help explain the relatively low temperatures recorded in the upper few centimetres of the lake during the latter stages of melt when the holes drilled for lake sampling purposes served to drain meltwater ponding on the surface of the black ice.

6.3.2 Prediction of lake temperature in the shallow littoral zone

The prediction of lake temperatures within the shallow littoral zone is an indirect method by which the effective mixing depth of meltwater with lakewater can be determined.

It is thought that, given the initial temperature of the lake water on day 1, it is possible to predict its temperature on day N given the daily volume of melt water entering the lake, its temperature and the daily solar radiation reaching the lake water beneath the ice cover from day 1 to day N.

The assumptions include complete mixing of the meltwater entering the lake and that the snowmelt water entering the lake has a temperature of approximately 1°C. The actual range of snowmelt water temperature recorded was .8°C to 1.4°C. Temperature readings were recorded each day snowmelt water runoff from the plots was sampled. This calculation focuses only on the littoral zone directly receiving overland flow, not streamflow, as such, the volume of snowmelt water entering the lake each day is determined from the calculated daily inflow via overland flow.

The period of interest is 2 June - 7 June 1980 when the ice cover was uniform consisting of candled black ice of approximately 25 cm depth. The initial defined area of littoral lake water examined is the volume of water within the 2 m contour. The area of lake concerned was determined from a bathymetric map of Elizabeth Lake (Figure 6-1). A mean depth of 1 m was assumed. The volume of water within this defined boundary was thus determined (approximately 44×10^3 m^3). For the initial day's calculation (2 June), the total incoming snowmelt water was 13.5×10^3 m^3, approximately 31% of the lake water within the defined portion of the littoral zone. The third assumption is the volume of water within the assigned littoral zone boundary remains the same, that is the incoming melt water simply replaces the lake water.

The calculation involves three components; incoming meltwater, the lake water present and incoming solar radiation. The temperature of the lake water is calculated by dividing the incoming meltwater volume by the lake water within the defined boundary. This produces a replacement factor of lake water with meltwater. This fraction is used to determine the meltwater contribution to the water temperature of the lake water by multiplying the fraction by 1°C. The reciprocal of this fraction, multiplied by the original lake temperature, produces the lake water contribution to the new temperature. The two numbers are summed and added to the increase in temperature provided by the days total radiation. The assumptions for percentage transmission through the ice are those reported above in section 6-3. The absorption of radiation at mean depth is derived from the extinction coefficients quoted by Wetzel (1975) from unproductive lake water between 720 and 500 nm. For this example, absorption of 50% was used. Roulet (1982) confirms this figure from measurements taken during the 1980 springmelt on Elizabeth Lake.

Determination of the lake temperature along the littoral zone was done using the data recorded from sites A, B, C, F and G. The mean water temperature on 2 June was 2.15°C. Assuming a mean depth of 1 m, the mean calculated temperature on 7 June is 3.42°C, the actual mean temperature was 3.67°C. The computed fractions contributing to the daily mean temperature within the 2 m contour are illustrated in Figure 6-4.

It is assumed that the cooler predicted littoral zone temperature is due to the fact that the predetermined volume of lake water within which the meltwater is mixing is not sufficiently large enough. The calculation was repeated for greater volumes of lake water which will accommodate the 3 and 4 m depth contours.

Light transmission reaching the 1.5 m (used as the mean depth for the 3 m contour mixing zone) and 2.0 m depth (mean value within the 4 m contour mixing zone) was assumed to be 40% and 30% respectively. Similar light transmission percentages at these depths are reported by

Figure 6-4.

Wetzel (1975) for a decaying ice sheet on an unproductive lake in Michigan.

The proportional fractions of lake water, solar radiation and snowmelt water contributing to the daily mean temperature within the littoral zone to a 3 and 4 m depth are illustrated in Figure 6-4. The predicted mean temperatures on 7 June for the 3 and 4 m depths are 3.66°C and 3.84°C respectively. The curve illustrated in Fig. 6-4 demonstrates that, according to this calculation, the effective temperature mixing depth, where the predicted and actual curves cross, is approximately 3 m.

Earlier predictions were not accomplished because of the tremendous variation in the composition of lake ice in the early melt period. This diversity would not allow an accurate calculation of solar radiation penetrating the ice cover.

6.4 Conclusions

The implications for nutrient transfer from land to lake are significant. If snowmelt water nutrient concentrations are elevated above the lake water, adsorption of nutrients by the sediment may occur as the meltwater flows along the sediment surface. This may partially explain the apparent reduction of land-source nutrients by the lake during springmelt.

If the mixing of snowmelt and lake water apparent in Elizabeth Lake is widespread in the eastern subarctic those interested in assessing nutrient budgets should take this into consideration. Outside of the Labrador geosyncline in the Canadian Shield where the aquatic systems are poorly buffered against the moderate loading of acidic precipitation the implications of snowmelt mixing with lake water are significant because the hydrogen ion load, relatively unbuffered by the terrestrial system because of frozen soil, will interact with the sediment in the littoral zone. This mixing process will increase the area of sediment-H^+ ion contact. Subsequently, the increased H^+ ion load reaching the water body, coupled with the mixing pattern, may limit the capacity of lakes to buffer acidic precipitation over an extended period of time.

CHAPTER 7

CONCLUSIONS

7.1 Introduction

This chapter will summarize the major findings of this research. Table 7-1 lists the hypotheses postulated inthe early part of the thesis and states whether the hypotheses have been confirmed, rejected or whether the results are inconclusive. Accompanying discussion will examine the major findings in greater detail.

The latter section of this chapter will summarize the significance of these results and address the question of future studies.

7.2 Snowpack accumulation of water and nutrients, related to plant communities

The mean snowpack water equivalence at peak snowyear in the tundra plant community, 15.3 cm was substantially less than the recorded mean values in the woodland, 49.9 cm, or the forest snowpack, 46.9 cm. The low snow accumulation on the tundra is due largely to the topographical position: exposed ridges where there are few barriers to wind erosion of deposited snow and little terrain roughness (Granberg, 1978) which might induce snowpack accumuation.

The woodland snowpack sampling sites displayed a larger range of water equivalence values, s = 21.9 cm, than either the tundra (s = 13.0 cm) or forest (s = 13.0) snowpacks. The wider range in the woodland is attributable to distinct topographical change and what has commonly been referred to as the 'edge' effect. Water equivalence values recorded in the woodland snowpack within approximately 40 metres of the forest - woodland boundary were substantially greater than samples taken further away from the boundary. The mean water equivalence of the sampled sites within this 'edge' was 68.7 cm (n = 17); the mean value of the other samples taken within the woodland snowpack was 47.8 cm (n = 143).

In Table 7-1 hypothesis 1 addresses the influence of plant communities on snowpack nutrient content. The results indicate the forest snowpack had the most elevated mean concentrations of TP, TDP, K^+ and Na^+. The Ca^{2+} concentration was most pronounced in the woodland and the Mg^{2+} concentration was highest in the tundra snowpack. The NO_3^- concentrations in the tundra and forest were equal and somewhat elevated above the woodland concentration. Though the mean differences indicate the forest snowpack is enriched above that recorded in the tundra and woodland snowpacks, few of these differences are statistically significant. The differences appear more statistically than ecologically significant. For example, the TP concentrations in the forest snowpack, though only 1.31 and 2.94 g L^- greater than the woodland and tundra respectively was determined to be statistically significant.

The significant contribution of coniferous litter to the chemistry of the annual snowpack in the Montmorency Forest, Quebec (reported by Jones, 1984) appears not to be as pronounced in the subarctic snowpack of Elizabeth Lake. Elevated K^+ concentrations usually indicative of or attributable to organic matter within the snowpack is essentially equal in the forest (.09 mg L^-), woodland (.06 mg L^-) and tundra (.07 mg L^-) snowpacks.

Manuel (1983) reports elevated nutrient concentrations in the lower portions of the subarctic snowpack. This is attributable to vertical movement of water from organic layers at the base of the snowpack. With the exception of TP in the forest snowpack, the data from the Elizabeth ble 7-1. Summary of the study hypotheses and results.

Hypothesis	Results
1. The nutrient concentrations in the snowpack will reflect the plant community the snowpack is in. It was hypothesized that nutrient concentrations would be highest in the forest then woodland and lastly the tundra.	inconclusive (section 7.2)
2. Overland flow due to saturated concrete frost is a dominant physical process operating on the Elizabeth Lake terrestrial catchment during the springmelt period.	confirmed (section 7.3 and 7.4)
3a. Snowpack source P will not be retained by the terrestrial ecosystem but transferred to downslope bodies of water.	confirmed (section 7.5)
b. Snowpack source NO_3^- will be retained by the terrestrial ecosystem during springmelt.	confirmed in tundra rejected in woodland and forest (section 7.5)
c. Snowpack source Ca^{2+}, Mg^{2+}, Na^+, K^+ will not be retained by the terrestrial ecosystem during springmelt.	confirmed (section 7.5)
4a. P will be scoured from the organic horizons above the frozen mineral soil surface during springmelt and transferred to downslope water bodies.	confirmed (section 7.5)
b. NO_3^- will not be scoured from the organic horizons above the frozen minreal soil during springmelt.	confirmed in tundra rejected in woodland and forest (section 7.5)
c. Ca^{2+}, Mg^{2+}, Na^+ and K^+ will be scoured from the organic horizons above the frozen mineral soil during snowmelt and transferred to downslope water bodies.	confirmed (section 7.5)
5. Scoured nutrient mass discharging from the terrestrial portion of the study catchment will be proportionally greater during the initial part of the snowmelt runoff period.	rejected in forest (except for TP) confirmed in woodland for Ca^{2+}, Mg^{2+}, TDP rejected in woodland for K^+, Na^+, TP, NO_3^- not measured in tundra
6. Significant mixing of terrestrial source snowmelt water and lake water occurs.	confirmed (section 7.6 and 7.7)

Lake catchment does not indicate elevated nutrient concentrations at the base of the snowpack. The TP concentration at the forest snowpack base is thought to be primarily attributed to deposition, as the dissolved fraction (TDP) shows only a statistically insignificant increase from the upper snowpack to the base.

7.3 Discharge pattern and water balance for the meltwater runoff plots

Five meltwater runoff plots were installed on the Elizabeth Lake basin to gauge overland flow and concomitant nutrient mass flux through the springmelt period. Three of the five plots worked as intended, one in each of the major plant communities. It is concluded that overland flow, though not occurring on 100% of the terrestrial catchment is a dominant process during snowmelt. This statement is based on observation at the base of the snowpack at numerous sites during the melt period and the hydrological balance for Elizabeth Lake discussed later in this section.

Meltwater runoff plots discharged between 89 and 96% of their calculated snowpack water equivalence. THe discrepancy is relatively small and may be accounted for by leakage, infiltration and evaporation. The melt in the tundra was very intense lasting only 5 days; approximately 50% of the snowmelt runoff plot water equivalence discharged within one 24 hour period (30 April 1980). A bimodal meltwater runoff pattern was first recorded at the woodland and forest runoff plots starting 2 May 1980 with the forest melt of greater duration than the woodland melt. This was a product of a greater meltwater volume and the increased tree crown cover which reduced direct radiation on the snowpack.

Diversion of meltwater runoff by dense snowlayers on slopes in the forest and woodland snowpacks was observed and recorded. This lateral flow resembles that described by Colbeck (1977), though density rather than an impermeable ice layer is thought to initiate the process. It was estimated approximately 6% of the total water equivalence was diverted downslope by this lateral flow. There are significant implications of this process for terrestrial and aquatic chemistry in the subarctic, discussed later.

7.4 Generation of snowmelt runoff water to Elizabeth Lake via overland flow

The daily meltwater input to Elizabeth Lake through the melt period was generated by a hydrological calculation involving a total of approximately 70% of the total snowpack water equivalence on the Elizabeth Lake catchment.

The calculation plus measured stream input approximates, on a daily basis, the actual meltwater input to the lake (as determined from stage plus lake discharge) quite closely. This is added evidence to support the confirmation of hypothesis number 2 in Table 7-1. Infiltration of a significant portion of the snowpack water into the soil/till mantle would have resulted in a more pronounced hysteresis between input and lake output.

7.5 Nutrient flux from the snowmelt runoff plots

In Table 7-1 hypotheses 3, 4 and 5 address the nutrient mass discharge from the runoff plots. For all nutrients except for NO_3^- in the tundra plot, the total discharging mass was far in excess of the mass determined for the runoff plot snowpack prior to the initiation of meltwater flow.

The lateral flow of meltwater downslope by dense stratigraphic layers within the snowpack resulted in the discharge of snowpack source nutrients to the lake prior to contact with the ground.

Nutrient mass balance indicates that scour of various ions from the base of the snowpack occurs in the three plant communities during the melt period. A portion of this is attributed to chemical reaction (cation exchange) and a portion, especially during the latter part of the melt when H^+ concentration in the snowpack is substantially reduced, attributed to the flushing effect of flowing water.

The exsolving pattern determined for the woodland and forest snowpacks aided in discerning a daily pattern of nutrient scour from the base of these respective snowpacks.

During the latter portion of the melt period, scoured nutrent concentrations declined linearly with time; TDP in the woodland and TP' TDP' Ca^{2+}, Mg^{2+}, Na^+ and K in the forest. This pattern occurred despite an accompanying surge and recession of meltwater runoff. This is indicative of a reduction of these available nutrients mentioned at the base of the respective snowpacks.

7.6 The interaction of meltwater and lakewater

Deuterium/hydrogen (D/H) values in snowmelt runoff, lake water, black ice and lake discharge were determined to discern the physical movement of snowmelt water within the lake. The D/H values of the important fractions of the hydrological equation used for this determination were different enough to separate the water of one source from the water of another. It was determined that snow meltwater can be separated from lake water in the shallow littoral zone. The differences apparent in approximately 1 metre of water are reduced in approximately 2 metres of water. It is assumed complete mixing of snow meltwater and lake water occurred.

A simple model, involving original lake temperature and mass, daily radiation and the mass and temperature of the daily addition of meltwater are used to predict the water temperature within the littoral zone. This indicates, for Elizabeth Lake, the effective mixing zone for meltwater and lake water for the latter period of the melt is approximately 3 metres.

7.7 Significance of results and suggestions for further studies

7.7.1 Nutrient loss

Moore (1983, 1984) reports a significant percentage of first year litterfall decomposition occurs just prior to the formation of the annual snowpack and through the snowyear. As the snowmelt runoff is a major process responsible for removal of nutrients potentially available for plant growth, it is conceivable that a substantial fraction of these nutrients will be washed out of the organic layers during the springmelt runoff. It is possible that this spring scouring of nutrients may be a major factor contributing to low growth rates of vegetation in the subarctic. The ecological importance of this seasonal nutrient scouring has yet to be established.

7.7.2 Lake nutrient dynamics

Current attempts to understand the nutrient dynamics of subarctic lakes such that land use in the subarctic can be determined in a rational manner have focused on the applicability of the empirical model of Dillon and Rigler (1975) to predict phosphorus concentrations in subarctic lakes (Smith et al. 1984).

The application of this empirical model, originally derived for temperate dimictic lakes of the Canadian Shield, to lakes in the subarctic must account for differences between the two systems, as those differences affect the model. The primary and major difference noted between the two systems is the notable contribution of nutrients from the terrestrial portion of the catchment during springmelt.

Of the factors comprising the Dillon and Rigler model those which will be affected by the difference in the two systems are the spring loading of P from the catchment and the retention of a significant portion of this load by the lake. These differences should be recognized and examined before application of the model to subarctic lakes is attempted. The significant spring loading of NO_3^- is of importance in N limited aquatic systems.

7.7.3 The influence of mineral soil impermeability during springmelt on the capacity of subarctic ecosystems to buffer acidic precipitation

The Labrador geosyncline, within which the Elizabeth Lake catchment is located, is relatively unaffected by acidic precipitation because of the high buffering capacity provided by the carbonate sediments. The geosyncline represents a reasonably small fraction of the eastern subarctic; most of which is comprised of Canadian Shield Precambrian rock, chiefly granite and gneiss, the buffering capacity of which is reportedly very low.

The climatic conditions affecting the Labrador geosyncline affect the Canadian Shield (Canada, 1978). The climatic evidence suggests that the process of overland flow believed to be dominant during springmelt within the Labrador geosyncline (this study; Fitzgibbon, 1977; Price, 1975) is also predominant in the subarctic Canadian Shield.

Within the poorly buffered Canadian Shield systems the dominance of overland flow during the springmelt period in the subarctic has significant implications for the interactions of acidic precipitation and the terrstrial and aquatic portions of the catchment.

In the subarctic, the frozen largely impermeable soil will mean the acid pulse during spring in aquatic systems will be far more pronounced as there will be reduced buffering of approximately 50% of the atmospheric acid loading. If mixing of snowmelt runoff and lake water occurs as suggested by the D/H results discussed earlier, the capacity of the littoral sediments to buffer the acids will be reduced in terms of time, relative to the littoral sediments in the temperate zone of the Canadian Shield.

7.7.4 Further studies

Further studies should attempt to assess the ecological importance of the nutrient transfer from land to water body during the spring melt. This would entail detailed examination of the change in mass of available nutrients within plots in tundra, woodland and forest sites through the year. If the seasonal changes can be accurately defined for the organic horizons within which the snowmelt water flows, the significance of the recorded scouring during springmelt to the terrestrial catchment can properly be assessed.

As it has been shown here that impermeable ground has significant implications for snowmelt runoff chemistry, further studies should investigate the physical conditions governing the formation of saturated concrete frost. These studies could range from an examination of factors influencing the spatial and temporal distribution of the phenomena to detailed examinations employing lysimeters. The use of in situ probes to record the soil moisture content change and concomitant temperature would aid in understanding the spatial and temporal changes.

One of the major conclusons at a recent workshop on acidic snowmelt runoff sponsored by Environment Canada (Marmorek et al. in prep.) was that in order to understand chemical perturbations in the natural ecosystems, a better understanding of the movement of water within the terrestrial system was needed. This workshop mainly examined the work of researchers studying temperate systems. It seems that if those working in the comparatively well studied temperate system argue for a greater understanding of these systems then by comparison much remains to be done in the subarctic. This study has investigated the springmelt runoff in one subarctic catchment and reported major differences in the flow of water during springmelt between the northerly system and the temperate systems to the south. The apparent differences between the two systems should be considered when applying knowledge derived from temperate systems to subarctic systems.

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Appendix A

Plant Community	Plot number	Strata	Dominant species	Species significance	Sociability Index	Subdominant species*	Species Significance	Sociability index
close spruce-moss forest	1	tree	*Picea glauca*	7	1	*Picea mariana*	2	1
		shrub	*Betula glandulosa*	3	2	*Ledum groenlandicum*		
						Alnus crispa		
						Rubus spp.		
						Vaccinium vitisidaea		
		herb				*Cornus canadensis*		
						Linnaea borealis		
						Viburnum edule		
						Pyrola spp.		
		moss	*Pleurozium schreberi*	8	4	*Aulacommium polustre*		2
		lichen				*Cladonia* spp.		2
	2	tree	*Picea glauca*	7	1			
			Picea mariana	5	1			
		shrub	*Betula glandulosa*	2	2	*Ledum groenlandicum*		
			Alnus crispa	2	1	*Ribes* spp.		
						Vaccinium spp.		
		herb				*Pyrola* spp.		
						Lycopodium annotinum		
						Linnaea borealis		
						Selaginella Selaginoides		
		moss	*Pleurozium schreberi*	6	4			
			Hylocomium splendens	5	4	*Hypnum crista-castrensis*		2
		lichen				*Cladonia* spp.		2
	3	tree	*Picea mariana*	6	1			
			Picea glauca	4	1			
		shrub	*Alnus crispa*	2	1			
			Betula glandulosa	2	2	*Rubus* spp.		
						Empetrum		
		herb				*Lycopodium annotinum*		
						Viburnum edule		
						Pyrola spp.		
						Linnaea borealis		
		moss	*Hylocomium splendens*	6	4	*Hypnum crista-castrensis*		2
			Pleurozium schreberi	5	3	*Polytrichum* sp.		2
		lichen				*Cladonia* spp.		2

Appendix A continued

Plant Community	Plot number	Strata	Dominant species	Species significance	Sociability Index	Subdominant species*	Species Significance	Sociability index
	4	tree	*Picea glauca*	7	1			
		shrub	*Vaccinium uliginosum*	2	1	*Ledum groenlandicum*		
			Betula glandulosa	2	2	*Salix* spp.		
		herb				*Linnaea borealis*		
						Selaginella Selaginoides		
						Lycopodium spp.		
						Cornus canadensis		
						Vaccinium vitis-idaea		
		moss	*Pleurozium schreberi*	6	4	*Sphagnum* sp.		1
			Aulacomnium palustre	4	4			
			Hylocomium splendens	3	2			
		lichen	*Cladonia* sp.	2	2			
open spruce	1	tree	*Picea mariana*	2	1	*Picea glauca*		2
		shrub	*Ledum groenlandicum*	5	3	*Empetrum* spp.		
			Betula glandulosa	5	2	*Alnus crispa*		
						Vaccinium uliginosum		?
		herb				*Petasites frigida*		
						Lycopdium spp.		
		moss	*Pleurozium schreberi*	5	3			
		lichen	*Cladonia Alpestris*	7	4	*Cladonia* spp.		
	2	tree	*Picea mariana*	2	1	*Picea glauca*		5
		shrub	*Betula glandulosa*	6	3	*Vaccinium uliginosum*		?
			Ledum groenlandicum	4	2	*Vaccinium angustifolium*		
						Alnus crispa		
						Salix reticulata		?
						Salix glauca		
		herb				*Lycopodium* spp.		
						Cornus canadensis		
		moss	*Pleurozium schreberi*	5	3			
		lichen	*Cladonia Alpestris*	6	4	*Cladonia* spp.		

Appendix A continued

Plant community	Plot number	Strata	Dominant species*	Species significance	Sociability Index	Subdominant species*	Species Significance	Sociability index
	3	tree	*Picea mariana*	4	1			
		shrub	*Betula glandulosa*	4	2	*Alnus crispa*		
						Ledum groenlandicum		
						Salix spp.		
						Betulanna exilis		?
						Arctostophylos spp.		
		herb				*Deschampsia* spp.		2
						Lycopodium spp.		2
		moss	*Pleroxium schreberi*	3	2	*Calamagrostis canadensis*		
			Cladonia rangiferous-Alpestis	7	4	*Eladonia* spp.		
	4	tree	*Picea mariana*	3	1			
		shrub	*Betula glandulosa*	2	2	*Ledum geonlandicum*		
						Salix glauca		
		herb				*Lycopodium* spp.		
						Cornus canadensis		
						Petasites frigida		
		moss				*Dicranum fuscescens*		
		lichen	*Cladonia* spp.	8	4			
	5	tree	*Picea mariana*	4	1			
		shrub	*Ledum goenlandicum*	2	2	*Betula glandulosa*		
						Salix spp.		
						Betula nana		
						Alnus crispa		
		herb				*Lycopodium* spp.		
						Vaccinium vitis-idaea		
		moss				*Dicranum fuscescens*		
						Pleroxium schreberi		
		lichen	*Cladonia alpestris*	7	4			
			Cladonia rangiferous	4	2			

Appendix A continued

Plant Community	Plot number	Strata	Dominant species	Species significance	Sociability Index	Subdominant species*	Species Significance	Sociability index
Tundra	1	tree	*Picea mariana*		1			
		shrub				*Ledum groenlandicum*		
						Salix hastata		
						Salix spp.		
						Betula spp.		
		herb				*Lycopodium annotinium*		
						Lycopodium spp.		
		moss	*Tortella* spp.	2	2	*Dicranium* spp.		
		lichen	*Cladonia alpestris*	6	4	*Cladonia* spp.		
	2	tree						
		shrub				*Salix* spp.		
						Betula spp.		
		herb				*Lycopodium* spp.		
						Carex spp.		
		moss	*Dicranium* spp.	3	2	*Pleurozium schreberi*		
		lichen	*Cladonia* spp.	5	3			
	3	tree						
		shrub				*Salix* spp.		
						Betula spp.		
						Alnus crispa		
						Vaccinium vitis-idaea		
		herb				*Carex* spp.		
						Dryas integrifolia		
						Lycopodium spp.		
		moss				*Dicranium* spp.		
						Pleurozium schreberi		
		lichen	*Cladonia alpestris*	5	3	*Cladonia* sp.		
			Cladonia rangiferous	3	2			

* subdominant species are less than 5%.
for all subdominant species: species significance and sociability index are assumed to be 1 unless otherwise stated

Appendix B Soil moisture

	Site Number	Soil Nov.	x	Soil March	x	Litter Nov.	x	Litter March	x	Vegetation Nov.	x	Vegetation March	x
Tundra sites	8	39.65		25.79		82.56		65.67		85.27		78.60	
		84.05	65.67	23.05	21.80	86.87	83.62	68.02	67.87	83.69	83.69	74.01	75.28
		73.3		16.56		81.42		69.94		82.13		73.23	
	2	17.9		33.3		84.6		61.49		84.80		81.08	
		16.3	15.47	31.31	36.12	83.41	81.13	67.75	64.83	91.85	89.77	73.09	76.17
		12.2		43.76		75.37		65.25		92.68		74.34	
	23	23.71		N.D.		81.85		63.37		86.29		69.73	
		46.1	32.06	57.12	48.83	84.31	81.19	68.07	63.79	89.99	86.91	75.80	73.25
		26.37		40.54		77.42		59.93		84.44		74.23	
	4	32.3		52.17		76.98		70.91		78.90		75.49	
		39.0	35.65	37.19	42.65	69.49	76.76	67.98	70.61	88.08	83.52	75.22	75.71
		N.D.		38.59		83.81		72.93		83.58		76.41	
	28	6[illegible].50		59.62		45.03		58.98		72.80		66.83	
		55.57	49.26	16.47	45.41	67.02	64.98	63.98	60.99	83.03	78.84	70.13	68.61
		25.72		70.13		82.88		60.01		80.70		68.88	
Tundra runoff plot	upper	38.01	40.23	33.96	41.35	83.42	81.77	71.29	78.52	84.31	85.94	80.51	79.71
		42.44		48.74		80.12		85.74		87.56		78.9	
	mid	40.22	41.10	38.99	40.43	89.62	86.32	83.39	77.74	89.50	90.56	82.87	77.36
		41.98		41.87		83.02		72.08		91.63		71.85	
	lower	25.32	27.91	27.10	28.71	79.78	77.34	64.92	65.54	82.00	79.22	66.34	68.96
		30.50		30.32		74.89		66.16		76.43		71.57	
Woodland	21	24.1		27.01		82.05		75.06		88.13		70.13	
		30.0	33.07	32.37	33.29	79.63	77.85	73.08	72.38	87.17	87.25	76.67	71.52
		45.1		40.51		71.68		69.00		86.46		69.75	
	7	14.1		17.81		73.24		64.56		87.54		72.34	
		13.5	12.17	15.17	14.37	75.34	72.49	70.52	66.84	86.63	88.12	74.60	74.48
		8.9		10.13		68.90		65.43		90.20		76.50	
	20	16.2		30.00		73.45		60.47		78.54		70.20	
		23.0	18.10	22.27	24.23	60.51	65.60	63.05	61.47	74.20	77.46	69.55	70.25
		15.1		20.43		72.83		60.90		79.64		71.00	
	30	17.3		20.53		77.84		62.35		72.51		70.11	
		35.0	31.13	28.63	29.30	80.50	79.25	70.55	68.78	83.51	80.10	68.34	70.02
		41.1		38.74		79.41		73.45		84.30		71.61	
	22	18.61		33.75		88.04		67.96		93.94		79.10	
		10.80	15.09	60.06	47.82	79.50	83.58	50.05	61.69	85.07	89.46	58.42	69.1
		15.86		49.65		83.20		67.05		89.38		69.78	

	30	17.3		20.53		77.84		62.35		72.51		[illegible]	
		35.0	31.13	28.63	29.30	80.50	79.25	70.55	68.78	83.51	80.10	68.34	70.02
		41.1		38.74		79.41		73.45		84.30		71.61	
	22	18.61		33.75		88.04		67,96		93.94		79.10	
		10.80	15.09	60.06	47.82	79.50	83.58	50.05	61.69	85.07	89.46	58.42	69.1
		15.86		49.65		83.20		67.05		89.38		69.78	
	34	21.99		38.16		78.64		55.32		87.36		72.26	
		76.95	42.39	37.52	38.61	85.29	80.54	60.00	60.23	83.52	87.86	73.36	75.03
		28.25		40.14		77.68		65.36		92.69		79.46	
	47	58.87		35.09		79.74		69.53		87.34		81.69	
		51.09	52.49	29.49	28.26	80.76	79.32	68.06	68.84	81.91	83.92	68.96	71.61
		47.50		20.19		77.47		68.94		82.51		64.18	
	15	56.0		20.48		87.94		59.61		82.41		82.42	
		28.3	35.93	25.92	22.80	50.92	84.85	59.59	62.65	92.46	88.05	74.77	77.17
		23.5		22.01		85.69		68.76		89.28		74.31	
	38	24.1		64.03		80.60		65.05		84.11		72.37	
		16.3	18.47	34.74	41.07	75.35	78.69	72.63	69.49	90.40	89.29	79.01	74.83
		15.0		24.43		80.12		70.80		93.36		73.11	
	37	22.1		14.27		84.32		81.39		97.58		68.24	
		16.0	26.27	33.74	32.10	83.00	85.08	83.02	83.52	84.37	85.82	72.80	71.98
		40.7		48.28		87.93		86.15		80.52		74.89	
	42	53.3		23.14		79.66		68.93		79.63		74.83	
		42.1	42.57	35.64	26.88	83.27	81.11	66.89	64.83	86.01	85.04	62.54	70.66
		32.3		21.85		80.40		58.66		89.47		74.62	
	3	18.17	15.53	23.95	19.34	72.33	70.06	63.43	59.26	88.90	89.34	85.59	82.59
		12.88		14.72		67.78		55.09		89.78		79.59	
	38	32.85	30.29	22.57	29.11	78.13	75.98	65.18	61.50	82.95	84.69	78.65	76.85
		27.73		29.65		73.83		57.81		86.43		75.05	
	4	11.98	12.32	12.23	14.31	53.19	58.95	49.27	57.15	89.91	90.56	73.63	75.75
		12.65		16.38		64.72		65.03		92.10		77.86	
	48	37.82	35.17	35.64	31.26	70.13	69.84	64.72	61.06	88.30	83.85	72.11	75.68
		32.52		26.88		69.55		57.40		79.40		79.25	
Woodland	upper	38.50	40.50	40.21	40.02	75.09	77.55	52.58	66.02	92.23	90.62	80.41	80.79
runoff		42.50		39.83		80.00		79.45		89.01		81.16	
plot	mid	29.85	28.13	30.00	29.76	83.21	81.23	75.81	68.06	79.01	80.56	78.83	74.29
		26.40		29.51		79.24		70.31		82.11		69.75	
	lower	26.47	27.78	22.55	26.92	73.09	75.26	64.55	67.07	85.37	84.17	78.44	77.71
		29.08		31.28		77.43		69.59		82.97		76.97	
Forest	50	15.9		20.86		82.96		65.96		87.97		75.49	
		9.2	14.37	28.22	23.61	80.97	81.26	72.85	70.26	92.11	88.56	74.31	76.6
				[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	

		42.1	42.57	35.64	26.88	83.27	81.11	66.89	64.83	86.01	85.04	62.54	70.66
		32.3		21.85		80.40		58.66		89.47		74.62	
	3	18.17	15.53	23.95	19.34	72.33	70.06	63.43	59.26	88.90	89.34	85.59	82.59
		12.88		14.72		67.78		55.09		89.78		79.59	
	3B	32.85	30.29	22.57	29.11	78.13	75.98	65.18	61.50	82.95	84.69	78.65	76.85
		27.73		29.65		73.83		57.81		86.43		75.05	
	4	11.98	12.32	12.23	14.31	53.19	58.95	49.27	57.15	89.91	90.56	73.63	75.7
		12.65		16.38		64.72		65.03		92.10		77.86	
	4B	37.82	35.17	35.64	31.26	70.13	69.84	64.72	61.06	88.30	83.85	72.11	75.68
		32.52		26.88		69.55		57.40		79.40		79.25	
Woodland	upper	38.50	40.50	40.21	40.02	75.09	77.55	52.58	66.02	92.23	90.62	80.41	80.79
runoff		42.50		39.83		80.00		79.45		89.01		81.16	
plot	mid	29.85	28.13	30.00	29.76	83.21	81.23	75.81	68.06	79.01	80.56	78.83	74.29
		26.40		29.51		79.24		70.31		82.11		69.75	
	lower	26.47	27.78	22.55	26.92	73.09	75.26	64.55	67.07	85.37	84.17	78.44	77.71
		29.08		31.28		77.43		69.59		82.97		76.97	
Forest	50	15.9		20.86		82.96		65.96		87.97		75.49	
		9.2	14.37	28.22	23.61	80.97	81.26	72.85	70.26	92.11	88.56	74.31	76.6
		18.0		21.75		79.84		71.98		85.61		80.00	
	11	20.1		22.22		81.67		68.77		86.02		69.01	
		22.0	21.87	23.57	22.29	77.79	78.46	72.05	64.33	83.01	84.29	72.29	71.87
		23.5		21.07		75.92		62.18		83.84		74.30	
	24	25.4		37.16		76.90		62.15		85.27		73.28	
		23.0	30.80	62.18	50.45	74.20	74.23	66.60	64.25	91.70	86.72	75.00	75.80
		44.0		52.00		71.58		64.00		83.19		79.12	
	3	39.16		32.57		82.01		65.98		89.72		72.23	
		28.24	29.54	29.85	32.48	74.49	76.44	62.47	63.75	84.24	86.78	70.08	71.96
		21.21		35.01		72.83		62.80		86.38		73.56	
	10	33.9		32.3		77.50		70.71		85.34		67.08	
		38.44	33.04	29.51	30.94	76.01	77.74	73.65	68.18	86.23	86.65	65.96	69.17
		26.79		31.00		79.73		60.18		88.38		74.48	
	27	28.10		32.30		79.55		64.28		92.80		77.44	
		37.61	31.53	36.43	32.95	80.17	78.90	65.44	67.47	86.26	88.02	76.33	78.00
		28.87		30.12		76.99		72.68		85.01		80.23	
Woodland	upper	42.01	38.84	45.79	40.01	92.24	90.49	80.73	79.98	94.60	95.30	88.80	88.8
runoff		35.67		35.22		88.75		79.22		96.00		88.10	
plot	mid	34.56	36.29	36.03	33.60	94.68	92.86	86.71	82.35	90.66	89.40	89.57	87.98
		38.01		31.16		91.03		77.98		88.14		86.38	
	lower	56.32	58.35	62.21	59.76	89.01	91.69	84.14	81.99	94.56	92.39	81.03	84.64
		60.37		57.30		94.36		79.83		90.23		88.25	

Appendix C Woodland runoff plot mass balance (continued).

Date	Ca^{2+}				Mg^{2+}			
	Runoff mg	Snowpack mg	Scour mg	Scour concentration mg L^{-1}	Runoff mg	Snowpack mg	Scour mg	Scour concentration mg L^{-1}
May 2	862.15	332.83	531.33	0.719	236.08	110.69	125.39	0.170
3	116.89	107.27	9.62	0.040	40.58	35.72	4.74	0.006
8	14.24	13.13	1.10	0.022	6.10	4.70	1.40	0.002
9	126.72	86.62	39.90	0.076	73.87	33.90	39.97	0.076
12	204.31	185.06	19.25	0.032	108.14	58.93	49.21	0.082
13	341.85	164.61	177,24	0.332	85.42	52.49	33.05	0.062
14	549.37	435.09	114.29	0.082	140.82	138.27	2.55	0.002
15	830.07	657.64	170.43	0.097	300.11	200.48	99.63	0.057
16	1140.85	1012.53	130.33	0.058	425.25	295.25	130.01	0.058
17	2786.95	1680.91	1108.77	0.298	780.03	490.86	290.39	0.078
18	1130.82	294.74	838.09	0.466	179.82	100.97	78.49	0.044
19	1583.95	433.08	1150.87	0.436	211.41	148.23	63.18	0.024
20	264.66	80.20	184.06	0.376	53.83	27.46	26.37	0.054
21	50.33	16.06	34.29	0.347	12.76	5.49	7.31	0.074
22	55.39	19.33	35.89	0.306	11.76	6.62	5.13	0.044
23	182.86	59.95	122.91	0.336	32.93	20.53	12.39	0.034
24	52.93	27.27	25.66	0.156	23.21	9.32	13.85	0.084
25	69.17	30.08	39.90	0.217	20.29	10.33	9.96	0.054
26	32.28	17.68	14.74	0.136	8.65	6.06	2.59	0.024
27	519.30	304.76	216.54	0.116	185.65	104.37	81.41	0.044
28	818.04	461.15	354.89	0.126	197.44	158.59	38.88	0.0137
29	1186.96	884.21	302.76	0.136	431.33	303.75	121.5	0.024
30	423.06	366.92	58.15	0.261	178.85	125.63	53.22	0.024
31	338.85	222.56	116.29	0.862	122.23	76.18	45.93	0.034
June 1	128.32	56.74	73.58	0.707	76.30	19.44	56.86	0.164
	13816.46	7947.82	5860.62	5.148	3942.68	2543.00	1399.68	1.329

Appendix C   Woodland runoff plot mass balance (continued).

	Na+				K+			
Date	Runoff (mg)	Snowpack (mg)	Scour (mg)	Scour concentration (g/L^{-1})	Runoff (mg)	Snowpack (mg)	Scour (mg)	Scour concentration (g/L^{-1})
May 2	517.50	280.60	234.60	.23	317.10	132.55	184.55	.25
3	104.88	90.85	14.03	.02	145.45	43.01	102.44	1.31
8	21.37	11.52	9.82	.01	24.91	3.79	21.11	.03
9	205.86	79.58	126.27	.24	121.21	12.12	109.09	.21
12	246.33	166.29	80.27	.12	306.54	52.39	254.15	.42
13	213.67	147.89	65.78	.09	354.25	99.3	215.83	.40
14	522.10	388.70	131.33	.02	436.75	222.09	214.66	.15
15	618.70	588.80	28.98	.01	707.71	427.75	277.61	.16
16	917.70	901.60	16.10	.02	782.00	339.78	445.74	.20
17	1561.70	1495.00	66.70	.18	742.90	563.04	179.86	.05
18	609.50	285.2	326.60	.13	735.08	34.04	699.89	.39
19	765.90	416.30	347.30	.14	817.19	50.83	766.36	.29
20	141.91	77.28	64.63	.15	132.16	9.42	122.77	.25
21	30.59	15.48	15.18	.18	31.55	1.88	29.25	.30
22	40.02	18.63	21.39	.15	34.09	2.27	31.83	.31
23	106.49	57.73	55.43	.11	87.58	7.094	80.54	.22
24	44.62	26.22	18.40	.05	38.01	3.17	34.83	.21
25	38.64	28.98	9.66	.06	33.20	3.56	29.64	.16
26	23.78	17.07	6.71	.06	20.53	2.07	18.46	.17
27	519.80	294.40	225.40	.12	389.83	3.59	354.25	.19
28	593.40	446.20	144.90	.05	546.21	54.35	509.47	.18
29	1186.80	853.30	335.00	.06	1294.21	88.37	1192.55	.22
30	581.90	354.20	227.70	.10	649.06	43.01	606.05	.27
31	434.70	214.59	219.88	.16	339.39	26.16	313.91	.23
June 1	138.69	54.74	83.95	.24	124.73	6.65	118.08	.34
	10,189.00	7,311.70	2877.3		12711.41	2279.53	6912.88	

Appendix C Woodland runoff plot mass balance.

Date	TP Runoff (mg)	TP Snowpack (mg)	TP Scour (mg)	TP Scour concentration (µg/l)	TDP Runoff (mg)	TDP Snowpack (mg)	TDP Scour (mg)	TDP Scour concentration (µg/l)	NO_3^- Runoff (mg)	NO_3^- Snowpack (mg)	NO_3^- Scour (mg)	NO_3^- Scour concentration (mg/l)
May 2	19.27	9.51	9.76	13.23	16.15	2.36	13.79	18.69	199.17	189.34	9.80	.02
3	5.56	3.07	2.49	10.44	4.32	.76	3.56	14.93	69.16	61.19	7.96	.03
8	1.86	.35	1.51	29.68	1.04	.06	.98	19.26	10.68	7.38	3.32	.07
9	16.53	2.11	14.41	27.30	9.19	.13	9.06	17.16	163.62	47.50	116.08	.22
12	18.06	6.48	11.58	19.27	11.82	2.69	9.13	15.19	198.31	116.82	81.49	.14
13	17.57	5.76	11.81	22.11	13.94	2.39	11.55	21.62	186.96	103.90	83.06	.16
14	31.13	15.20	15.93	11.31	21.72	6.31	15.41	10.94	408.48	273.95	134.56	.10
15	47.38	24.45	22.94	13.00	31.16	11.28	19.89	11.27	547.05	426.44	120.55	.07
16	63.64	39.33	27.37	12.23	40.78	19.50	21.28	9.51	693.92	669.09	24.80	.01
16	99.02	65.29	33.73	9.07	60.99	32.37	28.57	7.69	1189.41	1110.85	78.55	.02
18	46.37	9.73	36.64	20.39	27.30	1.18	26.13	14.55	431.15	187.06	244.09	.14
19	61.91	14.30	47.61	18.04	45.92	1.73	44.19	16.74	712.53	274.87	437.67	.17
20	11.97	2.65	9.32	19.03	9.55	.32	9.23	18.85	93.02	50.97	42.04	.09
21	1.79	.53	1.26	12.78	1.32	.06	1.25	12.68	16.76	10.17	6.57	.07
22	2.34	.64	1.70	14.44	1.42	.08	1.35	11.47	24.71	12.29	12.40	.11
23	7.37	1.98	5.39	14.74	4.78	.24	4.54	12.41	73.13	38.07	35.05	.10
24	3.48	.90	2.58	15.60	2.42	.11	2.31	13.97	38.03	17.26	20.76	.13
25	3.25	.99	2.25	12.20	2.26	.12	2.14	11.60	35.04	19.14	15.90	.09
26	2.05	.58	1.47	13.60	1.21	.07	1.13	10.45	17.29	11.24	6.08	.06
27	34.28	10.06	24.22	13.04	21.41	1.22	20.19	10.87	334.24	193.31	140.89	.08
28	54.49	15.28	39.20	13.89	26.68	1.85	24.83	8.80	564.06	293.81	270.24	.10
29	105.27	29.24	76.03	14.09	44.35	3.53	40.82	7.57	1294.99	560.32	732.96	.14
30	39.68	12.11	27.56	12.33	19.09	1.46	17.63	7.89	603.48	232.84	370.69	.17
31	26.65	7.35	19.30	14.21	13.73	.88	12.84	9.45	325.84	141.29	184.56	.14
June 1	2.01	1.87	.14	.40	.69	.23	.47	1.36	86.63	35.99	50.60	.15
	722.93	279.80	446.21		433.26	90.94	342.32		8317.74	5086.92	3230.82	

Appendix D Forest runoff plot mass balance.

Date	TP				TDP				NO_3^-			
	Runoff (mg)	Snowpack (mg)	Scour (mg)	Scour concentration (μg/l)	Runoff (mg)	Snowpack (mg)	Scour (mg)	Scour concentration (μg/l)	Runoff (mg)	Snowpack (mg)	Scour (mg)	Scour concentration (mg/L^{-1})
May 2	22.42	50.19	--	--	17.22	8.79	8.43	9.21	393.14	310.05	83.09	.09
3	37.78	50.22	--	--	25.87	8.20	17.67	11.76	616.38	370.20	246.18	.16
7	.60	.41	.19	4.70	.20	.03	.17	4.30	14.94	5.89	9.05	.22
8	1.20	.69	.51	7.31	.49	.06	.43	6.16	22.32	10.11	12.21	.18
9	5.32	3.17	2.15	6.88	1.86	.29	1.57	5.03	96.80	45.52	51.28	.17
13	15.61	4.85	10.76	22.36	5.67	.45	5.22	10.85	207.11	69.95	137.16	.28
14	59.31	11.97	47.34	38.81	41.19	5.61	35.58	29.17	537.01	279.04	257.97	.21
15	49.37	17.23	32.14	18.33	21.63	8.07	13.56	7.74	700.71	401.20	299.51	.17
16	45.79	15.87	29.92	18.55	16.59	7.42	9.17	5.69	532.05	369.58	162.47	.10
17	60.10	36.10	24.00	10.52	21.38	18.52	2.86	1.25	889.84	705.67	184.17	.08
18	93.35	55.45	37.90	10.91	30.37	28.58	1.79	.52	1071.53	1080.83	--	--
19	30.27	19.67	10.60	11.01	9.75	7.95	1.8	1.87	288.97	300.75	--	--
20	3.39	2.38	1.01	8.59	1.10	.97	.13	1.11	36.46	36.77	--	--
23	1.30	.98	.32	6.22	.41	.41	--	--	14.39	15.99	--	
24	12.73	4.40	8.33	15.42	4.12	1.99	2.13	3.94	118.81	109.76	9.05	.02
25	26.51	1.93	24.58	22.45	7.09	.88	6.21	5.67	197.19	146.34	50.85	.05
26	3.8	.32	3.48	18.94	1.09	.15	.94	5.12	44.09	24.49	19.60	.11
27	11.05	1.05	10.00	16.70	4.05	.48	3.57	5.96	137.66	80.12	57.54	.23
28	21.43	2.44	18.99	13.64	8.14	1.12	7.02	5.04	347.88	186.65	161.23	.12
29	26.72	3.77	22.95	10.74	11.24	1.72	9.52	4.45	513.44	286.49	226.95	.11
30	46.02	5.51	40.51	12.91	16.09	2.53	13.56	4.32	659.17	420.43	238.74	.08
31	47.53	6.68	40.85	10.76	15.30	3.06	12.24	3.23	1100.68	508.48	592.2	.16
June 1	32.31	4.14	28.17	11.94	11.79	1.89	9.90	4.20	707.61	315.92	391.69	.17
2	14.89	2.28	12.61	9.72	5.99	1.04	4.95	3.82	427.98	173.69	254.29	.20
3	25.41	4.71	20.70	7.71	11.28	2.16	9.12	3.40	1154.85	359.64	795.21	.30
4	14.22	2.46	11.76	8.38	6.48	1.13	5.35	3.81	407.01	187.98	219.03	.16
5	4.07	.78	3.29	7.34	1.42	.36	1.06	2.36	94.13	60.04	34.09	.08
6	3.12	.68	2.44	6.26	1.32	.31	1.01	2.59	66.21	52.17	14.04	.04
	715.62	270.12	445.50		299.13	114.17	184.96		11398.35	6890.75	4507.6	

Appendix D Forest runoff plot mass balance (continued).

Date	Ca2+ Runoff mg	Ca2+ Snowpack mg	Ca2+ Scour mg	Ca2+ Scour concentration mg L^{-1}	Mg2+ Runoff mg	Mg2+ Snowpack mg	Mg2+ Scour mg	Mg2+ Scour concentration mg L^{-1}
May 2	603.51	364.90	238.6	0.260	311.04	137.30	173.75	.189
3	842.1	340.85	501.25	0.333	135.23	164.03	--	--
7	8.08	1.564	6.50	0.161	3.23	2.61	0.62	.015
8	13.25	2.71	10.55	0.150	7.72	4.51	3.17	.045
9	74.99	12.19	62.76	0.201	43.74	20.17	23.45	.075
13	509.27	18.75	491.23	0.103	274.59	31.10	243.00	.505
14	962.4	292.73	671.68	0.550	500.58	100.72	399.74	.327
15	1437.59	421.05	1016.54	0.580	648.81	144.59	503.01	.287
16	1646.11	386.97	1259.14	0.780	660.96	133.65	528.53	.327
17	1301.25	986.46	312.78	0.137	569.84	228.42	342.63	.150
18	1798.49	1523.80	272.68	0.790	551.61	347.49	205.34	.059
19	587.47	425.06	163.01	0.169	308.61	96.84	211.41	.219
20	49.32	51.73	37.49	0.319	49.33	11.82	37.54	.319
23	25.66	22.66	3.11	0.061	13.37	5.16	8.20	.160
24	200.50	106.07	93.83	0.174	102.55	35.24	67.31	.125
25	437.1	47.19	390.98	0.357	196.83	47.14	149.45	.137
26	69.77	7.86	61.96	0.337	31.23	7.89	23.33	.127
27	394.99	25.66	368.92	0.617	143.37	25.76	117.98	.197
28	850.12	59.95	789.97	0.567	264.87	60.02	204.12	.147
29	1241.10	92.03	1150.87	0.537	427.68	92.22	335.34	.157
30	3075.67	134.94	2939.33	0.937	1160.33	138.23	1025.46	.327
31	1555.88	163.21	1393.48	0.367	607.50	164.03	443.48	.117
June 1	565.4	101.45	465.16	0.197	235.71	101.70	13.37	.057
2	673.68	55.74	619.55	0.477	272.16	55.80	21.63	.167
3	860.15	115.49	743.85	0.277	268.52	115.79	153.09	.057
4	350.88	60.35	290.73	0.207	112.27	60.51	51.76	.037
5	116.49	19.27	97.24	0.217	49.33	19.32	30.01	.669
6	81.8	16.74	64.96	0.167	34.99	16.77	18.23	.182
	20370.8	5878.66	14534.25	10.24	7987.41	2337.66	5650.97	4.445

Appendix D . Forest runoff plot mass balance (continued).

	Na^+				K^+			
Date	Runoff mg	Snowpack mg	Scour mg	Scour concentration mg L^{-1}	Runoff mg	Snowpack mg	Scour mg	Scour concentration mg L^{-1}
May 2	887.8	344.77	542.80	.593	512.21	224.83	287.78	0.314
3	931.5	411.7	519.80	0.346	856.29	209.58	645.15	0.430
7	14.95	6.53	8.42	0.208	17.40	0.98	16.42	0.406
8	27.83	11.27	16.65	0.239	14.66	1.68	12.98	0.186
9	109.49	50.60	58.65	0.188	75.07	7.51	67.64	0.216
13	356.5	77.74	278.30	0.580	360.80	11.50	349.55	0.726
14	621.0	266.80	354.20	0.291	731.17	24.63	590.41	0.484
15	1032.7	384.1	650.90	9.371	946.22	204.10	742.9	0.423
16	968.3	351.9	614.10	0.381	1098.71	187.68	907.12	0.563
17	685.4	625.6	59.57	0.262	637.3	469.20	170.87	0.075
18	864.8	954.5	--	--	1243.38	723.35	523.94	0.151
19	328.9	266.8	61.41	0.064	578.68	200.97	376.53	0.391
20	101.2	32.43	68.77	0.584	88.37	24.52	63.73	0.541
23	23.69	14.17	9.50	0.185	17.99	10.67	7.27	0.142
24	113.39	96.83	16.61	0.308	53.96	50.04	3.79	0.704
25	305.90	129.49	177.10	0.162	240.86	22.29	218.57	0.200
26	73.37	21.62	51.75	0.282	60.61	3.72	57.09	0.310
27	388.7	71.07	317.40	0.532	203.7	12.20	191.59	0.320
28	724.5	164.68	558.90	0.402	527.85	28.35	500.48	0.359
29	1283.4	253.00	1030.40	0.482	918.85	43.56	875.84	0.410
30	2479.4	370.30	2109.10	0.672	1294.21	50.83	1255.11	0.400
31	1934.3	448.50	1485.80	0.391	1251.20	77.42	1176.91	0.310
June 1	708.4	278.3	427.80	0.181	330.40	50.44	282.30	0.120
2	595.7	153.4	443.90	0.342	453.56	26.43	426.19	0.330
3	724.5	317.4	407.10	0.152	295.60	54.74	240.86	0.895
4	294.4	166.06	128.57	0.918	210.36	28.58	181.82	0.129
5	147.89	53.13	94.76	0.212	44.97	9.15	35.70	0.80
6	109.02	46.00	63.02	0.162	43.01	7.94	34.92	0.895
	16836.0	6189.3	10646.70	0.815	13133.69	2893.40	10240.29	8203.18