SOME ASPECTS OF THE HYDROLOGY OF ICE-DAMMED LAKES: OBSERVATIONS ON SUMMIT LAKE, BRITISH COLUMBIA

by

Robert Gilbert

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

in the Department

of

Geography

We accept this thesis as conforming to the

required standard

THE UNIVERSITY OF BRITISH COLUMBIA

November, 1969

Department of Geography

The University of British Columbia
Vancouver 8, Canada

Date November 1969

ABSTRACT

The first known self-draining of Summit Lake occurred in December 1961, followed by similar events in November 1965, September 1967, and November 1968. It has been noted that the rate of draining increases rapidly until the lake is empty (Mathews 1969). In August 1967 it was also noted that the runoff per unit area from the basin of Summit Lake, based on the rate of water volume change in the lake and overflow from the lake, was approximately one half the runoff per unit area from a glacierized basin to the north. It was suspected that at least part of this difference was due to leakage through the ice dam. More detailed observations made in July and August 1968 of the water balance of the lake basin indicate that, in August, there probably existed a leak possibly as large as 3 to 5 m^3 sec^{-1}. The tracing of lake water with fluorescent dye on three occasions also indicated the existence of a leak.

Records of lake temperature from surface to bottom were kept from July through September with the results that: a) the warmest water was found at the bottom, and the coldest at approximately one third depth in most cases, b) the warmest temperatures occurred in the north end of the lake in early July; water temperatures decreased southward toward the ice dam and at all locations through the summer, and c) a mean water temperature of approximately 1°C is estimated for July decreasing to 0.7°C by September.

For the 1965 draining a lake water temperature of 0.2°C is sufficient with the heat generated due to loss of potential energy to account for the enlargement of the tunnel in the terminal stages of draining, whereas

a water temperature of 0.9 °C is required for the 1967 flood.

No evidence of sudden density overturn of the lake water could be found either from the temperature measurements or the results of dye tracing in the lake water in 1969.

Water temperature records on three streams flowing into the lake indicate that from the entire drainage basin approximately 320×10^{10} calories per day of heat may have been advected to the lake in August 1968.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SYMBOLS USED IN TEXT

a, b, c,	Constants
A	Area of Summit Lake surface in square meters x 10^6
D'	Diameter of drainage tunnel in centimeters
E	Evaporation from Summit Lake surface in cubic meters of water
g	Acceleration due to gravity
H'	Head loss in centimeters of Summit Lake water
H"	Head of Summit Lake water measured above the tunnel exit in meters
h	Convective or eddy coefficient of conduction (Mathews 1969)
J	Conversion factor, Joules per calorie (4.186)
k	'proportionality function'
L	Length of the tunnel in the Salmon Glacier in meters
L'	Tunnel length in centimeters
n	Manning's roughness coefficient
Δp	Difference in hydrostatic pressure (page 16)
P_4	Precipitation as measured at gauge #4,200 meters from the Troy Creek gauging site in meters per day
P_ℓ	Calculated precipitation on the surface of Summit Lake in meters per day
Q	Discharge or rate of water flow in cubic meters per day per second

Subscripts

DI	Discharge from Daisy One Creek
i	Total inflow of water to Summit Lake
ol	Outflow from Summit Lake via a leak in the ice dam
nb	Net discharge in the Bowser River (Total discharge less the Summit Lake overflow)
on	Overflow from Summit Lake to the north

os Discharge from Other Side Creek

T Discharge from Troy Creek

Q' Discharge in m^3/sec

r Radius of the drainage tunnel in meters

R Hydraulic radius of the drainage tunnel (r/2) in meters

s Stage in feet (Bowser River)

S Hydraulic gradient of the water in the drainage tunnel

T_T Mean daily temperature at the Tide Camp Station in °C.

v Velocity of the water in the drainage tunnel in meters per second

V Volume of water passed from the lake from the beginning of the draining in cubic meters

ΔV Daily change in volume of the water of Summit Lake in cubic meters

z_i Thickness of ice in meters

z_w Depth of water in meters

ρ Density

<u>Subscripts</u>

i of ice
w of water

θ Temperature of water in tunnel at distance ℓ from entrance °C

θ_p Portion of tunnel water temperature due to head loss °C

θ_ℓ Portion of tunnel water temperature due to lake water temperature °C

θ_L Tunnel exit temperature Summit Lake water °C

ACKNOWLEDGMENT

Field work was carried out with the assistance of the Glaciology Subdivision, Department of Energy Mines and Resources, Canada. Thanks are due especially to Dr. A. D. Stanley, Head, Cordillera Section, and to the field crew under Mr. R. J. Rogerson, particularly Mr. O. T. Melo who assisted in the collection of all the data.

Granduc Operating Company, Vancouver and Stewart, kindly provided room and board at Tide Camp, the use of Granduc facilities and access to pertinent records.

Dr. W. H. Mathews and Dr. J. R. Mackay, University of British Columbia, and Dr. A. D. Stanley, Ottawa have made important suggestions and comments. These are appreciated by their adoption.

The University of British Columbia provided financial support in the form of a Fellowship.

PART I: THE ICE-DAMMED LAKE

A) Introduction

Glacier dammed or ice-dammed lakes are common features in areas of large valley glaciers. The importance of past and present lakes is recognised in the literature. Landforms created or altered by lakes associated with Pleistocene ice sheets are valuable indicators of conditions at that time and of subsequent change. Recent changes in ice-dammed lakes have been used as measures of glacier fluctuations.

The sudden drainings of ice-dammed lakes provide torrents that are powerful agents, altering channel character and valley form and disrupting human occupance downstream. With increasing settlement of these areas, particularly in North America, the importance of understanding this phenomenon increases.

This thesis reviews briefly some of the literature available on ice-dammed lakes, discusses some of the mechanisms postulated to be causes of the drainings and presents the results of preliminary studies of the water balance and thermal conditions of one lake in British Columbia.

Although earlier accounts of ice-dammed lakes exist, Rabot (1905) was the first writer to clearly direct earth scientists to the importance of the outbursts of ice-dammed lakes. He carefully documents the frequency and magnitude of drainings in all the areas of the world in which they had been observed at that date, drawing on accounts as early as the fifteenth century. Rabot's most complete accounts of drainings are those of European lakes. With the exploration and settling of other alpine areas other lakes became known.

Among the early descriptions of the drainings of North American ice-dammed lakes are those in geological reports,[1] and writing such as Bateman's account (1922) of the draining of Icy Lake associated with the spouting of a 'pothole' on the Kennecott Glacier, Kerr's account (1934) of the draining of Tulsequah Lake in August 1932, and Hanson's work (1932) on the varved clays of Tide Lake, British Columbia. Since 1960 the interest in ice-dammed lakes has heightened as witness the work of Marcus (1960) on Tulsequah Lake, Stone (1963a) on Lake George, Mathews (1965) on Strohn and Summit Lakes, Lindsay (1966) and Moravek (1968) on Casement Lake, and Mathews (1969) on Summit Lake. Stone (1963b) documents 53 ice-dammed lakes in southeastern Alaska and adjacent British Columbia and summarizes their characteristics, drainings and histories.

There is a literature of some size on ice-dammed lakes in other areas of the world. Ricker (1962) provides a brief descriptive account of ice-dammed lakes on Axel Heiberg Island and notes that they are also common on Baffin Island, Devon Island, Ellesmere Island and Greenland. He discusses the draining of Phantom Lake, Axel Heiberg Island.

The ice-dammed lakes of Iceland and Norway are well accounted at

---

[1] See for example A. F. Buddington, 1929, Geology of Hyder and vicinity, southeastern Alaska; U.S. Geological Survey Bulletin No. 807; J. T. Mandy, 1930, Report on the Taku River Area, Atlin Mining Division; B.C. Department of Mines Bulletin No. 1; F. H. Moffit, 1938, Geology of the Chitina Valley and adjacent area, Alaska; U.S. Geological Survey Bulletin No. 894.

least partially because of the disastrous effects of their drainings on settlement. Although ice-dammed lakes of Iceland have been documented since early settlement,[2] Wright's account (1935) of the draining of Hagvatn was one of the first formal writings. Thorarinsson (1939) provides a careful and detailed account of Icelandic ice-dammed lakes, describes their historical changes and notes the implications of these changes as indicators of glacier oscillations. In a later paper (1953) he reexamines the largest of these lakes particularly with reference to earthquakes, volcanic eruptions and the draining of the lake. Dybeck (1957) provides a brief account of the changes in size of Lake Porisdalurvatn since Wright's survey in 1935.

A thorough account of Norwegian ice-dammed lakes is provided by Liestol (1956) with considerations as to the mechanisms of draining. Later accounts of two of the lakes described by Liestol are provided by Aitkenhead (1959) and Howarth (1968).

The ice-dammed lakes of the Himalayas and of South America are somewhat less well known partly because of the remoteness of the areas in which they occur. Much of the information on Himalayan lakes is gained from European exploration early in this century. Hutchinson (1957) provides a summary of the findings to that date. A later account of an early ice dam on the Indus River is given by Hewitt (1964).

Descriptions of ice-dammed lakes in South America are provided by King (1934), Helbing (1935) (Rio Plomo, Nevado Glacier) and by

---

[2]For example Thorarinsson (1939) recounts a saga tale of a flood of 1201 A.D. which he attributes to Lake Graenalon.

Nichols and Miller (1952) (Lago Rico).

Freshfield (1905) notes the draining of two ice-dammed lakes in the Caucasus Mountains but no later reference to lakes in this area could be found.

Table I is a summary of the sizes of ice-dammed lakes that have been reported in the literature. Clearly many more lakes exist but records of their volumes are not readily available.

TABLE I

Recorded Volumes of Ice-dammed Lakes at the Date Given

Lake	Volume ($m^3 \times 10^6$)	Date	Source
Grimsvötn	10000	1936	Thorarinsson
Graenalon, Iceland	1500-2000	1939	Thorarinsson (1939)
Lake George, Alaska	1500[a]	1951	Stone (1963 (a))
Tulsequah Lake, B.C.	907	1910-20	Marcus (1960)
	229	1958	Marcus (1960)
Summit Lake, B.C.	250	1967	
Hagvatn, Iceland	150-200	1929	Thorarinsson (1939)
Østerdalsisen, Norway	145	1954	Liestol (1956)
Vatnsdaluratn, Iceland	120	1898	Thorarinsson (1939)
	35	1938	Thorarinsson (1939)
Nupslon, Iceland	100	1929	Thorarinsson (1939)
Demmevatn, Norway	35	1893	Liestol (1956)
	11.5	1937	Liestol (1956)
Mjolkedsvatn, Norway	34		Liestol (1956)
Gjanspsvatn, Iceland	30		Thorarinsson (1939)

TABLE I (cont'd)

Dalvatn, Iceland	20	1880	Thorarinsson (1939)
Brimkjelen, Norway	19.2	1937	Howarth (1968)
Strohn, B.C.	11	1960,61	Mathews (1965)
Marjelen, Switzerland	10.7	1878	Collet (1925)
	7.5	1892	Collet (1925)
	3.1	1913	Collet (1925)
Skedevatn, Norway	10	1820-48	Liestol (1956)
Strupbreen, Norway	9	1957	Aitkenhead (1959)
Casement Lake, Alaska	8.37	1965	Lindsay (1966)
Vernagt, Switzerland	7.9	1845	Rabot (1905)

[a]The volume is taken from a map presented in the paper by Stone (1963 (a)) and is not quoted from him.

B) Suggested Mechanisms of Draining

Many of the writers who have described ice-dammed lakes have tried to account for their draining. Some have noted that the causes may be complex and that the importance of any single mechanism with respect to others may change with time. The work has been hampered in part by the difficulty in obtaining data on the drainings. They are usually rapid and generally unexpected. As most of the lakes are in remote locations, on site observations are often impossible. The subglacial channel or channels cannot be examined directly; even their entrances and exits are commonly obscured soon after the floods by jumbles of collapsed ice. Nevertheless sufficient observations have been made that at least some mechanisms that may lead to the draining of ice-dammed lakes can be put forward. Those discussed here are: 1) overtopping and subsequent erosion of the ice dam, 2) floating of the ice dam, 3) melting of a tunnel beneath the ice dam, 4) failure or flow of the ice at depth due to water pressure, 5) seasonal variation in flow of the damming glacier, 6) drainage associated with volcanic and earthquake activity, and 7) drainage through a tunnel in bedrock.

1) Overtopping of part of the ice dam and subsequent erosion and melting of a channel through the glacier is an obvious but not common mechanism. Often the lake can float the ice adjacent to it and thus prevent overtopping. Liestol (1956, p. 128) provides an account of the draining of Lake Demmevatn in August 1897:

> On August 17 the water had attained such a high level that it began inundating the ice. A channel soon formed in the ice, gradually deepening and enlarging to a vast crevasse. The sides were overhanging, and from time to time large blocks

> dropped and partly blocked the outflow for some time. [The crevasse] gradually cut through to the very bottom as the drainage of the lake advanced.

It is interesting to note that, while a man-made tunnel through rock completed in 1899 kept the water level twenty meters below the former level and thus prevented overtopping, the lake drained in 1937, not by overtopping but through a hole about five meters in diameter at the bottom of the dam. The glacier had thinned considerably since 1899. This draining took only 3.5 hours causing a much more severe flood than had previous drainings which took two to three weeks (Liestol 1956).

Ricker (1962) provides an account of the overtopping of the Hugh Thompson Glacier, Axel Heiberg, by Phantom Lake. In this case the rate of melt of the spillway was much slower (1.5 meters in 7 days) presumably because of the cold temperature of the water. In the case of overtopping much more ice must be melted or removed to drain the lake than if the lake drained by a tunnel beneath the ice for only the bottom of the 'gorge' or crevasse is occupied by water. Thus the draining is likely to take longer and the flood be less severe.

2) Floating of the ice dam adjacent to the glacier may occur when the water reaches approximately nine tenths the thickness of the ice. That is, floating will occur when $z_i \rho_i = z_w \rho_w$ (Thorarinsson 1939) per unit area of each water and ice.[3] Except for the case of very narrow ice dams where the term 'critical zone' in Thorarinsson's sense applies, this will not be so. For large ice dame until the upward force on the ice front created by the buoyancy of the ice is sufficient to

[3] Thorarinsson's correction for crevasses is not considered here.

produce failure or deformation of the ice its upward movement cannot occur. Glen (1954) and Moravek (1968) conclude that $z_w \rho_w$ must be greater than $z_i \rho_i$ for floating to occur because of freezing of the glacier to bedrock. This is doubtful at least in the case of 'temperate glaciers' where basal temperatures are near 0°C.

As z_w increases the zone of floating will increase until it penetrates beneath the glacier and draining occurs. Clearly this simple picture is complicated by addition of the third dimension and a change in thickness of the ice away from the ice dam.

As many ice-dammed lakes are located in tributary valleys the floors of which are much higher than the main valley and thus the glacier thickness is much greater than the lake depth, floating can occur only in the immediate vicinity of the ice dam, if anywhere. A second consideration raised by a number of authors is that once the ice has floated and enough water escaped to lower the ice back to its bed the leak will be sealed again. The lake will experience a series of minor fluctuations but will never drain completely. Marcus (1960) suggests that floating need only occur in the immediate vicinity of the ice front, the region he refers to as the 'critical zone', so that water may gain access to tunnels in the ice which remain continuously open. In view of the work of Haefeli (1952) there is serious question as to whether a tunnel would remain open. Consider also that some ice-dammed lakes after a long period of non-draining have drained just as rapidly as when drainings were close together.

Aitkenhead (1959) suggests that once floating has occured the glacier does not settle evenly on its bed or that icebergs wedge beneath it leaving a passage for water. The second suggestion is doubtful since a) lake surface bergs would pass through the tunnel with the last not the first of the water and b) any ice that was wedged beneath the glacier might be crushed and assimilated into the bed of the glacier by the weight of the ice settling on it.

Nichols and Miller (1952) suggest that tension crevasses may form in the base of a thin dam due to floating of the ice. This would then provide a channel for escape of the water. Such may occur when an ice tongue from a side valley crosses a main valley damming its stream. In many cases, however, crevasses formed by this method would be transverse to the direction of water flow so that if they were used the route of the water through the glacier would be very indirect.

3) Liestol (1956, p. 123) states that if 'the water from the lake has in some way forced a small passage beneath the ice it will, by melting, be able to extend and keep open a tunnel.' That is, the volume of ice melted from the tunnel to a given instant is a function of the total amount of water that has passed through the tunnel. Assuming the tunnel to be straight and circular in cross section:

$$L\pi r^2 = f(V) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{I,1}$$

Equation I,1 cannot be given as a proportion statement since the relation between the tunnel and lake water volume change is not constant. (see Mathews 1969, Table 3) Let a proportionality function be introduced and written as $k = k(t)$ evaluated from t_o, the beginning of leakage (which may be long before the draining), so that at time t:

$$(L\pi r^2)_t\ k_t = V_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad I,2$$

Now assuming a single, straight circular tunnel Manning's formula may be used as an approximation for the velocity of flow in the tunnel (Mathews 1969):

$$v = \frac{R^{2/3}\ S^{1/2}}{n} = \left(\frac{r}{2}\right)^{2/3} \frac{S^{1/2}}{n} \quad \ldots\ldots\ldots \quad I,3$$

and

$$Q_{ol} = \pi r^2\ v \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad I,4$$

Solving I,2, I,3, and I,4 (Appendix I)yields:

$$Q_{ol} = \frac{V_t^{4/3}\ S_t^{1/2}}{a\ k_t^{4/3}} \quad \ldots\ldots\ldots\ldots\ldots \quad I,5$$

a, a constant

where S decreases as the lake empties.

k = k(t) is a function of 1) the heat emergy generated by friction (the difference between the potential energy lost and the kinetic energy gained by the water), 2) the temperature of the water before it enters the tunnel, and 3) the efficiency of heat transfer; that is, the amount of heat used to melt ice rather than pass out of the tunnel as sensible heat in the water. Mathews (1969) calculates for Summit Lake that:

> ...it can be inferred that of the 1.39 calories/cm^3 created through loss in potential energy in the tunnel at the start of the flood only about 10% is lost by advection from the tunnel, the remaining 90% being available for melting ice of the tunnel walls. Later the percentage of available heat expended in melting drops to more than 50% and it becomes more problematical if this method is sufficient to account for the enlargement of the tunnel.

For Summit Lake, Mathews (1969) obtained the empirical equation:

$$Q_{o1} = b\ V^{c}\ ,\ \text{where}\ c \doteq 1.5 \quad \ldots\ldots\ldots\ldots\ldots \quad \text{I,6}$$

The agreement of the two equations (I,5 and I,6) is reasonably close especially when it is considered that:

a) S and k vary

b) The tunnel may be neither straight nor circular

c) There may be more than one tunnel (see figure 6 and Marcus (1960) who noted five separate outlets for Tulsequah Lake).

d) The Manning Formula may not be strictly applicable in this case.

e) Some stoping may occur in the tunnel due to the pressure and turbulence thus increasing its size at a rate faster than would be predicted.

It is in connection with this mechanism of tunnel enlargement by melting that floating of the ice to allow water underneath may be seen as a triggering mechanism in at least some cases.

4) Glen (1954) points out that if ice and water surfaces are at the same elevation the hydrostatic pressure of the water will be greater by an amount

$$\Delta p = (\rho_w - \rho_i)\ gz \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{I,7}$$

Thus the horizontal stress component (σ_1) will be greater than the vertical compressive force (σ_3) by Δp and there will be shear stress (τ) at 45° of $\Delta p/2$ where

$$\tau = -\frac{(\sigma_1 - \sigma_3)}{2} \sin 2\alpha\ ,\ \alpha = \pi/4$$

Glen's work (1953) indicates that when ice is subjected to a shear stress of greater than one bar flow takes place. That is, failure will occur when

$$\Delta p/2 = 1 \text{ bar}$$

or

$$(\rho_w - \rho_i)\, gz = 2 \text{ bars}$$

or

$$z = \frac{2 \times 10^6}{(1-\rho_i)980} \qquad \text{I,8}$$

Thus the depth at which ice might be expected to fail is approximately 200 meters if ρ_i is assumed to be 0.90 gm. cm^{-3}.

Several problems arise. First, by this mechanism the tunnel would occur at the lowest part of the ice. Several writers have noted that some lakes do not drain completely (see, for example, figure 4). Either the tunnel was not at the lowest part of the dam or the tunnel plugged with ice before draining was complete. Second, it is questionable whether this failure could occur at a rate rapid enough to produce a tunnel over the distances required by some ice-dammed lakes. Third, it is required by Glen that $z_i = z_w$ which is usually not true for ice-dammed lakes. The same reasoning could be followed for $z_i > z_w$ but the depth for failure increases. Fourth, floating of the ice front would be expected before z_w reached z_i. Fifth, some rock debris may be in the ice at its base where the tunnel would be expected thus altering the shear strength and density of the ice.

5) It has been noted by many writers that the draining of an ice-dammed lake often occurs at approximately the same time of the year whether the draining is annual or less often. It may be that differential rates of ice movement associated with the changing seasons may lead to stress

and fracturing at depth. For example, in autumn the upper regions of a glacier may begin to move more slowly than the lower where warmer temperatures still prevail. As far as is known, this idea receives but scant attention in the literature (see for example, Sharp, 1960, p. 37-38) and no application to the problem of the draining of ice-dammed lakes has been attempted.

6) In Iceland, a relation in timing between earthquakes, volcanic eruptions and the draining of ice-dammed lakes has been noted. Thorarinsson (1953) suggested that earthquakes may be caused by the release of pressure on the draining of Lake Grimsvotn on Vatnjökull. Tryggvason (1960) lists five possibilities:

a) Subglacial volcanic eruption melts the ice as well as causing the earthquakes.

b) The draining of the lake leads to the earthquake.

c) The draining of the lake leads to volcanic eruption and associated earthquakes.

d) The earthquakes are caused by the collapse of the glacier after the draining.

e) The earthquakes cause the draining of the lake by weakening the ice dam.

Morrison (1958) quotes Klebelsberg (Handbuch der Gletscherkunde und Glaciolgeologie, (no date)) who noted drainings or increased ablation associated with volcanism in Spitsbergen, Alaska, Ecuador and Kamchatka. For most drainings however, there is no documented evidence of these associations.

7) Both Glen (1953) and Marcus (1960) quote Kerr (1934) as postulating a tunnel in the bedrock under the Tulsequah Glacier through which the escaping water flowed. Both discredit the idea and such a tunnel probably does not exist although seepage may occur through ground moraine under some glaciers. Kerr, however, did not suggest a tunnel through rock but rather

> ...an under-ice passage which carried water to the end of the main glacier. Now most of the time this is blocked, but once in a while, probably because of the breaking off of a berg it opens up. Once started the rush of water with its 900-foot head increases the size of the tunnel and there is no stoppage until most of the water has gone and some of the bergs floating on the top are washed into the tunnel mouth, blocking it again. (Page 645)

Indeed, he is the first writer this student could find to postulate mechanism #3.

C) Conclusions

Clearly, the draining of each ice-dammed lake has causes unique to itself. To state that one origin is more important than the others in providing a general solution to the draining of ice-dammed lakes is impossible. In the case of Summit Lake, several causes appear more likely than others. Overtopping did not occur. Because the drainings started with a low discharge and increased to a maximum at the end of the draining, the tunnel enlarging mechanism of Liestol (1956) appears to be one important cause. Since draining did not occur for many years when the lake was full but did occur in 1968 when the lake was 17.7 meters below its level when full, floating of the dam is thought to play a minor role if any in the draining even though it is recognised that the glacier has become thinner. The pattern of fall drainings suggests that seasonal variation in the flow rate of the damming glacier, the warming of lake water in the summer, or some other event controlled by the seasons may lead to the draining.

PART II: THE CASE STUDY - SUMMIT LAKE

A) Introduction

1) Location and History: Summit Lake (latitude 56° 13' N., longitude 130° 05' W.) is located in the Boundary Ranges of the Coast Mountains near the British Columbia-Alaska boundary (figure 1). It is one of the larger ice-dammed lakes whose size has been recorded. (Table I) The Salmon Glacier which dams the lake originates in an accumulation area that feeds several large glaciers, the largest of which is approximately 26 kilometers long. The Salmon itself is 20 kilometers long and dams Summit Lake at 13 kilometers from the terminus. Meltwater from the Salmon Glacier terminus flows via Salmon River 20 kilometers to the head of the Portland Canal.

Access to the lake has been excellent since 1965 when an all weather road joined the port of Stewart with the Granduc Operating Company town site at the terminus of the Berendon Glacier. Prior to this time horse trails from the end of the road north of Ninemile (figure 1) provided the only summer, ground access to the lake.

Summit Lake, when full, is 5.25 kilometers long and varies in width from 0.45 to 1.25 kilometers (figure 2). Its depth increases southward reaching a maximum in excess of 200 meters at the ice face. When full the surface elevation (826 meters a.s.l.) is controlled by an outlet over bedrock to the north. Overflow passes into Bowser River and eventually to Nass River.

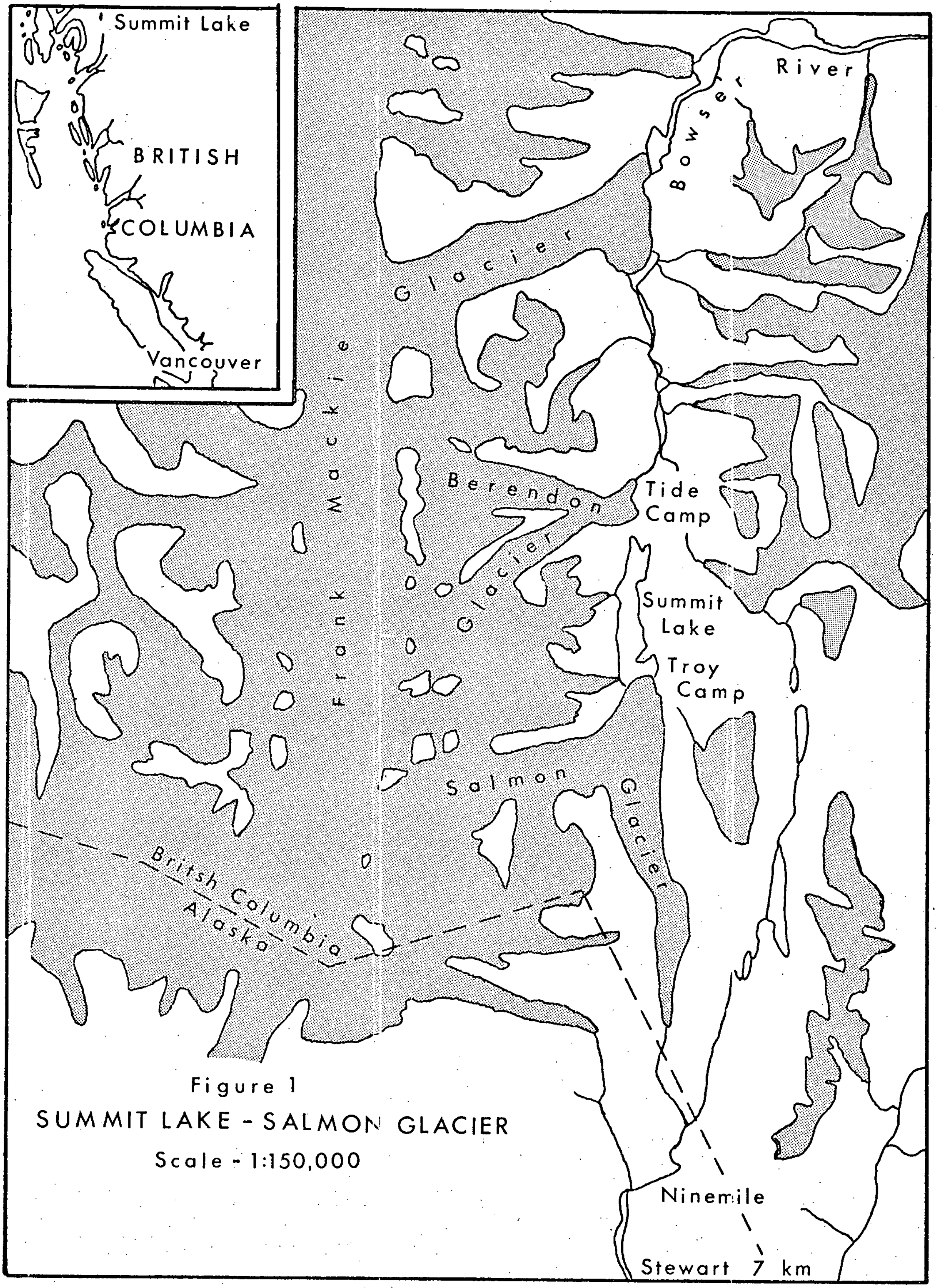


Figure 1
SUMMIT LAKE - SALMON GLACIER
Scale - 1:150,000

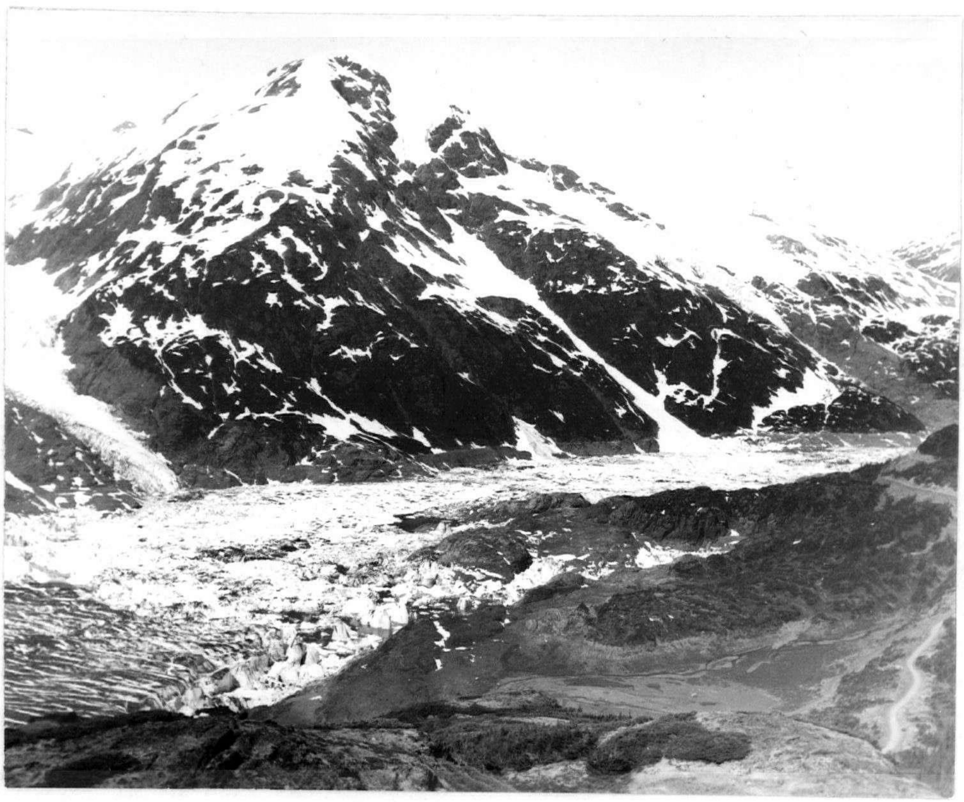


Figure 2 a: General View of Summit Lake and the Salmon Glacier Looking northwest. July 19, 1968.

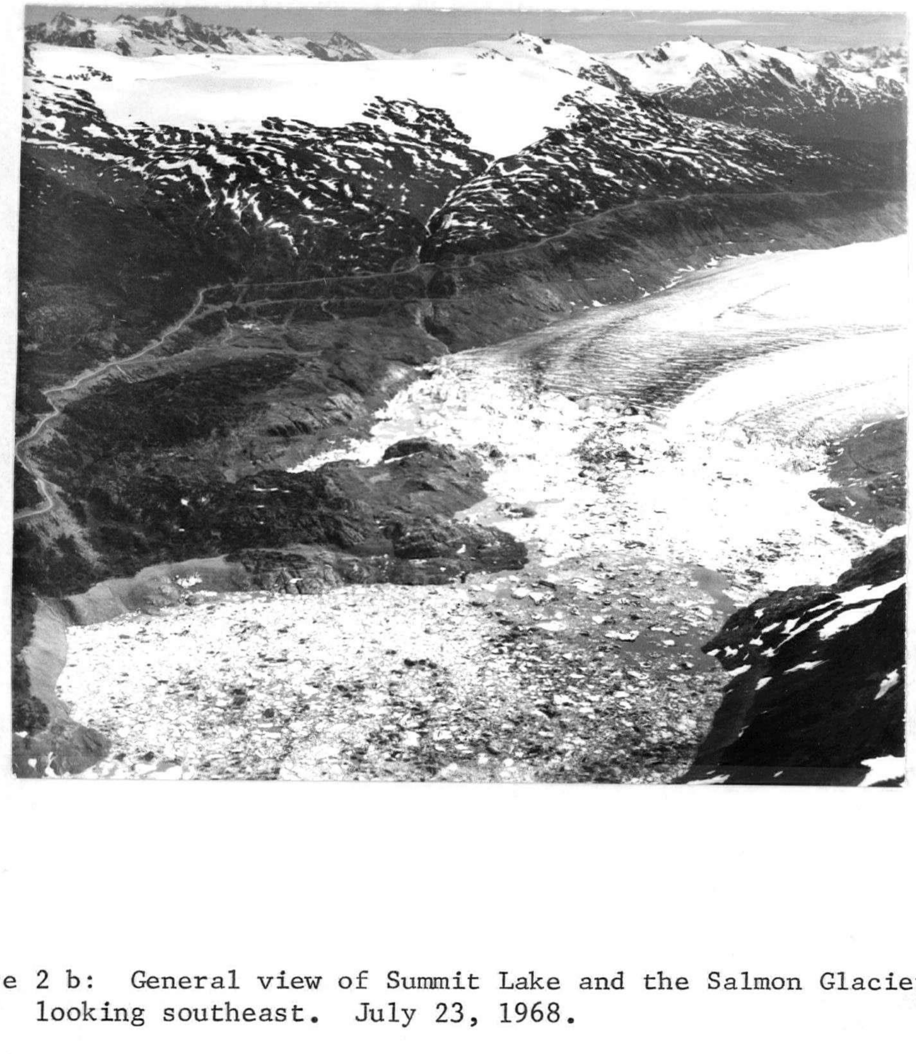


Figure 2 b: General view of Summit Lake and the Salmon Glacier looking southeast. July 23, 1968.

Figure 2 c: General view of Summit Lake and the Salmon Glacier looking south from the air 25 meters above the water surface. July 30, 1968.

During an earlier ice advance the Berendon Glacier and its lateral moraine blocked this outlet and another, 400 meters to the east and 29 meters higher was used (ie. 855 m.a.s.l.). This outlet can be traced 500 meters north to a small lake dammed by an end moraine of the Berendon Glacier. For a distance of 400 meters north from the lake no clear channel is visible but beyond this there are two parallel channels running north and east 900 meters to a poorly formed delta in Tide Lake. These channels apparently carried Summit Lake overflow as well as melt from the Berendon Glacier. The 400 meter gap in this channel between Summit and Tide Lakes may be the result of supraglacial or englacial flow in the Berendon Glacier.

An amabalis fir at elevation 840 meters a.s.l. (and hence below the upper-outlet) on the slope above Summit Lake in the lake basis was dated at 230+ years. Other fir and mountain hemlock also below the second overflow channel were dated at 150+ years indicating that the present overflow has been used for perhaps as long as 300 years. Haumann (1960) suggests that there may have been two other channels farther east with floors at 885 and 920 meters a.s.l. when the Berendon Glacier formed an even more effective dam on the north but there is less evidence for this.

The Salmon Glacier was also much larger in the past. The earliest map available is that of the International Boundary Commission dated 1920. On this map the Salmon Glacier and a small glacier coming down from west of Summit Lake are joined and flow north for about 500 meters beyond the present ice terminus in Summit Lake. As well as Summit Lake a smaller lake, Daisy Lake, was dammed. The shore line indicates a water level of about 890 meters a.s.l.

Haumann (1960) draws the conclusion that the size of the Salmon Glacier in 1920 was nearly equal to that of the supposed maximum of the midnineteenth century because horse trails he attributes to a gold rush in the 1840's pass within 10 meters of the water level of Daisy Lake. He quotes no reference for this date. McConnell (1913) states that placer mining began in the Portland Canal region in 1898. Thus the International Boundary Survey of 1895 for the report of that year was probably one of the first explorations of the Summit Lake region. The map accompanying the report shows the Salmon Glacier to within a very short distance of Summit Lake. The trails to which Haumann refers are probably from the mining of the first three decades of this century.

The shrinking of Salmon Glacier since 1920 has been rapid. Figure 3 is a profile of the Salmon from Haumann's map (1949 and 1957 photography) and a map prepared by the Department of Energy, Mines and Resources from photography taken August 4, 1968. The mean annual ablation for the period 1957 to 1968 varies from over 7 meters per year near the south terminus to less than 2 meters per year west of the 'turn'. This agrees reasonably well with the figures presented by Haumann (1960) indicating that the ablation is of a rate similar to that for 1949-57. However, a noticable difference in the rate of lowering between these periods does occur in the area of the ice dam (2.2 compared with 5.6 meters per year). Since the 1968 photography was taken when the water level of Summit Lake was 30.4 meters below the high water mark, this difference may indicate that the dam is floated somewhat when the lake is full. The initiation of the draining of Summit Lake in 1961 may well be associated with the rapid shrinkage of Salmon Glacier since 1920's.

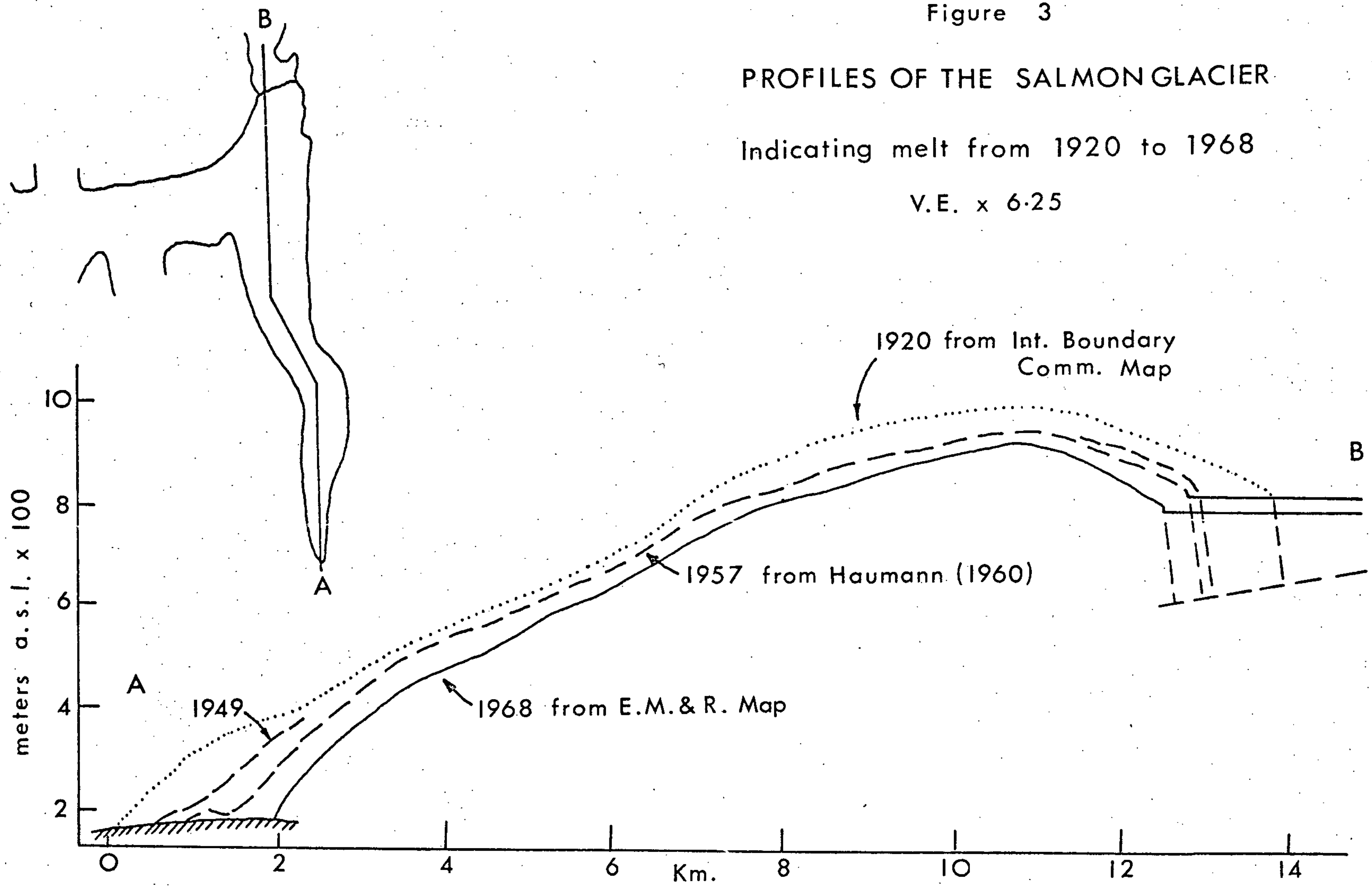


Figure 3

PROFILES OF THE SALMON GLACIER

Indicating melt from 1920 to 1968

V.E. x 6·25

2) Record of the Self-Draining Events: From the beginning of human occupance of the area about 1900 until 1961 there is no record of a draining of Summit Lake. It is unlikely that such an event would pass unnoticed as Stewart was a thriving town by 1908 and Hyder Alaska, built shortly after on piles above the Salmon River delta, would have been badly flooded. Mathews (1965) provides an account of the 1961 draining:

> Eyewitness accounts indicate that the flood began about December 26 though the river was reported to have been unusually muddy as early at the 22nd. The river rose rapidly on the 27th and reached a crest in the afternoon of the 28th, at which time it was choked with icebergs. The flood subsided rapidly on the afternoon of the 29th and by 4:00 p.m. the river was down almost to normal winter flow, though it remained muddy. (pp. 49-50)

A tunnel entrance in the west side of the ice dam was noted from the air several days later but the tunnel did not reach the surface at any point on the glacier. The lake began to refill with spring melt in May 1962. 'In May 1963 the lake was reported to be at least half full and by autumn of that year it was again overflowing to the north' (Mathews, 1965).

The drainings of November 1965 and September 1967 were observed and records kept. Mathews (1969) presents these observations and his calculations of discharge, tunnel size and thermal relations in the tunnel. On November 14, 1965 surface overflow to the north ceased for a second time; the flood terminated December 1 with the lake empty. By August 19, 1967 the lake was again full and overflowing but during the night of September 11-12 overflow again ceased. There is evidence to suggest that an appreciable leak had developed before September 11. This draining terminated September 17, although the lake was not completely empty (figure 4). After each draining the Granduc Operating Company road required extensive repair but other damage was small as the valley is largely uninhabited.

In all the drainings the water passed beneath or through the Salmon Glacier for the entire distance between the lake and the glacier terminus (figure 6). The only exception reported by Mathews (1969) was 'a patch of wet snow which developed 2 km. upstream from the terminus' in the 1965 draining.

The water level reached 808.3 meters a.s.l. in late October or early November 1968 (as determined in 1969 from the high water mark) when another draining began. Heavy snow cover prevented observers from determining the exact time the water level began to fall. As this high water mark is 17.7 meters below the level of the lake when full, a volume of 70.5 x 10^6 cubic meters or about 28% of the volume of the lake was not filled before draining began.[1] On November 17 the water level was surveyed and found to be 789.0 meters a.s.l. at 0920 and 787.9 meters at 1340. Thus the lake level was falling at 0.22 meters per hour and had dropped some 20 meters from the high water mark of October. Based on the elevation-area equation (page 50) this would give a mean discharge under the Salmon Glacier of approximately 200 m^3 sec^{-1} for this period. Discharge records kept by U.S. Geological Survey personnel at Ninemile indicate a flow of about 270 m^3 sec^{-1} on November 13. If the assumption is made that the latter represents 'base flow' with only a small leak (say less than 20 m^3 sec^{-1}) the discharge due to the flood is about

[1] Volume derived from the elevation-area equation see page 50.

Figure 4: Summit Lake from the air looking south to the Salmon Glacier.
1600 hours September 19, 1967. Photo: J. R. Plommer

Figure 5: The Salmon River at Ninemile. 1800 hours September 17, 1967. Approximate discharge, 2800 cubic meters per second (Mathews 1969). Note destroyed road bridge. Photo: J. R. Plommer

Figure 6: Tunnels at the terminus of the Salmon Glacier through which the water of Summit Lake discharged. 1600 hours September 19, 1967. Photo: J. R. Plommer

230 m^3 sec^{-1} on November 17, not greatly different from that calculated from the drop in lake level. Poor weather from November 17 on prevented further surveying of the lake level. The flood reached a peak of 1640 m^3 sec^{-1} at 2300 hours on November 19 after which the discharge dropped quickly to less than 20 m^3 sec^{-1}.

By May and June of 1969 the lake surface was rising at approximately one meter per day with unusually warm spring weather. By July 15 although the rate of rise had slowed to approximately 0.3 meters per day the water level stood at 782.5 meters a.s.l. only 7.7 meters below the level on the same date in 1968.

B) The Investigation of Summit Lake

1) Preliminary Work: Although the depth of Summit Lake probably reaches 200 meters at the ice face, the thickness of the Salmon Glacier south of the lake may exceed 700 meters (Doell 1963). Thus the causes of the drainings are likely to be complex. Mathews' work (1969) indicates that once draining has started, the passage of water through the glacier enlarges the tunnel or tunnels but the mechanism that initiates the draining has not been explained. Marcus' (1960) suggestion that the tunnel is blocked until floating occurs is doubtful in the case of the Salmon Glacier for several reasons:

1) No tunnel could have existed for some years prior to 1961
2) There is evidence (for example Haefeli, 1952) that any empty tunnel at that depth would close quickly.
3. In each case the draining of Summit Lake has started slowly, the rate increasing to a peak just as the lake emptied. The burst of a dam or release of a plug would cause a sudden break of water from the glacier.

Mathews (1964) makes the suggestion, based on observations in a mine tunnel that reached the Leduc Glacier 150 meters below the surface, that free water hydraulically connected to the surface water may exist at depth if unusual conditions exist. In Mathews' case the unusual conditions were 'access to the based of the glacier of relatively warm mine water, perhaps under high pressure when the workings were abandoned and flooded...' (p. 239) and in this case, access to the base of the glacier (at least at the face of the ice dam) of water of Summit Lake.

It is proposed then, that water may be continuously passing under the Salmon Glacier from Summit Lake. If the water temperature is very close to 0°C and the leak is small, the water may not be able to increase the size of the tunnel, or the rate of increase may be nearly equal to the rate of closing by deformation. Further, if warm water enters the tunnel, the enlargement of the leak and subsequent drainage may occur. If the surface of the lake either near or far from the dam were warmed from zero through the summer a density overturn might occur as the water warmed bringing water with a temperature of up to 4°C to the base of the dam. That a number of ice-dammed lakes drain in the summer or fall strengthens this speculation. On the other hand, the drainings of Summit Lake have occurred in December, November, September, and November. Except for the September event the drainings have occurred some three months after the period of greatest heating of the water surface. However, this <u>might</u> reflect the length of time required to enlarge the tunnel so that a leak might be noticed by the casual observer.

This proposed leak can be expressed in terms of the water balance equation:

$$Q_{ol} = (Q_i + P_\ell A) - \Delta V - (Q_{on} + E) \quad \ldots\ldots\ldots \quad \text{II,1}$$

The hydrologic problem of Summit Lake first came to this student's attention during 1967 when preliminary mass balance measurements were being made on the Berendon Glacier. In conjunction with Mr. E. Skeleton, Granduc Operating Company, lake water level records and discharge records on the overflow stream (Q_{on}) were kept. Water level readings were made at 0800 hours each day and the area-elevation equation from the 1968 work (see page 50) was used to calculate ΔV. Discharge measurements were made by wading with a standard Price meter and stage readings were taken twice daily from which the hydrograph was interpolated to obtain Q_{on}. Discharge measurements were also made on the Bowser River immediately below the Berendon Glacier from a cableway with a Price meter (figure 10). Although continuous stage recording was not available in 1967 a hydrograph was interpolated from spot readings usually made twice daily. The net discharge (Q_{nb}) is obtained by subtracting the Summit Lake overflow (Q_{on}) from the discharge measured in the Bowser River. These are summarized in Appendix II. The mean values for August for each of the water balance components measured are:

	Runoff	
	Volume	Depth
	$m^3 \times 10^4 day^{-1}$	$m \times 10^{-2} day^{-1}$
$\Delta V + Q_{on}$	92	1.4
Q_{nb}	210	2.6

Although the results were preliminary and may be subject to error, it is indicated that the discharge per unit area from the basin of the Berendon Glacier was almost twice the input to the Summit Lake Basin. This difference might be due to:

1) Difference in elevation of the basins which would affect the timing of the contribution of meltwater, the amount of meltwater and possibly precipitation.
2) Difference in amount of the basin areas that are snow and ice covered which would affect condensation, evaporation, and contribution of meltwater.

3) Difference in amounts of vegetation, soil and standing water in the basins which might affect evapotranspiration and storage.

4) Continuous leakage of Summit Lake through or under the Salmon Glacier.

A more complete study of the lake was carried out in 1968 a) in an attempt to define some of the terms of the water balance to verify a leak (Q_{ol}) under the Salmon Glacier, b) to measure the lake temperatures, and c) to attempt to verify a leak under the Salmon Glacier by means of dye tracing.

2) Investigation of the Terms of the Water Balance Equation, 1968:

a) Water input to the lake (Q_i) and rainfall on the lake surface ($P_\ell A$): Clearly it is impossible to measure all the water that flows into Summit Lake. Although the road runs the full length of the lake on the east side, some of the streams proved impractically small to measure. The west side of the lake was inaccessible until the floating ice cleared sufficiently to allow approach by boat. Because a small glacier on the west side (figure 2a) calves directly into the lake, direct measurement of meltwater input to Summit Lake is impossible. A large contributor of water to the lake is the Salmon Glacier but here too direct measurement is impossible. The boundary of the area of the Salmon Glacier thought to be contributing water to the lake is assumed to be the height of ice and a medial moraine. It includes a small tributary glacier on the north side. Figure 7 and Table IV indicate

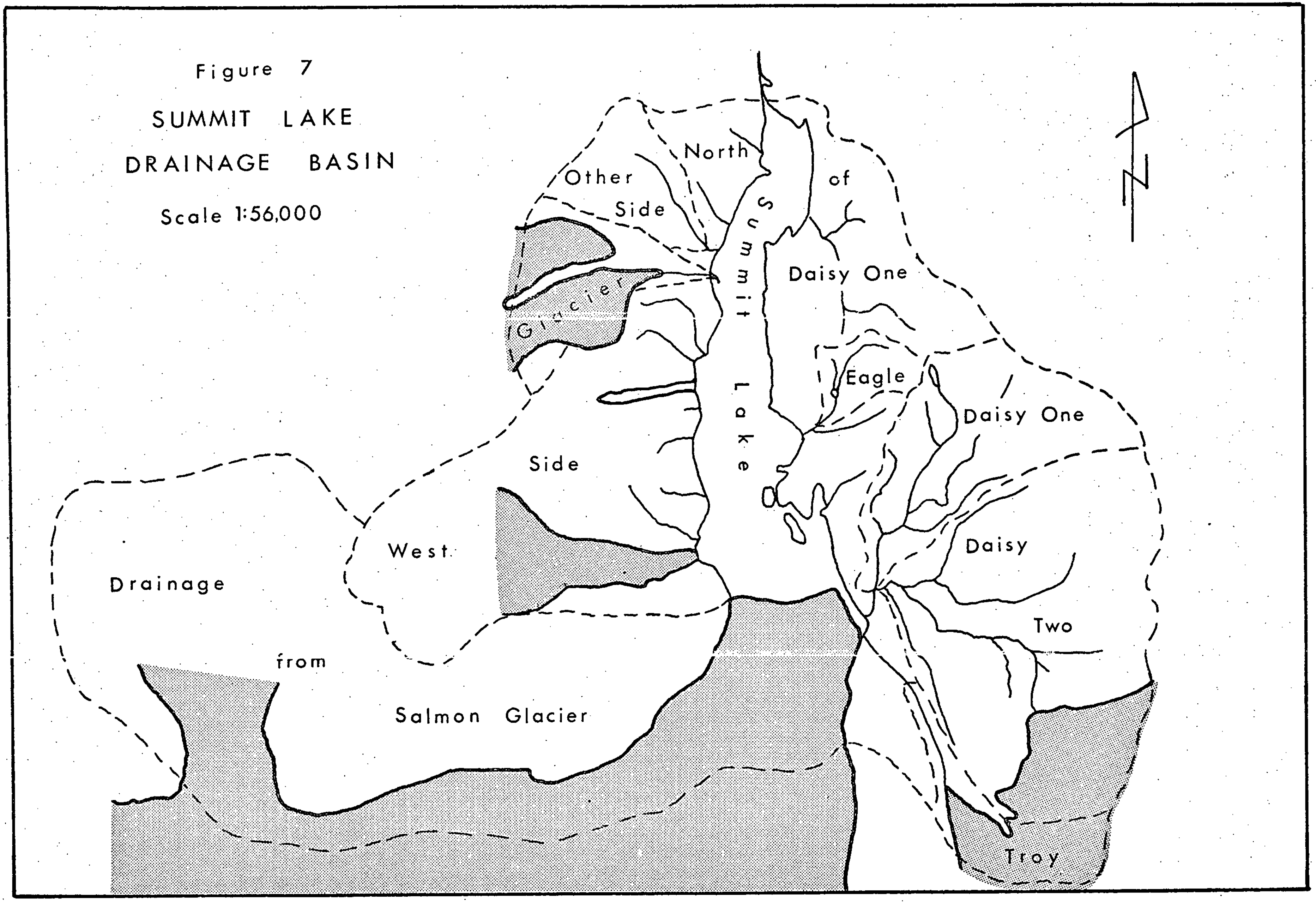


Figure 7
SUMMIT LAKE
DRAINAGE BASIN
Scale 1:56,000

TABLE II

Areas in Square Kilometers of Drainage Basins within the Summit Lake Drainage Basin

Daisy One	3.70	
Daisy Two	8.61	
Troy	1.80	
Eagle	0.80	
Glacier	2.21	
Other side	1.46	
Area outside specified basins but within Summit Basin	17.25	35.82
Area with Summit Lake:		
at 795.6 meters a.s.l.	3.20	
at 800 "	3.36	
at 805 "	3.54	
at 810 "	3.73	
at 815 "	3.94	
at 820 "	4.13	
at 825 "	4.35	4.35
Area of Salmon Glacier thought to be contributing water to Summit Lake		23.42
Total		63.59

the stream basins, the portion of the Salmon Glacier and their areas that are contributing water to Summit Lake as defined for this thesis.

Discharge in the four largest streams on the east side[2] was measured from early summer (figure 8). For each of these streams a rating curve was established using a Price meter (figure 9). In each case a 'best fit' line was estimated by eye. Stage records on the three largest streams were kept with recording diaphragm gauges (Ottboro 004), a float gauge (Stevens Type F) and a 'home made' float gauge. Staff gauges and control points provided checks. Daily discharges (summarized in Appendix III) were calculated from twelve hour mean stage readings taken from the recorders. Discharge measurements were made over most of the observed stage range in each case. Discharge measurements were discontinued on Eagle Creek after August 5 when the discharge dropped below 5000 m^3 day^{-1}.

By early August the lake ice had cleared sufficiently to allow access to the west side of the lake by boat. Metering stations were established on the two largest creeks and discharge records kept. After only nine days of record a severe rain and flood washed out the gauge on Glacier Creek and altered the channel form. No attempt was made to re-establish the gauge.

All the metering sections were established at least in part on unconsolidated material, but except in the case of Glacier Creek, the sections were not observed to shift during the summer. It is suspected

---

[2]For the most part, the names of streams used in this thesis are not officially recognised. They are used here for convenience only.

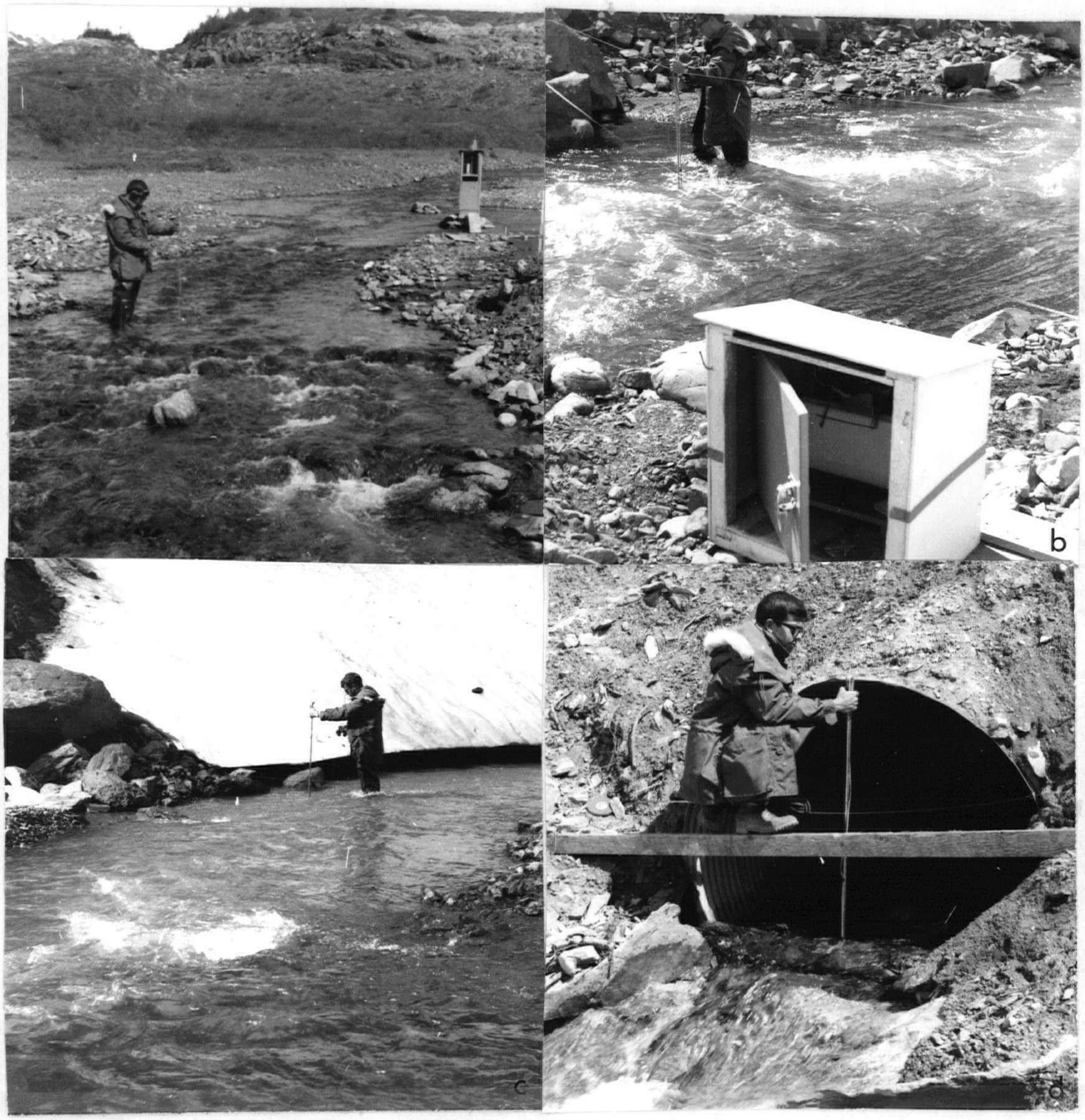


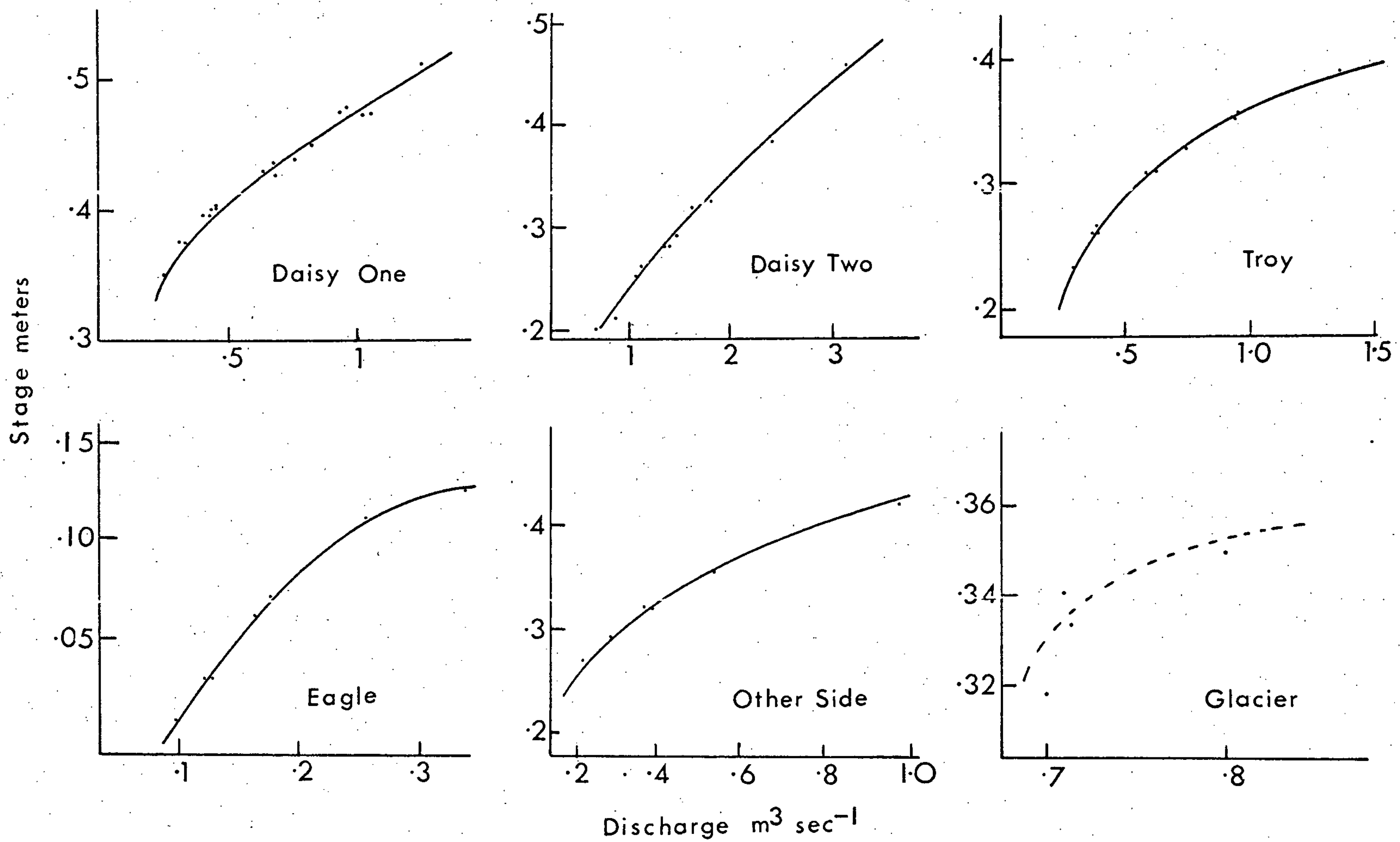
Figure 8: Streams flowing into Summit Lake on which discharge records were kept in 1968.

a) Daisy One
b) Daisy Two
c) Troy
d) Eagle

Figure 8 (cont'd)
e) Other Side
f) Glacier

Figure 9

RATING CURVES FOR STREAMS FLOWING INTO SUMMIT LAKE



however, that some groundwater flow escaped unrecorded. This would mean that the discharge from these basins would be underestimated.

These observations were used to a) extend the estimates of discharge for those streams for which only a short observational record is available and b) provide an estimate of the discharge from the adjacent parts of the Summit Lake basin that could be measured as follows:

i) The periods for which water balance estimates were made are July 15 to 31 and August 1 to 31.

ii) Discharge records for this period are complete for the streams Daisy One and Daisy Two.

iii) Discharge records for Troy Creek are complete from July 25 to August 31. In an attempt to estimate the discharge from July 15 to 24 a stepwise multiple linear regression was performed of Troy Creek discharge against the discharge of the other creeks and the climatic parameters measured[3] for the period July 25 to August 31 with the result:

$$Q_T = 2.008 + 1.378\ Q_{DI} + 0.1774\ P_4 \quad \text{.......... II,2}$$

with $R^2 = 0.876$

Daily discharges calculated from this equation agree closely with spot readings taken in early July.

---

[3]Continuous records of temperature, humidity and wind were kept at Tide Camp, Troy Camp and on the ridge between the Berendon and Summit Basins. Precipitation records were kept at Tide, Troy and at five points along the road from the north end of the lake to the Salmon Glacier. Incident short wave radiation and sunshine duration were recorded at Tide Camp.

iv) The discharge per unit area from the area north of Daisy One Creek to the north end of the lake was estimated from the discharge from Daisy One. It is felt that the elevation, snow cover, vegetation, aspect, etc. of the two areas are similar enough that the discharge from Daisy One should be representative of the area to the north. Further, a student's 't' test on the paired variables of discharge per unit area from Daisy One Creek and Eagle Creek was run for July 15 to 31 with the following results:

Period	Daily difference in discharge between Daisy One and Eagle meters day^{-1} Mean $\bar{x}$	Standard deviation s	't'	Level of Significance
July 15-31	0.128	0.324	1.64	88.2%

Thus it is indicated that for this period the null hypothesis of no difference between Daisy One and Eagle Creeks cannot be rejected at the 95% confidence limit and that the discharge for Daisy One is probably representative of the area to its north.

v) Discharge records for Other Side Creek are complete from August 16 to September 21. In an attempt to estimate the discharge from August 1 to 15 a stepwise multiple linear regression of Other Side discharge against the discharge of the other creeks and the climatic parameters for the period August 16 to September 21 was run with the results:

$$Q_{os} = - 0.3352 + 0.2806\ Q_T + 0.1585\ T_T \quad \ldots\ldots \qquad \text{II,3}$$

with $R^2 = 0.792$

Daily discharges calculated from this equation agree closely with spot readings taken in this period.

vi) A similar regression was attempted for Glacier Creek for its period of discharge record, August 13 to 21, but the highest R^2 that could be obtained was 0.543 and the only variable accepted was the discharge of Daisy Two. Rather than attempt to estimate the discharge of Glacier from this poor correlation the daily discharges per unit area of Daisy Two Creek were used as an underestimate of the discharge of the entire west side of the lake for July 15 to 31 and as an underestimate of the discharge for Glacier Creek and the area to its south for August 1 to 31. It is felt that this is indeed an underestimate for the mean value of measured discharge in m x 10^{-2} day^{-1} for the streams are:

	Aug. 1-31	Aug. 13-21
Daisy Two	0.975	0.945
Glacier		2.88
Other Side		1.36

vii) Because the Salmon Glacier and the Berendon Glacier have comparable size, aspect, range of altitude, and are subject to approximately the same weather conditions, it is felt that discharge per unit area of the Berendon should approximate that of the Salmon Glacier. Thus the discharge per unit area of the Berendon measured at the Bowser River gauging section[4] was used to estimate the discharge of the area of

[4]The stage records are taken from a Stevens A 35 recorder and metering was done from a cableway erected by the Water Survey of Canada (figure 10). The rating curve (figure 11) was found to fit the equation

$$\text{Log } Q = 0.07532 + 0.48211\ s$$

with a standard error of estimate of 0.0064 and was therefore used for the calculations.

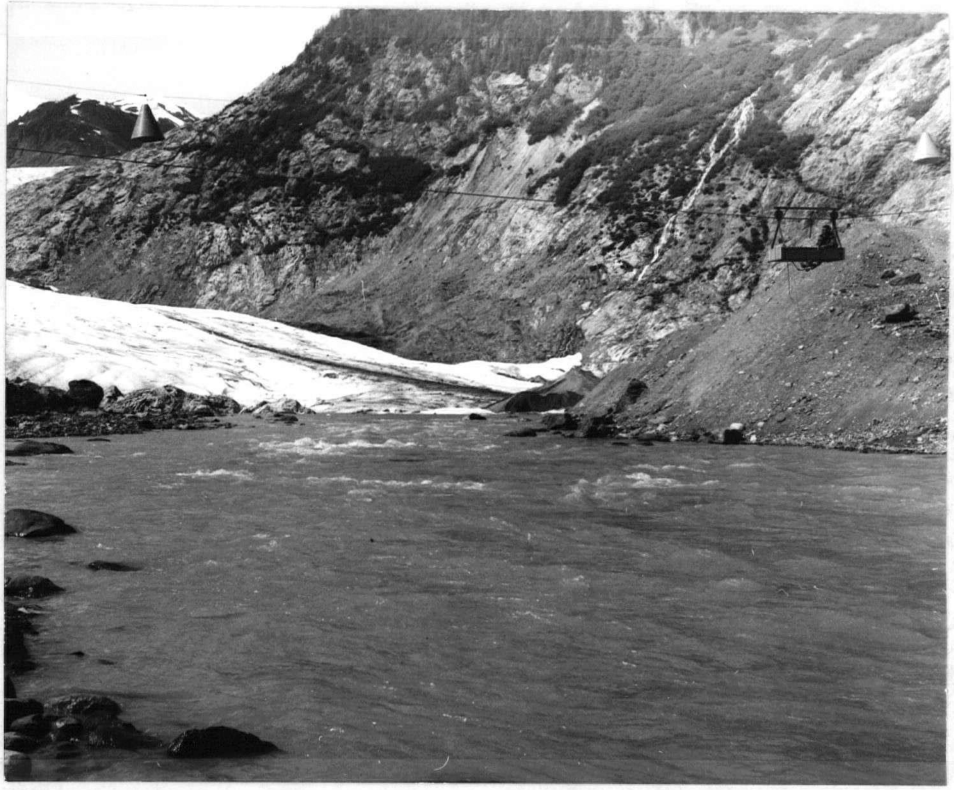


Figure 10: The metering section of the Bowser River below Berendon Glacier.

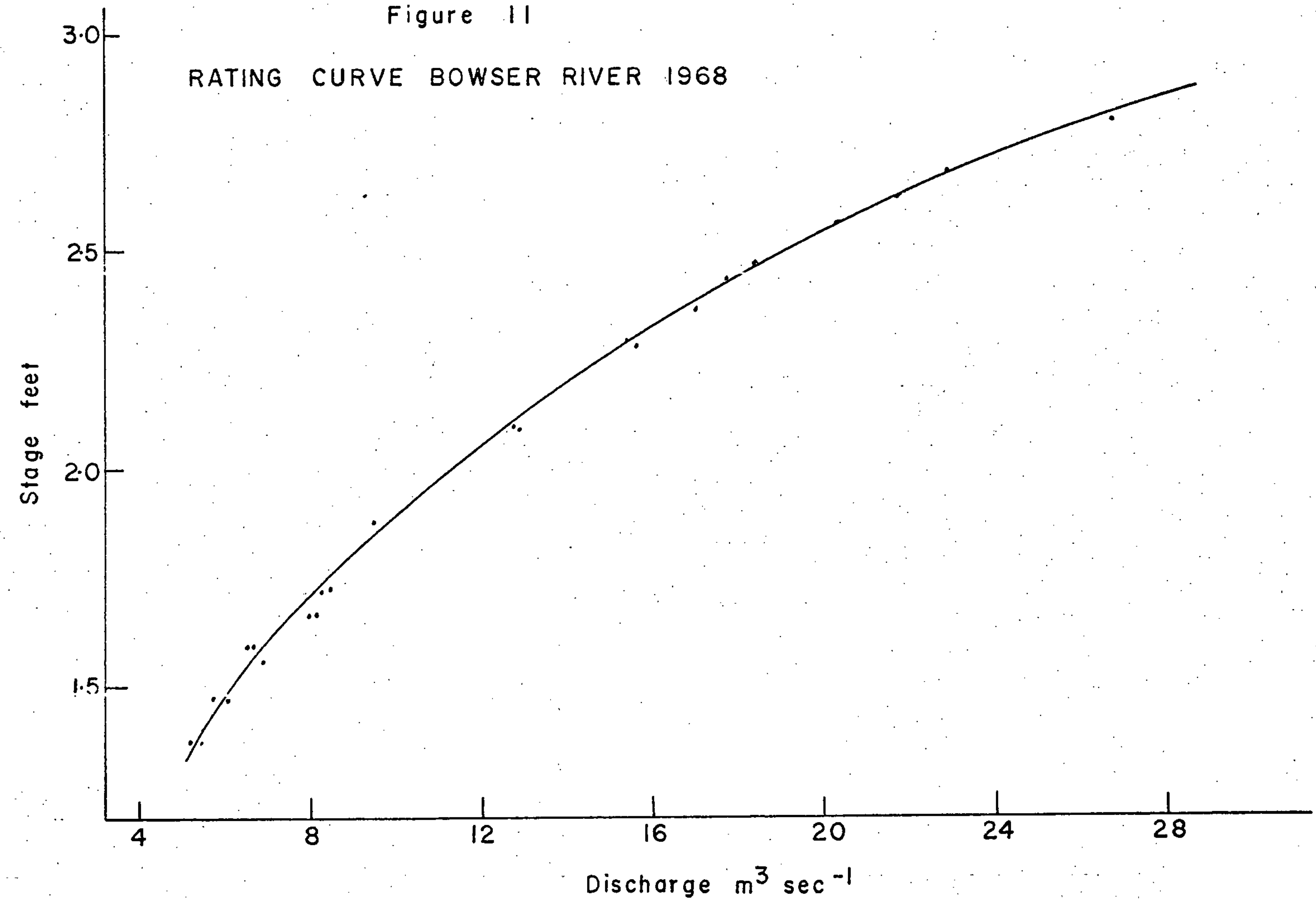


Figure 11
RATING CURVE BOWSER RIVER 1968
3·0
2·5
2·0
1·5
Stage feet
4
8
12
16
20
24
28
Discharge m3 sec -1

the Salmon thought to be contributing to Summit Lake. It is felt that this too will be an underestimate as a) there appears to be considerable groundwater flow from the Berendon Glacier through outwash that is not measured and b) the values of discharge calculated by this student for the Bowser River are nearly always slightly below those calculated by the Water Survey of Canada from the same data because icebergs commonly formed a partial dam in or below the metering section which resulted in erroneously high stage readings for which no correction was made in W.S.C. calculations.

Because the area of the Salmon Glacier contributing water to Summit Lake is not well known a further underestimate of the area thought reasonable was provided by taking three quarters, two thirds, one half and one third of the area of the Salmon estimated to be contributing water to Summit Lake.

viii) The rainfall on Summit Lake in $m^3 \times 10^4$ day^{-1} ($P_\ell A$) was estimated from two rain gauges, one near the north end and one near the south end of the lake, each considered to estimate half of the area of the lake.

In summary, the input of water to Summit Lake is estimated from the following:

for July 15 to 31:

Salmon Glacier input (from Berendon Glacier measurements)

Troy Creek (from regression equation and measured input)

Daisy Two Creek measured input

Daisy One Creek measured input

Eagle Creek measured input

Area north of Eagle-Daisy One (from Daisy One measurements)

West Side of Summit Lake including Other Side and Glacier Creeks (from Daisy Two measurements)

Rainfall on Summit Lake.

for August 1 to 31:

Salmon Glacier, Troy Creek, Daisy One, Daisy Two, rainfall as before

Area north of Daisy One including Eagle (from Daisy One measurements)

Other Side Creek.

Area south of Other Side Creek, west of Summit Lake (from Daisy Two measurements)

The values obtained from these measurements and calculations are summarized in Appendices III and IV and figure 12.

b) The change in volume of Summit Lake (ΔV): An Ottboro 004 diaphragm gauge obtained to record continuous level change proved unsatisfactory as the tube between the diaphragm head and the bellows in the instrument could not be buried deeply enough to prevent heat from the ground warmed by the sun from expanding the air inside and seriously affecting the readings. If the tube was buried deeply it was impossible to pull it up as the water rose continuously. Several alternate methods were tried but a technique using two five meter staff gauges (figure 13) that could be moved up slope alternately and that could be read with a telescope from the road was settled on. Icebergs knocking over these

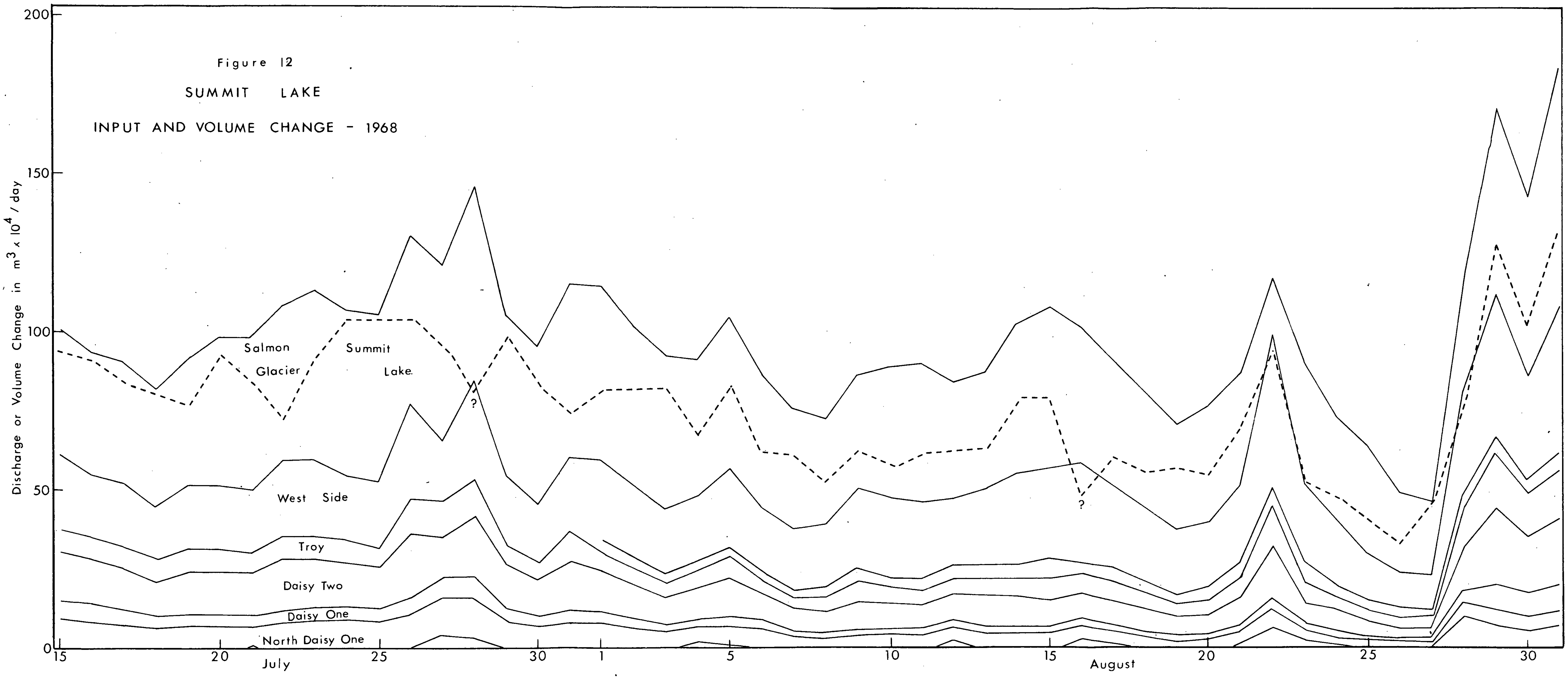


Figure 12
SUMMIT LAKE
INPUT AND VOLUME CHANGE - 1968
Discharge or Volume Change in $m^3 \times 10^4$ / day
200
150
100
50
0
Salmon
Glacier
Summit
Lake
?
West Side
Troy
Daisy Two
Daisy One
North Daisy One
15
20
25
30
1
5
10
15
20
25
30
July
August

Figure 13: Staff gauges to record the rate of rise of the water surface of Summit Lake.

gauges presented some problem.

The absolute elevation of the gauges was established regularly through the summer with a theodolite from a base line tied into the Granduc Operating Company survey network. It is felt that relative measures of daily elevation change are accurate to ± 1 centimeter and that absolute values are correct to ± 10 centimeter at least with respect to the Granduc net.

On August 4, 1968 air photographs of the lake were flown from which a map of scale 1:10,000 and contour interval of five meters in the vicinity of the lake was prepared by the Surveys and Mapping Branch of the Federal Government. From this map the area within each contour was measured to determine the area-elevation relationship as follows:

$$A = -27.793 + 0.0389 \; El \quad \text{..................} \quad \text{II,4}$$

between 795.7 and 825 meters a.s.l. with $r^2 = 0.9990$. Because of the very good coefficient of determination it is felt that this equation could be used to estimate surface area down to 785 meters a.s.l. From this equation the area corresponding to each elevation reading was found and then the volume change found by multiplication of the mean area between the two readings and the corresponding elevation change. The results corrected for the period midnight to midnight each day are given in Appendix IV and figure 12.

<u>c) Discharge to the north (Q_{on}) and Evaporation (E)</u>: In 1968 Q_{on} was zero. It is felt that evaporation from the lake surface (E) was small because of a) the cold water temperatures (see page 55) and b) the large proportion of the lake area covered by icebergs; thus

evaporation is not considered here. Neither is evaporation from streams between the gauging section and the lake considered for the distance is short and it is suspected that the amount of water lost is small--certainly within the measuring and estimating errors discussed above.

d) <u>Evidence for a leak</u>: The stage is now set to test the null hypothesis that

$$(Q_i + P_\ell A) - \Delta V = 0$$

ie $\quad Q_{o1} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad$ II,5

where $\quad Q_{on} = 0$, and $E = 0$

by means of a Student's 't' test on paired variables where

$$t = \frac{\bar{x} - 0}{\sqrt{s^2/n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{II,6}$$

with degrees of freedom n - 1.

For the periods July 15 to 31 and August 1 to 31 equation II,5 was calculated as described above using:

1) all of the area of the Salmon Glacier thought to be contributing water to Summit Lake.
2) Three quarters of this area.
3) Two thirds of this area.
4) One half of this area.
5) One third of this area.

with the results as shown in Table III.

Thus it is indicated that unless only one half or less or the area of the Salmon Glacier thought to be contributing water to Summit Lake is

TABLE III

Results of Student's 't' Tests on Paired Variables

$(Q_i + P_\ell A)$ and ΔV, Summit Lake, 1968

Case	Daily Difference $(Q_i + P_\ell A) - \Delta V$ $m^3 \times 10^4\ day^{-1}$ Mean $\bar{x}$	Standard Deviation s	't'	Level of Significance
For July 15-31:				
1	16.83	17.24	4.025	> 99.9%
2	0.838	15.60	0.217	18.7%
3	-7.157	15.30	-	-
For August 1 to 31:				
1	27.13	12.08	12.507	> 99.9%
2	16.68	11.24	8.264	> 99.9%
3	13.19	11.02	6.664	> 99.9%
4	6.22	10.71	3.236	99.7%
5	-0.74	10.56	-	-

actually doing so there is, in August, a leak under the Salmon Glacier which may be as large as $27 \times 10^4 \ m^3 \ day^{-1}$ ($3 \ m^3 \ sec^{-1}$) using the data as presented, and may be larger is the underestimates built into the calculations[5] are considered. The case for July 15 to 31 is more doubtful.

3) Results of the Dye Tests

As a further test for a leak it was proposed to place dye in the lake and to try to detect its presence in the Salmon River below the glacier. The tests and analysis were carried out by Mr. D. A. Fisher of the Glaciology Subdivision, Ottawa and it is with his permission that the results are summarized in this thesis.

Rhodadmine B, a fluorescent dye, was placed in Summit Lake near the ice dam on July 30, August 9, and August 19, the first time by dropping the dye in boxes fastened with water soluble cement from a helicopter, the second by lowering glass bottles of dye into the lake from a raft and by placing dye in Daisy Two and Troy Creeks, and the third by dropping a perforated barrel of dye from a heliocopter. Sampling, both continuous and discrete, was carried out at Ninemile (figure 1) and the fluorescence measured in a fluorometer.

After each dye drop fluorescence of the river water rose significantly above the background fluorescence at the 95% confidence level.

---

[5]These are the underestimates discussed above that possible groundwater leakage in the input streams was unmeasured, that Daisy Two input was used to estimate Glacier and West Side input, and that Bowser River discharge used to estimate Salmon Glacier input does not include groundwater flow through a large area of outwash, all of which if measured would increase the calculated Q_i.

The times of travel are calculated as 39, 48, and 52 hours and a leak of between 0.02 and 20 m^3 sec^{-1} is estimated by Mr. Fisher.

Among the difficulties associated with this method of leak detection are:

1) the possibility of contamination at the sampling site.
2) the dilution of the dyed lake water by meltwater from the glacier and by tributary streams to the Salmon River above the sampling site.
3) the possibility of absorption of dye onto sediment particles which would be concentrated in the faster flowing parts of the river not near the shore where the samples were taken.
4) the impossibility of knowing how much dye escaped from the containers, the dilution and the mixing of the dye in the lake water, the amount of dye that did not leave the lake and the time interval between the drop and the time the dye actually began to move under the glacier.

In 1969 20 litres of Rhodamine WB dye were placed in the lake near the surface at 1500 hours on July 24 at location A (figure 14). Water sampling was carried out at the bottom, mid-depth and surface at locations B, C, and D 800, 1500, and 2400 meters respectively south of A to try to detect a current or currents in the lake water with the results:

1) Within a half hour a clearly visible dye mark about 10 meters wide and 50 meters long had spread north from the drop point in the direction of the wind.
2) South of the drop point no trace of dye was detected until 70 hours later when a strong trace was found at the bottom at B

and a weak trace at mid-depth (14 meters). Using a Turner Model III fluorometer twenty four hours later the traces at bottom and mid-depth at B were both weak and a trace so weak as to be questionable was found at C. No traces were found at D.

It is felt that the results indicate that there is almost no movement of lake water, or at most a very weak current moving the warmer water at the north end of the lake towards the south and that the movement detected may have been either the dispersion of the dye through the lake water or the more dense than water dye seeking the lower depths at the south end of the lake.

4) Lake Water Temperatures:

A thermistor on a 400 foot (124 meter) wire cable with a wheatstone bridge was used to record lake temperatures when surface ice conditions permitted access to the center of the lake by boat. Temperatures were taken at 5 foot (1.52 meter) intervals from the surface to the bottom. Surface temperatures were taken in the shade of the boat in an attempt to prevent solar heating of the probe. The instrument was read to $\pm$ 10 ohms. Since in the range 0°C to 2°C a change of approximately 360 ohms represents a change of 1 C°, a change in temperature of 0.03 C° is measurable. The calibration of the thermistor in ice water held through the summer of 1968 and 1969 and it is felt that the temperatures recorded are accurate to at least 0.1 C°. Position in the lake was determined by line of sight observations to two or more landmarks on shore. It was not possible to return to the initial test points through the summer because of ice conditions. The results of the tests are given in Appendix V and summarized in figure 14 and Table IV.

Despite the problems with surface ice, the results of the tests at least indicate the following:

1) The warmest temperatures were recorded in the north end of the lake in the early part of the summer.

2) Through the summer and as the depth increased the mean temperatures fell and generally the temperature range became smaller in the north part of the lake.

3) The water temperatures near the south end appear to have increased slightly through the summer.

4) Of the 22 tests, in 17 the coldest temperatures occurred somewhat below the surface and above mid depth while the warmest water was found at or near the bottom; in another four the warmest water was at the surface, and in only one (test 4) was the coldest water near the surface.

5) The warmest temperature recorded was 2.6°C, well below the temperature of maximum density. No density overturn of the water could be detected by changes in temperatures.

6) Because of the paucity of data it is impossible to calculate the mean water temperature for the whole lake, but it appears that the mean for the early part of the summer may have been approximately 1°C., falling by October to about 0.7°C. Thus perhaps the mean temperature of the water that passed through the glacier in November was 0.5°C.

It is of interest to recalculate the exit temperature (θ_L) from

Figure 14

LOCATION OF TEMPERATURE PROFILES & DYE TEST SITES IN SUMMIT LAKE

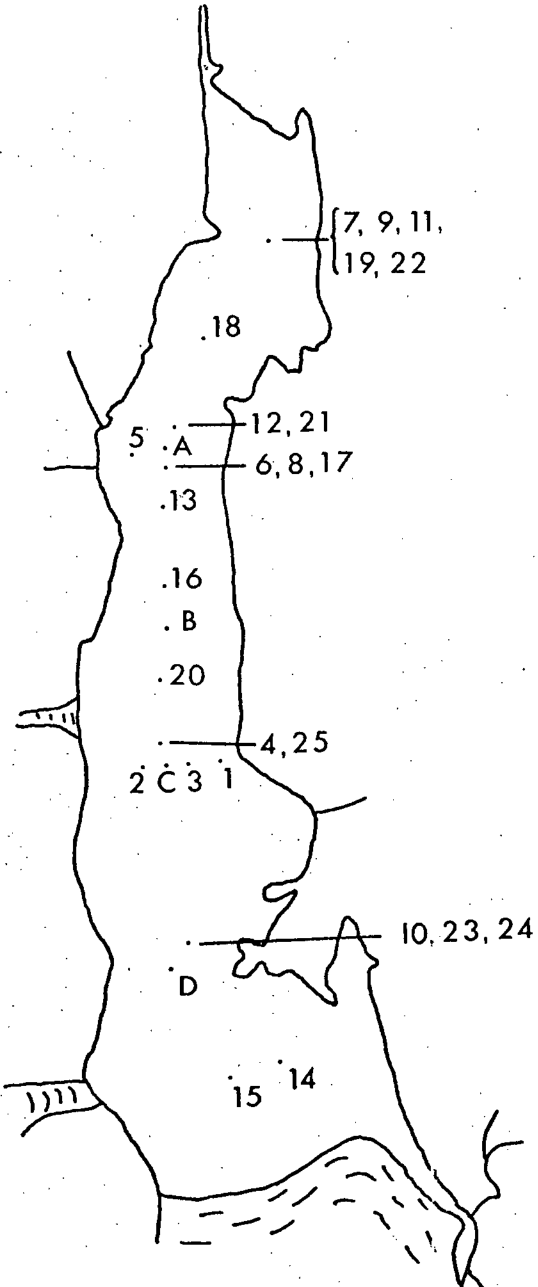


TABLE IV

Summary of Summit Lake Water Temperatures

1968 and 1969

Test	Date	Mean Water Temp. C	Max. Temp. C	Min. Temp. C	Depth meters
	1968				
1	July 6	0.2	0.5	0.1	19.8
2	July 13	0.3	0.6	0.2	42.4
3	July 13	0.4	0.6	0.2	40.5
4	July 18	0.4	0.6	0.4	25.0
5	July 25	1.9	2.2	1.6	11.6
6	July 25	1.4	2.0	0.9	12.3
77	July 25	2.1	2.6	1.8	12.8
8	July 31	1.0	1.6	0.6	14.5
9	July 31	1.6	2.2	1.5	14.5
10	Aug. 9	0.4	0.4	0.2	36.0
11	Aug. 13	1.5	1.6	1.4	18.9
12	Aug. 13	1.1	1.5	0.9	19.8
13	Aug. 13	0.9	1.0	0.8	18.9
14	Aug. 16	0.6	0.8	0.4	111.0
15	Aug. 16	0.6	0.8	0.4	-
16	Aug. 27	0.7	1.4	0.4	35.1
17	Aug. 27	0.8	1.0	0.7	16.2
18	Aug. 27	1.0	1.2	0.8	21.6
19	Aug. 27	1.1	1.3	1.1	24.4
20	Sept.22	0.6	0.9	0.6	49.4
21	Sept.22	0.7	0.9	0.7	23.2
22	Sept.22	0.7	1.1	0.0	29.6
	1969				
23	July 12	0.5	0.7	0.1	40.0
24	July 16	0.4	0.7	0.4	38.1
25	July 18	0.4	0.6	0.3	39.7

Mathews' work (1969) allowing for positive lake water temperatures. Heat loss by conduction to the ice and advection from the tunnel equals the heat content of the water in the lake plus the heat due to decrease in potential energy. Thus:

$$Q' \frac{H'}{L'} \; d\ell \; \frac{\rho g}{Jx10^{7}} + Q'\rho c \; (\theta_p + \theta_\ell) = Q'\rho c \; (\theta_p + d\,\theta_p + \theta_\ell)$$

$$+ \, h\pi D' \; (\theta_p + \theta_\ell) \; d\ell \quad \ldots\ldots\ldots\ldots \quad II,7$$

Equation II,7 is integrated to obtain

$$\theta = \theta_p + \theta_\ell = \frac{Q'\rho H' g}{H' h D \pi J 10^{7} L'} \left(1 - e^{-\frac{hD'\ell\pi}{Q'\rho c}} \right)$$

$$+ \, \theta_\ell \; e^{-\frac{hD'\ell\pi}{Q'\rho c}} \quad \ldots\ldots\ldots\ldots\ldots \quad II.8$$

where the last term in equation II,8 represents the increased temperature of the water at a distance ℓ from the tunnel entrance due to the initial temperature of the lake water. Mathews' values of exit temperature assuming lake water temperature of 0°C are given in Table V with the new exit temperatures assuming lake temperatures of 0.2 to 1.4° C.

It can be seen that in the early stages of the flood nearly all the heat content of the lake is advected to the ice. In the terminal stages the amount drops to 35%.

As a check on the feasibility of tunnel enlargement by melting the ice melt at each time during the drainings given by Mathews' (1969) may be calculated as:

TABLE V

Summit Lake Water Tunnel Exit Temperatures for

Initial Water Temperatures from 0°C to 1.4°C

Date and Time		Initial Water Temperature (θ_ℓ) °C							
		0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
1965									
Nov. 11		0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Nov. 18		0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Nov. 25		0.36	0.36	0.37	0.37	0.37	0.38	0.38	0.39
Nov. 26		0.44	0.45	0.46	0.46	0.47	0.48	0.49	0.50
Nov. 27	1530	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
Nov. 28	1000	0.66	0.69	0.72	0.76	0.79	0.83	0.86	0.89
Nov. 29	1200	0.84	0.90	0.97	1.03	1.09	1.16	1.22	1.29
Nov. 30	1030	0.95	1.05	1.15	1.24	1.34	1.44	1.54	1.64
Dec. 1	0600	0.80	0.93	1.07	1.20	1.33	1.46	1.60	1.73
1967									
Sept.10	Noon	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Sept.11	Noon	0.28	0.28	0.28	0.28	0.29	0.29	0.29	0.29
Sept.12	Noon	0.37	0.37	0.38	0.38	0.39	0.39	0.40	0.40
Sept.13	Noon	0.47	0.48	0.49	0.50	0.51	0.53	0.54	0.55
Sept.14	Noon	0.57	0.59	0.61	0.64	0.66	0.68	0.70	0.73
Sept.15	Noon	0.73	0.77	0.82	0.86	0.91	0.95	1.00	1.04
Sept.16	Noon	0.92	1.00	1.08	1.17	1.25	1.33	1.41	1.49
Sept.17	Noon	1.04	1.16	1.26	1.39	1.51	1.63	1.75	1.86
Sept.17	1820	1.05	1.18	1.31	1.44	1.57	1.70	1.83	1.96

$$\frac{Q}{\rho_i x 80 x 10^6} \left(\frac{gH''}{J x 10^{-3}} + (\theta_\ell - \theta_L) 10^6 \right) m^3 \, sec^{-1} \quad \ldots\ldots\ldots \qquad II,9$$

where $g = 9.81 \text{ m sec}^{-2}$

$\rho_i = 0.90$

ignoring the kinetic energy of the water leaving the tunnel. These values are set down in Table VI. As an approximation of the ice melt in each period the average of the instaneous ice melt figures at the beginning and end of the period was taken and multiplied by the length of the time period with the result that for the 1965 draining in the terminal stages a lake water temperature of 0.25°C is required for complete explanation of tunnel enlargement by melting whereas in the 1967 draining a temperature of 0.9°C is required. The latter figure agrees with the 1968 observations for the September lake water temperatures and the former is reasonable for water temperature in November, the month in which the 1965 flood occurred.

If the pressure of the overburden of ice is tending to close the tunnel at the same time as it is melting, then somewhat higher water temperatures would be required to explain enlarging. Also it is noted that only in the terminal stages of the draining are positive lake temperatures required. This agrees with the observation that the coldest water in the lake is found near the dam thus being the first to pass through. The warmer water at the north end of the lake would pass through near the end of the flood.

The availability of lake water with temperature above 0°C provides one answer to the problem raised by Mathews (1969) of no heat available at the upper end of the tunnel and thus no enlargement until

TABLE VI

Ice Melt in m^3 sec^{-1} at given Times During

1965 and 1967 Floods

Date and Time		Initial Water Temperature (θ_ℓ)°C							
		0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
1965									
Nov. 11		0.032	0.037	0.042	0.047	0.051	0.056	0.061	0.066
Nov. 18		0.092	0.11	0.12	0.13	0.15	0.16	0.18	0.19
Nov. 25		0.50	0.59	0.68	0.77	0.87	0.96	1.05	1.14
Nov. 26		0.74	0.89	1.03	1.18	1.32	1.46	1.61	1.76
Nov. 27	1530	1.26	1.52	1.80	2.05	2.32	2.58	2.85	3.11
Nov. 28	1000	1.78	2.19	2.58	2.98	3.38	3.77	4.16	4.56
Nov. 29	1200	3.17	3.96	4.76	5.55	6.34	7.14	7.93	8.72
Nov. 30	1030	5.71	7.25	8.88	10.3	11.8	13.4	14.9	16.4
Dec. 1	0600	17.4	20.1	22.8	25.4	28.1	30.8	33.4	36.1
1967									
Sept.10	Noon	0.21	0.25	0.28	0.32	0.35	0.39	0.42	0.45
Sept.11	Noon	0.33	0.39	0.45	0.50	0.56	0.61	0.67	0.73
Sept.12	Noon	0.55	0.65	0.75	0.85	0.95	1.05	1.15	1.25
Sept.13	Noon	0.87	1.04	1.21	1.38	1.56	1.73	1.90	2.07
Sept.14	Noon	1.29	1.55	1.83	2.09	2.35	2.62	2.89	3.16
Sept.15	Noon	2.17	2.66	3.14	3.63	4.12	4.61	5.10	5.59
Sept.16	Noon	4.37	5.49	6.60	7.71	8.83	9.94	11.5	12.2
Sept.17	Noon	7.57	9.69	11.8	13.9	16.0	18.1	20.3	22.4
Sept.17	1820	7.81	10.6	13.3	16.1	18.8	21.5	24.3	27.1

some distance downstream.

During July 1969 as the lake was refilling from the 1968 draining several more tests were carried out to determine lake water temperature (see Appendix V). The water temperatures at site 4,25 taken July 18, 1968 and 1969 are approximately the same. The water temperatures taken at site 10,23,24 are almost the same, although the 1969 temperatures were taken almost a month earlier, except that the water was slightly warmer during test 23 on July 12, 1969. This similarity of temperature is noted although there were fewer icebergs in 1969 and so more water surface exposed to solar heating.

The only published reference to measurements of the temperature in an ice-dammed lake to this student's knowledge is the reference in Liestol (1956 pp. 123-4). He states that

> In Demmevatn [Norway] daily observations of temperature were made in 1897... [during which time] the mean temperatures in Demmevatn varied between 1 and 1.5°C but the depth for the measurements has not been stated.

Nor was the distance from the ice dam stated, but these figures are in reasonable agreement with those for Summit Lake near the north end of the lake, but above those closer to the ice dam.

5) Stream Temperatures

A record of stream temperatures for Daisy One, Daisy Two and Troy Creeks was kept for August from which the daily mean water temperatures were calculated from a smooth curve through the twice daily readings. These figures multiplied with the daily mean discharge figures give an estimate of the heat input to the lake from these streams (see Appendix V). The mean daily heat input from these three streams (area 14.11 km^2)

for August is 113.1 x 10^{10} calories per day. If it is assumed that this may be used as an estimate of the heat input to the entire lake from the basin except the area of the Salmon Glacier (40.18 km^2) then this is

$$\frac{113 \times 10^{10} \times 40.18}{14.11} = 320 \times 10^{10}$$

calories per day. If it is further assumed that the temperature of the melt from the Salmon is 0°C, that the mean water temperature in the lake is 1.0°C for the summer and that the energy budget terms of net radiation, sensible heat transfer and latent heat transfer are zero or at least sum to zero, then the mean temperature of the mean input (Q_i) is

$$\frac{320 \times 10^{10}}{96.01 \times 10^{10}} = 3.3 \text{ °C}$$

where 96.01 is the average inflow in m^3 day^{-1} x 10^4 from the area of the Summit basin that does not include Salmon Glacier. The decrease in temperature of the water is 3.3 - 1.0 = 2.3°C which represents a heat loss sufficient to melt

$$\frac{2.3 \times 96.01 \times 10^{10}}{80 \times 10^{6}} = 2.8 \times 10^4 \text{ m}^3 \text{ day}^{-1}$$

of ice or 8.6 x 10^5 m^3 of ice during August.

While this result is subject to a number of uncertain conditions it does indicate that the heat from the streams available to melt either icebergs or the ice dam is small. Indeed the small portion of icebergs above water appeared to be melting much faster than that below water as what appeared to be tiny "wave cut terraces" around the sides of the larger floating bergs were seen to rise above the water through the season.

On the other hand, the heat content of the lake water, low as the water temperature is, is probably derived largely from the warm water of the incoming streams.

C) Conclusions

The limitations of a water balance study to determine a leak from Summit Lake are apparent to the reader: limitations such as short term records that are available for the input streams, the impossibility of measuring all the surface water input and of having to use estimates based on less than the best information to fill in these gaps, the difficulty in determining the area of the Salmon Glacier contributing to Summit Lake and of knowing the runoff from it, as well as a number of lesser difficulties. Nevertheless, as a conscious effort was made not to overestimate the input terms of the water balance and as it is difficult to manipulate the water balance terms to avoid a net loss, it is felt that in August 1968 there existed a leak of approximately 3 m^3 sec^{-1} from Summit Lake. The results of the dye tests also indicate, perhaps more strongly, the existence of a leak although the difficulty of determining its size is greater because of problems of release, time of travel, absorption, dispersion, etc.

The results of the temperature tests indicate that the heat content of the input streams is largely lost from the lake water. Lake water temperatures are low (less than 1°C in the vicinity of the dam and only slightly warmer (up to 2°C) at the north end of the lake). However, the heat content of the lake water contributes significantly to the enlarging of the tunnel at least for the one event for which records are available when water temperatures would be significantly above 0°C (September 1967).

In most tests the temperature of the water changed only a small amount for top to bottom of the lake and it is unlikely that a sudden overturn or circulation of water brought warm water to the base of the ice dam. Dye testing in the lake seems to confirm that there is very little water movement at least during the summer.

It seems reasonable to assume that the initiation in 1961 of what may become a regular draining event is related to the thinning of the ice dam over a period of years. It also seems reasonable that there is a seasonal control on the draining since all the events have occurred in the fall or early winter. If it is assumed that a leak was detected three questions arise:

1) In view of the fact that Summit Lake drained when it was just under three quarters full, something which had not occurred previously, how valid is the general statement 'Summit Lake is though to be leaking at least three months before it drains' with respect to previous drainings?
2) Does a leak begin several months before draining or is the leak continuous?
3) Does the leak simply become larger until it is noticable as a draining or is it relatively the same size until some triggering mechanism starts enlarging the tunnel?

For the first question, clearly no information is available prior to 1968. However a study of the water balance of other ice-dammed lakes may shed light on the history of Summit Lake. The methods used here are not good enough to provide answers to the second and third questions except to state that there appears to be some evidence that the leak was larger, and thus more readily detectable, in August than during the last half of July. But the evidence is not strong enough to conclude that the leak started at zero sometime after the lake began to fill, and that it continued to enlarge until the lake emptied; that is, that the observed draining was merely the end of a exponental enlargement of the tunnel.

The fall draining 'cycle' might indicate that, whether the leak is continuous or constant, a seasonally controlled factor initiates or triggers the enlarging of the leak. Apparently the proposed mechanism of fall overturn that would bring the warmer, more dense water (up to 4 °C) to the base of the glacier does not occur in Summit Lake. However, some warming of the lake does occur in the summer both from the heat content of the inflowing streams and from the heating of the lake surface.

Clearly, no solutions have been provided to the questions raised by the draining of Summit Lake but perhaps the work described here may provide clues that will be the basis for a more refined study of the characteristics of the leak and the mechanisms of tunnel enlargement at the time of draining.

BIBLIOGRAPHY

Aitkenhead, N.,
1959, Observations on the drainage of a glacier-dammed lake in Norway; Journal of Glaciology, Vol. 3, No. 27, pp. 607-609.

Bateman, A. M.,
1922, Kennecott Glacier of Alaska; Bulletin of the Geological Society of America, Vol. 32, pp. 527-539.

The draining of Icy Lake is described on page 536.

Collet, L. W.,
1925, Les Lacs, Leur Mode de Formation - Leurs Eaux - Leur Destin Elements d'Hydrogeologie, Paris, 320 pp.

Doell, R. R.,
1963, Seismic depth study of the Salmon Glacier, British Columbia; Journal of Glaciology, Vol. 4, No. 34, pp. 425-437.

Dybeck, M. W.,
1957, An ice margin lake in Iceland; Geographical Journal, Vol. 123, Part 1, pp. 127-130.

Freshfield, D. W.,
1905, Note appended to Rabot's paper describing two floods in the Caucasus Mountains; Geographical Journal, Vol. 25, pp. 547-548.

Glen, J. W.,
1953, Experiments on the deformation of ice; Journal of Glaciology, Vol. 2, No. 12, pp. 111-114.

1954, The stability of ice-dammed lakes and other water-filled holes in glaciers; Journal of Glaciology, Vol. 2, No. 15, pp. 316-318.

Haefeli, R.,
1952, Observations on the quasi-viscous behaviour of ice in a tunnel in the Z'Mutt Glacier; Journal of Glaciology, Vol. 2, No. 12, pp. 94-99

Hanson, G.,
1932, Varved clays of Tide Lake, British Columbia; Transactions of the Royal Society of Canada, Ser. 3, Vol. 26, Sect. 4, pp. 335-339.

Haumann, D,
1960, Photogrammetric and glaciological studies of Salmon Glacier; Arctic, Vol. 13, No. 2, pp. 74-110.

Helbing, R.,
1935, The origin of the Rio Plomo ice dam; Geographical Journal, Vol. 85, pp. 41-49.

Hewitt, K.,
1964, The Great Ice Dam; Indus, Journal of the West Pakistan Water and Power Development Authority, Lahore, Vol. 5, No. 6, pp. 18-30.

Howarth, P. J.,
1968, A supraglacial extention of an ice-dammed lake, Tunsbergdalsbreen, Norway; Journal of Glaciology, Vol. 7, No. 51, pp. 413-419.

Hutchinson, G. E.,
1957, A Treatise on Limnology, Vol. I, J. Wiley and Sons Inc., New York.

International Boundary Commission,
1895, Report of December 31, 1895, British Case - Alaska Boundary - Appendix

Kerr, F. A.,
1934, The ice dam and floods of the Talsekwe, British Columbia; Geographical Review, Vol. 24, No. 4, pp. 643-645.

King, W. D. V. C.,
1934, The Mendoza River Flood of 10-11 January 1934; Geographical Journal, Vol. 84, No. 4, pp. 321-326.

Liestol, O.,
1956, Glacier-dammed lakes in Norway; Norsk. Geogr. Tidsskr., Vol. 15, pp. 122-149.

Lindsay, J. F.,
1966, Observations on the level of a self-draining lake on the Casement Glacier, Alaska; Journal of Glaciology, Vol. 6, No. 45, pp. 443-445.

Marcus, M. G.,
1960, periodic drainage of glacier-dammed Tulsequah Lake, British Columbia; Geographical Review, Vol. 50, pp. 89-106.

Mathews, W. H.,
1964, Water Pressure under a glacier; Journal of Glaciology, Vol. 5, No. 38, pp. 235-240.

1965, Two Self-dumping ice-dammed lakes in British Columbia; Geographical Review, Vol. 55, No. 1, pp. 46-52.

1969, The record of two jokulhlaups;(presented at the Symposium on the Hydrology of Glaciers, September 7-13, 1969, Glaciological Society, Cambridge, England.)

McConnell, R. G., 1913,
1913, Portions of Portland Canal and Skeena Mining Divisions, Skeena District, B.C.; Geological Survey of Canada, Memoir 32.

Moravek, J.R.,
1968, Some Geographical Aspects of Ice-dammed, Self-draining Lakes: A Case Study of Casement Lake, Glacier Bay, Alaska; unpublished M. Sc. thesis, University of Tennessee, June 1968, 84 pp.

Morrison, C.C.,
1958, Glaciers and Human Acitivities; in Geographic Study of Mountain Glaciation in the Northern Hemisphere, C.C. Morrison (ed.), American Geographical Society, Part 9, Chapter 1, pp. 1-27.

Nichols, R. L. and M. M. Miller,
1952, The Moreno Glacier, Lago Argentino, Patagonia; Journal of Glaciology, Vol. 2, pp. 41-50.

Rabot, C.,
1905, Glacial reservoirs and their outbursts; Geographical Journal, Vol. 25, pp. 534-547.

Ricker, K.,
1962, Polar ice-dammed lakes; Canadian Alpine Journal, Vol. 45, pp. 149-151.

Sharp, R. P.,
1960, Glaciers: Condon Lectures, Oregon State System of Higher Education, Eugene Oregon, 78 pp.

Stone, K. H.,
1963 (a), The annual emptying of Lake George, Alaska: Arctic, Vol. 16, No. 1, pp. 26-40.

1963 (b), Alaskan ice-dammed lakes; Annals of the Association of American Geographers, Vol. 53, pp. 332-349.

Thorarinsson, S.,
1939, The ice-dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations; (Chapter IX of Vatnajokull: Scientific results of the Swedish-Icelandic investigations 1936-37-38); Geografiska Annaler, Vol. 21, pp. 216-242.

1953, Some new aspects of the Grimsvotn problem; Journal of Glaciology, Vol. 2, No. 14, pp. 267-275.

Tryggyason, E.,
1960, Earthquakes, jokulhlaups and subglacial eruptions; Jokull, Ar. 10, pp. 18-22.

Wright, J.,
1935, The Hagvatn Gorge; Geographical Journal Vol. 86, No. 3, pp. 218-234.

A P P E N D I C E S

Appendix I

The discharge relation through a tunnel in the ice whose size is being increased by the water passing through it.

$$1\pi\, r_t^{\,2} k_t = V_t \quad \ldots\ldots\ldots \quad (1)$$

$$v = \left(\frac{r}{2}\right)^{2/3} \cdot \frac{S^{1/2}}{n} \quad \ldots\ldots\ldots \quad (2)$$

$$Q = \pi r^2 v \quad \ldots\ldots\ldots \quad (3)$$

From (1)
$$r_t = \left(\frac{V_t}{1\pi k_t}\right)^{1/2} \quad \ldots\ldots\ldots \quad (4)$$

From (1) and (3)
$$Q_t = \frac{\pi v_t V_t}{k_t 1\pi} = \frac{v_t V_t}{k_t 1} \quad \ldots\ldots\ldots \quad (5)$$

From (2) and (4)
$$v_t = \left(\frac{1}{2}\left(\frac{V_t}{1\pi k_t}\right)^{1/2}\right)^{2/3} \cdot \frac{S_t^{\,1/2}}{n}$$

$$= V_t^{\,1/3} \cdot \frac{S_t^{\,1/2}}{2^{2/3}\, n(1\pi k_t)^{1/3}} \quad \ldots\ldots\ldots \quad (6)$$

From (5) and (6)
$$Q_t = \frac{V_t}{k_t 1} \cdot V_t^{\,1/3} \frac{S_t^{\,1/2}}{2^{2/3}\, n(1\pi k_t)^{1/3}}$$

$$= \frac{V_t^{\,4/3} S_t^{\,1/2}}{ak^{4/3}}$$

where $a = 2^{2/3}\, n 1^{4/3} \pi^{1/3}$ = constant

APPENDIX II

Daily observations of the volume change of Summit Lake (ΔV), the overflow from Summit Lake to the North (Q_{on}) and the net discharge in the Bowser River (the total daily discharge less Q_{on}) (Q_{nb}) in $m^3 \times 10^4$ day^{-1} for August 1967.

Date	ΔV	Q_{on}	Q_{nb}
1	64	0	130
2	64	0	140
3	77	0	150
4	64	0	160
5	90	0	170
6	77	0	160
7	77	0	170
8	90	0	270
9	180	0	350
10	170	0	570
11	180	0	350
12	120	0	230
13	66	0	180
14	79	0	180
15	79	0	170
16	66	0	150
17	66	0	170
18	66	0	190
19	93	0	260
20	130	11	310
21	110	20	200
22	27	34	150
23	0	45	120
24	0	45	120
25	0	65	170
26	0	160	290
27	0	130	270
28	0	91	230
29	0	79	240
30	0	74	170
31	0	62	150

Mean Standard	92	210
Deviation	39	94
Mean (m x 10^{-2} day -1)	1.4	2.6

APPENDIX III

Discharge of the Bowser River at Berendon Glacier; Summary of the Discharges of Streams Draining into Summit Lake

Date	Discharge per Day - cubic meters x 10^4						
	Daisy One	Daisy Two	Troy	Eagle	Glacier	Other Side	Bowser River
May 18							82.37
19							75.92
20							88.79
21							92.71
22							71.80
23							64.73
23							60.58
25							53.12
26							47.45
27							43.18
28							42.32
29							42.45
30							47.54
31							47.39
Sum							
June 1							47.16
2							51.86
3							56.49
4							55.40
5							50.94
6							49.58
7							51.70
8							55.23
9							57.47
10	9.44						66.42
11	7.61						68.84
12	6.65						67.29
13	6.69						66.75
14	6.58						68.07
15	6.98			1.63			72.16
16	5.28			1.55			71.12
17	4.93			1.47			71.17
18	6.31			1.39			75.88
19	4.94			1.32			77.08
20	3.83			1.32			70.96
21	3.94			1.26			62.43
22	4.24			1.32			60.05
23	4.57			1.47			60.25
24	5.40			1.55			63.47
25	7.95			1.47			53.12

26	9.28			1.47		87.45
27	5.78			1.47		90.07
28	4.73			1.47		87.15
29	6.08			1.55		100.98
30	6.48			2.25		125.39
Sum	127.68					2061.51
July 1	6.35			2.08		136.25
2	8.72			1.74		137.79
3	8.73			1.74		142.71
4	9.36			1.74		167.42
5	9.53			1.95		177.55
6	7.01			1.32		169.04
7	6.48			1.32		158.44
8	12.01			1.32		180.58
9	9.07			1.39		222.70
10	8.48			1.47		210.71
11	7.47			1.39		193.54
12	6.63			1.26		180.14
13	5.38			1.19		163.40
14	4.49			1.12		139.64
15	3.80	15.41	(7.3)	1.06		139.97
16	3.93	12.63	(7.4)	1.00		142.43
17	3.65	12.85	(7.0)	0.94		134.40
18	3.35	11.11	(6.6)	0.94		126.81
19	3.50	13.21	(6.8)	0.88		135.50
20	3.48	13.22	(6.8)	0.88		159.73
21	3.33	13.26	(6.6)	0.88		160.51
22	3.89	15.57	(7.4)	0.76		170.64
23	4.32	15.38	(8.9)	0.71		179.60
24	4.32	13.56	(8.0)	0.71		173.77
25	4.14	13.82	5.98	0.66		175.18
26	5.03	19.46	11.37	0.76		185.22
27	6.03	12.71	10.95	0.76		188.03
28	6.48	20.35	11.70	0.73		202.72
29	4.15	12.77	6.28	0.65		184.14
30	3.37	11.46	5.59	0.66		168.31
31	3.76	15.27	9.83	0.58		189.43
Sum	180.23					5196.29
Aug. 1	3.50		6.08	0.58	(3.0)	196.13
2	2.72		4.97	0.54	(2.8)	177.23
3	2.27		4.30	0.51	(2.7)	163.62
4	2.12		4.82	0.51	(2.6)	153.36
5	2.87		6.94		(3.2)	163.20
6	2.72		4.04		(2.4)	152.95

7	1.60	16.48	3.39		(2.4)	134.76
8	1.33	16.04	3.72		(2.5)	124.41
9	1.75	8.40	5.73		(3.2)	132.19
10	1.97	7.80	4.81		(3.1)	143.92
11	1.75	7.42	4.86		(2.6)	151.46
12	1.99	8.14	4.95		(2.9)	137.03
13	2.07	8.35	4.89	6.11	(3.5)	144.29
14	2.07	9.05	6.16	6.70	(3.7)	168.33
15	2.12	9.20	7.13	6.49	3.76	176.15
16	2.10	8.66	6.51	6.28	3.28	157.25
17	1.79	7.92	5.97	6.14	2.89	134.42
18	1.58	7.23	4.59	5.99	2.45	127.98
19	1.27	6.02	3.72	6.11	2.48	123.83
20	1.25	6.72	4.06	6.16	3.00	134.87
21	1.86	8.98	6.63	6.48	3.00	125.02
22	3.76	16.22	12.47		6.00	152.78
23	1.81	7.24	5.45		3.27	140.36
24	1.66	6.59	4.42		2.28	119.40
25	1.25	4.71	3.52		1.72	121.15
26	1.04	4.23	2.75		1.38	90.67
27	0.98	4.00	2.81		1.30	85.90
28	3.97	14.46	12.47		4.05	104.63
29	8.06	23.95	18.21		5.54	157.75
30	6.78	17.73	13.13		3.92	167.66
31	8.34	21.54	14.49		5.76	213.73
Sum	80.35		197.99			4476.42
Sept.1	3.59		5.68		2.66	176.2
2			3.86		1.91	126.3
3			5.09		1.52	110.5
4			8.79		2.44	142.7
5			9.43		2.28	178.2
6			7.23		4.64	225.5
7			7.25		2.21	156.0
8			10.88		3.15	199.1
9			7.54		2.44	192.6
10			4.56		2.17	176.2
11			4.27		1.66	136.2
12			2.58		1.27	92.6
13			2.20		0.85	71.7
14			4.36		1.04	83.7
15			2.52		0.84	87.5
16			3.31		1.05	90.5
17			2.44		0.89	75.8
18			2.01		0.60	54.4
19			1.85		0.50	50.8
20			1.70		0.39	46.5
21			1.73		0.32	44.0
22			2.02			

Numbers in brackets indicate estimated values

APPENDIX IV

Total input of water from all sources to Summit Lake ($Q_i + P_\ell A$), the daily volume change of Summit Lake (ΔV), and the estimated leak from Summit Lake through the Salmon Glacier ($Q_{o1} = Q_i + P_\ell A - V$) in $m^3 \times 10^4$ day^{-1}

Date	$Q_i + P_\ell A$	ΔV	Q_{o1}
July 15	101.2	94.0	7.2
16	93.5	91.2	2.3
17	90.4	84.3	6.2
18	82.5	80.8	1.8
19	91.0	77.5	13.4
20	97.9	92.0	5.9
21	98.1	84.8	13.3
22	108.7	72.0	36.7
23	112.7	91.7	21.0
24	106.4	103.6	2.7
25	104.9	103.6	1.2
26	130.3	103.0	27.4
27	120.5	95.4	25.1
28	145.1	81.2	63.9
29	105.1	98.8	6.3
30	94.2	83.3	10.9
31	115.3	74.5	40.7
Aug. 1	113.4	81.7	31.8
2	101.4	82.0	19.4
3	92.5	83.4	9.1
4	91.6	66.0	25.6
5	104.6	81.2	23.4
6	86.8	62.4	24.4
7	75.7	61.9	13.8
8	72.9	52.8	20.1
9	86.9	61.0	25.9
10	88.4	57.9	30.5
11	89.6	61.0	28.5
12	84.8	61.8	22.9
13	87.9	62.6	25.4
14	102.7	78.5	24.4
15	107.5	78.9	28.6
16	101.5	47.3	54.1
17	91.0	60.9	30.1
18	80.8	56.5	24.3
19	71.9	57.3	14.6
20	76.4	54.6	21.8

21	86.2	68.7	17.6
22	145.9	94.8	51.1
23	91.0	52.5	38.5
24	72.3	48.5	23.8
25	63.2	41.0	22.2
26	49.1	33.7	15.4
27	46.8	45.1	1.7
28	116.5	78.3	38.2
29	170.9	127.1	43.8
30	142.2	103.6	38.6
31	183.9	132.5	51.4

APPENDIX V

Water Temperatures in Summit Lake 1968 and 1969

Calibration of Thermistor

Temperature °C	Standard Resistance ohms	Calibrated Resistance ohms
0	7355	7440
1	6990	7085
2	6645	6730
3	6319	6404

WATER TEMPERATURES IN SUMMIT LAKE 1968

Test Number: 1
Date: July 6
Water surface elevation (meters a.s.l.): 786.4
Mean water temperature: 0.2°C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.5	724
3.0	0.4	730
4.6	0.2	734
6.1	0.2	737
7.6	0.1	739
9.1	0.2	736
10.7	0.2	736
12.2	0.2	738
13.7	0.2	736
15.2	0.2	737
16.8	0.2	736
18.3	0.2	735
19.8	0.2	736 bottom

Test Number: 2
Date: July 13
Water surface elevation (meters a.s.l.): 789.6
Mean Water Temperature: 0.3°C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.4	730
3.0	0.2	736
4.6	0.2	734
6.1	0.2	733
7.6	0.2	733
9.1	0.2	733
10.7	0.2	733
12.2	0.2	733
13.7	0.2	733
15.2	0.2	733
18.2	0.3	732
21.3	0.3	732
24.4	0.3	732
27.4	0.3	731
30.5	0.4	730
33.5	0.4	730
36.6	0.4	728
40.0	0.5	724
41.1	0.6	723
42.4	-	- Bottom

Test Number: 3
Date: July 13
Water surface elevation (meters a.s.l.): 789.6
Mean Water Temperature: 0.4°C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.3	731
3.0	0.2	736
6.1	0.3	732
9.1	0.3	732
12.2	0.3	732
15.2	0.3	732
18.2	0.3	732
21.3	0.3	732
24.4	0.3	732
27.4	0.4	730
30.5	0.4	728
33.5	0.4	726
36.6	0.4	726
40.0	0.6	722
40.5	-	- Bottom

Test Number: 4
Date: July 18
Water Surface Elevation (meters a.s.l.): 791.2
Mean Water Temperature: 0.4°C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.4	729
3.0	0.4	730
6.1	0.4	729
9.1	0.4	726
12.2	0.6	723
15.2	0.6	723
18.2	0.4	726
21.3	0.4	726
24.4	0.4	726
25.0	-	- Bottom

Test Number: 5
Date: July 25
Water Surface Elevation (meters a.s.l.): 793.2
Mean Water Temperature: 1.9°C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.8	680	
3.0	1.6	684	
4.6	1.6	683	
6.1	2.0	672	
7.6	2.0	672	
9.1	2.0	670	
10.7	2.1	669	
11.6	2.2	667	Bottom

Test Number: 6
Date: July 25
Water Surface Elevation (meters a.s.l.): 793.2
Mean Water Temperature: 1.4°C

Depth (meters)	Temperature (°C)	Resistance (Ωx 10)	
0.0	1.1	703	
3.0	0.9	708	
4.6	0.9	707	
6.1	1.2	702	
7.6	1.5	690	
9.1	1.8	680	
10.7	1.9	674	
12.2	1.8	677	
12.3	1.8	680	Bottom

Test Number: 7
Date: July 25
Water Surface Elevation (meters a.s.l.): 793.2
Mean Water Temperature: 2.1° C

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	2.0	672	
3.0	1.8	681	
4.6	1.8	679	
6.1	1.8	678	
7.6	1.8	678	
9.1	2.0	672	
10.7	2.5	656	
12.2	2.5	655	
12.8	2.6	653	Bottom

Test Number: 8
Date: July 31
Water Surface Elevation: (meters a.s.l.): 794.8
Mean Water Temperature: (°C): 1.1

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.6	720	
1.5	0.6	720	
3.0	0.6	721	
4.6	0.8	717	
6.1	0.8	717	
7.6	0.8	717	
9.1	1.3	697	
10.7	1.4	694	
12.2	1.4	691	
13.7	1.6	688	
14.5	1.6	687	Bottom

Test Number: 9
Date: July 31
Water Surface Elevation (meters a.s.l.): 794.8
Mean Water Temperature: (°C) 1.6

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.7	682	
1.5	1.5	690	
3.0	1.6	688	
4.6	1.6	687	
6.1	1.5	690	
7.6	1.5	690	
9.1	1.6	688	
10.7	1.6	684	
12.2	1.8	678	
13.7	2.1	669	
14.5	2.2	667	Bottom

Test Number: 10
Date: August 9
Water Surface Elevation (meters a.s.l.): 796.8
Mean Water Temperature (°C): 0.4

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.4	729	
1.5	0.4	729	
3.0	0.4	729	
4.6	0.4	728	
6.1	0.4	729	
7.6	0.4	729	
9.1	0.3	733	
10.7	0.3	732	
12.2	0.4	731	
15.2	0.4	731	
18.2	0.4	731	
21.3	0.4	731	
24.4	0.4	730	
27.4	0.4	727	
30.5	0.4	726	
33.5	0.4	726	
36.0	0.4	726	Bottom

Test Number: 11
Date: August 13
Water Surface Elevation (meters a.s.l.): 797.6
Mean Water Temperature (°C): 1.5

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.5	690	
11.5	1.6	685	
3.0	1.4	694	
4.6	1.4	693	
6.1	1.4	693	
7.6	1.4	693	
9.1	1.4	693	
10.7	1.4	693	
12.2	1.4	691	
13.7	1.4	691	
15.2	1.4	691	
16.8	1.5	690	
18.3	1.6	687	
18.9	1.6	687	Bottom

Test Number: 12
Date: August 13
Water Surface Elevation (meters a.s.l.): 797.6
Mean Water Temperature (°C) 1.1

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.2	699	
1.5	1.2	699	
3.0	1.0	706	
4.6	1.0	709	
6.1	1.0	706	
7.6	1.0	707	
9.1	0.9	710	
10.7	0.9	710	
12.2	1.0	708	
13.7	1.0	108	
15.2	1.0	708	
16.8	1.1	704	
18.2	1.2	701	
19.8	1.5	690	Bottom

Test Number: 13
Date: August 13
Water Surface Elevation (meters a.s.l.): 797.6
Mean Water Temperature (°C): 0.9

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.0	707	
1.5	0.8	713	
3.0	0.9	711	
4.6	0.8	712	
6.1	0.8	712	
7.6	0.8	715	
9.1	0.8	713	
10.7	0.8	713	
12.2	0.8	713	
13.7	0.8	713	
15.2	0.8	713	
16.8	0.8	713	
18.2	0.8	713	
18.9	0.8	713	Bottom

Test Number: 14
Date: August 16
Water Surface Elevation (meters a.s.l.): 798.2
Mean Water Temperature (°C): 0.6

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.5	725	
1.5	0.5	725	
3.0	0.4	729	
4.6	0.4	727	
6.1	0.4	727	
7.6	0.4	727	
9.1	0.4	728	
10.7	0.4	727	
12.2	0.4	727	
13.7	0.4	727	
15.2	0.4	728	
16.8	0.4	728	
18.3	0.4	727	
19.8	0.4	727	
21.3	0.4	727	
24.4	0.4	727	
27.4	0.4	727	
30.5	0.5	725	
33.5	0.6	724	
36.6	0.6	723	
40.0	0.6	724	
42.7	0.6	724	
45.7	0.6	724	
48.8	0.5	725	
51.8	0.6	722	
54.9	0.6	721	
56.4	0.6	721	
61.0	0.6	720	
64.0	0.6	722	
67.1	0.6	722	
70.1	0.6	720	
73.2	0.6	720	
76.2	0.7	719	
79.2	0.7	718	
82.3	0.8	717	
85.3	0.8	717	
88.4	0.7	718	
91.4	0.7	718	
94.5	0.8	717	
97.5	0.8	717	
100.6	0.8	717	
103.6	0.8	716	
106.7	0.8	715	
109.7	0.8	717	
111.0	0.8	716	Bottom

Test Number: 15
Date: August 16
Water Surface Elevation (meters a.s.l.): 798.2
Mean Water Temperature (°C): 0.6

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.5	725	
1.5	0.4	729	
3.0	0.4	730	
6.1	0.4	730	
9.1	0.4	730	
12.2	0.4	730	
15.2	0.4	728	
18.3	0.4	727	
21.3	0.4	727	
24.4	0.4	726	
27.4	0.4	726	
30.5	0.4	726	
33.5	0.4	726	
36.6	0.5	725	
40.0	0.5	724	
42.7	0.6	722	
45.7	0.6	723	
48.8	0.6	723	
51.8	0.6	722	
54.9	0.6	721	
57.9	0.6	721	
61.0	0.6	721	
64.0	0.6	720	
67.1	0.7	719	
70.1	0.7	719	
73.2	0.7	718	
76.2	0.7	718	
79.2	0.7	718	
82.3	0.8	717	
85.3	0.8	717	
88.4	0.8	716	
91.4	0.8	715	
94.5	0.8	716	
97.7	0.8	716	
100.5	0.8	717	
103.6	0.8	715	
106.7	0.8	717	
109.7	0.8	715	
112.8	0.8	714	
115.8	0.8	713	
120.4	0.8	713	No Bottom

Test Number: 16
Date: August 27
Water Surface Elevation (meters a.s.l.): 800.1
Mean Water Temperature (°C): 0.7

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.8	717
1.5	0.6	721
3.0	0.4	728
4.6	0.6	724
6.1	0.6	724
7.6	0.5	725
9.1	0.6	723
10.7	0.6	723
12.2	0.6	723
13.7	0.6	723
15.2	0.6	723
16.8	0.6	721
18.3	0.6	720
19.8	0.6	720
21.3	0.6	720
22.9	0.7	719
24.4	0.7	719
25.9	0.7	719
27.4	0.7	718
29.0	0.7	717
30.5	0.8	714
32.0	1.1	704
33.5	1.2	702
35.1	1.4	694 Bottom

Test Number: 17
Date: August 27
Water Surface Elevation (meters a.s.l.): 800.1
Mean Water Temperature (°C): 0.8

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.8	717
1.5	0.8	716
3.0	0.7	718
4.6	0.7	719
6.1	0.7	719
7.6	0.7	718
9.1	0.7	718
10.7	0.7	719
12.2	0.7	719
13.7	0.8	716
15.2	0.9	710
16.2	1.0	707 Bottom

Test Number: 18
Date: August 27
Water Surface Elevation (meters a.s.l.): 800.1
Mean Water Temperature (°C): 1.0

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.0	707	
1.5	1.0	709	
3.0	1.0	709	
4.6	0.9	710	
6.1	0.9	711	
7.6	0.9	711	
9.1	0.8	712	
10.7	0.8	712	
12.2	0.8	712	
13.7	0.9	711	
15.2	1.0	709	
16.8	1.2	702	
18.3	1.2	702	
19.8	1.2	700	
21.3	1.2	700	
21.6	1.2	700	Bottom

Test Number: 19
Date: August 27
Water Surface Elevation (meters a.s.l.): 800.1
Mean Water Temperature (°C): 1.1

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	1.2	700	
1.5	1.2	609	
3.0	1.2	700	
4.6	1.1	703	
6.1	1.2	702	
7.6	1.1	703	
9.1	1.2	702	
10.7	1.2	702	
12.2	1.1	703	
13.7	1.1	703	
15.2	1.2	702	
16.8	1.2	702	
18.3	1.2	702	
19.8	1.2	702	
21.3	1.2	702	
22.9	1.2	701	
24.4	1.3	698	Bottom

Test Number: 20
Date: September 22
Mean Water Surface Elevation (meters a.s.l.): 805.3
Mean Water Temperature (°C): 0.6

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.9	711	
1.5	0.8	713	
3.0	0.8	717	
4.6	0.7	718	
6.1	0.6	721	
9.1	0.6	722	
12.2	0.6	722	
15.2	0.6	722	
18.3	0.6	722	
21.3	0.6	723	
24.4	0.6	723	
27.4	0.6	723	
30.5	0.6	723	
33.5	0.6	723	
36.6	0.6	723	
40.0	0.6	720	
42.7	0.7	719	
45.7	0.7	718	
49.4	0.8	713	Bottom

Test Number: 21
Date: September 22
Water Surface Elevation (meters a.s.l.): 805.3
Mean Water Temperature (°C): 0.7

Depth (Meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.7	718	
1.5	0.7	718	
3.0	0.7	718	
4.6	0.7	718	
6.1	0.7	718	
7.6	0.7	718	
9.1	0.7	718	
12.2	0.7	718	
15.2	0.7	718	
18.3	0.7	718	
21.3	0.8	712	
23.2	0.9	711	Bottom

Test Number: 22
Date: September 22
Water Surface Elevation (meters a.s.l.): 805.3
Mean Water Temperature (°C): 0.7

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.0	743	
1.5	0.6	723	
3.0	0.6	723	
6.1	0.6	723	
9.1	0.6	722	
12.2	0.6	722	
15.2	0.6	722	
18.3	0.8	716	
21.3	0.8	715	
24.4	0.8	712	
27.4	0.9	709	
29.6	1.1	704	Bottom

Ten centimeters of wet snow on the water surface.

WATER TEMPERATURES IN SUMMIT LAKE 1969

Test Number: 23
Date: July 12
Water Surface Elevation (meters a.s.l.): 782.5
Mean Water Temperature (°C): 0.5

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.1	738	
1.5	0.1	739	
3.0	0.2	735	
6.1	0.7	719	
9.1	0.6	721	
12.2	0.6	723	
15.2	0.6	723	
18.3	0.6	722	
21.3	0.6	722	
24.4	0.6	722	
27.4	0.6	722	
30.5	0.6	722	
33.5	0.7	719	
36.6	0.7	719	
40.0	0.7	719	Bottom

Test Number: 24
Date: July 16
Water Surface Elevation (meters a.s.l.): 783.0
Mean Water Temperature (°C): 0.4

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)	
0.0	0.7	719	
1.5	0.7	718	
3.0	0.4	726	
4.6	0.4	731	
6.1	0.4	731	
9.1	0.4	731	
12.2	0.4	731	
15.2	0.4	730	
18.3	0.4	730	
21.3	0.4	730	
24.4	0.4	729	
27.4	0.4	728	
30.5	0.4	729	
33.5	0.4	727	
36.6	0.4	727	
38.1	0.4	727	Bottom

Test Number: 25
Date: July 18
Water Surface Elevation (meters a.s.l.): 783.4
Mean Water Temperature (°C): 0.4

Depth (meters)	Temperature (°C)	Resistance (Ω x 10)
0.0	0.6	724
1.5	0.4	726
3.0	0.3	732
6.1	0.4	731
9.1	0.4	731
12.2	0.4	731
15.2	0.4	731
18.3	0.4	730
21.3	0.4	728
24.4	0.4	728
27.4	0.4	728
30.5	0.4	728
33.5	0.4	727
36.6	0.4	727
38.1	0.5	725
39.7	0.5	724 Bottom

APPENDIX VI

Heat content in gm. cal. x 10^{10} day^{-1} for Daisy One, Daisy Two and Troy Creeks calculated as the product of the mean daily water temperature and the daily discharge, August 1968

Date	Daisy One	Daisy Two	Troy	Total
1	30.7	91.0	16.3	138.1
2	27.2	91.4	14.2	132.7
3	24.1	86.8	14.6	125.5
4	21.9	93.1	14.9	129.9
5	26.1	95.3	19.3	130.7
6	25.7	64.6	11.3	101.6
7	15.1	55.2	9.9	80.2
8	11.4	45.8	9.5	66.6
9	16.2	65.7	18.9	100.8
10	18.4	65.6	15.9	99.8
11	17.0	62.3	14.1	93.4
12	16.2	59.0	14.3	89.4
13	19.2	67.8	13.5	100.4
14	20.5	82.8	20.0	123.3
15	18.4	73.6	20.3	112.4
16	17.2	62.5	18.2	97.9
17	14.8	54.2	16.8	85.9
18	13.1	54.4	12.4	79.9
19	10.5	42.1	9.7	62.4
20	11.4	55.2	13.6	80.3
21	15.4	65.1	18.4	98.9
22	33.1	120.8	43.4	197.3
23	16.3	55.9	19.1	91.3
24	14.9	53.2	17.2	85.3
25	10.6	33.4	10.2	54.1
26	8.7	28.8	8.0	45.4
27	8.4	27.5	8.9	44.3
28	29.0	93.7	42.4	165.1
29	55.7	148.0	66.5	270.2
30	48.8	103.2	41.4	193.4
31	61.3	124.9	46.1	232.3