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Drainings of Ice-Dammed Summit Lake, British Columbia

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SCIENTIFIC SERIES NO. 20

INLAND WATERS DIRECTORATE,
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Cat. No.: En 36-502/20

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Acknowledgments

The study was carried out as part of an MA program at the University of British Columbia with field assistance from the Glaciology Division, Inland Waters Directorate, Department of the Environment (then Glaciology Subdivision, Inland Waters Branch, Department of Energy, Mines and Resources). Thanks are due especially to Dr. A. D. Stanley, Head, Cordillera Section, and to the field crews in 1968 and 1969.

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

Professors W. H. Mathews and J. R. Mackay, University of British Columbia, made important suggestions and comments which were gratefully accepted.

Abstract

Drainings of ice-dammed Summit Lake have been reported in 1961, 1965, 1967, 1968 and 1970. In 1968, tests were carried out on (1) a water balance model for the lake equating inflow and precipitation to volume change in the filling lake, (2) determination of overflow when full, and (3) detection of water leakage under or through the ice dam. The results indicated that if one half of the area of the damming glacier did actually contribute inflow, a leak of 3 to 5 $m^3 s^{-1}$ existed in August 1968, three months before the fourth draining.

Lake water temperatures were recorded from July to September 1968 and in July 1969. Warmest water (2.6°C) was found farthest from the dam in early summer. Temperature decreased at all locations from mid July. A mean water temperature of 1°C in July decreasing to 0.7°C by late September was estimated.

The existence of a small tunnel associated with a continuous leak, and enlarging of this tunnel by melt provides a rational explanation for the catastrophic drainings of Summit Lake. Mathews (in press) calculated that the heat generated by potential energy loss during draining is sufficient to account for tunnel enlargement in all but the terminal stages of draining. Recalculation of Mathews' work, allowing for positive lake water temperatures, indicates that for the drainings of 1965, 1967, 1968 and 1970, lake water temperatures of 0.2°C, 0.9°C, 0.15°C, and 1.1°C, respectively, were required to account completely for tunnel enlargement in the terminal stages.

Drainings of Ice-Dammed Summit Lake, British Columbia

R. Gilbert

INTRODUCTION

Ice-dammed lakes are widely distributed over the world in areas of large valley glaciers. Their occasional catastrophic drainings (jökulhlaup) have received little attention to date even though these events may be significant geomorphic and hydrologic agents in shaping landscape. Exceptions occur where floods from drainings have had a disruptive effect on man's occupancy of land in valleys below the damming glaciers. Thus, much of the literature on ice-dammed lakes is concerned with a description of the lakes and their periodic drainings, rather than on investigations of the mechanisms that cause these drainings. 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 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 frequently obscured by jumbles of collapsed ice soon after the floods.

This report summarizes studies that were carried out on an ice-dammed lake in British Columbia. The lake has been draining periodically since 1961. Water-balance and thermal regime of the lake were studied in an attempt to determine if minor leaking occurred through the dam some months before the draining, and to investigate the role of the heat content of the lake water in enlarging the leak.

SUMMIT LAKE: LOCATION AND KNOWN 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 border. Salmon Glacier, which dams the lake, originates in an accumulation area that feeds several large glaciers, the largest of which is approximately 26 km long. Salmon Glacier itself is 20 km long and dams Summit Lake 13 km from the terminus. Meltwater from the Salmon Glacier terminus flows southward via Salmon River 20 km to the head of Portland Canal. Summit Lake, when full, is 5.25 km long and varies in width from 0.45 to 1.25 km (Fig. 1). Its depth increases southward reaching a maximum of more than 200 m at the ice face. When full, the surface elevation, 826 m a.s.l., is controlled by an outlet over bedrock to the north. Overflow passes into Bowser River and eventually to Nass River.

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

An amabilis fir at elevation of 840 m a.s.l., and hence below the upper outlet on the slope above Summit Lake, was dated at 230 years, indicating that the water has used the present overflow channel 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 m a.s.l., when the Berendon Glacier formed an even more effective dam on the north. But there is very little evidence to support the suggestion.

Salmon Glacier was also much larger in the past. The earliest map available is that of the International Boundary Commission dated 1920. At this time Salmon Glacier and a small glacier coming down from the west of Summit Lake were joined, and flowed north for about 500 m beyond the present ice terminus in the lake. In addition to Summit Lake a smaller lake, east of the present ice front, was dammed. The shore line indicates a water level of about 890 m a.s.l.

Since 1920 shrinking of Salmon Glacier has been rapid. Figure 2 shows a profile of the glacier according to Haumann's (1960) map which is based on 1949 and 1957 photography and a map prepared by the Department of Energy, Mines and Resources from photography taken on

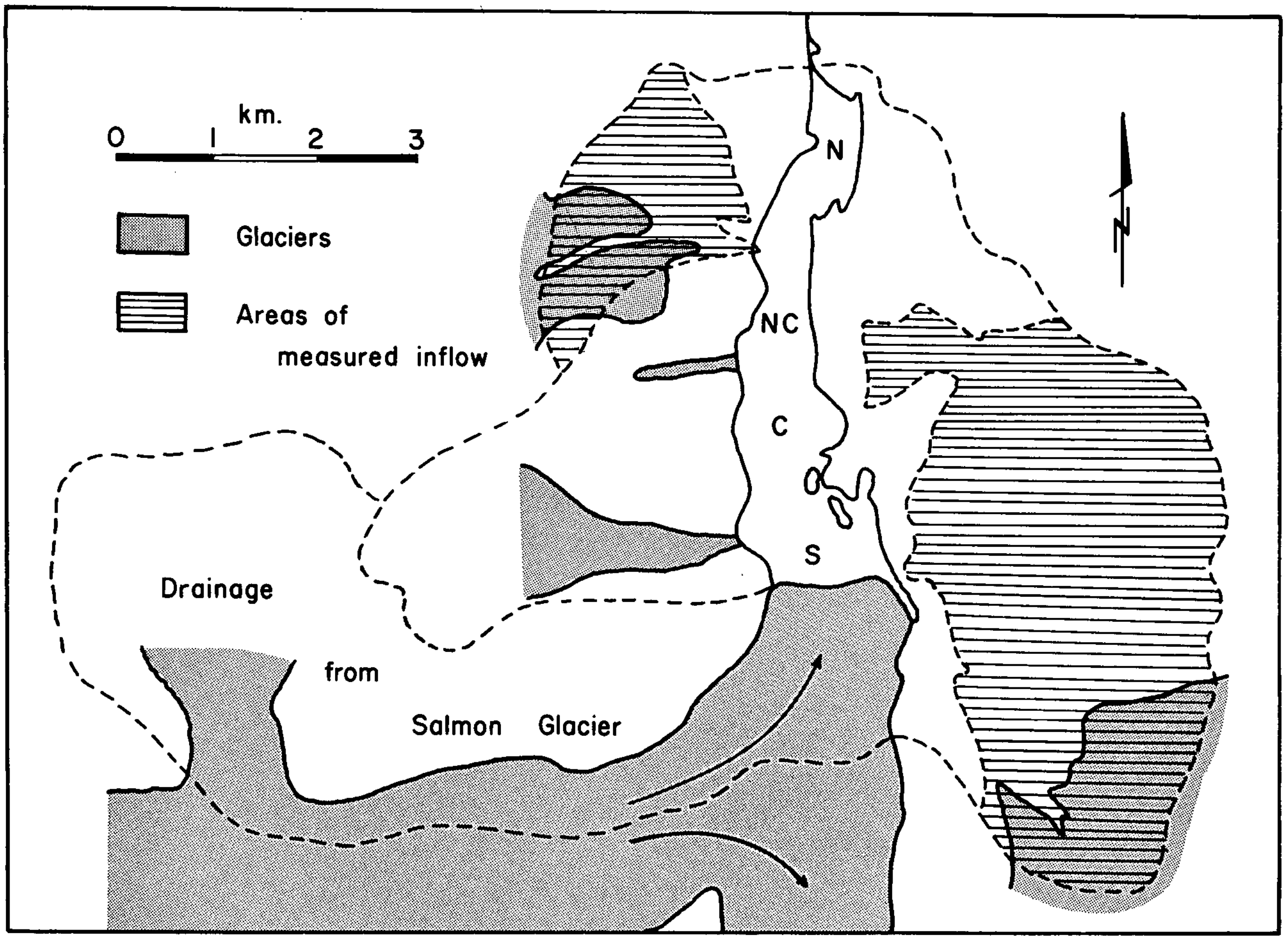

Figure 1. Drainage basin of Summit Lake

August 4, 1968. The mean annual ablation for the period 1957 to 1968 varies from more than 7 m per year near the south terminus to less than 2 m per year southwest of the lake. The figures agree reasonably well with the figures presented by Haumann (1960), indicating that the ablation rate is similar to that for 1949-57. However, a noticeable difference (2.2 m compared with 5.6 per year) in the rate of lowering between these periods does occur in the area of the ice dam. Since the 1968 photography was taken when the water level of Summit Lake was 30.4 m below the high water mark, this difference indicates that the dam ice terminus may have floated when the lake was full. The initiation of the draining of Summit Lake in 1961 may well be associated with the rapid shrinkage of Salmon Glacier.

SUMMIT LAKE: DRAINING EVENTS

From the beginning of human occupancy of the area at about 1900 until 1961, there is no record of Summit Lake draining. It is likely that there were no drainings for a long period before this as large mature fir and cedar on the banks of Salmon River were killed when their roots were flooded in the 1961 and 1965 drainings.

Mathews (1965, pp. 49-50) 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 as 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."

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

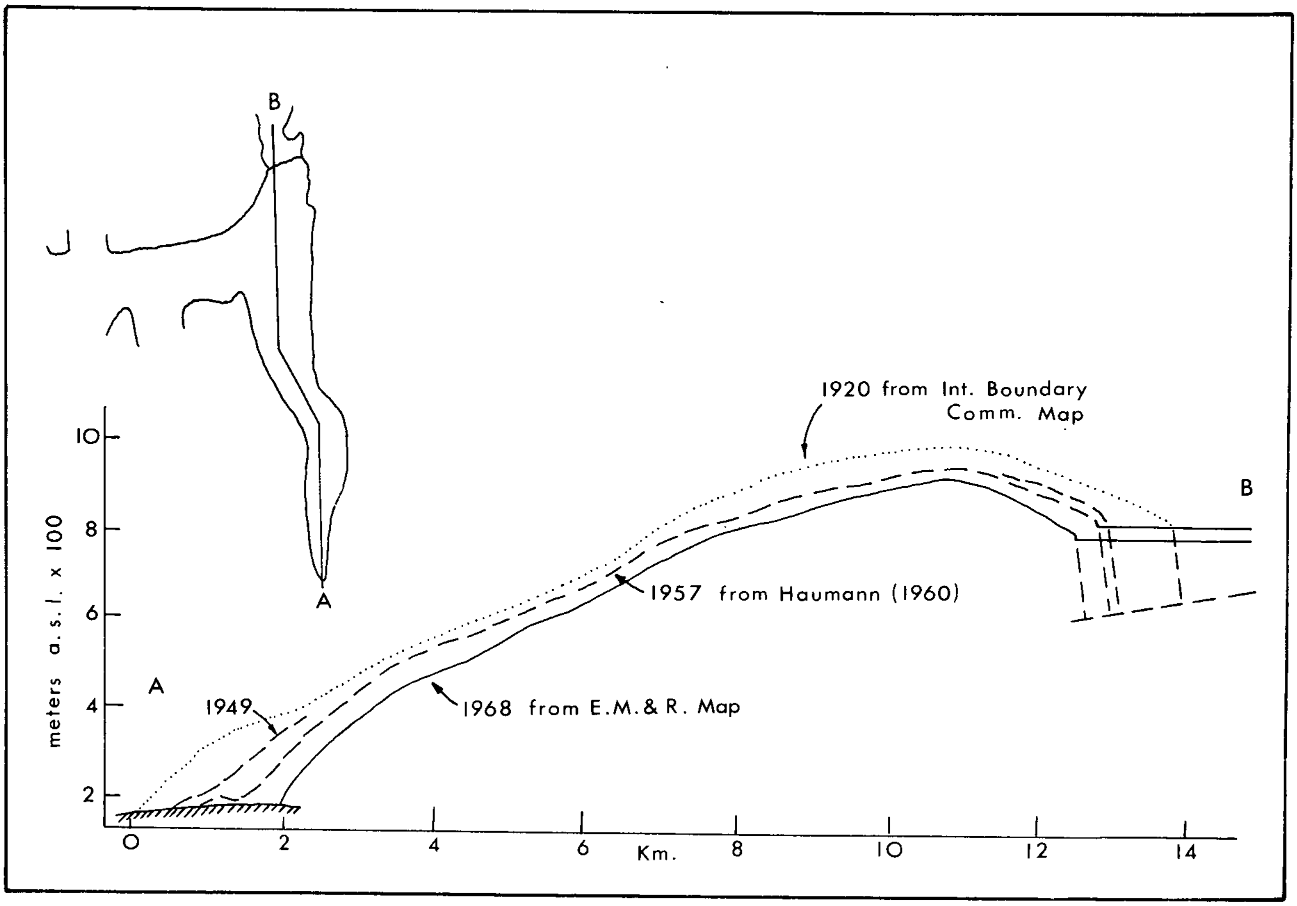

Figure 2. Longitudinal profiles of Salmon Glacier showing surface lowering from 1920 to 1968

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 over-flowing to the north". (Mathews, 1965, p. 51)

The drainings of November 1965 and September 1967 were observed and recorded. Mathews (in press) 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 when the lake was empty. By August 19, 1967, the lake was 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 (Fig. 3). After each draining the mining access road in the valley required extensive repair (Fig. 4), but other damage was small as the valley is largely uninhabited. Figure 5 indicates that the draining in 1967 may have been slightly more rapid than the draining in 1965.

The water level reached 808.3 m a.s.l. in late October or early November 1968, 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 m below the level of the lake when full, a volume of $70.5 \times 10^6 m^3$ or about 28% of the volume of the lake was not filled before draining began. Stream-gauging data for Salmon River provided by the United States Geological Survey indicated that the flood reached a peak of $1640 m^3 s^{-1}$ at 2300 hours on November 19 (Fig. 5), after which time the discharge dropped quickly to less than $20 m^3 s^{-1}$. The slower rate of increase in discharge is possibly a function of the colder lake water temperatures combined with less water in the lake at the beginning of this draining.

Again, in 1970, the lake drained after reaching a maximum level of 821.7 m a.s.l., only 4.3 m below the level when full, on August 1. That is, only 7% of the lake volume

Figure 3. Summit Lake looking south to Salmon Glacier at 1600 hours, September 19, 1967, just after completion of draining

Figure 4. Salmon River at the peak of the 1967 Hood, 1800 hours, September 17, 1967

remained to be filled. The maximum observed discharge determined from the rate of volume change in the lake occurred at 1600 hours, August 8 (Fig. 5). However, the lake was only half empty at this time. If the rate of change of discharge on August 8 to 1600 hours is extrapolated until the lake became empty, then a maximum discharge of approximately $2600 m^3 s^{-1}$ may have occurred sometime between 0600 and 0800 hours, August 9. This discharge figure is reasonable in view of Mathews' data (in press) for the drainings when the lake was full.

SUMMIT LAKE: WATER BALANCE

During the preliminary mass balance studies on Berendon Glacier by the Glaciology Subdivision, Inland Waters Branch in 1967, records were kept of the rate of refilling of Summit Lake from the 1965 draining (ΔV), the overflow to the north when full (Q_{on}) and the runoff from Berendon Glacier Basin (Q_{nb}). For August 1967 these data for the adjacent basins may be summarized:

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

These preliminary data indicate that the runoff per unit area from Berendon Glacier Basin was almost twice that from Summit Lake Basin. It was felt that differences in basin hypsometry, aspect, snow, glacier and vegetation cover were insufficient to explain this difference and that significant quantities of water may have been leaking through or under Salmon Glacier at least a month before the initial phase of draining was first noticed.

The proposed leak may be expressed in terms of a simple water balance model:

$$Q_{ol} = Q_i + P - \Delta V - Q_{on} - E$$

where: Q_{ol} is the flow through the proposed leak
Q_i is the inflow to the lake
P is the precipitation on the lake surface
ΔV is the volume change of the lake water
Q_{on} is the overflow to the north from the lake
E is the evaporation from the lake surface all in cubic metres per day.

During the summer of 1968 the terms of this model were investigated as the lake was refilling after the

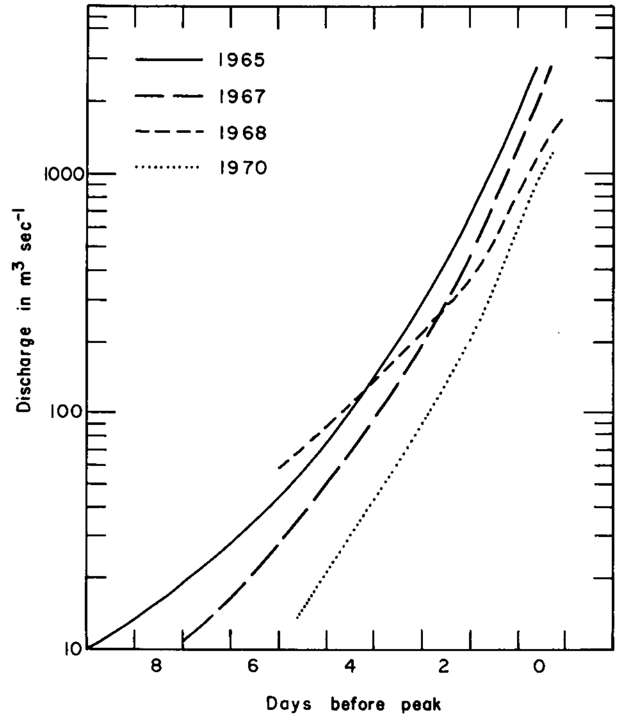

Figure 5. Discharge during four recorded drainings of Summit Lake, based on change in lake volume in 1965, 1967, and 1970, and on volume change and discharge measurements in Salmon River, 1968

September 1967 draining. A summary of the data is provided in Appendix 2.

Inflow was measured through most of July and August on four streams draining the east side of Summit Lake and for shorter periods on two streams on the west side (Fig. 1). Flow from the remaining areas of the basin could not be measured regularly because of difficulty of access or because several glaciers calve directly into the lake. The area of Salmon Glacier contributing melt to the lake presented further difficulty because its boundaries are ill-defined and the rate of ablation was only roughly known. Knowledge of flow of various measured streams was used to estimate the inflow from the rest of the non-glacierized portion of the basin. The estimate was based on the similarity of landscape and of spot readings of flow in the measured and unmeasured areas and on the non-significance of Student's 't' tests on paired variables of daily runoff of streams in adjacent areas. Whenever doubt existed, the lowest inflow values were used in order to detect a possible leak. Inflow from that area of Salmon Glacier which, on the basis of ice-surface topography, is tributary to Summit Lake was estimated from spot readings of ablation and from ablation and runoff data for the adjacent Berendon Glacier which is

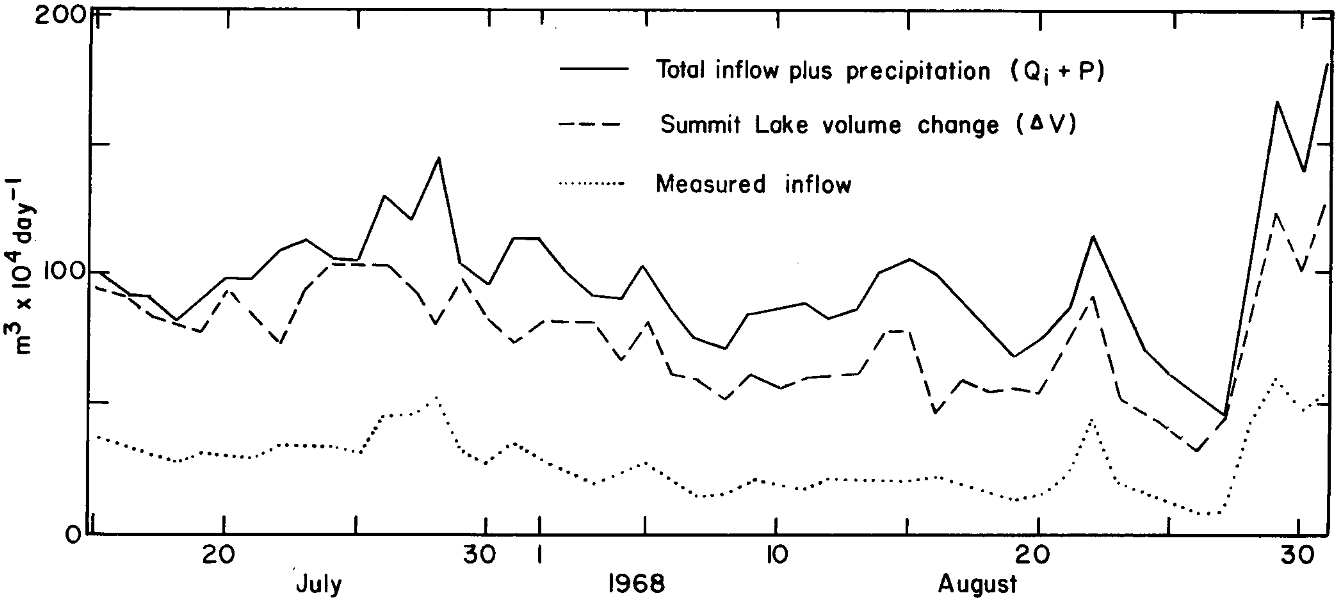

Figure 6. Inflow and volume change in Summit Lake during the Summer of 1968

of similar size, aspect and elevation. Because of the uncertainty of the area of Salmon Glacier that actually contributes inflow, a further underestimate was provided by considering the total area, three quarters, two thirds, and one half of the area in the calculation of inflow.

The other terms of the water balance were measured or estimated through the same period. From aerial photographs taken on August 4, 1968, when the water level of the lake was 33 m below the maximum water level, a large scale contour map of the exposed lake bed was produced. From this map a linear hypsographic relation of the form

$$A = -27.793 + 0.0389 E_s$$

with coefficient of determination $r^2 = 0.999$ was determined, where A is the lake surface area in km^2 and E_s is the surface elevation in m a.s.l. This and twice-daily readings of water-surface elevation provided a measure of the daily water volume change (ΔV). Of the remaining terms of the water balance, precipitation on the lake was estimated from rain gauges at each end of the lake; overflow to the north in 1968 was zero, and evaporation from the lake was considered insignificant because much of the lake surface was covered with floating ice; the water temperature was close to 0°C., and cool damp air was noted pooled over the lake surface much of the time. These observations of the terms of the water balance are summarized in Figure 6.

A Student's 't' test on the difference between the paired daily values of total input to the lake ($Q_i + P$) and the volume change in the lake (ΔV) was performed for the periods July 15 to 31 and August 1 to 31, 1968 with the results that for the first period a leak significant at 95% confidence was detected only when all of the area of Salmon Glacier tributary to Summit Lake was considered. For the second period, a significant leak could be detected when less than one half of this area was considered, and with $3 m^3 s^{-1}$. Were less conservative estimates of total input taken into consideration, the leak may have been as large as $5 m^3 s^{-1}$.

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. D.A. Fisher (in press) placed rhodamine B, a red fluorescent dye, in Summit Lake near the ice dam on July 30, August 9, and August 19, 1968. Three different methods were used to put the dye into the lake. In the first method, the dye, placed in boxes fastened with water soluble cement was dropped from a helicopter; in the second, glass bottles of dye were lowered into the lake from a raft and the dye placed in two streams flowing into the lake near Salmon Glacier; in the third method a perforated barrel of dye was dropped from a helicopter. Sampling, both continuous and discrete, was carried out in Salmon River below Salmon Glacier, and the fluorescence measured with a Turner 111 fluorometer. After each drop of dye, fluorescence of the river water rose significantly above the background fluorescence at the 95% confidence level. The times of travel are calculated as 39, 48, and 52 hrs and a leak of between 0.02 and 20 $m^3 s^{-1}$ (in press).

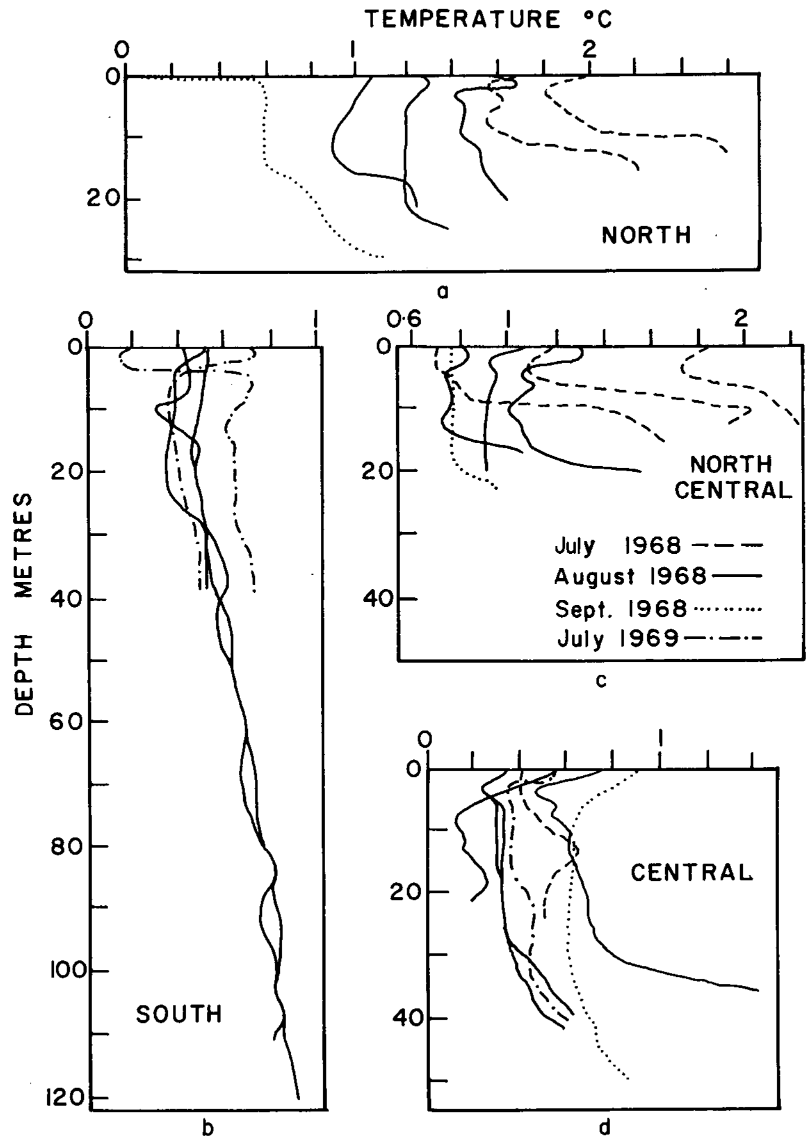

Figure 7. Water temperatures in Summit Lake, 1968-1969

SUMMIT LAKE: THERMAL CONDITIONS

Temperatures of ice-dammed lake water even slightly above 0°C may be significant in determining the manner and rate of draining. Summit Lake temperatures were recorded with a thermistor probe from surface to bottom at various points in the lake as often as floating ice conditions would permit through the summers of 1968 and 1969. The results of these tests are summarized in Figure 7 and in Appendix 3.

It can be seen that the warmest temperature recorded was 2.6°C in the summer of 1968 in the relatively ice-free north end of the lake. As the lake filled, the temperatures in the north of the lake decreased while those in the central and south increased slightly. Of the 25 tests, 20 had the lowest temperatures just below the surface and above mid-depth, while the warmest water was found at or near the bottom; in another four tests the warmest water was at the surface, and in only one test was the coldest water found near the surface. There was no evidence of appreciable circulation nor of an overturn of the lake water due to density differences. Tests taken in 1969 agree very well with those taken at the same location in 1968, although the lake had drained in the interim and the water level in 1969 was 7-10 m below that at the same time in 1968. The mean water temperature in the early part of the summer of 1968 appears to have been approximately 1°C decreasing by

October to 0.7°C largely as a result of cooling of water in the northern part of the lake.

There are very few records of temperatures in other ice-dammed lakes, Liestøl (1956, pp. 123-4) 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.

The distance from the ice dam was not stated. 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. The temperatures reported by Hattersley-Smith and Serson (1964) in the fresh water layer of a lake in Northern Ellesmere Island are similar to those in Summit Lake despite great climatic differences between the two locations.

DISCUSSION OF DRAINING MECHANISMS

A number of mechanisms for draining ice-dammed lakes have been proposed, each of which is more or less significant in the draining of individual lakes. The three most commonly discussed are overtopping of the ice dam, floating of the dam to allow escape of water beneath, and melting of a tunnel through the ice dam.

Overtopping of the ice dam and subsequent erosion of a channel through the ice is an obvious but not common mechanism. Lake George, Alaska, one of the largest ice-dammed lakes, drains in this manner (Stone, 1963) and others have been reported (Ricker 1962, Liestøl 1956). The outlet to the north prevents Summit Lake from overtopping the ice dam and at no time during the drainings did water flow over the glacier surface, although Mathews (in press) noted a patch of wet snow which developed 2 km upstream from the terminus in the 1965 draining.

One of the reasons why overtopping is not common is that, in some cases, the ice dam floats on the lake allowing water underneath the glacier. Since Salmon Glacier is more than 600 m thick within 2 km of Summit Lake (Doell, 1963) floating cannot occur except in the immediate vicinity of the dam. Marcus (1960) suggests that floating need occur only at an ice face for water to gain access to tunnels which remain continuously open in the ice. In view of the work of Haefeli (1952) and others, there is serious question whether a tunnel would remain open. It should be noted that Summit Lake drained as rapidly when the drainings were close together as after a long period without draining (Fig. 5).

Liestøl (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. Mathews (in press) considered thermal conditions within the tunnel and inferred

> . . . . that of the 1.39 calories/cm³ 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.

Mathews' work on water temperatures in tunnels assumes that a lake water temperature of 0°C can be expanded to consider positive lake water temperatures in view of the findings reported above. The relation equating heat loss by conduction to the ice and advection from the tunnel to the heat content of the lake water and the heat generated due to the loss in potential energy is integrated to solve for the tunnel water temperature (Gilbert, 1969):

$$\Theta = \frac{Q_{ol}\,\rho_w\,g\,H}{h\,\pi\,D\,L}\left[1 - \exp\left(-\frac{h\,\pi\,D\,l}{Q_{ol}\,\rho_w\,c}\right)\right] + \Theta_l \cdot \exp\left(-\frac{h\,\pi\,D\,l}{Q_{ol}\,\rho_w\,c}\right)$$

where D is the tunnel diameter in metres
- Θ is the tunnel water temperature in °C
- Q_{ol} is the discharge in the tunnel in $m^3 s^{-1}$
- ρ_w is the density of water in kg m^{-3}
- H is the head in metres
- g is acceleration due to gravity
- h is the coefficient of head transfer in Wm^{-2} °C^{-1}
- L is the horizontal tunnel length in metres
- l is the horizontal distance down the tunnel in metres at which the temperature is taken
- c is the specific heat of water in kJ kg^{-1} °C^{-1}
- Θ_l is the lake water temperature in °C

The new values of temperature of water leaving the tunnel (at $l = L$), assuming positive temperatures of a lake water are shown in Figure 8. It can be seen that in the early stages of the drainings nearly all the heat content of the lake is advected to the ice. In the terminal stages the amount of heat advected drops to 35%.

To investigate the feasibility of tunnel enlargement by melting, the ice melt at any time during the drainings was

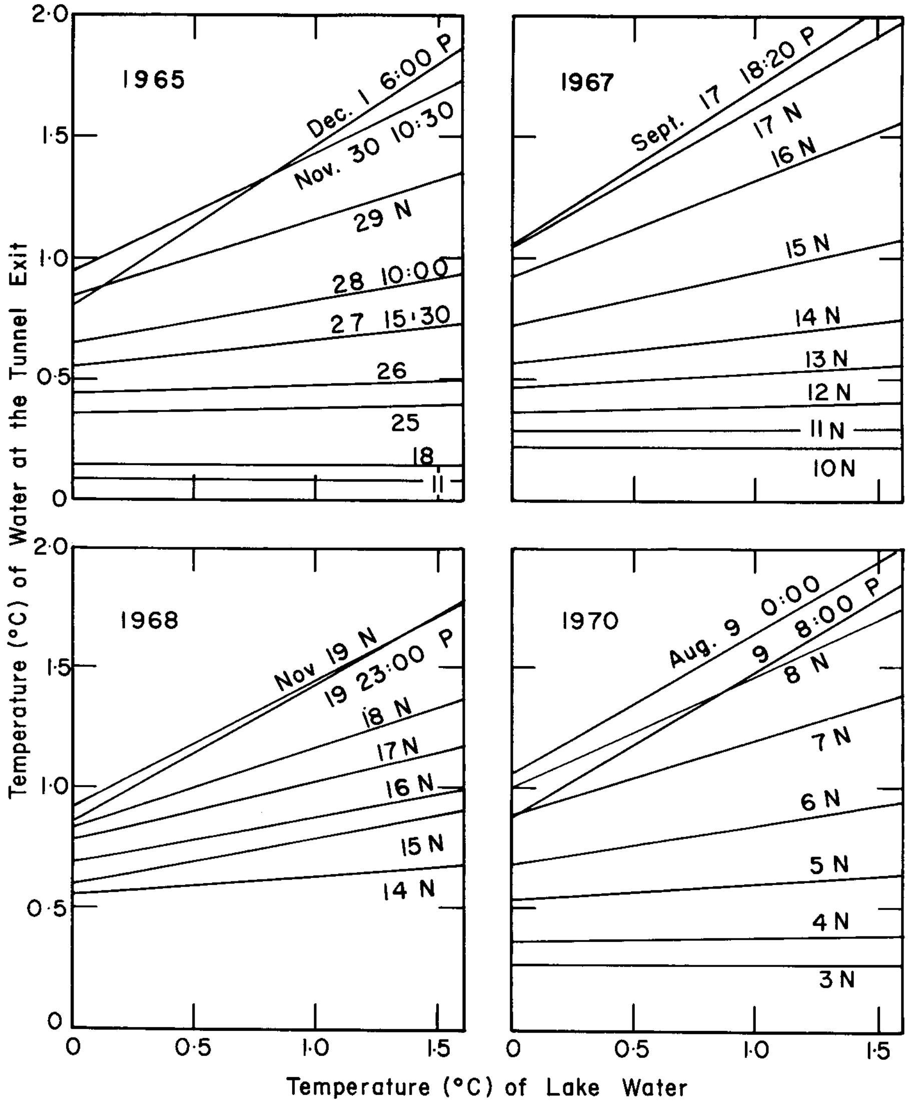

Figure 8. Calculated water temperatures at tunnel exit at given times during four drainings of Summit Lake

calculated as

$$M = \frac{\rho_w Q_{ol}}{\rho_i F} \left[gH + c\,(\Theta_l - \Theta) \right]$$

where M is the volume of ice melted in $m^3 s^{-1}$

ρ_w is the density of water and ρ_i is the density of ice in $kg\ m^{-3}$

Q_{ol} is the tunnel discharge in $m^3 s^{-1}$

F is the heat of fusion of ice in $J\ kg^{-1}$

H is the head in metres

c is the specific heat of water in $J\ kg^{-1}\ {}^\circ C^{-1}$

Θ and Θ_l are the temperatures of water at outlet and in lake in °C

As an approximation of ice melt between any two periods at which observations were made or estimated (Fig. 8) the average instantaneous melt was multiplied by the length of the time period. By equating these figures to the calculated rate of tunnel enlargement by Mathews' method (in press) and solving for lake water temperature, it was determined that the following lake water temperatures are required to explain tunnel enlargement due to melting:

November	1965	0.25°C
September	1967	0.9°C
November	1968	0.15°C
August	1970	1.1°C*

*Assuming discharges of 1500 $m^3 s^{-1}$ at 0000 hrs, August 9, and 2600 $m^3 s^{-1}$ at 0800 hrs, August 9.

The September 1967 and August 1970 temperatures are in reasonable agreement with measured temperatures of lake water even though the following assumptions were made: simple tunnel geometry (a single straight cylindrical tunnel), the lack of ice stoping by water, no closing of the tunnel by overburden pressure, the suitability of the coefficient of eddy conduction used by Mathews (in press), and in the last case, a peak discharge of 2600 $m^3 s^{-1}$. The two winter drainings require much lower lake temperatures. It is suspected that the water at the shallower north end of the lake which would pass through near the end of the draining is nearly 0°C in the winter considering the temperatures recorded in October 1968 (Fig. 7).

Even if the above is accepted as sufficient reason to allow draining at the observed rate once it has started, the water balance data indicate that there was an appreciable leak three months before draining began in 1968 and there is some evidence to suggest that the leak was larger in August than in July. However, it is not known if the lake had been leaking since the previous draining and if water found its way under the entire glacier before the 1961 draining.

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

All the five recorded drainings occurred between August and December. In 1970, draining did not occur until August even though the lake contained more water much earlier in the season than had been necessary to allow the 1968 draining. By the end of summer 1969, the lake was only seven metres below the level on the same date in 1968 but draining did not occur. This may represent a critical difference and explain why draining was postponed a year as a result.

Water temperatures are warmest in summer and fall. It may be that warmer water is required to enlarge the tunnel at a rate more rapid than the tunnel closure by the overburden of ice.

All this speculation indicates how limited is the understanding of the draining of ice-dammed lakes. The work described here provides the basis for a quantitative analysis. The inaccuracies in the water balance approach for this basin make the method unacceptable for more detailed study. To verify the proposed melt model, an accurate recording of outflow below the glacier is essential, together with direct observations of temperatures of water leaving the tunnel during floods. More information is required on the tunnel or tunnels including size, shape, depth, and route through the ice, rate of closing and hydraulic characteristics. Such information may become available as a result of advances in radar technology.

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APPENDIX 1

Summary of Daily Observations at Summit Lake in August 1967

Volume change ($\triangle V$) of Summit Lake, 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}

Date	$\triangle V$	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		92	210
Standard Deviation		39	94
Mean Depth (m x 10^{-2} day^{-1}		1.4	2.6

APPENDIX 2

Summit Lake: Water Balance Summary, 1968

Total inflow to the lake plus precipitation ($Q_i + P$); Volume change of Summit Lake ($\triangle V$), and the estimated leak (Q_{ol}) from Summit Lake through Salmon Glacier

Date		$Q_i + P$	$\triangle V$	Q_{ol}	
		$m^3 x 10^4 day^{-1}$	$m^3 x 10^4 day^{-1}$	$m^3 x 10^4 day^{-1}$	$m^3 sec^{-1}$
July	15	101.2	94.0	7.2	0.83
	16	93.5	91.2	2.3	0.26
	17	90.4	84.3	6.2	0.72
	18	82.5	80.8	1.8	0.20
	19	91.0	77.5	13.4	1.55
	20	97.9	92.0	5.9	.68
	21	98.1	84.8	13.3	1.54
	22	108.7	72.0	36.7	4.26
	23	112.7	91.7	21.0	2.44
	24	106.4	103.6	2.7	0.31
	25	104.9	103.6	1.2	0.13
	26	130.3	103.0	27.4	3.18
	27	120.5	95.4	25.1	2.91
	28	145.1	81.2	63.9	7.43
	29	105.1	98.8	6.3	.73
	30	94.2	83.3	10.9	1.26
	31	115.3	74.5	40.7	4.73
Aug.	1	113.4	81.7	31.8	3.69
	2	101.4	82.0	19.4	2.25
	3	92.5	83.4	9.1	1.05
	4	91.6	66.0	25.6	2.97
	5	104.6	81.2	23.4	2.72
	6	86.8	62.4	24.4	2.83
	7	75.7	61.9	13.8	1.60
	8	72.9	52.8	20.1	2.33
	9	86.9	61.0	25.9	3.01
	10	88.4	57.9	30.5	3.54
	11	89.6	61.0	28.5	3.31
	12	84.8	61.8	22.9	2.66
	13	87.9	62.6	25.4	2.95
	14	102.7	78.5	24.4	2.83
	15	107.5	78.9	28.6	2.32
	16	101.5	47.3	54.1	6.29
	17	91.0	60.9	30.1	3.50
	18	80.8	56.5	24.3	2.82
	19	71.9	57.3	14.6	1.69
	20	76.4	54.6	21.8	2.53
	21	86.2	68.7	17.6	2.04
	22	145.9	94.8	51.1	5.94

Summit Lake: Water Balance Summary, 1968 (Cont'd)

Date	$Q_i + P$ $m^3 x10^4 day^{-1}$	ΔV $m^3 x10^4 day^{-1}$	Q_{o1} $m^3 x10^4 day^{-1}$	$m^3 sec^{-1}$
23	91.0	52.5	38.5	4.47
24	72.3	48.5	23.8	2.76
25	63.2	41.0	22.2	2.58
26	49.1	33.7	15.4	1.79
27	46.8	45.1	1.7	0.19
28	116.5	78.3	38.2	4.44
29	170.9	127.1	43.8	5.09
30	142.2	103.6	38.6	4.48
31	183.9	132.5	51.4	5.97

APPENDIX 3

Summit Lake: Water Temperatures (°C), 1968 and 1969

NORTH SECTION

Depth Metres	1968					
	July 25	July 31	Aug 13	Aug 27	Aug 27	Sept 22
0.0	2.0	1.7	1.5	1.0	1.2	0.0
1.5	1.8	1.5	1.6	1.0	1.2	0.6
3.0	1.8	1.6	1.4	1.0	1.2	0.6
4.6	1.8	1.6	1.4	0.9	1.1	0.6
6.1	1.8	1.5	1.4	0.9	1.2	0.6
7.6	2.0	1.5	1.4	0.9	1.1	0.6
9.1	2.5	1.6	1.4	0.8	1.2	0.6
10.7	2.5	1.6	1.4	0.8	1.2	0.8
12.2	2.6	1.8	1.4	0.8	1.1	0.8
13.7		2.1	1.4	0.9	1.1	0.8
15.2		2.2	1.4	1.0	1.2	0.9
16.8			1.5	1.2	1.2	1.1
18.3			1.6	1.2	1.2	
19.8			1.6	1.2	1.2	
21.3				1.2	1.2	
22.9				1.2	1.2	
24.4					1.3	

NORTH CENTRAL SECTION

Depth Metres	1968						
	July 25	July 25	July 31	Aug 13	Aug 13	Aug 27	Sept 22
0.0	1.8	1.1	0.6	1.2	1.0	0.8	0.7
1.5	1.7	1.0	0.6	1.2	0.8	0.8	0.7
3.0	1.6	0.9	0.6	1.0	0.9	0.7	0.7
4.6	1.6	0.9	0.8	1.0	0.8	0.7	0.7
6.1	2.0	1.2	0.8	1.0	0.8	0.7	0.7
7.6	2.0	1.5	0.8	1.0	0.8	0.7	0.7
9.1	2.0	1.8	1.3	0.9	0.8	0.7	0.7
10.7	2.1	1.9	1.4	0.9	0.8	0.7	0.7
12.2	2.2	1.8	1.4	1.0	0.8	0.7	0.7
13.7		1.8	1.6	1.0	0.8	0.8	0.7
15.2			1.6	1.0	0.8	0.9	0.7
16.8				1.1	0.8	1.0	0.7
18.3				1.2	0.8		0.7
19.8				1.5	0.8		0.8
21.3							0.9

CENTRAL SECTION

Depth Metres	1968						
	July 6	July 13	July 13	July 18	Aug 27	Sept 22	July 18
0.0	0.5	0.4	0.3	0.4	0.8	0.9	0.6
1.5	0.4	0.3	0.3	0.4	0.6	0.8	0.4
3.0	0.4	0.2	0.2	0.4	0.4	0.8	0.3
4.6	0.2	0.2	0.2	0.4	0.6	0.7	0.3
6.1	0.2	0.2	0.3	0.4	0.6	0.6	0.4
7.6	0.1	0.2	0.3	0.4	0.5	0.6	0.4
9.1	0.2	0.2	0.3	0.4	0.6	0.6	0.4
10.7	0.2	0.2	0.3	0.5	0.6	0.6	0.4
12.2	0.2	0.2	0.3	0.6	0.6	0.6	0.4
13.7	0.2	0.2	0.3	0.6	0.6	0.6	0.4
15.2	0.2	0.2	0.3	0.6	0.6	0.6	0.4
16.8	0.2	0.2	0.3	0.5	0.6	0.6	0.4
18.3	0.2	0.3	0.3	0.4	0.6	0.6	0.4
19.8	0.2	0.3	0.3	0.4	0.6	0.6	0.4
21.3		0.3	0.3	0.4	0.6	0.6	0.4
22.9		0.3	0.3	0.4	0.7	0.6	0.4
24.4		0.3	0.3	0.4	0.7	0.6	0.4
25.9		0.3	0.3		0.7	0.6	0.4
27.4		0.3	0.4		0.7	0.6	0.4
29.0		0.3	0.4		0.7	0.6	0.4
30.5		0.4	0.4		0.8	0.6	0.4
32.0		0.4	0.4		1.1	0.6	0.4
33.5		0.4	0.4		1.2	0.6	0.4
35.0		0.4	0.4		1.4	0.6	0.4
36.6		0.4	0.4			0.6	0.4
38.1		0.4	0.5			0.6	0.5
39.6		0.5	0.6			0.6	0.5
41.1		0.5				0.7	
42.7		0.6				0.7	
44.2						0.7	
45.7						0.7	
47.2						0.7	
48.8						0.8	

SOUTH SECTION

Depth Metres	1968				
	Aug 9	Aug 16	Aug 16	July 12	July 16
0.0	0.4	0.5	0.5	0.1	0.7
1.5	0.4	0.5	0.4	0.1	0.7
3.0	0.4	0.4	0.4	0.2	0.4
4.6	0.4	0.4	0.4	0.5	0.4
6.1	0.4	0.4	0.4	0.7	0.4
7.6	0.4	0.4	0.4	0.7	0.4
9.1	0.3	0.4	0.4	0.6	0.4
10.7	0.3	0.4	0.4	0.6	0.4

SOUTH SECTION (Cont'd)

Depth Metres	1968				
	Aug 9	Aug 16	Aug 16	July 12	July 16
12.2	0.4	0.4	0.4	0.6	0.4
13.7	0.4	0.4	0.4	0.6	0.4
15.2	0.4	0.4	0.4	0.6	0.4
16.8	0.4	0.4	0.4	0.6	0.4
18.3	0.4	0.4	0.4	0.6	0.4
19.8	0.4	0.4	0.4	0.6	0.4
21.3	0.4	0.4	0.4	0.6	0.4
22.9	0.4	0.4	0.4	0.6	0.4
24.4	0.4	0.4	0.4	0.6	0.4
25.9	0.4	0.4	0.4	0.6	0.4
27.4	0.4	0.4	0.4	0.6	0.4
29.0	0.4	0.4	0.4	0.6	0.4
30.5	0.4	0.5	0.4	0.6	0.4
32.0	0.4	0.5	0.4	0.6	0.4
33.5	0.4	0.6	0.4	0.7	0.4
35.0	0.4	0.6	0.4	0.7	0.4
36.6	0.4	0.6	0.5	0.7	0.4
38.1		0.6	0.5	0.7	0.4
39.6		0.6	0.5	0.7	
41.4		0.6	0.5		
42.7		0.6	0.6		
44.2		0.6	0.6		
45.7		0.6	0.6		
47.2		0.6	0.6		
48.8		0.5	0.6		
50.3		0.5	0.6		
51.8		0.6	0.6		
53.3		0.6	0.6		
54.9		0.6	0.6		
56.4		0.6	0.6		
57.9		0.6	0.6		
59.4		0.6	0.6		
61.0		0.6	0.6		
62.5		0.6	0.6		
64.0		0.6	0.6		
65.5		0.6	0.6		
67.0		0.6	0.6		
68.6		0.6	0.7		
70.1		0.6	0.7		
71.6		0.6	0.7		
73.2		0.6	0.7		
74.7		0.6	0.7		
76.2		0.7	0.7		
77.7		0.7	0.7		
79.2		0.7	0.7		
80.8		0.7	0.7		
82.3		0.8	0.8		
83.8		0.8	0.8		
85.3		0.8	0.8		

SOUTH SECTION (Cont'd)

Depth Metres	1968				
	Aug 9	Aug 16	Aug 16	July 12	July 16
86.9		0.8	0.8		
88.4		0.7	0.8		
89.9		0.8	0.8		
91.4		0.8	0.8		
93.0		0.8	0.8		
94.5		0.8	0.8		
96.0		0.8	0.8		
97.5		0.8	0.8		
99.1		0.8	0.8		
100.6		0.8	0.8		
102.1		0.8	0.8		
103.6		0.8	0.8		
105.2		0.8	0.8		
106.7		0.8	0.8		
108.2		0.8	0.8		
109.7		0.8	0.8		
111.3		0.8	0.8		
112.8			0.8		
114.3			0.8		
115.8			0.8		
117.3			0.8		
118.9			0.8		
120.4			0.8