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**LA THÈSE A ÉTÉ
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PHYSICAL LIMNOLOGY OF A SMALL SUB-ARCTIC ALPINE
LAKE, YUKON TERRITORY.

by
Richard E.C. Schwartzburg

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

UNIVERSITY OF OTTAWA
OTTAWA, CANADA, 1985



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ABSTRACT

A hydrogeological study was carried out on the headwater lake of Gladstone Creek, Yukon Territory, $61^{\circ}23'N$ $138^{\circ}3'W$, from June 2, 1981 to August 23, 1981. The study examined the routing of water to the lake as well as hydrological and hydrochemical parameters. These parameters were lake temperature, currents, precipitation, seiche activity and the analysis for the major ions of calcium, magnesium, sodium, potassium and the minor ions of iron, zinc, nickel, manganese and copper using atomic absorption spectrophotometry.

Because of periods of frequent and intense precipitation in June and early July the study was divided into wet and dry periods. The wet period lasted from June 2 to July 6 and was followed by the dry period. During the wet period the lake level rose due to direct precipitation, overland flow, saturated soil conditions and a groundwater discharge configuration. During the dry period the lake level decreased due to a lack of precipitation and a change to a groundwater recharge configuration.

During the study period the lake became thermally stratified with the subsequent deterioration of the thermocline and turnover resulting. The sequence of events was the same as those of lakes located in more southerly latitudes with the exception that the time frame for those events is much shorter for the study lake. This is due to its northerly location which results in longer periods of insolation over a shorter period of time.

The hydrochemical analysis of the lake water samples were divided into two segments: the analysis of lake water samples and the analysis of water derived from sediment samples from the lake bottom. The analysis of the lake water showed that calcium, magnesium, sodium and potassium increased in concentration through the study period. Regression analysis of the plots of concentration versus time showed calcium to have had the largest increase (slope = 0.24), the others significantly less (0.02, 0.03 and 0.002 respectively). Zinc was found to decrease (slope = -0.01) while the rest were below detectable limits. The analysis of the water derived from the sediment samples showed that calcium, magnesium and potassium decreased; sodium increased; copper, zinc and manganese were variable and iron was undetectable.

During the study period seiche activity was recorded fifteen times. The characteristic oscillatory motion of the lake was recorded on the outflow creek stage recorder. This allowed for a comparison between the calculated period of oscillation for the lake with the observed period of oscillation: these were 6.8 minutes for the calculated period and ranged from 5.5 to 7.5 minutes with a mean of 6.42 minutes for the observed period.

RESUME

Le lac à la tête du système hydrologique du ruisseau Gladstone, Territoire du Yukon, $61^{\circ}23'N$ $138^{\circ}3'O$ fut l'objet d'une étude hydrogéologique durant la période du 2 juin au 23 août, 1981. L'étude a comporté de l'observation du cheminement des eaux vers le lac et de la mesure de plusieurs paramètres hydrologiques et hydrochimiques. Ces paramètres furent la température du lac, les courants, la précipitation, les variations de seiches et l'analyse hydrochimiques des eaux par absorption atomique (calcium, magnésium, sodium, potassium, fer, zinc, nickel, manganèse et cuivre).

L'étude fut divisée en deux périodes: 1) la période humide (2 juin - 6 juillet) et 2) la période sèche (7 juillet - 23 août). Durant la période humide le niveau des eaux du lac s'élève dû à la précipitation, à l'écoulement des eaux de surface, aux conditions saturées du sol et une modèle de déchargement de l'eau sous-terrain. Durant la période sèche, le niveau du lac s'abaisse dû au manque de précipitation et une modèle de réchargement de l'eau sous-terrain.

Pendant la période d'étude, une stratification thermique fut observé, suivre par la détérioration de la thermocline et par la suite d'un renversement. La séquence des événements hydrologiques observés fut semblable à celle des lacs situés à des latitudes plus méridionales sauf que la durée était plus courte. Ceci est lié à des périodes d'ensoleillement plus longues sur une période de temps plus courte dû à la latitude du lac.

L'analyse hydrochimique fut divisée en deux parties:
1) l'analyse des échantillons d'eau du lac et 2) l'analyse de l'eau provenant des échantillons de sédiments du fond lacustre. Une augmentation de la concentration des ions calcium, magnésium, sodium et potassium a été observée pendant l'été. L'analyse de régression de la relation entre la concentration ionique et le temps a démontré que le calcium augmente le plus (pente=0.24) tandis que la pente des autres augmente très peu (0.02, 0.03 et 0.002 respectivement). Le zinc a diminué (pente=-0.01) tandis que les autres ions étaient sous la limite de détection. L'analyse de l'eau provenant des échantillons de sédiments a démontré que le calcium, le magnésium et le potassium ont diminué durant l'été tandis que le sodium a augmenté, le cuivre, le zinc et la manganèse étaient variables et le fer était sous la limite de détection.

Les variations de seiches furent mesurées quinze fois durant la période d'étude. L'oscillation du niveau du lac fut enregistrée par le lecteur de niveau d'eau placé à l'embouchure du lac. Ceci permis de faire une comparaison entre la période d'oscillation calculé et celle observée. La période calculée fut 6.8 minutes tandis que la période d'oscillation observée a varié entre 5.5 et 7.5 minutes avec une moyenne de 6.42 minutes.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to the following people for their support. First, to my supervisor and mentor Dr. Peter Johnson. Who could have known that first summer that our camp was going to be visited by an uninvited guest? Still, that did nothing to dampen a growing sense of love and awe for a place that was to become the focal point of life for the next four years. I therefore offer to you, Peter, my deepest thanks not only for fostering my love of the north but also for guiding me through those years that my research took direction and helping me through those times when as a new scientist I felt lost and needed direction.

Second, I would like to thank my parents who instilled in me the value a higher education. Children always find it difficult to admit when their parents were right about something all along.

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"All the rivers run into the sea;
yet the sea is not full; unto
the place from whence the rivers
come, thither they return again."

Ecclesiastes, 1, 7.

CHAPTER 1 INTRODUCTION

1.1 Introduction

Geomorphology has been described by many authors as a branch of physical geography that studies the origin and development of landforms (Bloom, 1978; Chorley, 1969; Gabler et al., 1975; Ruhe, 1975; Scheidigger, 1961; Strahler, 1974). This is too simplistic a definition, however, and according to Ritter (1978)

"...geomorphology is more than any definition can adequately express. Although it has identity, its boundaries are ill-defined and most certainly ephemeral."

Monkhouse (1960) described geography as an interdisciplinary science of which geomorphology is one of the fields of study and also includes climatology, cartography, pedology and hydrology. Ward (1975) said that complex interrelationships and interdependencies exist between the components of drainage basin hydrology and geomorphology. Strahler and Strahler (1977) strengthened this argument when they said that

"...the science of hydrology is inseparably interwoven with geomorphology."

The geographer uses hydrology as a tool towards a more complete understanding of the total landscape. The drainage basin, therefore, serves as the fundamental unit of

geomorphic systems because basins are separated by divides (Ritter, 1978). Furthermore, the drainage basin is a balance of processes, geomorphological, climatological, biogeographical and hydrological which work within it.

The single most important feature of the drainage basin is the main stream channel. It is on this feature that most studies tend to concentrate, ignoring any lakes present. Chorley (1969) referred to lakes as wide places in rivers and Hidore (1974) felt that a lake represented a temporary storage site between surface runoff and stream channels. The lake must, however, be studied as an integral part of the drainage basin hydrology and not treated merely as part of the stream channel.

1.2 Objectives

This study had three main objectives:

- 1) to investigate hydrological and hydrochemical components of a lake in relation to the lake basin geomorphology. By following a concept of the lake basin as part of a river basin hydrological and hydrochemical components such as flow conditions, storage, major cations and trace inorganics in the water (Ca, Mg, Na, K, Fe, Cu, Zn, Mn and Ni), and lake pH levels can be investigated in relation to basin morphology, climate, physical limnology and lithology.

2) to identify the routing under which water reaches the lake. Following the completion of the hydrochemical and hydrological investigations it should then be possible to identify how water reaches the lake (direct precipitation, groundwater flow or surface/subsurface flow).

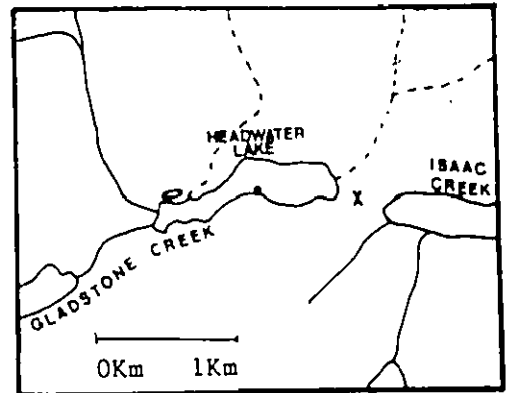
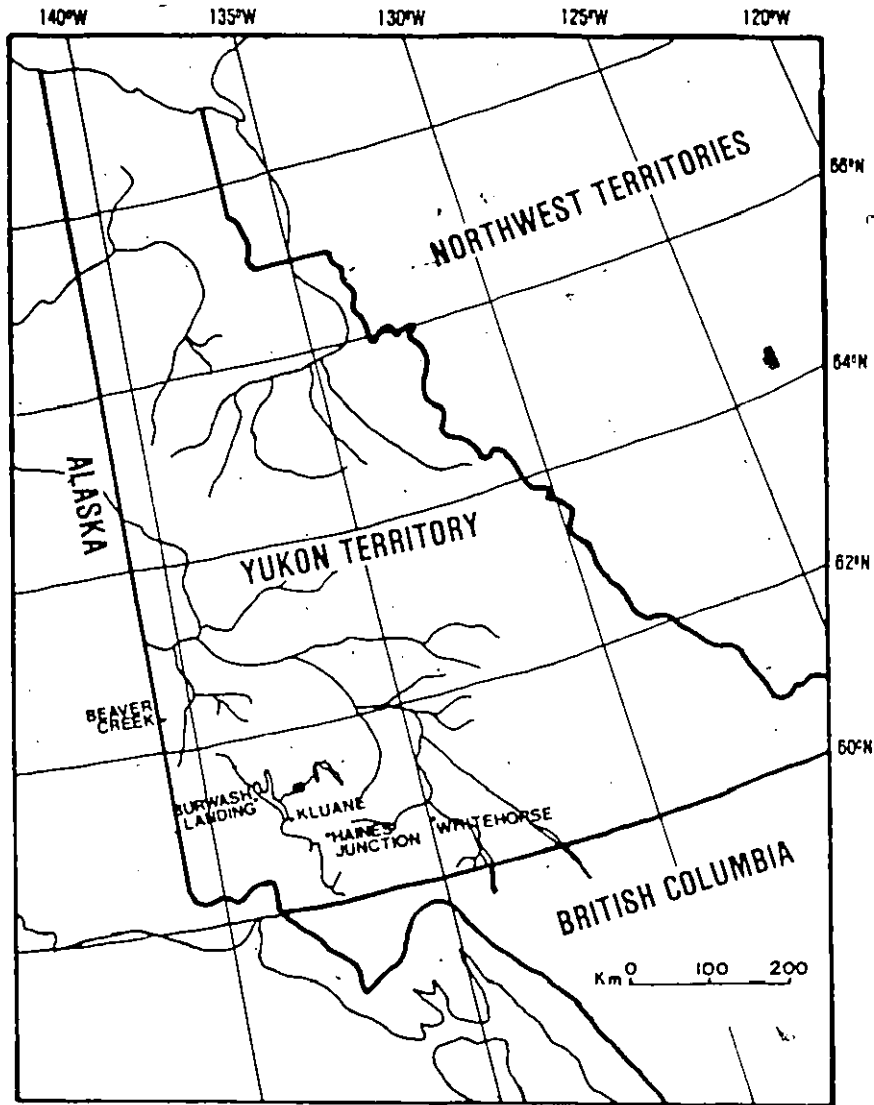
3) to produce a temporal-spatial analysis of the hydrochemical components given the hydrological and geomorphological controls. A temporal-spatial analysis of the hydrochemical data and their interrelationships together with the hydrological and geomorphological controls will be a starting point for the identification and description of the complex interconnections which exist within the drainage system.

f.3 Site justification

The study area is located in the Yukon Plateau which is dominated by the Ruby Range Batholith (Bostock, 1948; Douglas, 1977; Muller, 1967), (map 1.2). The Batholith consists mainly of hornblende-biotite granodiorite but at the head of Gladstone Creek there is a stock of alaskite (Douglas, 1977; Muller, 1967). Detailed mapping of the area has not been done and many local variations have been found to exist (P.G. Johnson, 1983, personal communication).

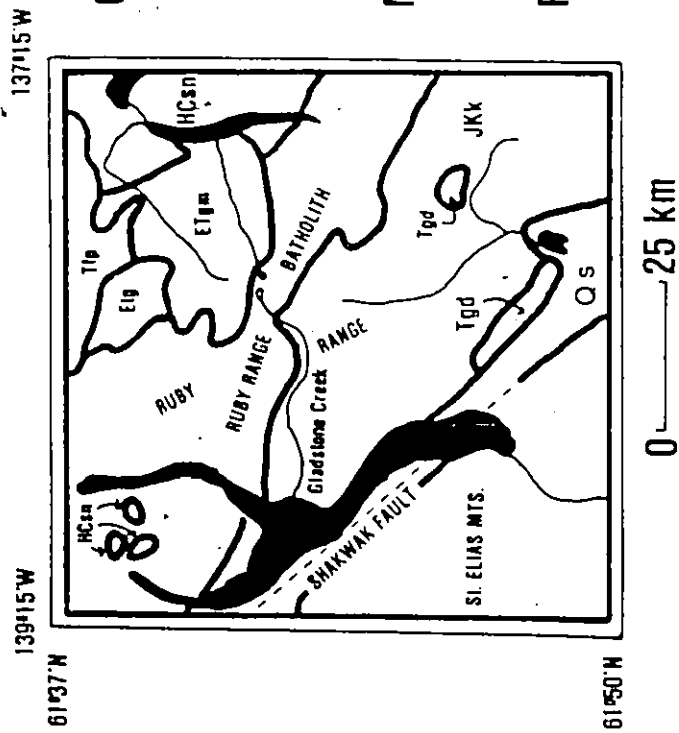
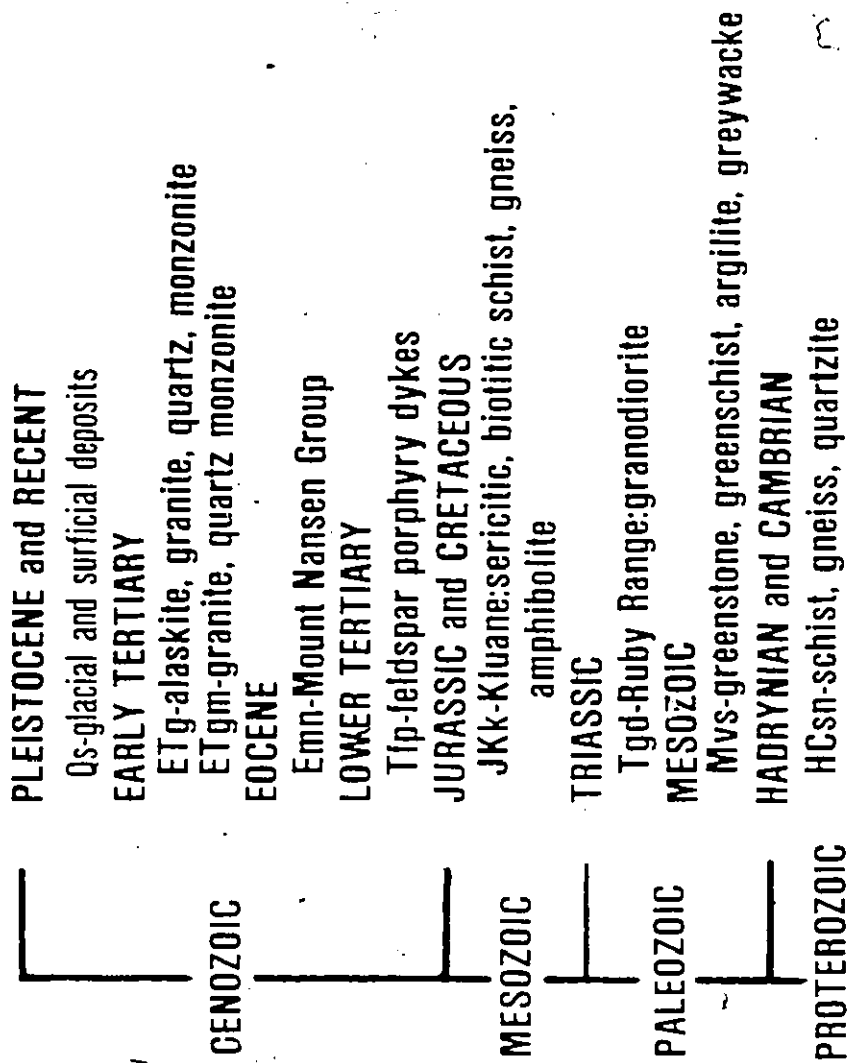
The area of study was the lake located at the

headwaters of Gladstone Creek, in the Ruby Range, Yukon Territory, 61°23'N 138°3'W (map 1.1). For convenience the lake is referred to as Headwater Lake in this study. It was chosen after air photo analysis and preliminary reconnaissance for several research projects during the 1980 field season. First, because the headwater lake of the Gladstone Creek system is the principal source of water for the creek and as such represents a baseline for research; second, because of the morphology of the lake basin, with the inflow and outflow creeks located approximately 100 to 150 metres apart at the western end (photo 1.1) the lake, little or no mixing of the main inflow water with the lake water occurs (discussed in detail in chapter 3); third, Gladstone Creek is located on the western side of the drainage divide between the Gladstone and Isaac Creek drainage basins, (which are part of the Yukon



■ study area
x met station

MAP 1.1 Study area



MAP 1.2 Geology

Adapted from R.J.W. Douglas (1977)



Photo 1.1 Location of main inflow and outflow creeks

and Alsek River drainage basins respectively). This allows for easier identification of the inputs to the lake (map 1.1) and also further justifies the closed-system approach. Lastly, this research was part of an inter-disciplinary project involving geomorphologists from the University of Ottawa and biologists from Queen's University conducted on behalf of the Northern Canada Power Commission.

1.4 Study site

1.4.1 Location and geomorphology

A number of geomorphological features occur in the valley immediately surrounding the lake. On the southern side there are two rock glaciers (photo 1.2) located at either end of the lake. On both sides there are debris slopes which are the result of the disintegration of exposed bedrock material (photo 1.3). On the northern side there are sand pillars (photo 1.4) located on the slopes of one of the small streams that drains the valley side. Also surrounding the lake are vegetated alluvial fans and debris cones with small creeks draining them (map 1.2, photos 1.5, 1.6). On both the northern and southern plateaus there are tors, felsenmeer and fossil patterned ground, which were formed by the paraglacial conditions during ice retreat in

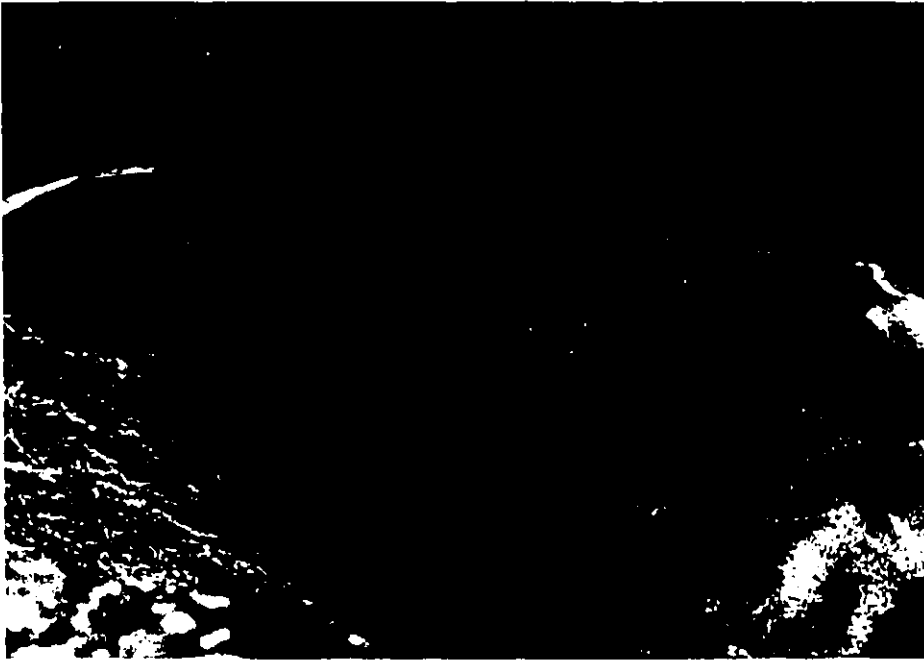


Photo 1.2 Rock glacier, eastern end of the lake.



Photo 1.3 Talus slope, south side of the lake



Photo 1.4 Sand pillars, northwest end of the lake.



Photo 1.5 Alluvial fan, south side of lake.



Photo 1.6 Alluvial fans, north side of the lake.

the mid to late Pleistocene (Johnson, 1983; Johnson and Kodybka, 1984).

1.42 Glacial history

The region experienced glaciation throughout the Pleistocene (Bostock, 1948, 1966; Campbell, 1967; Hughes et al., 1969; Johnson and Kodybka, 1984; Muller, 1967; Mulligan, 1963; Vernon and Hughes, 1966; Wheeler, 1961). In general, four glaciation events have been postulated, listed in increasing age they are: the McConnell, Reid, Klaza and Nansen advances (Bostock, 1966). Of these, Hughes et al. (1969) show only three: the McConnell, Reid and pre-Reid advances. Holocene glaciation episodes have lately come under some scrutiny (Burrows and Gellatly, 1982; Gellatly et al., 1984; Karlen, 1979). The presence of well vegetated stable rock glaciers suggests that during the Holocene the valley did not experience glaciation (P. Johnson, 1981; personal communication).

1.43 Climate

The study area is located in the rain shadow of the St. Elias Mountains and as a result of its northerly latitude experiences a continental-type climate characterized by long winters with short periods of daylight; this is in contrast to its short summers where the sun is above the horizon for more than nineteen hours at a maximum period (Muller, 1967). The weather systems tend to follow the Shakhwak Trench trending south to north.

Regional meteorological data collected at Beaver Creek, Burwash Landing, Haines Junction and Kluane Lake weather stations (map 1.1) give the following general regional information. A minimum winter temperature of -47°C with a mean of -20°C , mean spring temperatures of 10°C with maximums as high as 27°C and a summer mean of 17°C with a maximum as high as 32°C have been recorded for the period July 1980 to August 1981 (Environment Canada Atmospheric Environment Services). August is cooler as fall sets in and by September frost is common, although in areas of higher elevation snow has been recorded in early August.

Precipitation is light, around 270 mm were recorded during the study period (including estimates). Local valley climatic conditions can be highly variable in precipitation, wind and temperature regimes (see tables 1.1, 1.2, 1.3, 1.4, 1.5 and 1.6 for example) with respect to both the Shakhwak

Trench and the Ruby Range (a more detailed discussion of climate occurs in chapter four).

1.44 Hypotheses

It is hypothesized that inputs to the lake are limited to direct precipitation, surface flow and subsurface flow. Due to the location of the main inflow with respect to the outflow channel it is hypothesized that any contribution of water to the lake from this source is negligible. Furthermore, it is hypothesized that the processes of thermal stratification and subsequent turnover of the water mass occur in the same way as they do in lakes in more temperate locations but over a shorter period of time.

JUNE 1981

TEMPERATURE (°C)
DAY OF THE MONTH

STATION	MEAN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
BEAVER CREEK	17.3	15.0	11.0	14.0	11.0	M	16.0	14.0	15.5	18.5	19.0	M	M	M	21.5	20.0	21.0	20.0	21.0	M	M
	1.8	0.0	6.0	4.0	0.0	0.0	M	M	1.0	-3.0	0.5	4.0	-1.5	M	M	1.0	3.0	0.5	0.0	4.0	M
	9.6	7.5	8.5	9.0	7.5	M	M	M	7.5	6.3	9.5	11.5	M	M	M	10.5	12.0	10.3	10.5	M	M
BURWASH A	16.7	14.4	14.6	15.1	10.4	16.0	11.4	11.8	15.3	17.6	17.5	22.0	20.0	20.1	17.0	14.1	15.9	18.2	17.1	16.2	19.1
	1.8	6.1	1.8	-3.0	0.0	-2.0	3.0	1.3	-4.2	0.6	3.2	0.0	0.0	3.2	2.3	0.0	3.0	0.0	2.1	-0.2	-0.5
	8.9	11.4	8.1	5.8	7.6	4.2	7.2	6.6	5.6	9.1	10.4	11.0	11.7	9.7	7.1	9.5	9.1	9.6	8.0	9.3	M
HAINES JUNCTION	16.7	15.5	15.0	15.5	15.5	17.0	7.0	13.0	17.0	19.5	20.0	24.0	21.0	21.0	17.5	17.5	17.0	15.5	16.0	M	M
	1.7	M	5.0	-1.5	1.0	2.0	-2.5	2.0	-1.5	-3.0	-1.0	6.0	0.0	2.0	9.0	5.0	6.5	1.0	-1.0	M	M
	9.2	M	10.3	6.8	8.3	8.8	7.3	4.5	5.8	7.0	9.3	13.0	12.0	11.5	13.3	11.3	11.8	8.3	7.5	M	M
KLUANE LAKE	15.4	15.0	15.5	15.5	11.5	16.0	7.5	12.5	M	M	M	17.5	21.0	19.0	16.0	14.0	13.5	15.0	16.0	17.0	19.0
	2.8	3.0	0.5	0.5	1.5	1.0	-1.5	2.5	-1.0	-1.0	1.0	1.5	1.5	4.5	7.5	5.0	7.5	6.5	1.0	0.5	2.0
	9.1	9.0	7.8	8.0	8.5	6.1	7.3	5.0	5.8	M	M	9.5	11.3	11.8	11.8	9.5	10.5	10.8	8.5	8.8	10.5
HEAD-WATER LAKE	16.3	M	M	M	M	M	12.0	13.5	10.5	16.5	19.5	21.0	21.0	21.5	11.0	19.0	18.0	19.0	18.5	20.0	21.0
	2.0	M	M	M	M	M	1.0	1.0	0.5	-3.0	-1.5	2.5	0.5	2.5	5.0	5.0	2.5	1.0	0.5	0.0	2.0
	8.8	M	M	M	M	M	6.5	7.3	5.3	6.8	9.0	11.8	10.8	12.0	8.0	12.0	10.3	10.0	9.5	10.0	11.5

TEMPERATURE (°C)
DAY OF THE MONTH

STATION	MEAN	21	22	23	24	25	26	27	28	29	30	31
BEAVER CREEK		21.5	13.5	18.0	20.0	18.0	M	M	19.5	16.0	M	M
		M	-1.0	3.0	-1.0	1.5	5.0	M	M	3.0	4.5	M
		M	6.3	10.5	9.5	9.8	M	M	M	9.5	M	M
BURWASH A		18.0	12.3	16.2	16.6	13.3	17.0	18.9	15.1	14.1	18.4	
		1.5	6.7	7.0	-3.0	1.1	2.8	6.5	6.8	2.0	7.9	
		9.8	9.5	11.6	6.8	7.2	9.9	12.7	11.0	8.1	13.2	
HAINES JUNCTION		M	18.0	12.5	16.5	17.5	17.0	15.5	16.5	17.5	19.0	
		M	M	7.0	2.0	2.0	1.5	5.0	-1.5	-1.0	1.5	
		M	M	9.8	9.3	9.8	9.3	10.3	7.5	8.3	10.3	
KLUANE LAKE		18.0	12.0	12.5	16.0	14.5	17.5	18.0	16.5	M	M	
		3.0	6.0	6.5	1.5	3.5	4.0	4.5	1.0	3.0	6.0	
		10.5	9.0	9.5	8.8	9.0	10.8	11.3	8.8	M	M	
HEAD-WATER LAKE		12.5	12.0	12.5	16.0	13.5	19.5	18.8	19.0	13.2	15.0	
		2.5	5.0	2.0	1.0	1.5	1.0	5.5	2.5	3.0	6.0	
		7.5	8.5	7.8	8.5	7.5	10.3	12.2	10.8	7.8	10.5	

max - maximum
min - minimum
m - mean
T - trace
N/A - not available
H - missing

(source: Environment Canada Monthly Meteorological Records; June, 1981)

Table 1.1 June 1981 Temperature Regimes

TEMPERATURE (°C)

STATION	MEAN	DAY OF THE MONTH																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
BEAVER CREEK	max	16.5	19.0	M	M	16.0	11.5	19.5	15.5	24.5	M	M	24.5	20.0	25.0	22.0	20.5	M	M	23.5	20.5	
	min	M	-2.0	4.5	M	M	3.5	0.0	1.0	1.5	3.5	M	M	2.0	3.0	4.5	9.5	3.0	M	M	3.5	
	mn	11.9	M	3.5	M	M	7.5	9.8	8.3	13.0	M	M	M	11.0	14.0	13.3	15.0	M	M	M	12.0	
BURWASH A	max	16.0	12.0	13.3	13.6	17.2	17.4	20.5	22.2	20.0	21.0	22.6	23.1	23.6	23.7	23.8	20.5	21.1	19.5	19.6		
	min	2.8	5.0	3.8	5.1	1.2	2.9	3.7	7.5	7.2	8.8	1.1	6.7	3.2	6.2	8.8	10.4	9.5	2.3	8.7		
	mn	8.3	10.5	7.9	9.2	7.4	9.3	10.1	10.6	14.0	14.4	11.1	14.7	13.2	14.9	16.3	17.1	15.0	11.7	14.7	14.2	
HAINES JUNCTION	max	20.3	12.0	15.0	14.0	16.5	17.0	16.5	17.5	M	18.5	21.0	21.0	22.0	24.0	22.0	24.5	23.5	23.0	20.0	21.8	
	min	6.0	8.0	5.0	6.0	1.0	4.0	6.5	M	M	6.0	5.0	4.0	4.5	3.0	5.0	6.5	7.5	7.0	3.0	7.0	
	mn	13.2	10.0	10.0	10.0	8.8	11.5	10.3	12.0	M	M	13.5	13.0	13.0	14.3	12.5	14.0	15.5	15.0	11.5	14.3	
ELUJAJE LAKE	max	19.9	18.0	17.0	12.5	14.5	13.0	15.0	17.0	17.5	19.5	21.5	21.5	21.5	21.5	23.0	24.0	24.5	23.5	21.0	19.0	
	min	6.5	3.0	5.0	3.0	6.0	6.0	6.0	5.0	6.5	9.0	7.5	6.0	4.5	5.5	8.0	9.0	7.0	4.0	9.0	8.0	
	mn	13.3	12.5	10.0	8.8	8.0	10.5	11.5	11.5	11.5	11.5	13.0	13.0	13.8	13.3	13.0	14.3	16.0	16.8	15.3	12.5	14.0
HEAD-WATER LAKE	max	20.1	15.0	16.0	17.1	12.5	12.5	13.5	M	17.5	20.0	23.2	22.0	21.5	22.0	24.5	25.0	26.0	25.5	25.0	20.5	
	min	6.1	5.5	2.5	2.0	3.0	0.0	1.5	M	3.0	3.5	6.0	10.5	9.0	6.0	6.0	6.5	8.5	12.0	9.5	5.0	7.5
	mn	13.1	10.3	9.3	8.0	7.8	6.3	7.5	M	10.3	11.8	14.6	16.3	15.3	14.0	15.3	15.8	17.3	18.8	17.3	13.5	14.0

max - maximum
min - minimum
mn - mean
T - trace
N/A - not available
M - missing

(source: Environment Canada Monthly Meteorological Records; July, 1981)

TEMPERATURE (°C)

STATION	MEAN	DAY OF THE MONTH										
		21	22	23	24	25	26	27	28	29	30	31
BEAVER CREEK	max	20.5	22.5	22.0	M	24.0	23.0	26.0	16.5	17.5	M	
	min	3.0	2.0	9.5	5.5	M	M	5.0	7.5	9.0	1.5	2.5
	mn	11.8	12.3	15.8	M	M	M	14.0	16.8	12.8	9.5	M
BURWASH A	max	19.6	22.8	23.8	21.4	21.7	15.5	21.0	24.0	18.1	18.0	20.8
	min	8.7	1.5	4.5	5.3	5.7	8.8	9.2	1.1	5.0	8.1	7.1
	mn	14.2	12.2	14.2	13.4	13.7	12.2	15.1	12.6	11.6	13.1	14.0
HAINES JUNCTION	max	20.5	27.5	24.0	22.0	M	22.5	20.0	24.0	16.0	19.0	21.0
	min	6.0	8.5	4.5	7.5	10.0	M	8.0	4.0	5.5	9.5	10.0
	mn	13.3	18.0	14.3	14.8	M	M	14.0	14.0	10.8	14.3	15.5
KIJANE LAKE	max	19.0	23.5	23.5	22.0	23.5	20.0	20.0	24.5	15.0	19.0	20.0
	min	8.0	6.0	9.0	7.0	6.0	9.0	9.0	6.0	7.0	7.0	9.0
	mn	13.5	14.8	16.3	14.5	14.8	14.5	14.5	15.3	11.0	13.0	14.5
HEAD-WATER LAKE	max	23.5	26.0	25.0	24.5	23.0	20.5	20.5	24.0	25.5	11.0	19.0
	min	6.5	5.1	11.0	11.0	8.0	6.5	7.5	5.5	8.0	6.5	7.2
	mn	15.0	15.5	18.0	17.8	15.5	13.5	14.0	14.8	16.8	8.8	13.1

Table 1.2 July 1981 Temperature Regimes

PRECIPITATION (mm)

STATION	TOTAL	DAY OF THE MONTH																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
BLAVER CREEK	r 51.4 s 0.0 p 51.4	11.0	6.0	2.0	8.0	0	0	2.0			1.0	0	0	2.5	6.0					0
BURVASHII A	r 77.5 s 0.0 p 77.5	11.0	6.0	2.0	8.0	0	0	2.0			0.3	0	0	2.5	6.0	3.0	3.4	0.4	0.4	0
HAINES JUNCTION	r 26.6 s 0.0 p 26.6			1	1	1	2.8	2.6	1		0.3	0.2	5.2	5.2	5.2	1	2.5	1	0	0
KLUANE LAKE	r 37.2 s 0.0 p 37.2											2.0	1.4	1.6	4.0	3.6	4.8	0.4	2.8	
HEAD-WATER LAKE	r 239.9 s 0.0 p 239.9	N/A	N/A	N/A	27.5	9.0	44.0				4.0			14.0	1.0	23.5	35.0	5.0	17.8	3.0
		N/A	N/A	N/A	27.5	9.0	44.0				4.0			14.0	1.0	23.5	35.0	5.0	17.8	3.0

r - rainfall
s - snowfall
p - total precipitation
T - trace
N/A - not available
M - missing
C - amount included in total for the following day.
(source: Environment Canada Monthly Meteorological Records; June 1981)

PRECIPITATION (mm)

STATION	TOTAL	DAY OF THE MONTH										
		21	22	23	24	25	26	27	28	29	30	31
BLAVER CREEK	r 1.0 s 4.0 p 5.0	1.0	4.0			2.5	0	0	4.4	1.0		
BURVASHII A	r 5.7 s 1.0 p 6.7	5.7	1.0			0.5	3.8	2.0	1.2	1.5	0.8	
HAINES JUNCTION	r 2.2 s 4.3 p 6.5	2.2	4.3	1	1.2							
KLUANE LAKE	r 2.0 s 7.4 p 9.4	2.0	7.4	0.2	1.2	2.0	0.4					
HEAD-WATER LAKE	r 22.0 s 14.0 p 36.0	22.0	14.0	14.0		1.1	5.0					
		22.0	14.0	14.0		1.1	5.0					

Table 1.4 June 1981 Precipitation Data

AUGUST 1981 PRECIPITATION (mm)

STATION	TOTAL	DAY OF THE MONTH																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
BEAVER CREEK	r s 64.5	0	15.2	24.0	8.8					0	2.0		1.0				1.0				
BURWASH A	p r s 27.6 0.0 27.6	0	15.2	24.0	8.8					0	2.0		1.0								
HAINES JUNCTION	r s 39.3 0.0 39.3																				
KLUANE LAKE	r s N/A N/A N/A																				
HEAD-WATER LAKE	r s 0.0 T																				

PRECIPITATION (mm)

STATION	TOTAL	DAY OF THE MONTH																			
		21	22	23	24	25	26	27	28	29	30	31									
BEAVER CREEK	r s P	L	L	1.0																	
BURWASH A	r s P	L	L	1.0																	
HAINES JUNCTION	r s P	T	T																		
KLUANE LAKE	r s P	T	T																		

r - rainfall
s - snowfall
P - total precipitation
T - trace
N/A - not available
M - missing
C - amount included in total for the following day
L - amount of precipitation, if any, included in next amount shown; individual days unknown
(source: Environment Canada Monthly Meteorological Observations; August 1981)

Table 1.6 August 1981 Precipitation Data

CHAPTER 2 LITERATURE REVIEW

2.1 Hydrogeology

Hydrogeology has been defined as

"...the study of groundwater with particular emphasis given to its chemistry, mode of migration, and relation to the geologic environment."
(Davis and DeWiest, 1966).

Fetter (1980) simplified this definition, describing hydrogeology as encompassing

"...the interrelationships of geologic materials and processes with water."

The French naturalist Lamarck first used the term hydrogeology in 1802 (Lamarck, 1964). His meaning was almost identical to the term 'hydic geology' used by J.W. Powell (1885) which described it as the study of the

"...phenomena of degradation and deposition by aqueous agencies."

Mead (1919) gave the widest meaning to the term when he defined hydrogeology as the study of the laws of occurrence and movement of subterranean waters. He further stressed the special character of the study of

"...groundwater as a geological agent, the understanding of which would contribute to attain a comprehension of the birth and growth of rivers and drainage systems."

The physiography, surficial geology, solid geology, topography and vegetation of a drainage basin control the relationship between precipitation over the basin and water draining from it. Concurrently, the movement and chemistry of groundwater is heavily dependant upon geology; and both running water and groundwater affect the geology.

According to Born et al. (1979), although there is very sparse information concerning hydrogeology available, there are a number of parameters that can be defined and measured. The hydrogeologic regime of a lake is one which must be adequately assessed in order to properly manage lakes and shorelands. In order to assess the hydrogeologic regime there are certain parameters that one must evaluate. For example; regime dominance, seepage or drainage lake-type, flushing rates and groundwater potential (Anderson and Munter, 1981; Born et al., 1979; Fetter, 1980). It is these parameters that Born (1979) feels are important to the hydrogeologist especially when applied to such areas as planning and resource management. There are other parameters but these are of more specific interest; petroleum and chemical engineers, for example, would be interested in pore space for use in brine disposal (Kazmann, 1979).

Regime dominance is a descriptive term referring to the importance of groundwater in a lake's water budget.

Groundwater is dominant if it represents a significant proportion of the overall water budget. Characterizing regime dominance is a subjective judgement as to whether groundwater is a significant or insignificant hydrogeologic factor. Measurement of regime dominance is accomplished by water budget analysis for the lake basin using either field or modelling techniques (Born et al., 1979). Generally speaking, if a lake is situated in coarse-grained glacial outwash or coarse till it has a high rate of 'hydraulic communication'; the efficiency of the groundwater flow system in transmitting water to a lake.

Based on criteria developed by Born et al. (1979) seepage lakes are defined as surface water dominated and may have an inlet or outlet but not both, whereas a drainage lake has an inlet and an outlet.

Flushing rates, the time needed to completely change a body of water, depend upon the degree of mixing in a lake. Surface inflows to a stratified lake may replace the epilimnetic (upper layer) water many times over, but the hypolimnetic and metalimnetic (bottom layers) waters will only be affected during the seasonal turnovers.

The ideal criterion for determining the portion of a lake in a groundwater flow system is the groundwater potential distribution beneath the lake bottom. On-site measurement, however, is both difficult and expensive. Proxy criteria exist by which a lake can be classified.

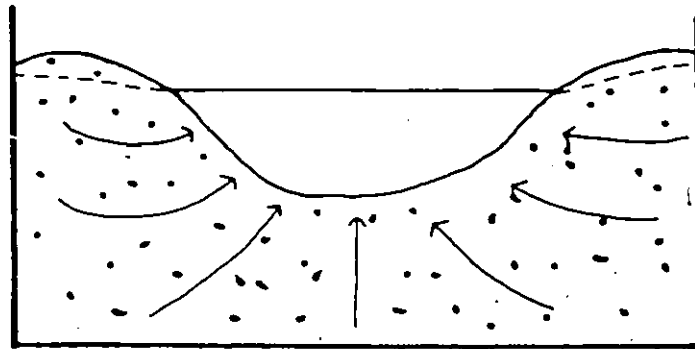
Temperature anomalies, water chemistries, certain ecological attributes, soil characteristics, and visible evidence of groundwater discharge (springs and seeps) can all help establish the flow-system configuration (Born et al., 1979).

There are three possible configurations of groundwater flow systems around a lake. They are: i) a discharge lake where the groundwater is discharged to the lake, ii) a recharge lake where the water is lost from the lake to the groundwater system and iii) a flow-through lake where the groundwater enters the lake from one side and leaves from another (Anderson and Munter, 1981; Born et al., 1979), (figure 2.1). Combinations of these configurations have also been shown to exist (figure 2.2).

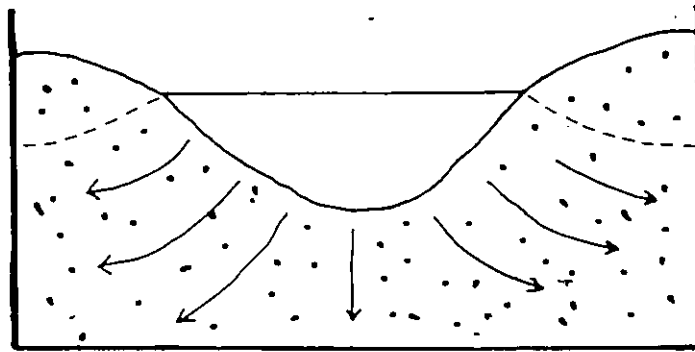
Where two lakes are in close proximity to each other and one is higher in elevation than the other, a groundwater divide may exist (Fetter, 1980). In early spring when the water table is high a groundwater divide may exist but as water levels drop the divide can disappear (figure 2.3). The resulting drop in the water table can turn the lake into a flow-through system (Anderson and Munter, 1981; Born et al., 1979; Fetter, 1980; Meyboom, 1967).

2.2 Hydrology

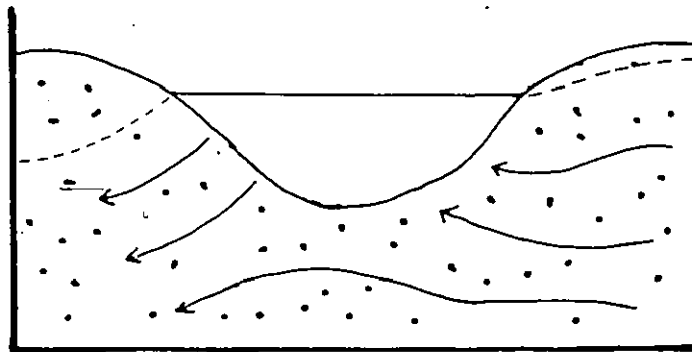
The hydrological regime of a lake basin is a fundamental aspect of the hydrogeology. Of the



a) Discharge lake

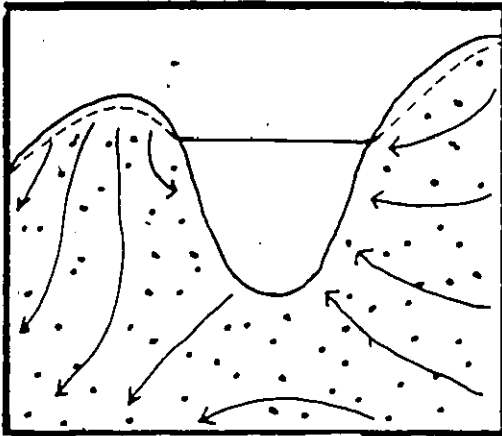


b) Recharge lake

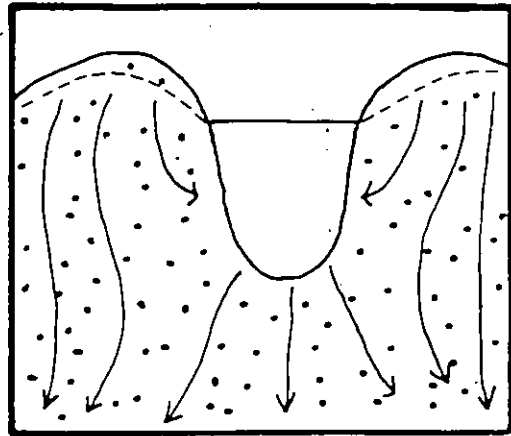


c) Flow-through lake

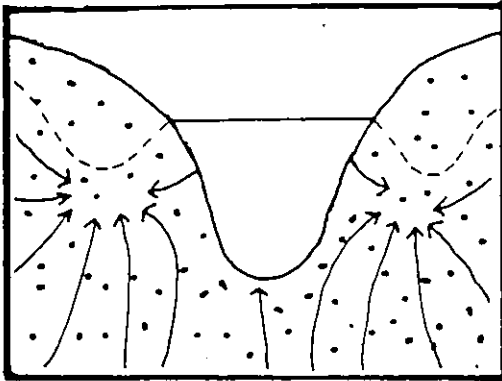
FIGURE 2.1 Three configurations of groundwater flow systems around lakes. (Born et al, 1979)



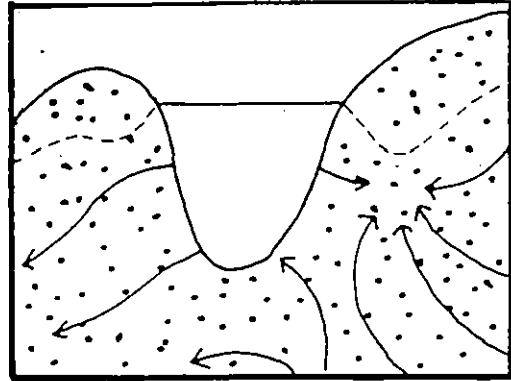
a) Shallow-discharge;
deep flow-through



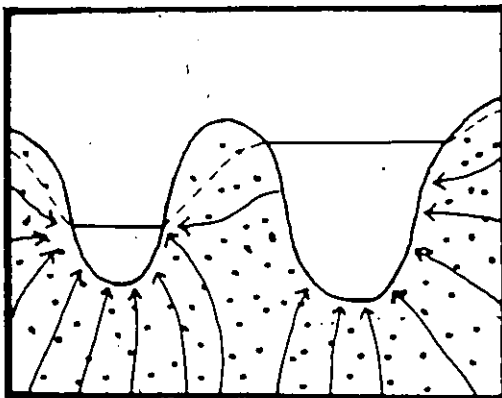
b) Shallow-discharge;
deep-recharge



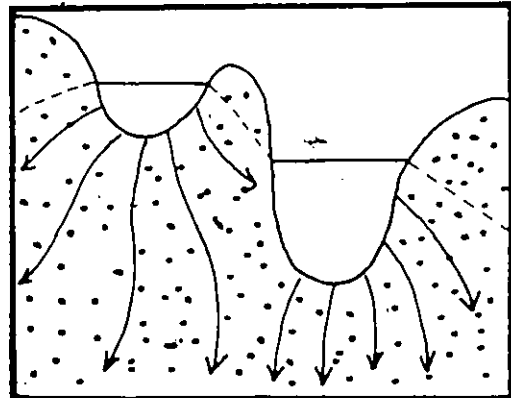
c) Shallow-recharge;
deep-discharge



d) Shallow-recharge;
deep-flow-through

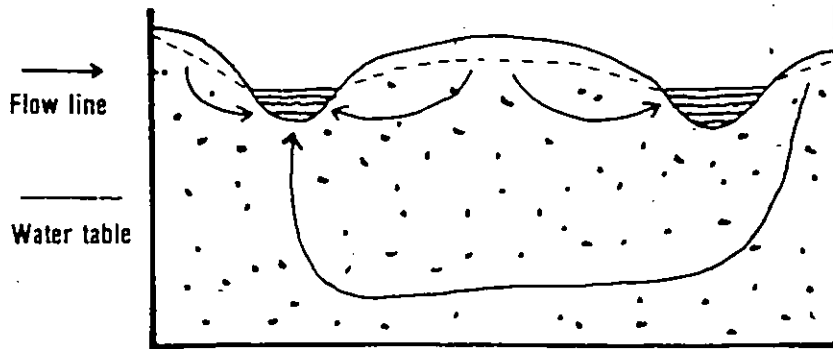


e) Shallow-flow-through;
deep-discharge

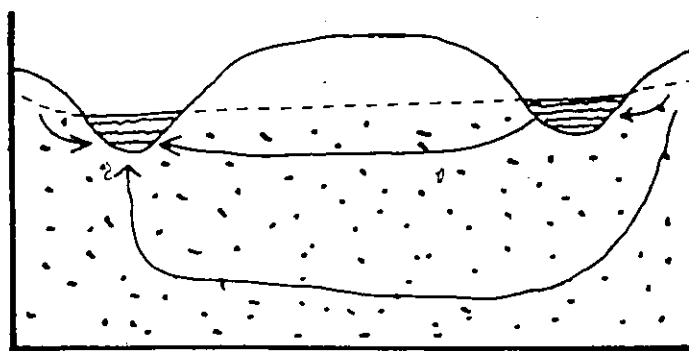


f) Shallow-flow-through;
deep-recharge

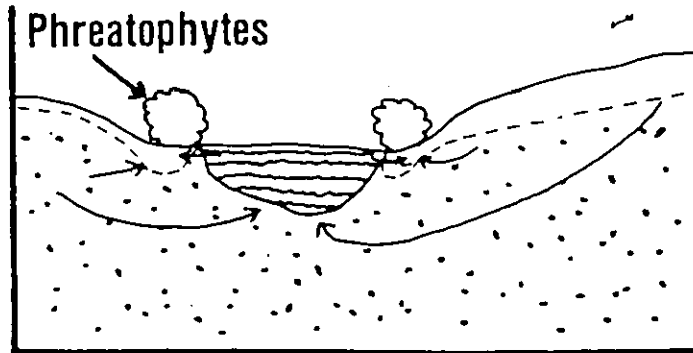
FIGURE 2.2 conceptual groundwater flow around lakes which intersect two flow systems. (Born et al, 1979)



High water table and interlake ground-water divide



Low water table and no interlake divide



Depressed water table due to phreatophytes: plants using large amounts of groundwater eg. willows

FIGURE 2.3 Groundwater-lake interactions. (Meyboom, 1967)

many controls and parameters that exist within the hydrological cycle the one major contributing factor to the hydrological regime of the lake basin is the storm-event response (Beven, 1978). A primary factor affecting the hydrology of a storm response is differences in topography. Beven (1978) concluded that subsurface flow is usually too late and too little to make a significant contribution to channel hydrographs. Stormflow seemed to be derived from direct channel precipitation and from precipitation on areas where the water table had risen enough to intersect the surface. Subsurface return flow coming to the surface in saturated areas also has a contributing effect to the hydrological response. Weyman (1974) has shown that in a small catchment basin there was a marked difference in response between the upper and lower parts of the basin which he attributed to soil and vegetation differences. Furthermore, Beven (1977a, 1977b) has confirmed that convergent slopes concave in section deliver the highest peak rates of subsurface flow which could occur within minutes of the end of the rainfall.

Downing and Peterka (1978) have found that precipitation and groundwater nutrient loading are probably not interdependent since rainfall charges subsurface waters which influences the rate of groundwater seepage. Furthermore, in spring and early summer, groundwater inflow

rates were found to be high as the result of snowmelt which in turn will have an effect on the chemical quality of the groundwater.

2.3 Hydrochemistry

In the study of landscape evolution the assumption is made that the physical processes of mechanical erosion, thermal expansion and contraction, frost action, and slope movements are the dominant influences. On closer examination, however, it is often found that chemical processes in the groundwater zone are the controlling influences (Freeze and Cherry, 1979). A sufficiently complete description of the quality of natural waters for use in the overall examination of the hydrogeological regime is a complicated matter (Karushhev, 1978) due to the influences of: chemical composition, the concentrations and state of chemical substances in it, the conditions of the interaction of individual components, the physical, biochemical and microbiological properties of the water, and its other characteristics. The factors that control water quality are all the processes that are at work within a water body. These processes, such as the supply and removal of chemical substances, movement and mixing of water masses, depend to some degree on hydrologic processes, the hydrologic regime, and the morphology of the body of water

(Freeze and Cherry, 1979).

Concentrations of the major, minor, and trace inorganic constituents (table 2.1) are controlled by the availability of the elements in the soil and rock through which the water has passed (Freeze and Cherry, 1979). Analysis of water samples and comparisons with surficial materials will give an indication of the travel path of the water.

The most important cation exchange reactions in groundwater systems are those involving $\text{Na}^+ - \text{Ca}^{2+}$, $\text{Na}^+ - \text{Mg}^{2+}$, $\text{K}^+ - \text{Ca}^{2+}$, and $\text{K}^+ - \text{Mg}^{2+}$ (Freeze and Cherry, 1979). The divalent ions normally have stronger adsorption affinity than the monovalent ions and the normal order of preference is

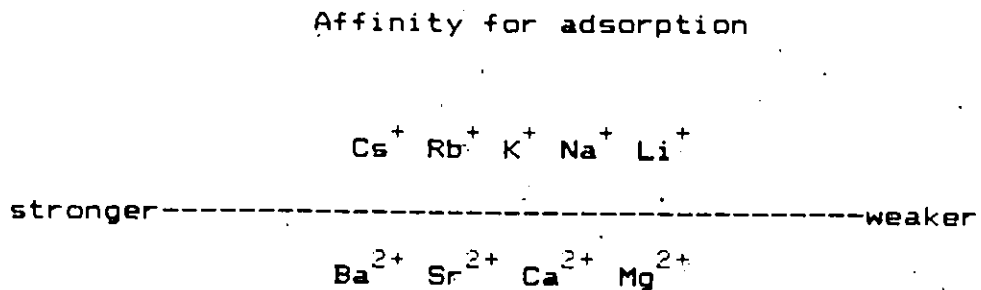


figure 2.41

Freeze and Cherry, 1979.

The dissolution of feldspars, micas and other silicate minerals is strongly influenced by the aggressive nature of water containing dissolved carbon dioxide- CO_2 . When CO_2 -charged waters low in dissolved solids meet

Table 2.1 Classification of Dissolved Inorganic
Constituents in Groundwater
(Elements in capitals chosen for analysis)

Major constituents (greater than 5 mg/L)	
Bicarbonate	Silicon
CALCIUM	SODIUM
Chloride	Sulphate
MAGNESIUM	
Minor constituents (0.01-10.0 mg/L)	
Boron	Nitrate
Carbonate	POTASSIUM
Fluoride	Strontium
IRON	
Trace constituents (less than 0.1 mg/L)	
Aluminum	Molybdenum
Antimony	NICKEL
Arsenic	Niobium
Barium	Phosphate
Beryllium	Platinum
Bismuth	Radium
Bromide	Rubidium
Cadmium	Ruthenium
Cerium	Scandium
Cesium	Selenium
Cobalt	Thallium
COPPER	Thorium
Gallium	Tin
Germanium	Titanium
Gold	Tungsten
Indium	Uranium
Iodide	Vanadium
Lanthanum	Ytterbium
Lead	Yttrium
Lithium	ZINC
MANGANESE	Zirconium

Source: Freeze and Cherry, 1979.

silicate minerals high in cations, aluminum and silicate cations and silica are leached. This leaves an aluminosilicate residue high in Al/Si, usually a clay mineral such as kaolinite, illite or montmorillonite. Further, the cations released to the water are normally Na^+ , K^+ , Mg^{2+} , and Ca^{2+} (Freeze and Cherry, 1979).

2.31 Elements analyzed: geochemistry

Rocks undergo weathering by many different processes, the most important being chemical weathering by fresh water. Though it is a product of natural distillation and condensation, rainwater is not pure, containing a number of dissolved substances; calcium, magnesium, sodium and potassium are a few of these (Sugawara, 1963).

The elements calcium, magnesium, sodium, potassium, iron, zinc, manganese, copper and nickel were selected for analysis for the following reasons. First they represented a cross-section of the elements from each of the three divisions of the major dissolved inorganic constituents as described in table 2.1. Second, design and financial limitations of the instrumentation restricted the selection of elements to be analyzed, which still suited the requirements of the study.

2.311 Calcium

The most important calcium minerals which decompose during weathering are plagioclase, pyroxene, amphibole, and epidote of igneous and metamorphic rocks and calcite, dolomite, anhydrite and gypsum of sedimentary rocks (Wedepohl, 1978). In natural waters the concentration of dissolved Ca is controlled mainly by dissolved carbonate, phosphate and sulphate ionic species.

Concentrations of Ca dissolved in rainwater have been found to be low, 0.94 ppm Ca for Japan (Bugawara, 1963) and for five North American and Swedish sites 0.60 and 1.2 ppm Ca (Gorham, 1961). The potential sources for Ca in rainwater are limited and soil dust is regarded as being the major one (Wedepohl, 1978). In river water, Livingstone (1963) has found an average Ca-content of 15 ppm ranging from less than 1 to 90 ppm. In calcareous regions, however, higher concentrations are not uncommon.

2.312 Magnesium

The most important magnesium minerals of igneous and metamorphic rocks which decompose during weathering are olivines, pyroxenes, amphiboles, biotites and chlorites, and of the sedimentary rocks dolomite, Mg-calcite and chlorites (Wedepohl, 1978). Clay minerals derived from the weathering

of these minerals form the major component of the sediments that are found. In adsorption processes the clay minerals are most effective, therefore, within the earth's sedimentary layer this process is largely controlled by clays. The adsorption of ions by clay minerals is an exchange reaction between solids and solutions. The various cations are not all equally replaceable and in general the replacing power is

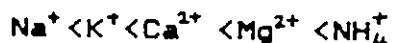


figure 2.51

Freeze and Cherry, 1979.

In river water Livingstone (1963) has found an average Mg-content of 4 ppm varying between less than 1 and 50 ppm. Magnesium in river water has been found to be mostly Mg^{2+} ions where complexing and the formation of ion pairs is negligible.

2.313 Sodium

Sodium concentrations in rain and snow are found to be the highest near the oceans and large cities since these are the major sources of inputs to the atmosphere (Gambell and Fisher, 1966; Gorham, 1961; Miyake, 1965). The salts in rainwater decrease in concentration during a single rainfall event (Miyake and Sigura, 1950). The mean Na-content of 42

analyses taken from Gorham (1961), Miyake (1965) and Gambell and Fisher (1966) is 1.4 ppm. The mean Na-content of 113 snow samples analyzed by Feth et al (1964) is 0.54 ppm ranging from a minimum of 0.1 ppm to a maximum of 3.7 ppm.

The concentration in river water varies with time as a function of discharge, tributary supply and groundwater discharge (Jordan et al, 1964; Livingstone, 1963). Data from Anderson and George (1966), Brown et al (1962), Cohen and Loetz (1964), Durum et al (1960), Hendrickson and Krieger (1964), Jordan et al (1964), Livingstone (1963), Miller (1961) and Silker (1964) totalling 639 rivers and streams gives an average Na-content of 39 ppm ranging from 0.1 to 154 ppm.

In groundwaters the Na-content is a function of weathering of Na-plagioclase followed by exchange of Ca for Na on the surfaces of the newly formed clay minerals (Wedepohl, 1978).

In lakewater Na-content is primarily a function of river and groundwater supply and secondly due to evaporation where it (evaporation) exceeds input. Wedepohl (1978) suggests that freely-draining lakes should have a mean Na-content in the tens of ppm whereas Livingstone (1963) suggests that closed lakes should show a mean in the 1000 to 10 000 ppm range.

2.314 Potassium

In precipitation the major source of potassium is the solution of sea salts taken up by wind and dust particles. Gorham (1961) reported K-concentrations of 0.2 to 0.3 ppm for several world-wide stations. In rivers and lakes the primary source of K is from weathering solutions such as groundwater and soil water (Miller, 1961). The K-content of rivers can reach high values where K-minerals are being dissolved (Baker et al, 1964).

Livingstone (1963) has indicated an average K concentration in rivers of 2.3 ppm. The K content of a single point can be variable, however, due to climatic conditions. Furthermore, K content usually decreases with increased discharge suggesting that the major source is groundwater.

With lakes, the K content is primarily a function of input versus evaporation. Lakes generally tend to be more stable in composition than rivers (Livingstone, 1963). Variations with time may occur due to evaporation rate changes, stratification, biological effects and stagnation. Data from several authors suggest a mean K content in 225 lake water samples of 55 ppm ranging from 0.2 to 7560 ppm (Brown et al, 1962; Kramer, 1962; Livingstone, 1963).

2.315 Zinc

Due to similarities in concentrations of zinc in rock types, the abundance of zinc in continental waters should not vary significantly. Variations can occur where oxidation of sphalerite occurs (Wedepohl, 1978). An average figure of 10 ppb in major continental waters is suggested by Wedepohl (1978). The United States Environmental Protection Agency (1976) found a mean value of 64 ug/l (64 ppb) for United States waterways. The higher value is probably the result of industrial pollution where zinc is widely utilized.

2.316 Manganese

Manganese values are widely scattered due to the range of potential redox conditions. Wedepohl (1978) suggests a tentative value of 7 ppb Mn. Konovalov (1966) and Turkenian and Scott (1967) have shown that manganese transport in the suspended sediment load of rivers and streams is very high, ranging from 320 to 15 000 ppm Mn (average 4300 ppm Mn) for 18 United States and one French and Chilean rivers each.

2.317 Nickel .

The chloride, nitrate and sulphate salts of nickel are highly soluble. In natural aerated waters the possible anions limiting the solubility of nickel are phosphate, carbonate and hydroxyl (Wedepohl, 1978). The amount of data on nickel concentrations in streams is small. Turekian and Kleinkopf (1956) surveyed 439 lakes and streams in Maine. While their results cannot be taken as representative, their average was a concentration of 0.2 ug Ni/l (0.2 ppb Ni). Sclater et al (1976) reported a value of 0.5 ug Ni/l (0.5 ppb Ni) for the Amazon River while Kontrovich et al (1963) had reported an average of 0.56 ug Ni/l (0.56 ppb Ni) for 820 surface and ground waters from Northwestern Siberia.

2.318 Iron

Since waters at the Earth's surface contain dissolved oxygen, iron is highly insoluble. In some waters unusually rich in organic matter the formation of chelates with dissolved organic species may enable dissolved iron to be present at appreciable concentrations in the presence of oxygen (Wedepohl, 1978).

Due to the majority of iron being reported as simple monomeric species (Fe^{2+} or $\text{Fe}(\text{OH})_3$) when in reality it is

present in a polymeric or colloidal state the values for truly dissolved iron in natural aerobic waters is unknown (Wedepohl, 1978). 'Suspended iron' (>0.5µm filter size) in natural waters is highly variable and related to nearby sources of sediment (Lewis and Goldberg, 1954). No meaningful average, therefore, can be calculated.

2.319 Copper

Local and minor mobilization of copper is to be expected at places of chemical rock weathering except where large bodies of copper sulphides are exposed. In natural waters there are low copper concentrations due to adsorption on clay minerals, iron oxides and organic residues as well as precipitation of complex carbonates (Wedepohl, 1978).

2.32 Effect of glacial deposits on water composition

Because glacial deposits are very variable in terms of mineralogical content the hydrochemistry is quite variable. In North America there are three main categories for the composition of groundwater in glacial deposits which are summarized in table 2.2.

Type I water is found in glacial deposits in parts of the Precambrian Shield, northern Minnesota, northern Maine, Vermont and New Hampshire. Type II water is found in

Table 2.2 Water Composition in Glacial Deposits

TYPE I WATERS: slightly acidic, very fresh waters (100 mg/L TDS), in which Na^+ , Ca^{2+} , and/or Mg^{2+} are the dominant cations and HCO_3^- is the abundant anion. These waters are soft or very soft.

TYPE II WATERS: slightly alkaline, fresh waters (1000 mg/L TDS), in which Ca^{2+} and Mg^{2+} are the dominant cations and HCO_3^- is the dominant anion. These waters are hard or very hard.

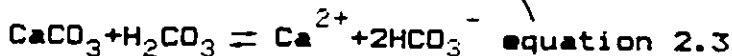
TYPE III WATERS: slightly alkaline, brackish waters (1000 to 10 000 mg/L TDS), in which Na^+ , Mg^{2+} , Ca^{2+} , HCO_3^- , and SO_4^{2-} generally occur in major concentrations. Most of this water has SO_4^{2-} as the dominant anion.

Freeze and Cherry, 1979.

southern Ontario and the midwestern United States. Type III water is found in the Interior Plains region of Canada and the United States (Manitoba, Saskatchewan, Alberta, North Dakota and Montana). The glacial deposits of Type I water were derived from igneous or metamorphic rock where the chemical evolution is controlled by interactions with aluminosilicate minerals. Even though Ca^{2+} and Mg^{2+} are dominant the waters are soft because the overall concentrations of these cations is low. Type II waters usually result from the dissolution of carbonate minerals. Cation exchange processes are commonly a modifying influence. Type III waters are distinguishable by much higher Mg^{2+} , Na^+ , and SO_4^{2-} and by somewhat higher Ca^{2+} concentrations. The combined influence of carbonate-mineral dissolution by water charged with CO_2 in the soil zone, dissolution of small amounts of gypsum, and exchange of Ca^{2+} for Na^+ and Mg^{2+} on montmorillonitic clays seems to be a reasonable explanation for the characteristics of Type III waters (Freeze and Cherry, 1979).

2.33 pH

pH has been measured both as a water quality parameter and as an indicator of H^+ ion concentration in the carbonate equilibrium equations:



These reactions essentially control concentrations of solutes in the water (Collins, 1983; Wetzel, 1975).

Furthermore, Wetzel (1975) has shown that in conditions where HCO_3^- and CO_3^{2-} are increasing, so does pH increase (figure 2.4).

2.4 Lakes temperatures and currents

The currents and the dispersion of contaminants and chemical constituents in a stratified lake are not well understood, not even in principle (Heinrich et al, 1981). Many physical and chemical processes are significantly affected by stratification. Processes such as: the dispersion of contaminants; the development of anoxia (oxygen-depleted water) in a shallow lake with a subsequent enhanced transfer of contaminants (eg. phosphorous and trace metals) from the sediments to the overlying water; and the resuspension of bottom sediments in a shallow lake.

The water movements in a lake are induced by the wind from which momentum is transferred to the water; by through-flow; and by horizontal density differences caused by surface cooling or heat flow from the sediments (Bengtsson, 1978).

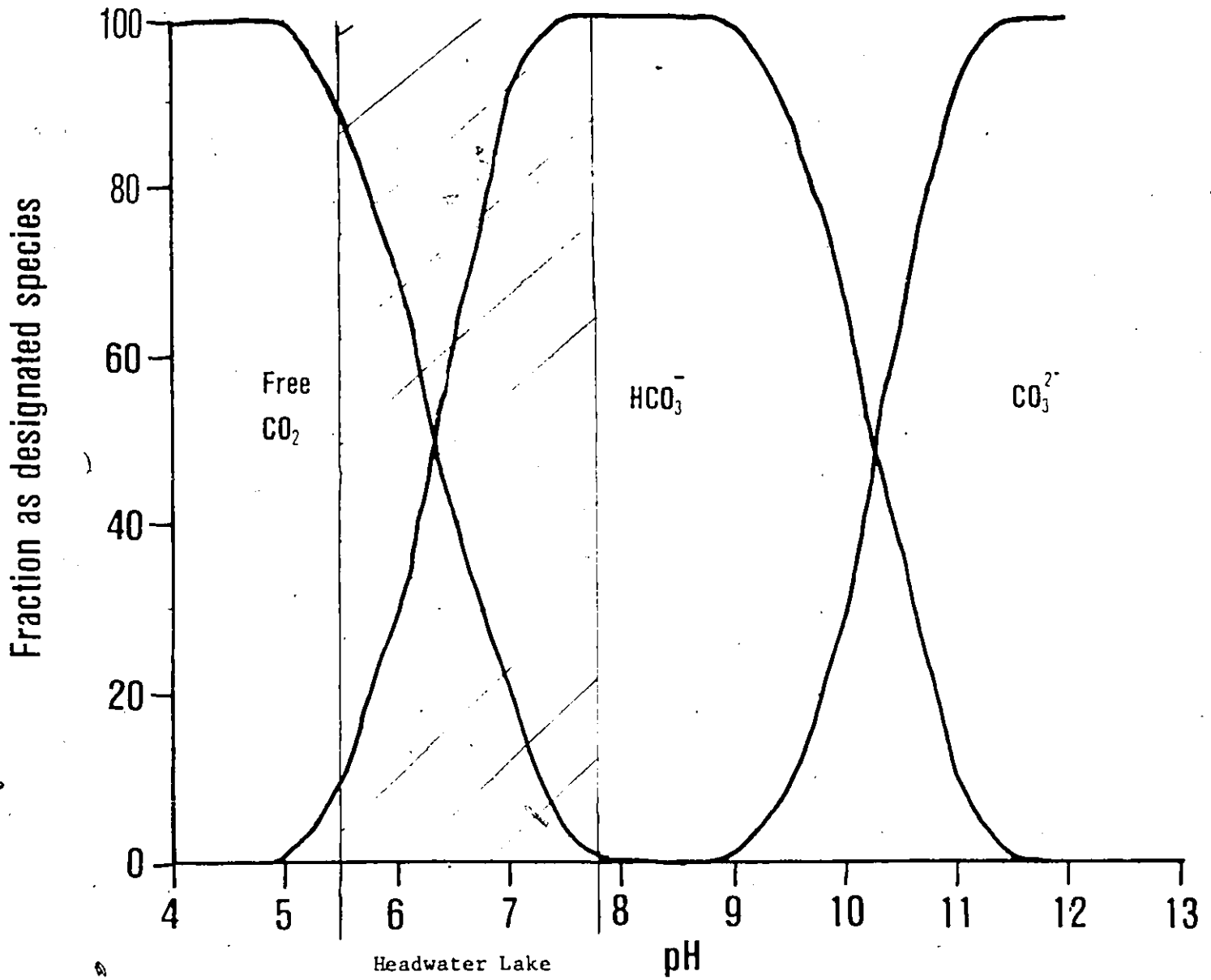


FIGURE 2.4 Distribution of major species of dissolved inorganic carbon

Wind action is characterized by the set-up of a current with a large production of turbulent energy close to the water surface (figure 2.5). In small lakes the turbulence level is usually unevenly distributed over the area of the lake because shelter effects of onshore structures make the windfield uneven and also because part of the flow in the lake will be boundary layer flow instead of fully developed turbulent flow (Hansen, 1978; figure 2.6).

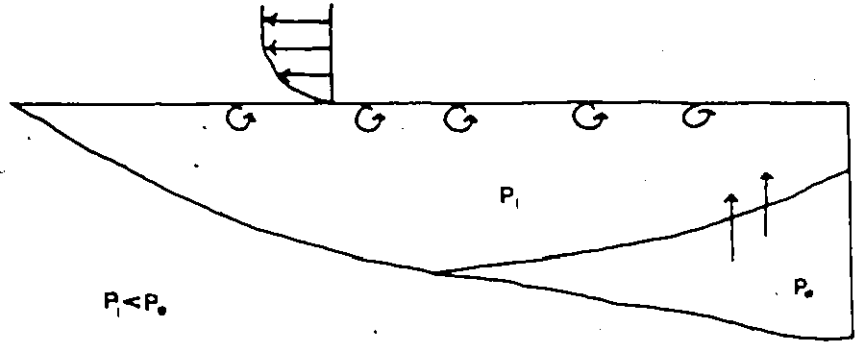
The most essential meteorological variable affecting the temperature of surface water is the air temperature of the preceding time period. The temperature gradient in the lake and the depth of the thermocline play an important role in the energy balance and mixing of water in the lake.

Some important dates in the course of water temperatures in a lake are as follows:

1. Ice break-up date. The mixing of water due to wind and rapid increase of water temperature begin.
2. The date of maximum mean temperature of the water mass.
3. The date of the beginning of the autumn homothermy (break-up of the thermocline and mixing of the water body). (Kuusisto, 1981)

2.5 Bathymetry

Many of the ongoing processes in a lake are modified in behaviour by the morphometry of the lake and its drainage

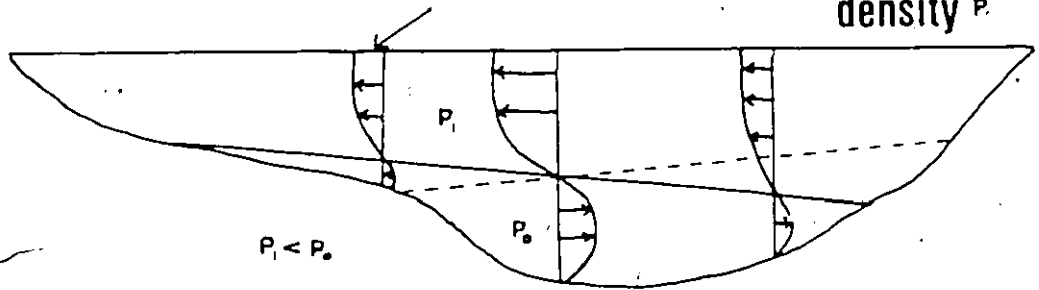


a) wind generated turbulent surface flow

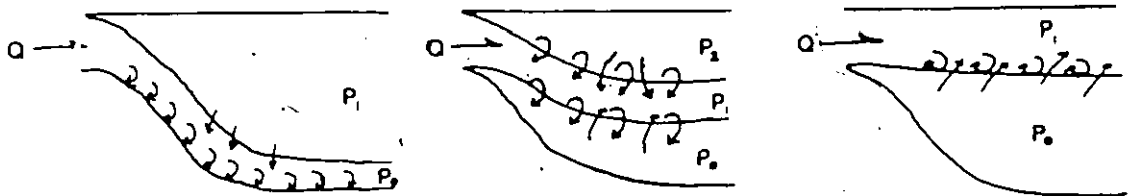
production of turbulence G

entrainment ↑

density P



b) turbulence caused by seiche motions



c) turbulence caused by inflow

FIGURE 2.5 Turbulence and mixing in stratified lakes.
(Hansen, 1978)

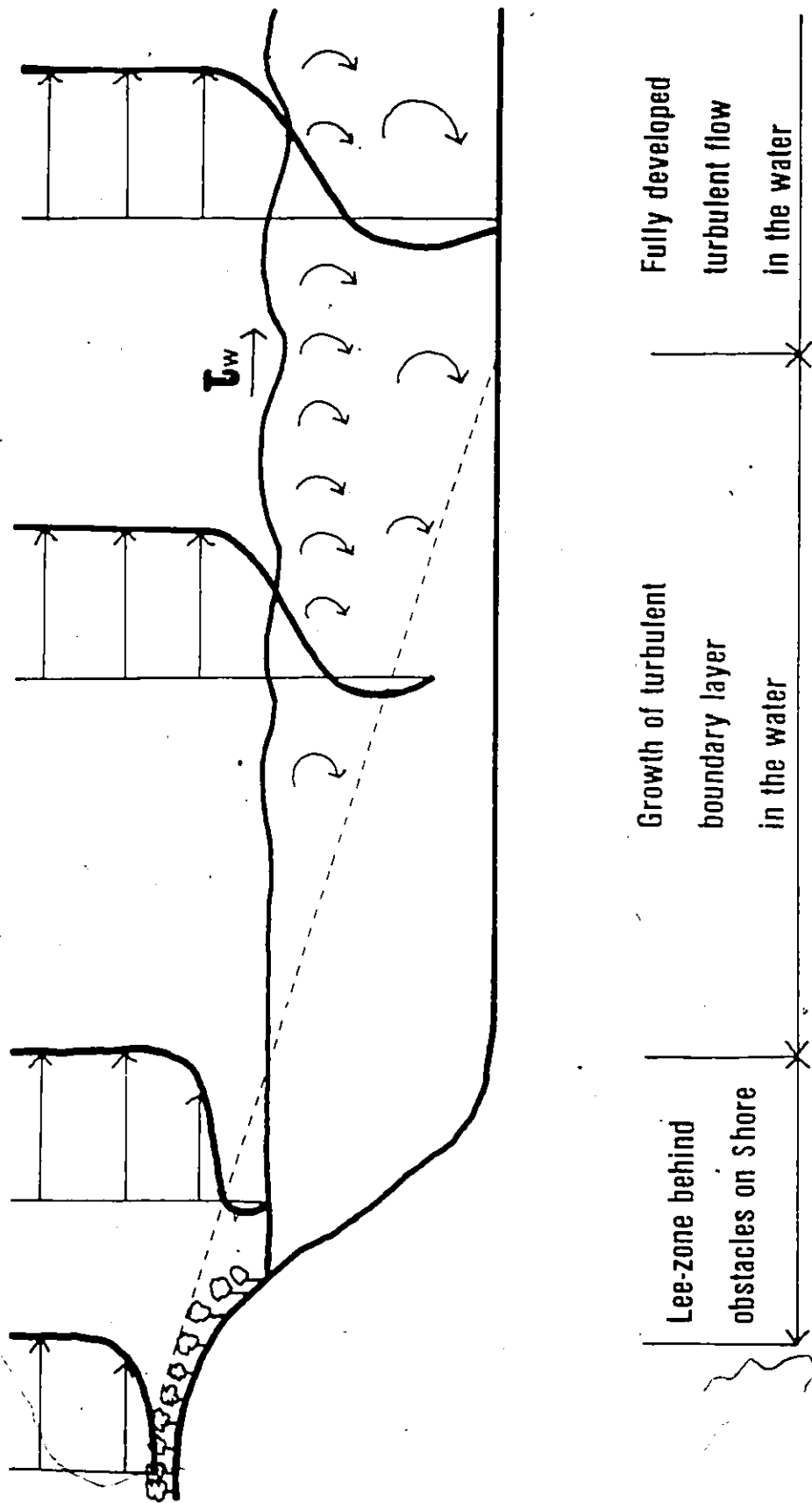


FIGURE 2.6 The development of a flow field in a lake. τ_w is the wind shear stress on the surface of a lake. (Hansen, 1978)

basin. Surficial flow, subsurface flow and currents are all processes that can be affected. Furthermore, in order to be able to visualize flow patterns in the lake and to determine as precisely as possible lake volumes, a detailed bathymetric map of the lake and surrounding area is required. When a computer-generated surface model combining bathymetric and topographic data is produced in such a way that multi-angled views and projections are utilized, conceptualization of the many processes working on the lake basin are easier to visualize.

2.6 Seiches

Displacement of the water mass of the whole lake, under specific meteorological conditions, gives rise to the rhythmic motions of the whole water mass involving both oscillations of the water surface and internal oscillations of isotherm depth. Standing surficial and internal waves are then created. These standing waves are known as seiches, a term which originally referred to the periodic 'drying' of exposed shallow littoral zones (Wetzel, 1975).

The most common cause of seiches is the wind-induced tilting of the water surface. When the wind stress is removed, the tilted water surface swings back towards equilibrium. Because of momentum the equilibrium is

overshot resulting in a rocking motion (figure 2.7).

Forel (1977) was the first to study seiche activity seriously. He showed that different forms of surface seiches exist: longitudinal seiches and transverse seiches. Both longitudinal and transverse seiches can be unimodal, bimodal or dicrotic (figure 2.8).

The most conspicuous example of long standing waves is the surface seiche which conforms to one or more resonant frequencies (free mode) particular to the lake basin. The free mode of the surface seiche is a surface wave whose movement affects the whole of the water mass (Wetzel, 1975). The periodicity of vertical movement at the antinodes of a surface seiche is a function of the length and depth of the basin (Wetzel, 1975). Particles at the node move horizontally with the same oscillatory rhythm as the vertical motion.

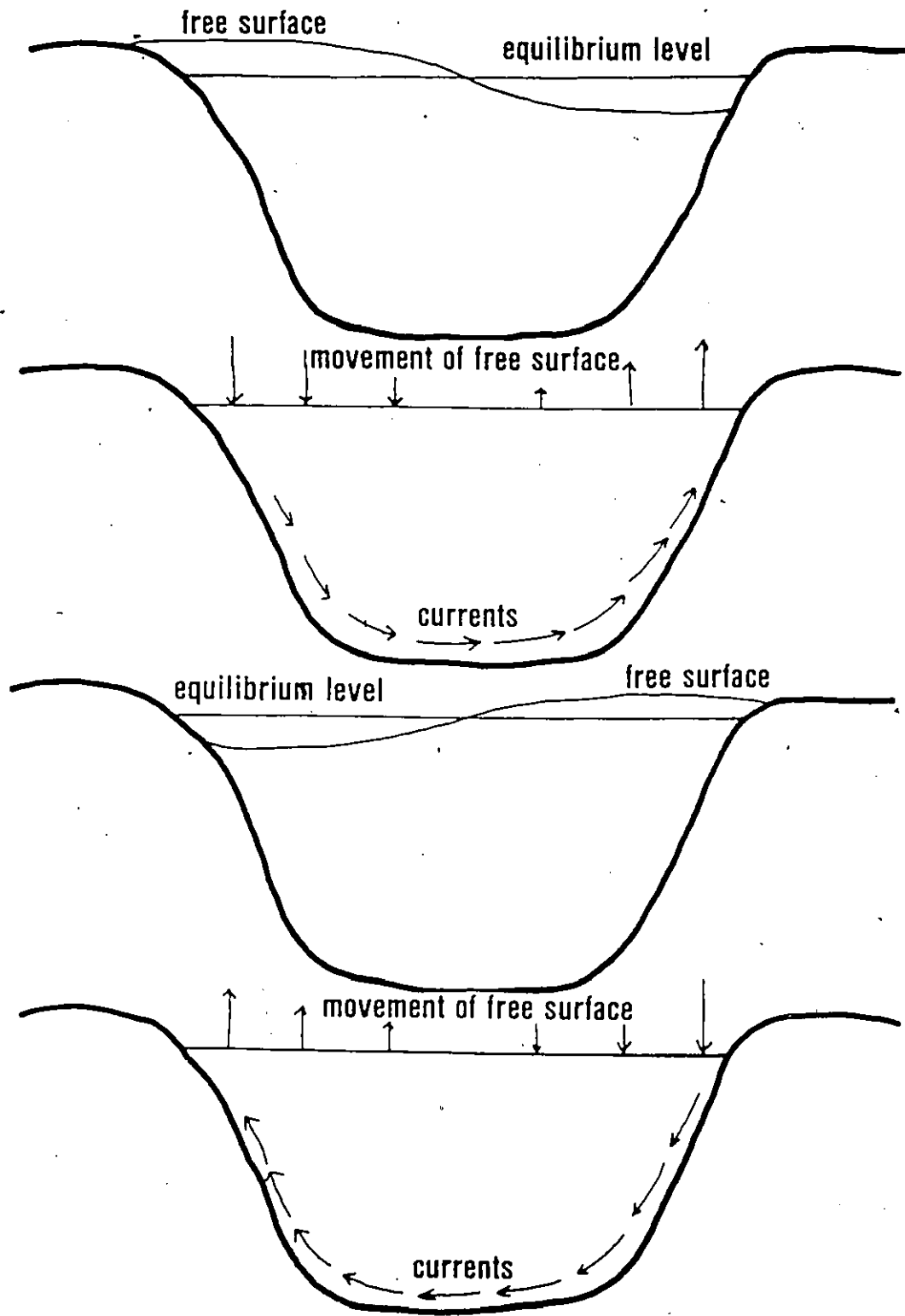
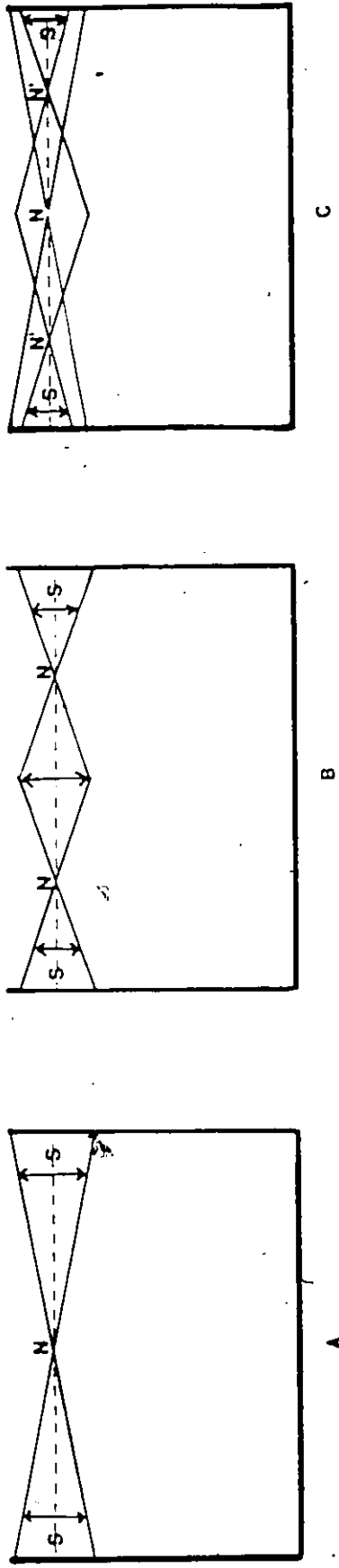


FIGURE 2.7 Four stages of a seiche cycle. (Lane, 1971)



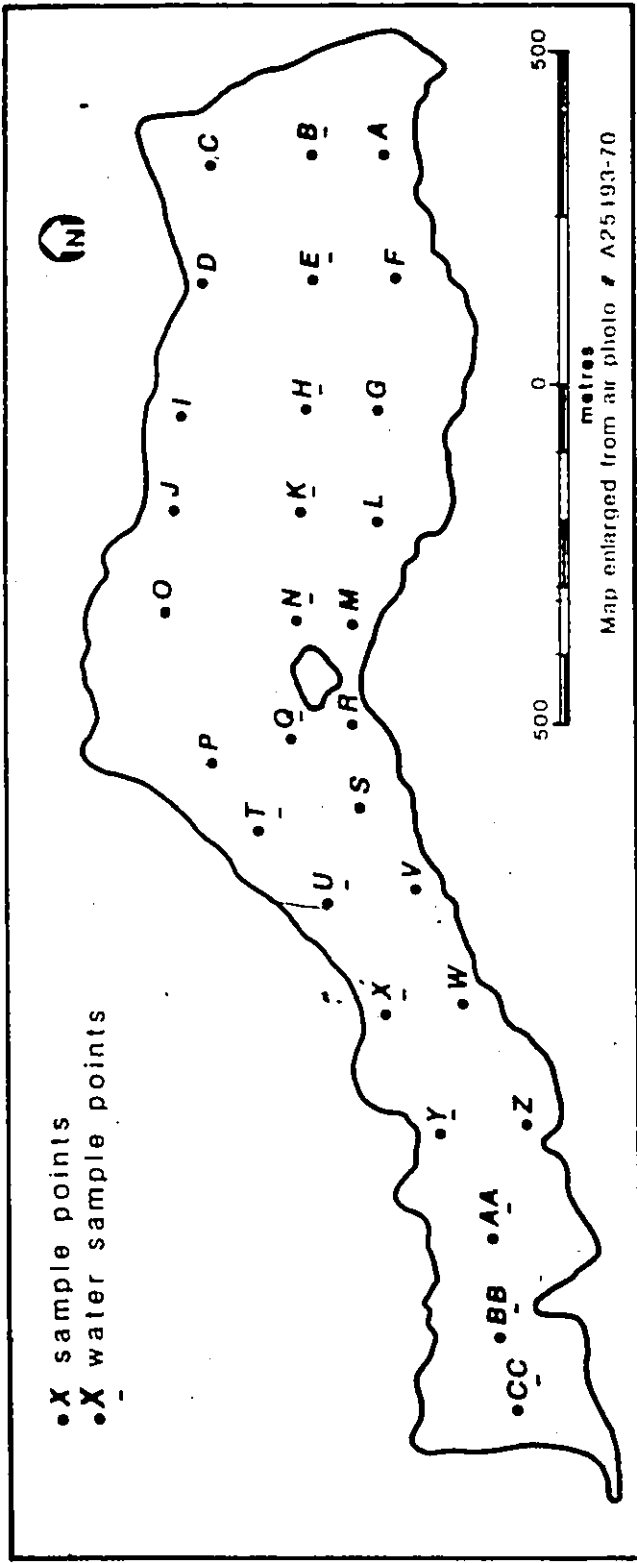
A, unimodal seiche; B, binodal seiche; C, dicrotic seiche.
 N, N' nodes; S, surface of water when immobile.
 Vertical arrows indicate oscillation. (Weich, 1952)

CHAPTER 3 FIELD AND LABORATORY TECHNIQUES

3.1 Study site

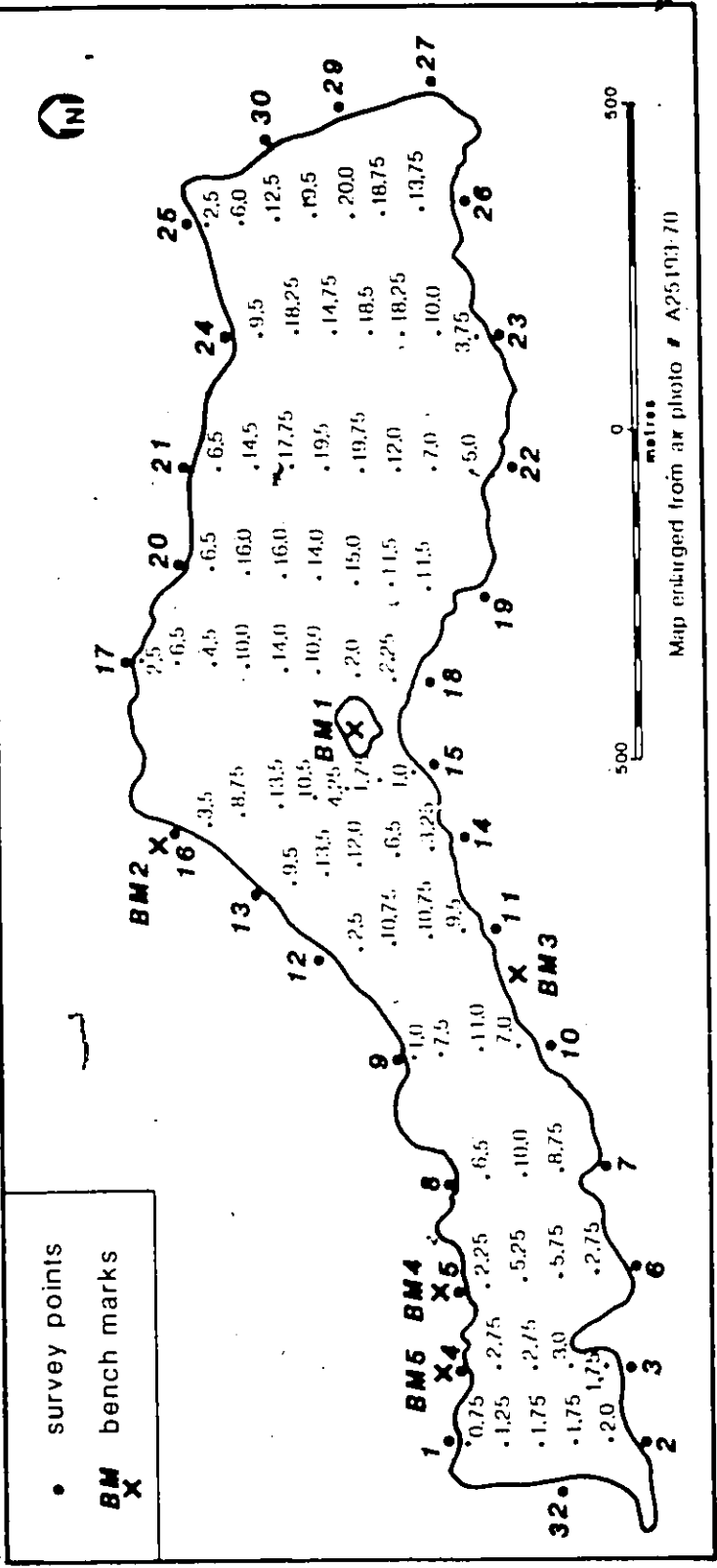
Kuusisto (1981) has shown that lakes with a complicated bottom topography present a problem when determining the dates of maximum and minimum temperature of a whole water mass. Previously, McNeely (1973) had shown that a single sample site can be used as representative of the whole mass of a lake provided it is the deepest point in the lake. Because no previous bathymetric work on the study lake had been done it was necessary to establish the morphology of the lake basin. A grid pattern was superimposed upon a map of the lake. The points were chosen to maximize the coverage for manual depth sounding in as short a time as possible (these points were later used for sonar profiling). The grid points were marked out around the perimeter of the lake using natural objects (trees, and piles of rocks) which were marked with fluorescent paint. The areas created by this grid pattern were approximately 100 by 150 metres and as a result twenty-nine sample points were generated with sample point B being located in the deepest section of the lake (maps 3.1 and 3.2). This site was then used in the collection of temperatures, currents, and water and sediment samples because it offered the best opportunity to observe changes in chemical stratification in

Headwater Lake - Yukon Territory



MAP 3.1 Sample point location

HEADWATER LAKE-YUKON TERRITORY



MAP 3.2 Spot depths

the water column and to observe seasonal overturn of the water mass.

3.2 Bathymetry

A series of sonar profiles of the lake were taken using the grid pattern established for the lake (map 3.1). A Raytheon model DE-719B Fathometer Precision Survey Depth Recorder was used. The results of the sonar profiles were transferred onto a map of the lake (map 3.2) from which a contour map of the lake bottom was generated (map 3.3). The contour map was digitized (turned into a numerical matrix) using the university's computing facilities. As well, a four by five km area of the topographic map sheet 115G/8E, Gladstone Creek, was also digitized. This area represents the hydrological basin of the Headwater Lake. Then, using XYNIMAP and VUBLOK, programmes developed by Professor D.H. Douglas of the Department of Geography, the digitized models were transformed into three dimensional perspective view surfaces. These surfaces can be viewed from any combination of heights, distances and angles as well as having the original contour intervals or interpolated contour intervals superimposed on the models. These models are then used as aids in studying the hydrological regime of the lake basin in terms of the direction of water flow, precipitation-event response and the effect of landforms on the water's travel

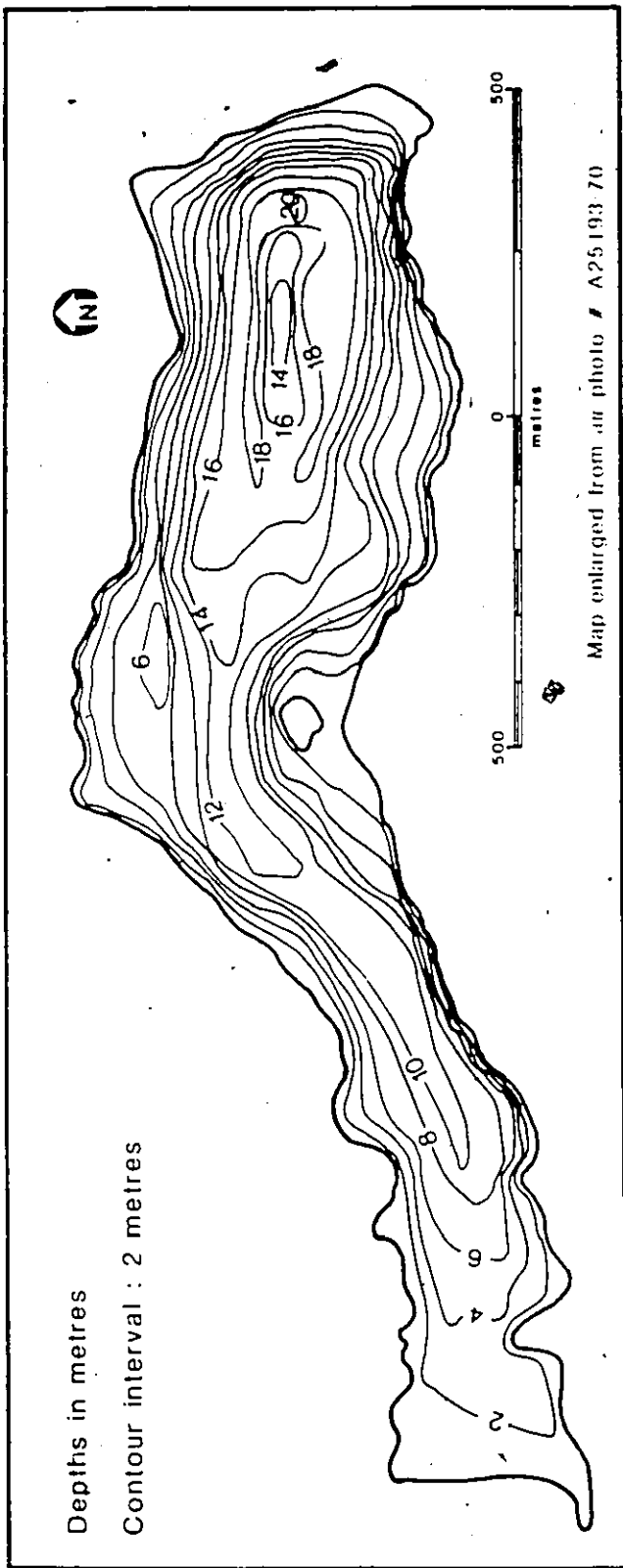
path and hydrochemistry (map 3.4 and map 3.5).

3.3 Hydrology

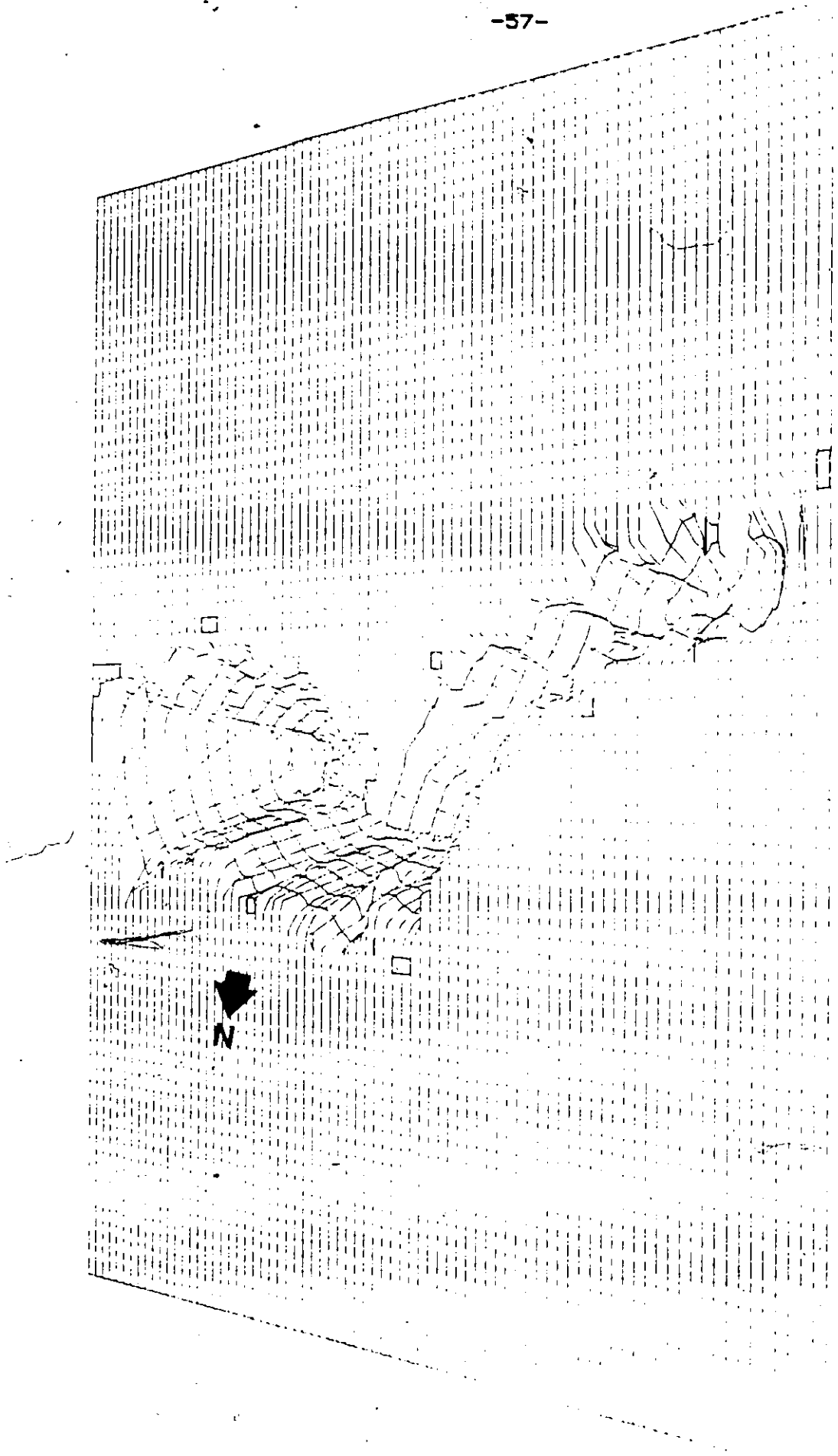
The investigation of temperatures and currents was undertaken to study the formation of thermal stratification and subsequent turnover to give some indication of the mixing processes that occurred within the lake. To study this, current readings were necessary to indicate the inflow of water below the lake's surface. Intensive current investigation was carried out at the beginning of the season at several key locations around the lake (rock glacier terminus, near the inflow and outflow, along the vegetated fans) with no reliable results due to low velocity currents. It is felt that the current meter, which works by the movement of water over the probe thus inducing an electromagnetic current, would not give accurate readings of vertical movements of the water column because it would not align itself properly into the low velocity currents. Furthermore, under wind conditions it was found that the drift of the boat was being recorded.

A sampling programme for temperatures and currents every 48 hours was established at sample point B. This frequency of sampling would adequately reflect changes in the water column.

Headwater Lake - Yukon Territory



MAP 3.3 Contour depths



MAP 3.4 Computer map Headwater Lake



MAP 3.5 Computer map Headwater Lake and Basin

Every nine days, temperature and current measurements were taken at all twenty-nine sample points to be used as a check against the data collected from site B and to give some indication of the overall picture. Occasionally, some difficulty was encountered with the sampling interval due to unsafe high wind conditions. During these periods, sampling was either divided over two days, or postponed until fair weather conditions returned. While these poor weather conditions did cause gaps in the continuity of the sampling, the high winds created unusual conditions that would not have been possible to examine otherwise (seiche activity and mixing of the water column).

The temperature and current measurements were taken concurrently using an Endeco Type 133 digital thermometer and a Marsh McBirney model 201 portable water current meter. Their cables were joined and marked in 0.5 m increments. Readings were then taken from the surface to the bottom at each 0.5 m interval.

The hydrothermal regime of a lake is controlled by air temperatures and wind movements which help to transfer thermal energy throughout the lake mass (Bengtsson, 1978). In order to properly evaluate the hydrothermal regime it was necessary to evaluate certain climatic parameters. To this end, climate data from a study under the direction of Dr. D. Lagarec of the University of Ottawa was made available from three MRI portable meteorological research stations that

were established on a transect across the valley at the eastern end of the lake (photo 3.1). Lake-air temperatures, stratification-mixing processes and wind, seiche activity-wind speed and direction are all interactions that can be evaluated. Finally, stage and discharge measurements of the inflow and outflow were conducted by R. Smith as a component of research into the effects of valley side deposits on streams. Such data is important for comparisons with the lake hydrochemistry data to allow for a broader understanding of the lake regime. The stream stage recordings were also used in the interpretation of the seiche activity that developed.

3.4 Hydrochemistry

Water samples were taken using a Van Dorn sampling bottle on a graduated cable. The samples were obtained at 5 m intervals from the surface to the bottom at site B every fourteen days. It was decided that both the depth and time intervals chosen were adequate to reflect changes in the water column over the study period.

The water samples were stored in 500 ml prewashed Nalgene bottles and returned to the university for analysis. Analysis of the samples was carried out in the laboratory of the Department of Geography. An Instrumentation Laboratories model IL357 atomic absorption spectrophotometer



Photo 3.1 Portable 'met' station

was used following the method described by Sotera and Stux (1979). Atomic absorption spectrophotometry was chosen as the method for analysis because of its widespread use in hydrochemical investigations (eg. Environment Canada, 1979, 1983).

Table 2.1 is a classification of dissolved inorganic constituents in groundwater. Of the six major ions which make up over 90% of the total dissolved solids in water sodium, magnesium and calcium can all be analyzed using atomic absorption (Freeze and Cherry, 1979). Furthermore, with the methods and materials available with atomic absorption the following constituents were also chosen for analysis: iron, potassium, copper, manganese, nickel and zinc. These elements provide a good selection from the three categories listed in table 2.1. The concentrations of these elements are controlled by their availability in the soil and rock through which the water has passed (Freeze and Cherry, 1979).

Sediment samples were taken three times during the season at site B, between site O and site P and at site CC. These samples were analyzed by X-ray diffraction for mineralogical content at the department of geology, University of Ottawa. The results are summarized in table 3.1.

Table 3.1 Mineralogical (X-ray diffraction) results

Site	June 9			July 22			August 22		
	B	Q-N	BB	B	Q-N	BB	B	Q-N	BB
chlorite	X	X	X	X		X	X	X	X
quartz	X	X	X	X	X	X	X	X	X
plagioclase	X	X	X	X	X	X	X	X	X
anorthite	X	X							X
muscovite	X	X							
albite		X			X				
illite				X			X	X	X
orthoclase				X		X			
pyroxene							X	X	

chlorite $Mg_3(Si_4O_{10})(OH)_2 \cdot Mg_3(OH)_6$

quartz SiO_2

plagioclase (feldspar series)-pure albite to anorthite

orthoclase (potassium feldspar series) $Na(AlSi_3O_8)$ $Ca(Al_2Si_2O_8)$

illite (mica-like clay minerals containing more water, and less substitution of Al for Si; essentially hydrous aluminum silicates with alkalis or alkaline earths present)

muscovite $KAl_2(AlSi_3O_{10})(OH)_2$

pyroxene group $XY(Si_2O_6)$; X-generally Na or Ca, Y-Mg, Fe(II), Fe(III), Al, Mn(II), Mn(III), or even Li or T.

CHAPTER 4 RESULTS

4.1 Climate

4.11 Temperature

Tables 1.1, 1.2 and 1.3 are summaries of the temperature regimes of Beaver Creek, Burwash Landing, Haines Junction, Kluane Lake and Headwater Lake. The data indicates that the temperature regime of the study area was similar to those of the other weather stations and hence are regional in nature. The monthly averages for maximum, minimum and mean temperatures ($^{\circ}\text{C}$) are as follows:

	June			July			August		
Beaver Creek	17.3	1.8	9.6	20.0	3.8	11.9	19.3	1.1	10.2
Burwash Landing	16.0	1.8	8.9	19.5	5.7	12.6	17.8	5.2	11.5
Haines Junction	16.7	1.7	9.2	20.3	6.0	13.2	17.4	6.2	11.8
Kluane Lake	15.4	2.8	9.1	19.9	6.6	13.3	-----n/a-----		
Headwater Lake	16.3	2.0	8.8	20.1	6.1	13.1	16.5	5.6	10.6

Table 4.1

Differences in the data are the result of variations in location and were expected.

4.12 Precipitation

Precipitation data was provided by two sources: an MRI portable meteorological station located on the drainage divide between Headwater Lake and the first lake of the Isaac Creek system, Dr. D. Lagarec's climatological research project, and by Environment Canada Weather Stations located at Beaver Creek, Burwash Landing, Haines Junction and Kluane Lake (map 1.1). The Environment Canada data was used for comparison with the field data to reflect differences between local and regional conditions. This is especially noteworthy when comparing frequency and magnitude of precipitation events. Tables 1.4, 1.5 and 1.6 are a summary of the precipitation events. It can be seen from this that at the beginning of the season the study area experienced frequent and intense periods of precipitation. While the precipitation data does reflect some regionality in storm systems it can be seen that local variations do exist. For the month of June the study area received 239.9 mm of precipitation compared to Beaver Creek (51.4 mm), Burwash Creek (77.5 mm), Haines Junction (26.6 mm) and Kluane Lake (37.2 mm). While precipitation did occur throughout the Shawkak Trench, in June, the orographic effect of the Ruby Ranges is reflected by the data. The period of frequent and intense precipitation that ended July 6 (the wet period)

produced high flow conditions in the deposits surrounding the lake and also created saturated conditions within the soil which controlled runoff to the lake. Evidence of these conditions was reflected by the appearance and persistence of puddles on the drainage divide, groundwater seeps along the exposed edge of the large fan on the northwest side of the lake, high flow rates of the creeks draining the vegetated fans, and marshy terrain around the lake.

4.2 Flow Conditions

Without the use of piezometers the measurement of flow conditions around the lake can be made using proxy criteria (Born et. al., 1979; see chapter two). Lake temperature measurements throughout the season did not reveal any anomalies that would indicate groundwater discharge to the lake. At the beginning of the season, however, an anomaly did exist. The temperature of the lake was not at 4°C even though the lake ice had only disappeared two days previously. The temperature ranged from 6.6°C at the surface to 5.1°C at the bottom, 17.5 m. Temperature measurements throughout the season did not indicate any inputs to the lake at a lower temperature, which would have been evidence of groundwater discharge. One small seepage was discovered on the northern side of the lake at the terminus of the vegetated fan near the backwater lake during

high flow conditions. Although not indicative of groundwater discharge by itself, it is evidence of the saturated conditions that did exist causing increased subsurface runoff. Table 4.2 is a comparison of lake volume changes and precipitation volumes. Discharge data on the inflow and outflow creeks, from R. Smith (1985), show that the volume of water in the two creeks are similar. So much so that the changes in lake storage cannot be attributed to them. This can be seen in the period from June 4th to June 6th; from June 14th to June 23rd; and from July 3rd to July 5th. From this it can be seen that lake volume changes as a result of direct precipitation are minimal. This suggests that lake level changes are the result of subsurface flow. With the change in meteorological conditions from a wet to a dry period, it is hypothesized that flow conditions at the beginning of the season were different from the end of the season. A preliminary survey of the headwater lake of Isaac Creek showed it to be approximately six metres higher than the study lake. Therefore, from the field observations in conjunction with the literature the hypothesized sequence of events is as follows.

First, the early season saturated conditions from snowmelt and precipitation created a groundwater divide between the two lakes. Groundwater flow was restricted to the lake basins of each drainage system. This groundwater flow was of the discharge type where water was being

discharged to the lakes. This is reflected in high lake levels. Concurrently increased subsurface flow and surficial runoff during precipitation events further increased lake levels.

Second, as precipitation events became less frequent, the groundwater regime changed. The groundwater divide between the two lakes disappeared and the hydraulic head from the Isaac Creek Lake caused groundwater to be discharged through the divide into the study lake. At this time the study lake had become a groundwater recharge system, thus creating a flow-through system. Groundwater entered the lake from the Isaac Creek end and was discharged into the groundwater system of Gladstone Creek.

4.3 Hydrochemistry

The hydrochemical data was analyzed by a simple regression technique to help illustrate the trends of the elements (figures 4.1 and 4.2). Calcium, magnesium, sodium and potassium all increased in concentration during the study period. Calcium had the greatest proportional increase, the slope of its regression line was 0.24, while the others were 0.02, 0.03 and 0.002 respectively. It is felt that the slopes of the regression lines of magnesium, sodium and potassium are so small that they do not reflect any significant change in concentration. The increases in both magnesium and sodium were similar and potassium was minimal.

Zinc, however, decreased through the season, the

CHANGE IN LAKE STORAGE (m³) COMPARED TO VOLUME OF RAINFALL (m³)
HEADWATER LAKE, YUKON TERRITORY

DATE	STORAGE	PRECIP.	DATE	STORAGE	PRECIP.	DATE	STORAGE	PRECIP.
06/02	0.0		06/30	-12,100		07/28	0.0	
06/03	-30,300		07/01	-24,200		07/29	0.0	
06/04	-18,200	18,975	07/02	-12,100		07/30	0.0	
06/05	- 6,100	6,210	07/03	-24,200	5,313	07/31	30,300	
06/06	-12,100	30,360	07/04	12,100	143,520	08/01	12,100	
06/07	6,100		07/05	12,100	2,070	08/02	0.0	
06/08	- 3,000		07/06	30,300		08/03	0.0	
06/09	- 3,000		07/07	30,300		08/04	- 6,100	
06/10	-12,100		07/08	18,200		08/05	0.0	
06/11	12,100	2,760	07/09	0.0		08/06	- 6,100	
06/12	12,100		07/10	0.0		08/07	-30,300	
06/13	18,200		07/11	0.0		08/08	0.0	
06/14	48,400	9,660	07/12	-36,300		08/09	- 6,100	
06/15	42,400	690	07/13	0.0		08/10	- 6,100	
06/16	12,100	16,215	07/14	-12,100		08/11	- 3,000	
06/17	42,400	24,150	07/15	- 6,100		08/12	- 3,000	
06/18	0.0	3,450	07/16	-12,100		08/13	- 6,100	
06/19	-12,100	12,282	07/17	12,100		08/14	- 6,100	
06/20	0.0	2,070	07/18	-18,200		08/15	-12,100	
06/21	24,200	15,180	07/19	0.0		08/16	-18,200	
06/22	90,700	9,660	07/20	18,200		08/17	0.0	
06/23	24,200	9,660	07/21	0.0		08/18	- 6,100	
06/24	-12,100		07/22	-18,200		08/19	0.0	
06/25	-36,300	759	07/23	0.0		08/20	3,000	
06/26	-18,200	345	07/24	-12,100		08/21	- 6,100	
06/27	-36,300		07/25	0.0				
06/28	-18,200		07/26	12,100				
06/29	-36,300		07/27	0.0				

STUDY PERIOD
TERMINATED

Storage data provided by R. Smith (1985).

Table 4.2

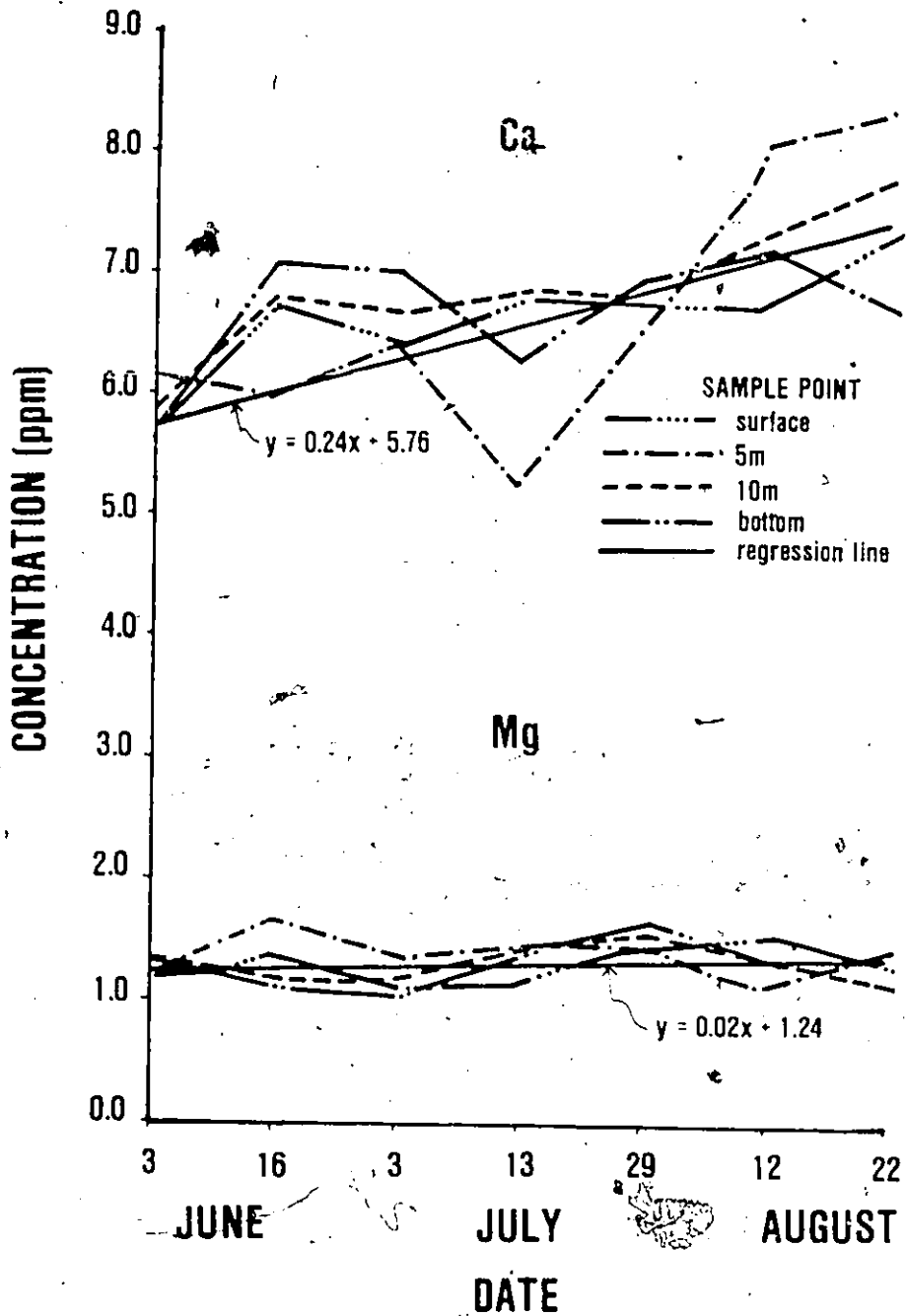


FIGURE 4.1 Lake water sample analysis Site B

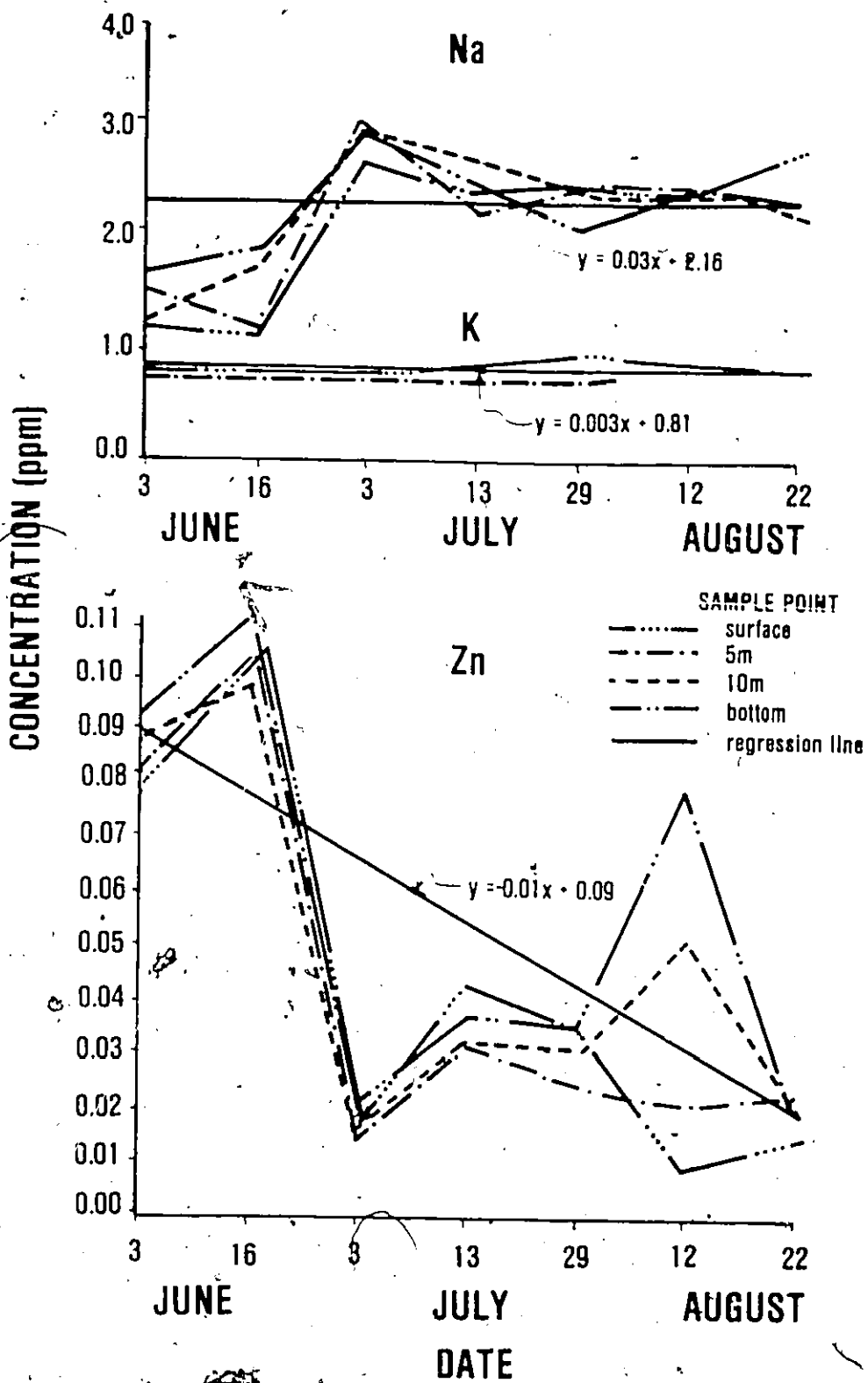


FIGURE 4.2 Lake water sample analysis Site B

slope of its regression line was -0.01. The higher increase in concentration of calcium is also reflected in the increase of lake pH (figure 4.3). The release of bicarbonate (reflected in higher Ca^{2+} concentrations) results in higher lake pH. The variability in the pH levels at the beginning of the season is the result of flushing of solutes from the deposits surrounding the lake and subsequent dilution by precipitation.

The analysis of water derived from the lake sediments revealed the following. Calcium and magnesium both decreased in concentration over the study period (figure 4.4). This is in contrast to the lake water samples which increased in concentration. This suggests that the sediments were losing ions to the water. The most probable reaction causing this is cation exchange, whereby ions on the surface of the sediment particles are exchanged with ions from the water. Overall, sodium increased and potassium decreased over the season (figure 4.5) in comparison with the lake water samples which both increased. The results for zinc were variable showing both increasing and decreasing trends, depending upon the sample site (figure 4.6). This variation could be the result of aquatic plant life or mineralogical differences. Copper and manganese were present in these samples, again showing variable behaviour (figure 4.6). The presence of both copper and manganese can be attributed to biological

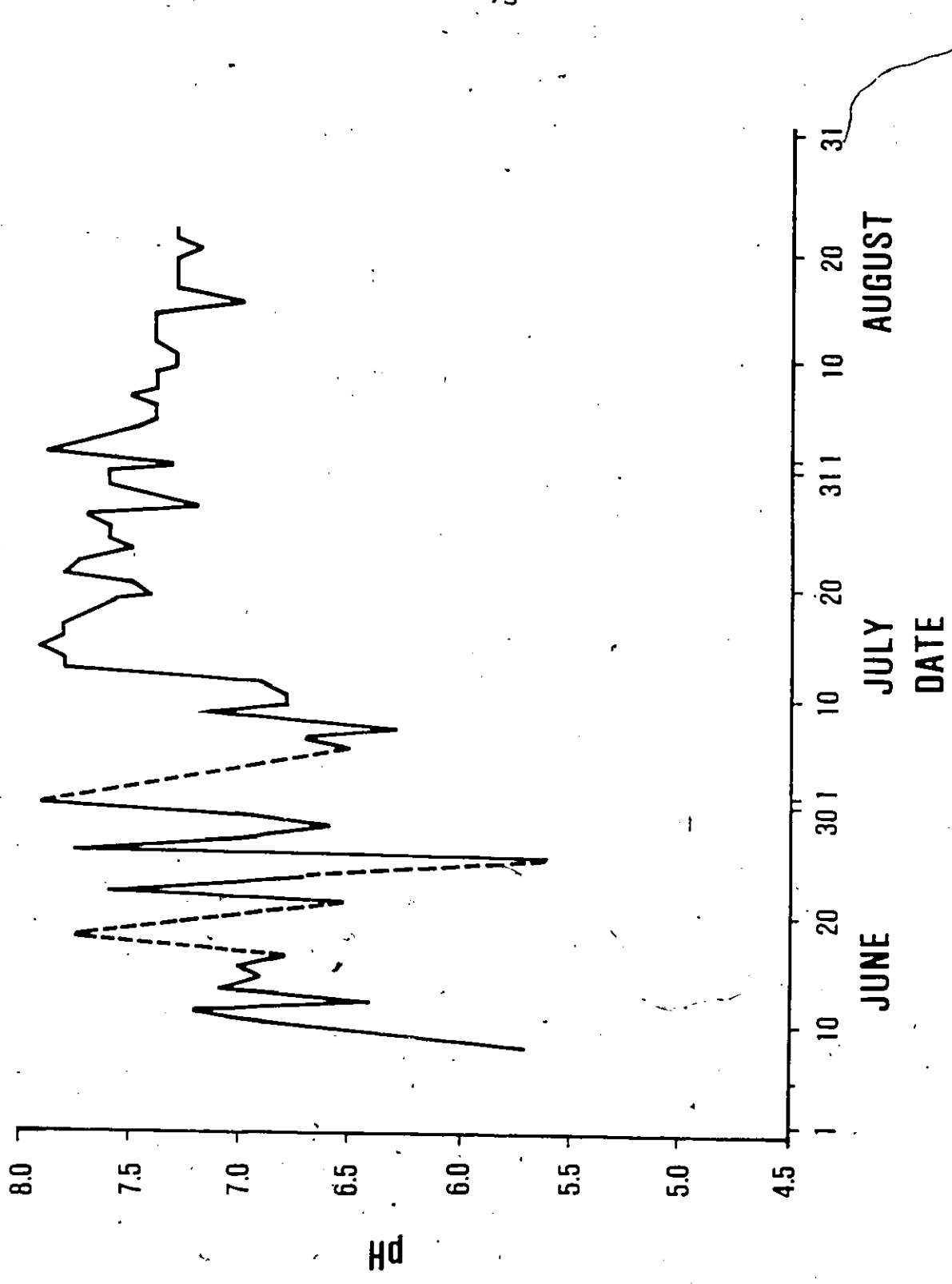


FIGURE 4.3 Lake pH

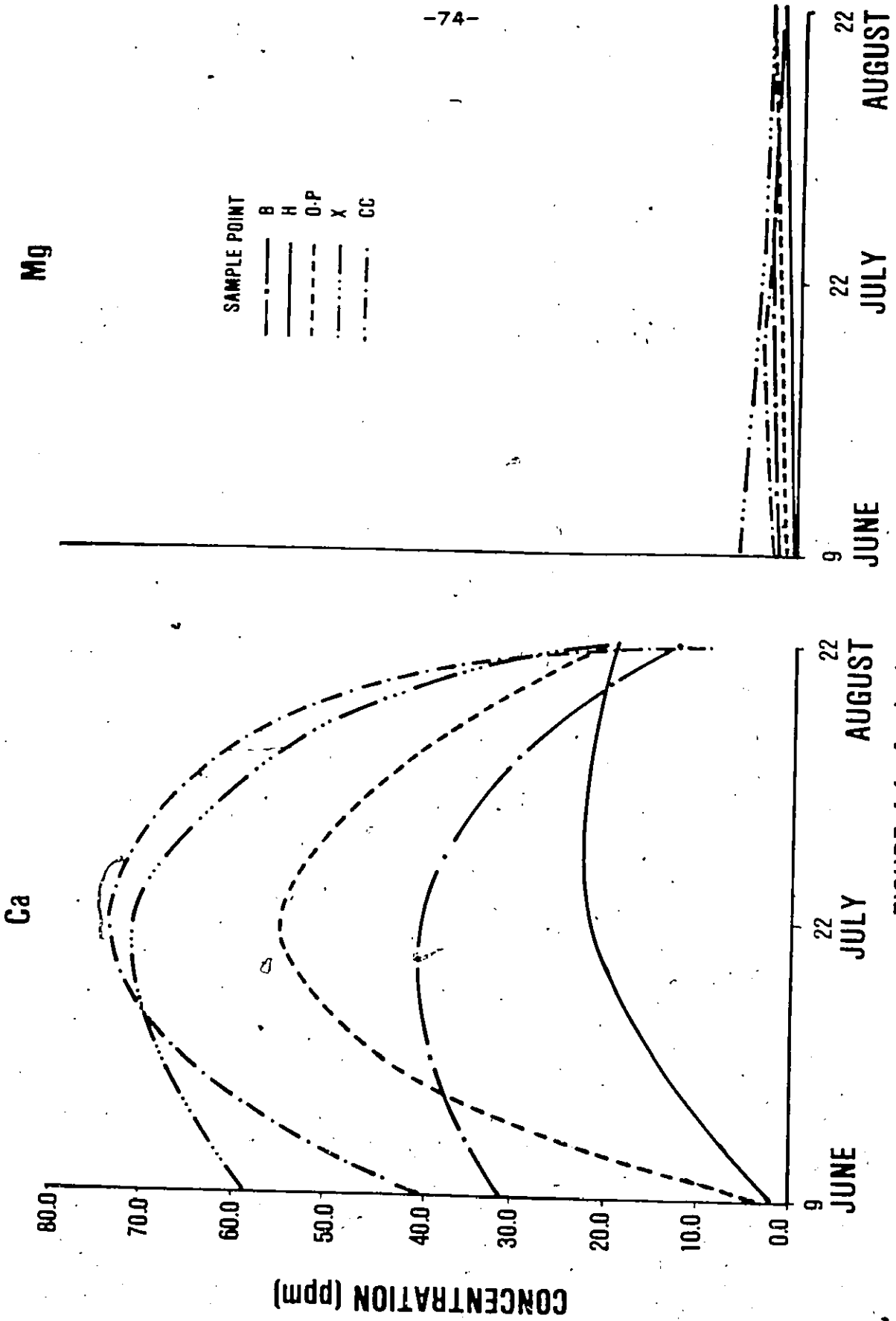


FIGURE 4.4 Analysis of water derived from lake sediments

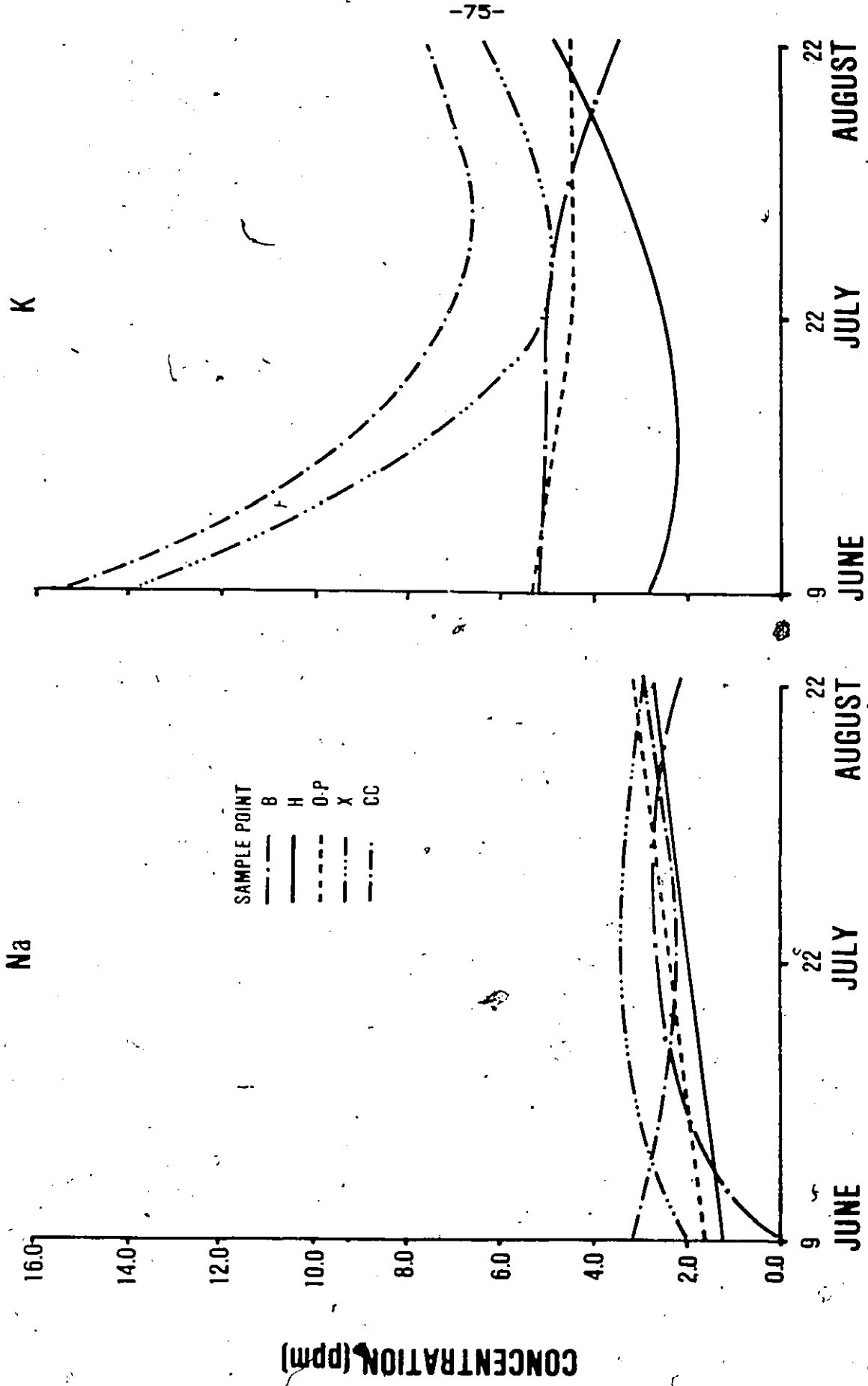


FIGURE 4.5 Analysis of water derived from lake sediments

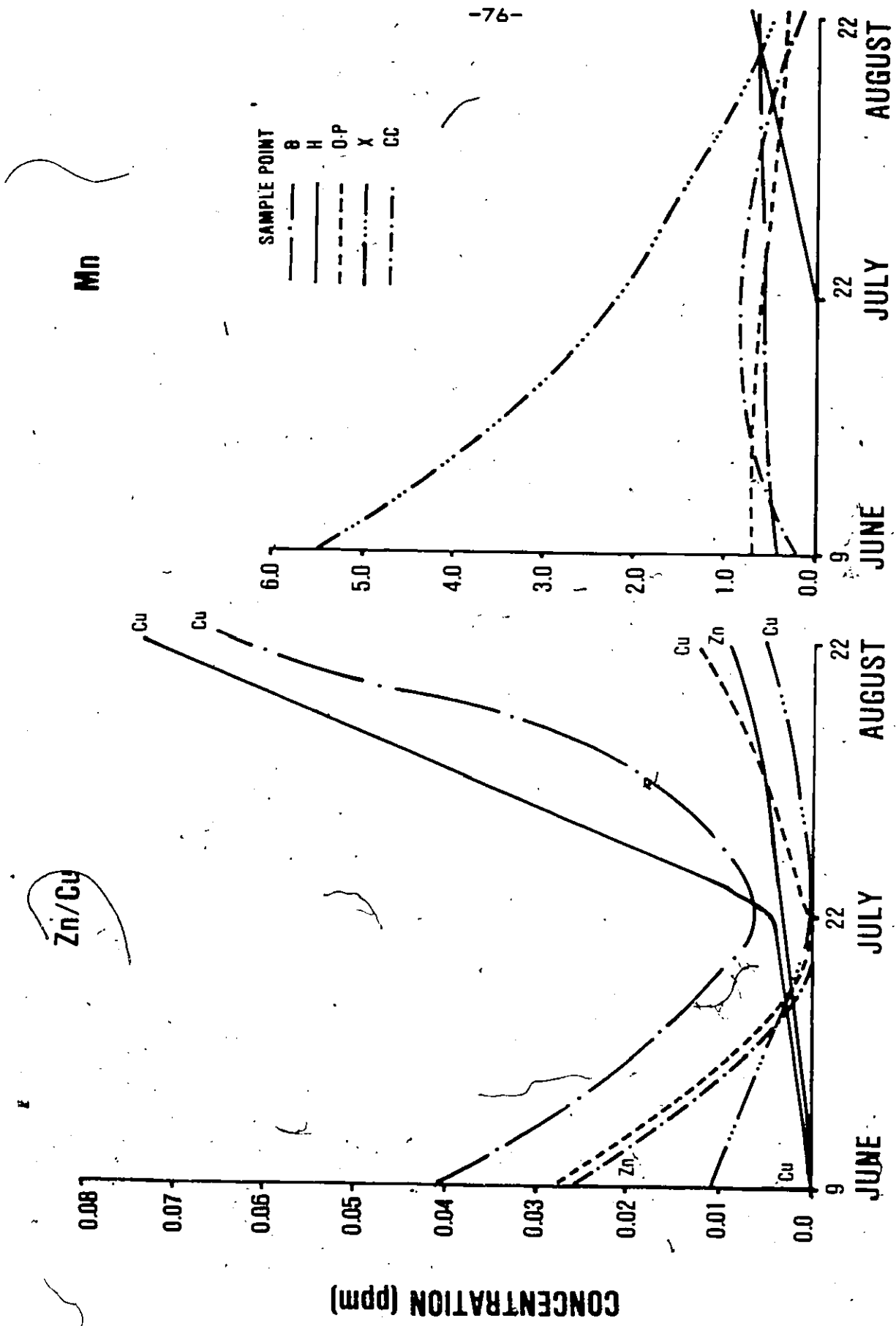


FIGURE 4.6 Analysis of water derived from lake sediments

conditions as these elements were the result of the decomposition of organic matter that was taken up in the sediment sample (Wetzel, 1975).

4.4 Mineralogy

The analysis of the lake bottom sediments by X-ray diffraction are summarized in table 3.1. All the mineralogical interpretation is provided by Hurlbut (1971). Plagioclase is a Na-Ca series of feldspars ranging from pure albite, $\text{Na}(\text{AlSi}_3\text{O}_8)$, to pure anorthite, $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$. Anorthite was present at the beginning of the season and was only detected at one location at the end of the season. Since anorthite is a calcium rich mineral, it is felt that it is the dissolution of this mineral that resulted in the increase in calcium concentration through the study period.

The presence of Mg, Na, and K can be attributed to the following minerals; albite, $\text{Na}(\text{AlSi}_3\text{O}_8)$, which appeared mainly at the inflow end of the lake through the study period; orthoclase, a K-feldspar series, $\text{K}(\text{AlSi}_3\text{O}_8)$, which appeared only at one sample point at the divide end of the lake; muscovite, a widespread rock-forming mineral that is characteristic of granites and granitic pegmatites, $\text{KA}l_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$, which was found only at the beginning of the study period; illite, a mica-like clay mineral series composed essentially of hydrous aluminum silicates with

alkalies or alkaline earths present; chlorite, $Mg_3(Si_4O_{10})(OH)_2$, a common mineral usually formed as an alteration of iron or magnesium silicates such as pyroxenes. In most chlorites there is substitution of Mg with Al, Fe(II) or Fe(III); the pyroxene group with the structure $XY(Si_2O_6)$. X and Y are large weakly charged cations with X generally being Na or Ca, and Y is Mg, Fe(II), Fe(III), Al, Mn(II), Mn(III), or even Li or Ti. Pyroxenes are common in igneous and metamorphic rocks and usually contain both Ca and Na in the X site and Mg, Fe(II), Fe(III), Al and some Ti(IV) in the Y site; quartz, the most common mineral found, was present throughout the season and has the general formula SiO_2 .

4.5 Hydrology

4.51 Lake Temperatures

Lake temperature readings commenced on June 2, 1981, at site B, only a few days after the ice disappeared from the lake, and terminated on August 24, 1981. The results of these readings are shown graphically in figure 4.7. Initial measurements show that the lake was above the temperature of maximum density of $4^{\circ}C$. Rapid heating of the lake occurred and thermal stratification began to form. This stratification persisted until mid August and only began to break up at the end of August when high winds induced

turbulence within the water body causing mixing of the water mass. When figure 4.7 is compared to figure 4.8, an isothermal plot of a mid-latitude lake in a study by Lane (1971), it can be seen that the pattern of thermal stratification is similar. The major difference between the two is that the process occurs much more quickly in the study lake than it does in the mid-latitude lake: the three month study period is similar to the months May to October in the mid-latitude lake. The same processes of turnover, mixing, thermal stratification, and break-up all occur in the study lake but because of its northerly location these processes are condensed in time by a factor of two.

4.52 Seiches

Seiche activity was recorded on the outflow stage recorder used by R. Smith in his research project. The results of the seiche occurrences are summarized in table 4.3. The 10 seiche events in August occurred within a 16 day period, one of six days and one of four days respectively. Using the formula from Whipple (1927), as shown in chapter two, the period of the oscillatory motion was calculated at 6.8 minutes. This compares with an observed period, taken from the stage charts, of from 6.0 to 8.5 minutes with a mean period of 6.42 minutes. The presence of the seiches is the direct result of persistent

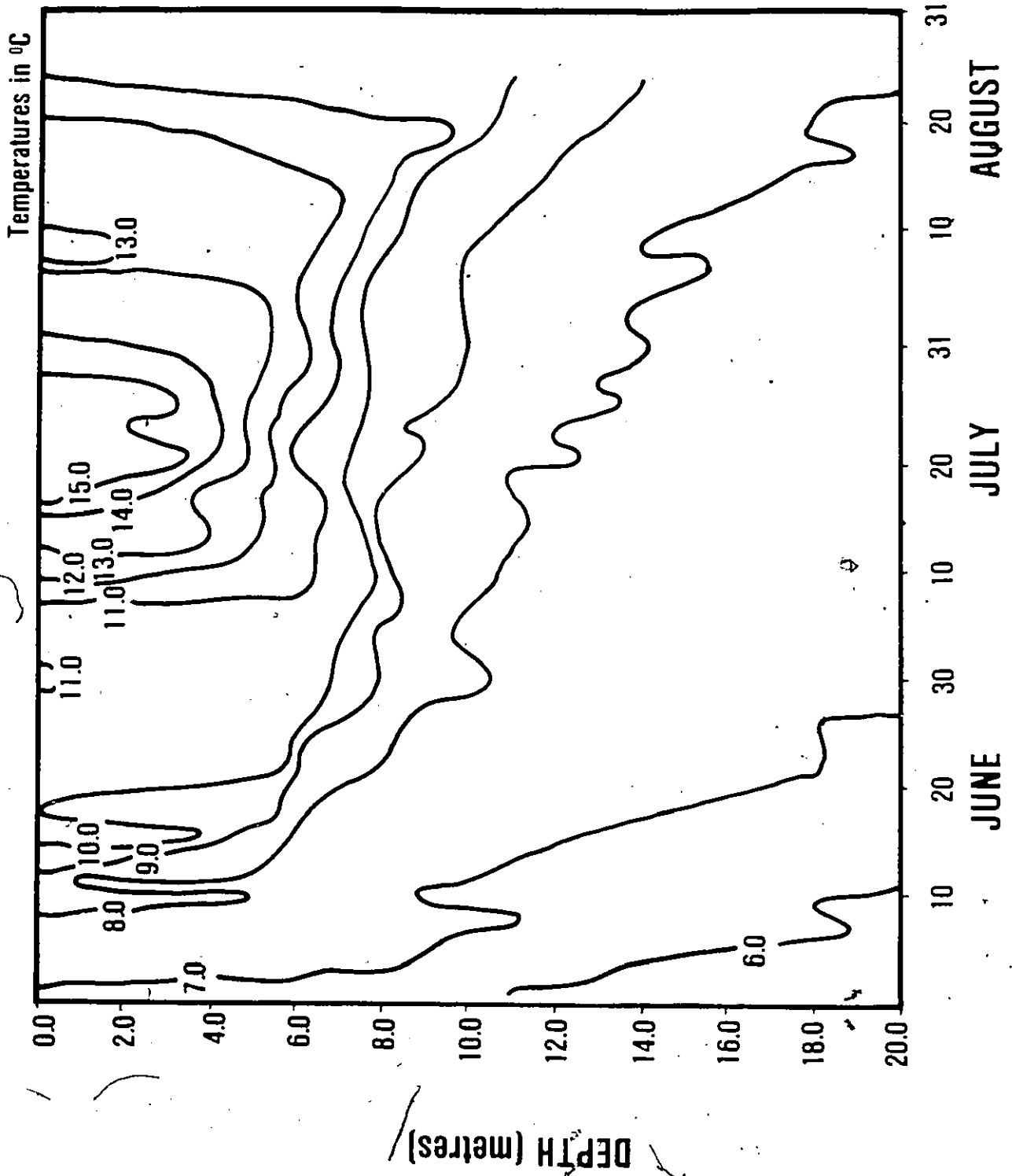


FIGURE 4.7 Lake isotherms

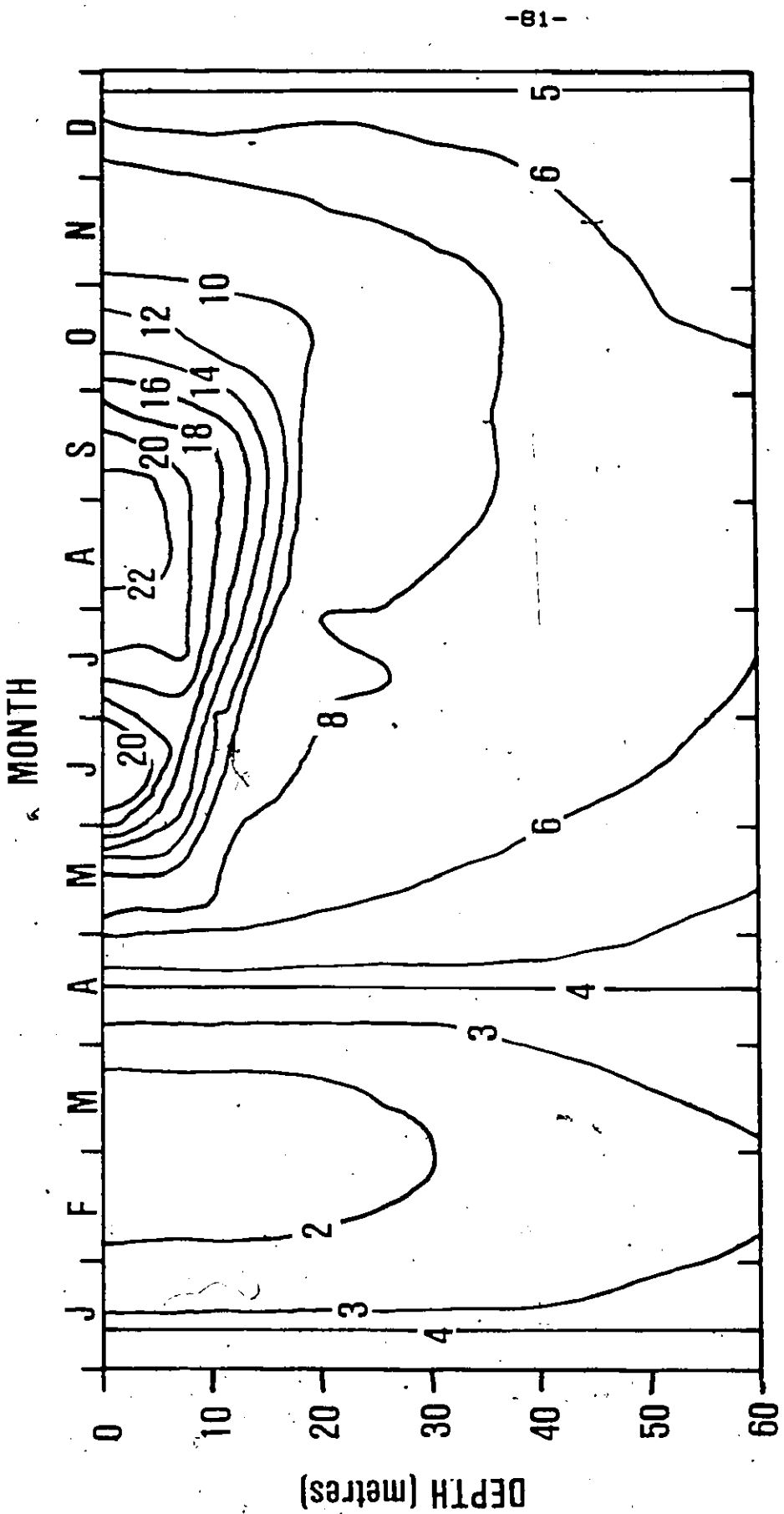


FIGURE 4.8 Temperature variations in a mid-latitude lake. (Lane, 1971)

table 4.3 Seiche Data
Headwater Lake, June-August, 1981

Period of oscillation of the water body as recorded on the outflow stage recorder.

Date	Time (hr)	Period (min)
06/30	9-22	6.0
07/01	12-18	6.0
07/02	11-22	6.0
07/07	14-20	8.5
07/11	15-20	6.7
07/17	16-20	6.0
07/18	13-10	6.7
07/19	14-19	6.7
07/24	13-23	6.0
25		
08/05	11-23	5.5
06		
08/10	15-19	7.5
08/13	12-22	6.6
08/14	13-23	6.6
08/15	9-1	6.0
16		
08/16	12-22	5.5

$$\bar{X} = 6.42 \text{ (mean)}$$

$$t = \frac{2L}{3600 dg} \quad t = 6.8 \text{ min}$$

(Whipple, 1927)

- t - time
- L - length of lake
- d - mean depth
- g - acceleration due to gravity

winds of sufficient velocity to induce movement in the water mass.

CHAPTER 5 CONCLUSIONS

According to the definition of seepage versus drainage lake-type the study lake is classified as a drainage lake because it has an inlet and an outlet. It is, therefore, a surface water dominated lake. Born et al (1979), however, point out that in such a lake groundwater can still constitute a significant portion of the water budget. Smith (1985) has found that groundwater is a factor present in the lake's water balance, but he was unable to produce any quantitative results. To further strengthen this point, it was found that during the wet period the lake level rose substantially. This is to be expected for the following reasons: the water table was saturated, direct precipitation occurred on the lake, overland flow increased, the outflow was limited to one channel and the groundwater was discharging to the lake during the spring and early summer, and the ground was still partially frozen. The lowering of the lake level during the dry period can be attributed to a lowering of the water table due to less precipitation, increased evaporation and a subsequent shift in the groundwater regime to a recharge condition.

Meyboom (1967) and Born et al (1979) have shown that in small lakes multiple groundwater flow conditions can exist. It is felt that this is the case with the study lake especially with the presence of wet and dry periods during

the season. The most probable scenario for the lake then is as follows: during the wet period groundwater discharge dominated followed by a shift to a groundwater recharge regime during the dry period with the possibility of a groundwater divide having existed between the study lake and the Isaac Creek lake. The disintegration of this divide could have resulted in the presence of a flow-through groundwater regime.

Because of the presence of permafrost, subsurface water flow is confined to the active layer. Furthermore, because of the relatively low elevation and latitude, the permafrost is not likely to be deep nor is it likely to be continuous. Groundwater flow would then occur both beneath the permafrost table and in the unfrozen zones.

The computer maps were useful in the portrayal of the lake basin. The maps illustrate how the lake's location at the bottom of the valley influences how water reaches the lake. The steep slopes in conjunction with the different landforms affect overland flow and subsurface flow, especially during the wet period.

The presence of various ions in the lakewater is the result of chemical weathering of the rock and surficial materials surrounding the lake as well as cation exchange between the water and the sediment. The X-ray diffraction analysis suggests that the likely sources of the ions analyzed is as follows: calcium from plagioclase, magnesium

from chlorite, sodium from feldspars such as anorthoclase, potassium from orthoclase and muscovite. The presence of zinc, manganese and copper is the result of chemical weathering of the bedrock and surficial materials as well. These elements are present as contaminants within the crystal lattices of such minerals as quartz, amphibole and feldspars.

The range of concentrations of calcium, magnesium, potassium, sodium and zinc were within the expected values as described in chapter two. Manganese levels were higher than expected but as pointed out in section 2.216, manganese values are variable due to a wide range of potential redox conditions.

The results of the lake temperature regime of the lake have shown the following. First, thermal stratification and subsequent turnover occur just as it does with lakes in lower latitudes with one significant difference; it occurs over a shorter time period. The northerly location affects the temperature regime in that the longer periods of insolation allow for the full development of thermal stratification while the shorter seasons condense the time frame of these events relative to lakes located in lower latitudes.

The contour map of the lake bottom shows that the lake is deeper at the eastern end than the western end. Furthermore, there are indications that the flow of

Gladstone Creek might have been the opposite of what it is today; from west to east. The presence of the divide indicates that the flow of the creek was interrupted. This might have occurred gradually over a long period of time.

The study was limited by the following factors. Failure of the current meter to perform to its expected capabilities, extreme wind conditions in conjunction with a craft unsuited to those conditions, and the short (one season) study period. It is felt that a study of the hydrogeological regime of that lake basin should be one that occurs over more than one season so that a comparison of results could be done. This would lend itself to a longer-term assessment of the data. It is also felt that the computer cartography could have been utilized to a greater extent than was done. The potential for the application of this technology to this type of research is large.

APPENDIX A - LAKE TEMPERATURE PROFILES, SITE B

TEMPERATURES (°C)
JUNE, 1981

Depth (m)	Day													
	2	5	8	10	11	13	15	17	19	20	22	24	26	29
0.0	6.6	7.9	7.5	8.8	8.3	9.8	10.2	10.0	10.3	10.1	10.8	10.6	10.9	11.0
0.5		7.9	7.5	8.6	8.1	9.7	10.2	10.0	10.2	10.1	10.8	10.6	10.9	10.9
1.0		7.9	7.5	8.4	8.0	9.7	10.2	10.0	10.0	10.1	10.8	10.6	10.8	10.9
1.5		7.8	7.5	8.3	8.0	9.7	10.2	10.0	9.9	10.1	10.8	10.6	10.8	10.9
2.0	6.5	7.8	7.5	8.3	8.0	9.7	10.2	10.0	9.9	10.1	10.8	10.6	10.8	10.8
2.5		7.7	7.5	8.3	7.9	9.7	10.2	10.0	9.9	10.1	10.8	10.6	10.8	10.8
3.0		7.7	7.5	8.2	7.9	9.6	10.2	10.0	9.8	10.1	10.8	10.6	10.8	10.8
3.5		7.7	7.5	8.2	7.9	9.6	10.2	9.9	9.8	10.1	10.8	10.6	10.7	10.8
4.0	6.3	7.7	7.5	8.2	7.9	8.6	10.1	9.9	9.8	10.1	10.8	10.6	10.7	10.7
4.5		7.7	7.5	8.1	7.8	8.5	9.4	9.9	9.8	10.1	10.8	10.5	10.7	10.7
5.0		7.6	7.5	8.1	7.8	8.3	8.9	9.9	9.8	10.1	10.8	10.5	10.7	10.6
5.5		7.6	7.5	7.9	7.8	8.0	8.1	9.9	9.8	10.0	10.8	10.5	10.7	10.6
6.0	6.2	7.6	7.5	7.8	7.8	7.9	7.9	8.3	8.4	10.0	10.2	10.1	9.7	10.6
6.5		7.5	7.5	7.8	7.7	7.6	7.8	7.9	8.0	8.4	9.0	9.1	9.1	10.5
7.0		7.5	7.5	7.8	7.6	7.5	7.6	7.8	7.8	8.0	8.5	8.8	8.7	9.9
7.5		7.5	7.5	7.7	7.5	7.4	7.5	7.7	7.7	7.8	8.2	8.5	8.5	9.9
8.0	6.2	7.4	7.4	7.2	7.3	7.3	7.4	7.7	7.6	7.7	8.1	8.2	8.2	9.0
8.5		6.7	7.4	7.1	7.2	7.3	7.4	7.6	7.5	7.6	7.9	8.0	8.1	8.7
9.0		6.7	7.4	6.9	7.1	7.2	7.4	7.6	7.5	7.5	7.8	7.9	7.9	8.5
9.5		6.6	7.4	6.9	7.1	7.2	7.3	7.5	7.5	7.5	7.8	7.8	7.9	8.4
10.0	6.2	6.0	7.4	6.8	7.0	7.1	7.3	7.4	7.4	7.4	7.8	7.8	7.8	8.3
10.5		6.5	7.3	6.8	7.0	7.1	7.2	7.3	7.3	7.4	7.7	7.7	7.7	7.9
11.0		6.4	7.1	6.8	6.9	7.0	7.2	7.2	7.3	7.4	7.6	7.6	7.6	7.7
11.5		6.4	6.8	6.6	6.8	7.0	7.2	7.2	7.3	7.3	7.5	7.5	7.6	7.6
12.0	6.1	6.4	6.7	6.6	6.8	6.9	7.1	7.1	7.3	7.3	7.5	7.5	7.5	7.5
12.5		6.2	6.6	6.5	6.7	6.8	7.0	7.1	7.2	7.3	7.4	7.5	7.5	7.4
13.0		6.2	6.6	6.5	6.7	6.7	7.0	7.1	7.2	7.2	7.4	7.4	7.4	7.4
13.5		6.1	6.5	6.4	6.7	6.6	7.0	7.0	7.2	7.2	7.4	7.4	7.4	7.3
14.0	5.6	6.1	6.5	6.4	6.6	6.6	6.9	7.0	7.2	7.2	7.4	7.4	7.3	
14.5		6.0	6.4	6.3	6.5	6.6	6.8	7.0	7.1	7.1	7.3	7.3	7.3	
15.0		6.1	6.4	6.3	6.5	6.5	6.8	7.0	7.1	7.1	7.3	7.3	7.3	
15.5		6.0	6.4	6.2	6.5	6.4	6.8	7.0	7.0	7.1	7.3	7.2	7.2	
16.0	5.2	6.0	6.3	6.2	6.5	6.4	6.8	7.0	7.0	7.0	7.3	7.1	7.2	
16.5		6.0	6.3	6.2	6.4	6.4	6.7	7.0	7.0	7.0	7.2	7.1	7.1	
17.0		6.0	6.3	6.1	6.5	6.4	6.7	6.9	6.9	6.9	7.2	7.1	7.1	
17.2										6.9				
17.5	5.1	5.9	6.3	6.1	6.4	6.3	6.7	6.9	6.9		7.1	7.1	7.1	
17.8					6.3	6.3	6.6		6.8		7.1			
18.0		5.9	6.2	6.0				6.9				7.0	7.0	
18.2				5.9				6.8					7.0	

TEMPERATURES (°C)
AUGUST, 1981

Depth (m)	Day									
	1	4	6	8	10	13	17	19	21	23
0.0	14.0	13.4	12.7	12.8	13.0	12.5	11.7	11.3	10.6	10.9
0.5	14.0	13.4	12.7	12.8	13.0	12.6	11.7	11.3	10.6	10.9
1.0	14.0	13.4	12.7	12.8	13.0	12.6	11.7	11.3	10.6	10.9
1.5	14.0	13.4	12.7	12.7	13.0	12.6	11.7	11.3	10.6	10.9
2.0	14.0	13.4	12.7	12.7	13.0	12.6	11.7	11.3	10.6	10.9
2.5	14.0	13.4	12.7	12.7	12.9	12.6	11.7	11.3	10.6	10.9
3.0	14.0	13.4	12.7	12.7	12.9	12.5	11.7	11.3	10.6	10.9
3.5	14.0	13.4	12.7	12.7	12.9	12.5	11.7	11.3	10.6	10.9
4.0	14.0	13.4	12.7	12.7	12.9	12.4	11.7	11.3	10.6	10.9
4.5	14.0	13.4	12.7	12.7	12.9	12.3	11.7	11.3	10.6	10.9
5.0	13.9	13.4	12.7	12.6	12.9	12.3	11.7	11.3	10.6	10.8
5.5	13.9	12.7	12.7	12.6	12.9	12.3	11.7	11.3	10.6	10.8
6.0	13.9	12.3	12.7	12.6	12.9	12.3	11.7	11.3	10.6	10.8
6.5	13.9	12.0	12.7	12.6	12.8	12.3	11.7	11.3	10.6	10.8
7.0	11.7	11.2	12.7	12.6	12.8	12.2	11.8	11.3	10.6	10.7
7.5	10.1	10.4	12.7	12.6	12.0	12.2	11.8	11.3	10.6	10.7
8.0	9.7	9.8	10.6	12.0	11.7	12.1	11.7	11.3	10.6	10.7
8.5	9.6	9.5	9.8	10.5	10.7	11.8	11.4	11.3	10.5	10.7
9.0	9.3	9.4	9.4	9.7	10.0	11.5	10.9	11.2	10.5	10.7
9.5	9.1	9.2	9.1	9.3	9.6	10.8	10.7	11.2	10.4	10.6
10.0	9.0	8.9	8.8	9.0	9.1	10.2	10.5	11.1	10.4	10.6
10.5	8.8	8.8	8.8	8.6	8.9	9.7	10.0	10.7	10.3	10.6
11.0	8.7	8.6	8.6	8.5	8.7	9.3	9.6	9.7	10.1	10.5
11.5	8.6	8.5	8.5	8.4	8.4	8.9	9.4	9.2	9.6	9.9
12.0	8.5	8.3	8.4	8.4	8.4	8.7	9.1	9.1	9.2	9.7
12.5	8.5	8.2	8.2	8.3	8.3	8.5	8.9	8.8	9.0	9.3
13.0	8.4	8.1	8.2	8.3	8.2	8.3	8.8	8.7	8.9	9.0
13.5	8.2	8.0	8.1	8.2	8.1	8.3	8.8	8.7	8.7	8.9
14.0	8.1	7.9	8.0	8.1	8.1	8.2	8.6	8.6	8.6	8.8
14.5	7.9	7.8	7.9	8.1	8.0	8.2	8.6	8.5	8.5	8.7
15.0	7.8	7.8	7.8	8.1	7.9	8.1	8.5	8.5	8.5	8.6
15.5	7.7	7.7	7.8	8.0	7.7	8.0	8.5	8.4	8.4	8.6
16.0	7.7	7.6	7.7	7.9	7.7	7.9	8.4	8.3	8.4	8.5
16.5	7.6	7.6	7.6	7.9	7.7	7.8	8.3	8.2	8.3	8.5
17.0	7.5	7.5	7.6	7.9	7.6	7.7	8.2	8.1	8.3	8.4
17.5		7.5	7.5	7.8	7.6	7.7	8.2	8.0	8.2	8.4
17.8			7.4							
18.0		7.4		7.8	7.6	7.7	8.1	8.0	8.2	8.4
18.2				7.7				7.9	8.0	
18.5						7.6	8.1			
19.0							8.0			

APPENDIX B - SEICHE DATA

DATE	TIME (hr)	WIND SPEED (km/h) (X)	DIRECTION
June 30	9-11	16.2	S
	11-13	24.3	W
	13-14	32.4	W
	14-17	24.3	S
	17-22	8.1	S-N
July 1	12-14	16.2	W
	14-15	24.3	W
	15-16	8.1	W
	16-17	8.1	E
	17-18	8.1	E
July 2	11-17	32.4	W
	17-20	16.2	E
	20-22	8.1	E
July 7	14-20	8.1	SE
July 11	15-19	8.1	SE
	19-20	16.2	SE
July 17	12-14	16.2	W
	14-15	12.8	W
	15-17	4.7	W
	17-20	16.2	W
July 18	9-11	16.2	E
	11-17	8.1	E
	17-18	16.2	E
July 19	15-18	16.2	E
	18-19	8.1	E
July 24 -25	13-21	16.2	W
	21-24	16.2	N
	24-5	16.2	E
	5-20	8.1	E
	20-23	16.2	E
Aug 5-9	11-12	16.2	E
	12-14	8.1	E
	14-15	16.2	W
	15-17	24.3	W
	17-18	16.2	W
	18-20	8.1	E
Aug 6	20-03	16.2	E-W
	3-7	8.1	W
	7-13	16.2	W

DATE	TIME (hr)	WIND SPEED (km/h) (X)	DIRECTION
Aug 7	13-16	8.1	W
	16-20	16.2	W
	20-23	8.1	W
	23-03	16.2	E
	3-4	8.1	E
	4-9	16.2	E
	9-12	16.2	W
	12-13	24.3	W
	13-14	16.2	W
	14-15	24.3	W
Aug 8	15-16	32.4	W
	16-23	16.2	W
	23-12	8.1	E
	12-15	24.3	W
	15-20	16.2	W-E
Aug 9	20-02	8.1	E
	2-23	16.2-8.1	NE
Aug 10	15-19	8.1	E
Aug 13	12-22	16.2	W
Aug 14			W
	13-23	16.2-8.1	SW-SE
Aug 15-16	9-15	16.2	S
	15-21	24.3-32.4	W
	21-01	16.2	W
Aug 16	12-18	8.1	W
	18-22	8.1	E

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