PERMAFROST AND LAKES IN THE MACKENZIE DELTA

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Abstract

An unusual feature of the Mackenzie Delta, compared to temperate deltas, is an extensive network of lakes. Permafrost plays an important role in controlling this high density of lakes. It influences the development of depressional basins, and ensures an adequate supply of water so that lake basins retain water and therefore do not freeze to the bed during the winter.

Permafrost has two contrasting effects on water availability. First, the high infiltration capacity of the frozen soils and the large heat flux into the underlying permafrost limit snow melt runoff into the lakes. Second, permafrost eliminates groundwater flow from the lakes, thereby reducing the water required to sustain the lakes. Detailed water balance measurements have shown that over the last 5 years the supply of water is similar in magnitude to the loss of water, enabling the lakes to remain perched above the surrounding channel system. Without permafrost, however, it is likely that groundwater outflow would dominate and these perched lakes would not be viable.

Résumé

Le delta du Mackenzie se distingue des deltas des climats tempérés par un réseau complexe de lacs. Le pergélisol joue un rôle important dans le contrôle de cette forte densité de lacs. Il influence le développement des dépressions du relief et assure une alimentation adéquate en eau de sorte que les bassins des lacs retiennent l'eau et ne gèlent donc pas jusqu'au fond en hiver. Le pergélisol a deux effets contrastants sur la disponibilité de l'eau. Premièrement, la grande capacité d'infiltration des sols gelés et les importants flux de chaleur dans le pergélisol sous-jacent limitent l'écoulement des eaux de fonte des neiges vers les lacs. Deuxièmement, le pergélisol empêche l'écoulement d'eaux souterraines depuis les lacs, diminuant ainsi la quantité d'eau requise pour maintenir leur niveau. Des mesures détaillées du bilan hydrique ont montré qu'au cours des 5 dernières années, l'alimentation en eau se compare en volume à la perte d'eau, ce qui permet au niveau des lacs de se maintenir au-dessus du niveau du réseau de canaux fluviaux environnant. Sans le pergélisol, il est toutefois probable que le bilan des eaux souterraines serait négatif et que ces lacs ne pourraient se maintenir ainsi perchés.

Introduction

An important feature of the Mackenzie Delta is the large number of lakes covering approximately 25% of its surface. Lewis (1988) noted that most arctic/subarctic deltas have high concentrations of lakes, while most large deltas in other climate zones do not. In the latter, interdistributary zones are dominated by marshes and swamps. Since high concentrations of lakes seems to be unique to arctic/subarctic deltas, it suggests that lake formation and evolution are affected by processes which are unique to northern climates. There are a number of possible factors, including slow accumulation of organic material due to low productivity or the occurrence of bottom fast ice in lakes and offshore areas where progradational lakes are forming. However, the most notable difference between arctic deltas and those occurring in other environments is the presence of permafrost.

Lewis (1988) outlined a number of ways in which permafrost may affect the development of lakes. These include accentuating existing relief between permafrost and non-permafrost areas due to frost heave, initiation of lake basins due to thermokarst activity, expansion of existing lake basins by thermokarst action, limitation of sediment consolidation because of the incompressibility of perennially frozen ground, and limitation of channel migration due to the increased stability of frozen banks.

Once a lake basin has formed, the importance of the lake to the ecosystem is dependent on an adequate supply of water. This means that the lake must retain water throughout the years, and must have sufficient water depth to prevent freezing to the bed during winter. Since Mackenzie Delta lakes are often only 1 to 1.5 m in depth and form a winter ice cover of approximately 0.6 m in thickness, only a small decrease in water depth would result in lakes freezing to the bed.

For low elevation lakes (often called no-closure lakes), water supply is not a problem since a channel connection to a main delta channel assures an adequate supply of water. Lewis (1988) found that no-closure lakes account for 24% of all lakes in the Mackenzie Delta, and the remaining 76% of lakes are closure lakes. Lewis (1988) suggested that most of these closure lakes are of thermokarst origin. These closure lakes are perched above the main channels and only receive water from the Mackenzie River during brief flood periods. As a result, they are more susceptible to water shortages. For these lakes, permafrost plays an important role in assuring a sufficient supply of water. The purpose of this paper is to analyze the role of permafrost in the hydrologic regime of lakes in the Mackenzie Delta.

The role of permafrost in the hydrologic regime of delta lakes

STUDY AREA, METHODOLOGY, AND LAKE WATER BALANCE

Field work was conducted at a small lake (unofficial name is NRC Lake) (0.069 km²), approximately 5 km southwest of Inuvik. The permafrost distribution around and beneath the lake was determined by Johnston and Brown (1964). NRC Lake has closure (at 3.8 m a.s.l.) as defined above, probably has a thermokarst origin, and is typical of many small perched lake basins.

The NRC Basin is approximately 0.43 km² in area, and is bowl shaped with the highest elevations (6.5 m a.s.l.) around the outside of the bowl (Figure 1) and lowest elevations (2.5 m a.s.l.) in the central portion of the basin. The central part of the basin is occupied by NRC Lake, which has a mean and maximum water depth in late summer of 0.88 and 1.6 m respectively, and a mean late summer water level of approximately 3.8 m a.s.l..

Lake basins, such as the NRC Basin, only accumulate water if they have a positive water balance. The principal water balance components are given by

$$P + E + Q_o + Q_{in} + Q_{sp} + Q_{sb} + Q_s = ds/dt \qquad (1)$$

where P is precipitation on the lake surface, E is evaporation from the lake surface, Q_o and Q_{in} are channel discharge into and out of the lake, Q_{sp} and Q_s are suprapermafrost groundwater and surface rill flow from the surrounding basin, Q_{sb} is subpermafrost groundwater flow through the talik beneath the lake, and ds/dt is the change in lake storage.

Marsh and Hey (1989) found that on average NRC Lake is flooded annually for a 19 day period in late May and early June. Flooding during the remainder of the summer is infrequent, with an estimated return period of 18 years. Between flooding events (usually an 11 month period for NRC Lake) the water balance simplifies to

$$P + E + Q_{sp} + Q_{sb} + Q_s = ds/dt \qquad (2)$$

Between flooding events, permafrost plays an important role in controlling both the supply of water to the lake from the surrounding basin (Q_{sp}, Q_s) and the loss of water from the lake (Q_{sb}).

In order to determine the magnitude of the components in equation 2, a study of the hydrologic regime of NRC Lake was carried out during the period 1984 to 1989. Precipitation was measured at sites in the centre of NRC Lake and beneath the forest canopy surrounding the lake. Evaporation from the lake and forest was calculated from the Priestley-Taylor approach (Marsh and Bigras, 1989; Rouse *et al.*,1977) using micrometeorological measurements made over both the lake and forest canopy. Runoff from the basin was determined by observing 7 groundwater wells around the perimeter of the lake and a single rill which drains approximately 5 % of the NRC basin (Figure 1). In addition, measurements of initial snow cover and melt infiltration were performed at a site within this sub-basin, with infiltration determined from twin probe gamma density measurements (Marsh, 1989). Groundwater flux through the talik beneath NRC Lake was measured using piezometers installed at depths of 3.8, 4.4, and 5.7 m beneath the centre of the lake. The final term in equation 2, change in lake storage, was determined from measurements of lake level.

BASIN RUNOFF

Field observations have shown that snow melt runoff from the NRC Basin to NRC Lake is usually negligible. Over the 6 year study period, only 1989 experienced significant snow melt runoff. During the other years, observations demonstrated that there was no surface flow emanating from residual snow banks and that there was no surface flow in the small rills draining the NRC Basin. In addition, measurements of lake level showed no appreciable rise in water level prior to lake flooding.

The lack of snow melt runoff is due primarily to the large infiltration capacity of the frozen soils in the NRC Lake basin. For example, during the spring of 1987 the snow water equivalent immediately before the beginning of melt was 92 mm. Of this, 8 mm sublimated and 75±16 mm infiltrated into the frozen soil (Marsh, 1989). This is in agreement with visual observations that the majority of the melt water infiltrated the soils, leaving little or no water for runoff. The high infiltration capacity of these silt/clay soils is due to their low soil moisture at freeze-up and the large soil macropores.

Due to the low hydraulic conductivity of the frozen soils (ie. Smith, 1985), the suprapermafrost groundwater flux does not begin until the active layer thawes. However, since the active layer thaws gradually, the release of infiltrated melt water is distributed over the entire summer period. This long lag time between the infiltration of meltwater into the soils and its availability for evaporation or runoff is due primarily to the cold ground temperatures and large ground heat flux which slows the thawing of the active layer and therefore the release of water. Only a small portion of this water reaches NRC Lake as runoff during the summer since:

(1) direct suprapermafrost groundwater flow to the lake is impeded by a small levee which extends around the lake shoreline. The only route with which suprapermafrost ground water flow may reach the lake is through the 9 small rills which cut through the levee (Figure 1). Since these rills have a small cross sectional area the amount of suprapermafrost groundwater flow to the lake is small. In 1984 for

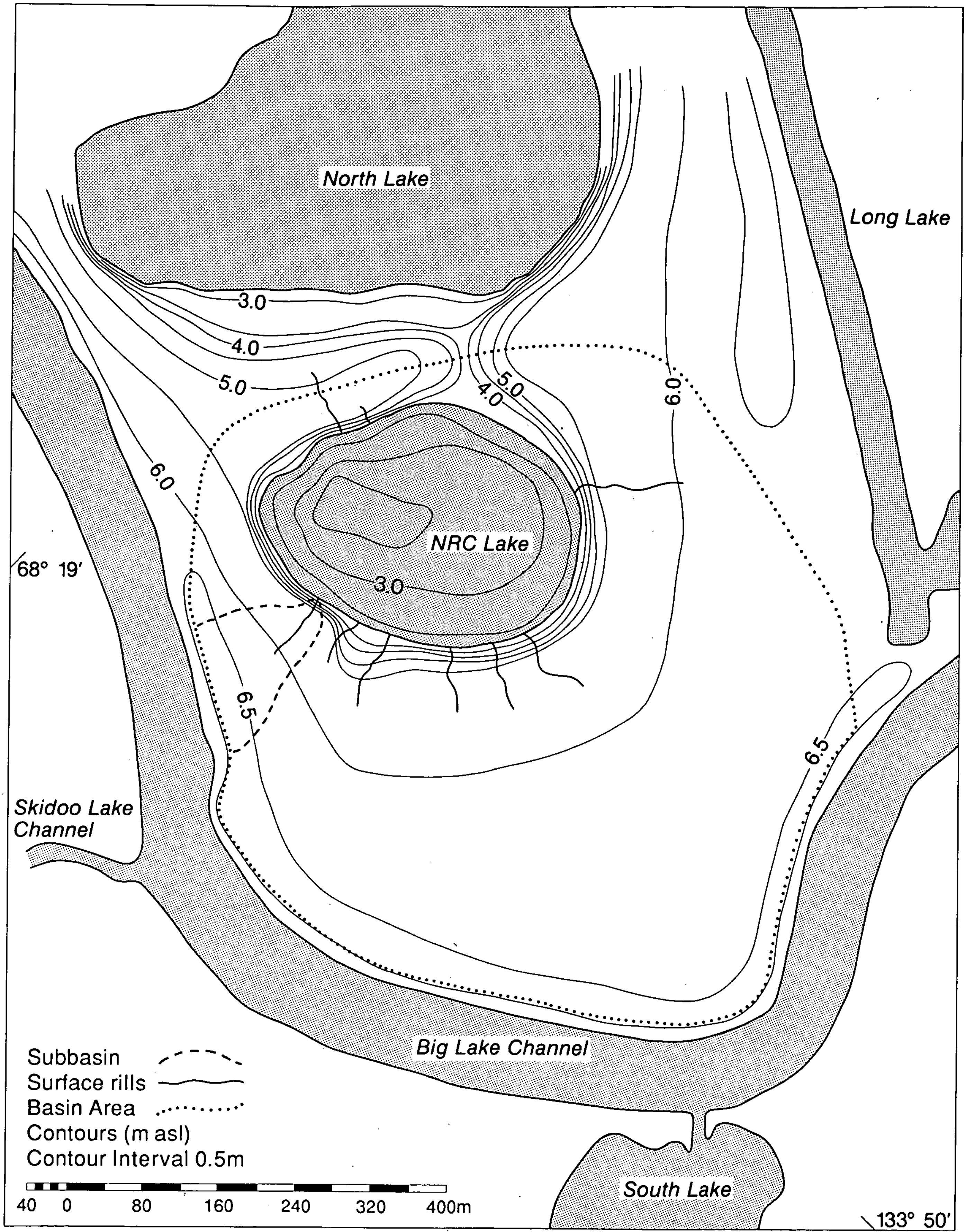

Figure 1. Topographic map of NRC Lake basin. The dotted line extending from the western side of NRC Lake indicates the approximate boundary of the sub-basin studied in detail.

example, it totalled only 2 mm averaged over the basin area, adding approximately 10 mm of water to the lake area.

(2) surface flow has never been observed in any of the 9 rills during the summer period.

(3) calculations suggest that evaporation is similar in magnitude to the initial snow water equivalent plus summer rainfall. In 1984, for example, assuming an α=1.13 for a forest site (Rouse *et al.*, 1977), basin evaporation was 150 mm. This can be compared to the total snow storage in the basin at the end of winter (100 mm) and rainfall measured at NRC Lake (91 mm) for a total of 191 mm. It is believed that the 41 mm of water which did not evaporate was stored in the active layer when measurements ceased in early September 1984.

Water balance calculations for NRC Lake (Marsh and Bigras, 1989; Marsh, 1986) demonstrate that runoff from the basin to the lake during July and August is negligible, thereby substantiating the claim that summer runoff to the lake is limited by the high infiltration capacity of the frozen soils, slow release of this melt water as the active layer thaws, and a high evaporation rate from the forest.

As mentioned above, snow melt runoff was only observed during the spring of 1989. It is interesting to contemplate the factors responsible for producing this event. Snow melt runoff only occurs if the snowmelt rate is larger than the infiltration rate, and/or the snow pack water equivalent is larger than the infiltration capacity of the frozen soil. This latter condition may occur when (a) there is high soil moisture at freeze-up thereby limiting the pore space available for water transport, (b) there is above normal snow storage at the end of winter, or (c) ground temperatures are colder than normal. Lower ground temperatures result in more rapid freezing of infiltration water and therefore sealing of pore spaces in the near surface layers, thereby limiting further infiltration. One possible mechanism for having colder than normal soil temperature during the melt period is for a rapid switch from "winter" to "spring".

Table 1 compares these factors for each of the study years. Since measurements of soil moisture at freeze-up were not available, precipitation during the two months (August and September) prior to freeze-up is used as an indication of soil moisture in Table 1. 1989 does not exhibit extreme values for any of these factors. Instead it appears that subtle variations in a number of factors combined to produce snowmelt runoff. For example, 1989 had near normal precipitation prior to freeze-up, had the second largest snow fall, followed by relatively low air temperatures immediately prior to the beginning of melt, followed by a sudden increase in air temperature on May 21. The following 7 day period had the warmest temperatures and therefore most rapid melt during any 7 day period immediately after the start of melt during the 6 year study period. It is hypothesized that this sequence of events led to the infiltration of melt water into colder than normal soil, and therefore soil with a lower infiltration capacity. In addition, since the daily snowmelt rates during the first week of melt were higher than during any other melt period, it is possible that the melt rates were larger than the infiltration rates. This combination of lower infiltration capacity and melt rates exceeding the infiltration rates would have limited the proportion of snow melt which was able to infiltrate the soil, thereby increasing runoff to the lake.

SUBPERMAFROST GROUNDWATER FLOW

Since NRC Lake is perched approximately 3 m above the surrounding channel system, groundwater flow from the lake to the channels would be expected. However, Johnston and Brown (1964) found that the southwest portion of NRC Lake has permafrost extending below 70 m, that the zone beneath NRC Lake is unfrozen, and that bedrock occurs at a depth of 70 m. These data suggest that the talik beneath the lake is a closed system with little groundwater flow to a regional sub-permafrost system. Temperature simulation by Smith (1975) for a lake/land/channel system similar to NRC Basin show that if the land between two water bodies is sufficiently narrow, permafrost will not extend to the depth of bedrock found at NRC Lake (Figure 2). Given that the land separating NRC Lake and North Lake is approximately 100 m in width, it is likely that the talik beneath NRC Lake is completely isolated. However, since there are no measurements of permafrost thickness in this point of the basin, the following field measurements and laboratory

Table 1
Precipitation and air temperatures at NRC Lake for 1984 to 1989.

	Precipitation (mm)		Air Temperature (°C)		
	Aug - Sept of previous yr.	Oct 1 - May 15	Date Daily mean rises above 0 °C[1]	Mean temp before melt[2]	Mean temp after melt[3]
1984	63.5	91.7	May 14	-3.2	+3.9
1985	77.2	94.7	May 16	-2.7	+4.7
1986	34.7	95.9	May 29	-4.2	+6.6
1987	67.3	137.9	May 22	-6.3	+4.3
1988	84.7	102.4	May 11	-6.7	+2.4
1989	66.9	115.6	May 21	-5.7	+7.2
mean 1951-80	67.5	132.7	May 21	---	---

note: (1) first day that air temperatures are consistently above 0 °C.
(2) mean air temperature for the 10 day period prior to temperature rising above 0 °C.
(3) mean air temperature for the 7 day period after temperature rises above 0 °C.

calculations were performed in order to determine if there is groundwater leakage from NRC Lake.

Piezometer measurements over a 3 year period showed that the hydraulic head was nearly constant with depth, indicating little to no groundwater flow. As a result of small errors in measuring the exact depth of the piezometer and in measuring the water level in the piezometer, the exact pressure gradient could not be determined. However, the measurements did demonstrate that if a hydraulic gradient existed, it was very small.

In order to confirm the piezometer measurements, a flow net analysis of groundwater flow was carried out. This analysis assumed that permafrost extended to bedrock around the west, south and east edges of the lake, but below the narrow strip of land between NRC Lake and the lake immediately to the north (unofficially called North Lake) the permafrost was only 60 m in thickness (similar to that shown in Figure 2), therefore allowing a 10 m thick non-frozen zone immediately above bedrock. This would allow groundwater flow from NRC Lake to North Lake through a 200 m wide section along the north shore of the lake. Since the sediments beneath NRC Lake are composed primarily of silts, with some clays and sands (Johnston and Brown, 1965), they have a low hydraulic conductivity estimated at between 10^{-8} and 10^{-6} m/s (Freeze and Cherry, 1979). Flow net calculations indicate that the flow from NRC Lake to North Lake range from 0.07 to 7.0 mm/year depending on the hydraulic conductivity.

A further check on the magnitude of groundwater flow from NRC Lake was carried out by comparing lake water levels prior to freeze-up in September to those at the end of winter (May). If substantial groundwater flow was occurring, then the lake level should drop over the 8 month winter period. Measurements have shown that lake levels increased over the winter due to the accumulation of snow on the lake ice cover. Errors involved in the measurement of snow storage make it impossible to say conclusively if there was any groundwater flow from the lake over the winter period, however, it could not be more than 10 mm.

These measurements and calculations do not conclusively show that there is no groundwater flow from NRC Lake, but they indicate that if flow occurs, its magnitude must be very small.

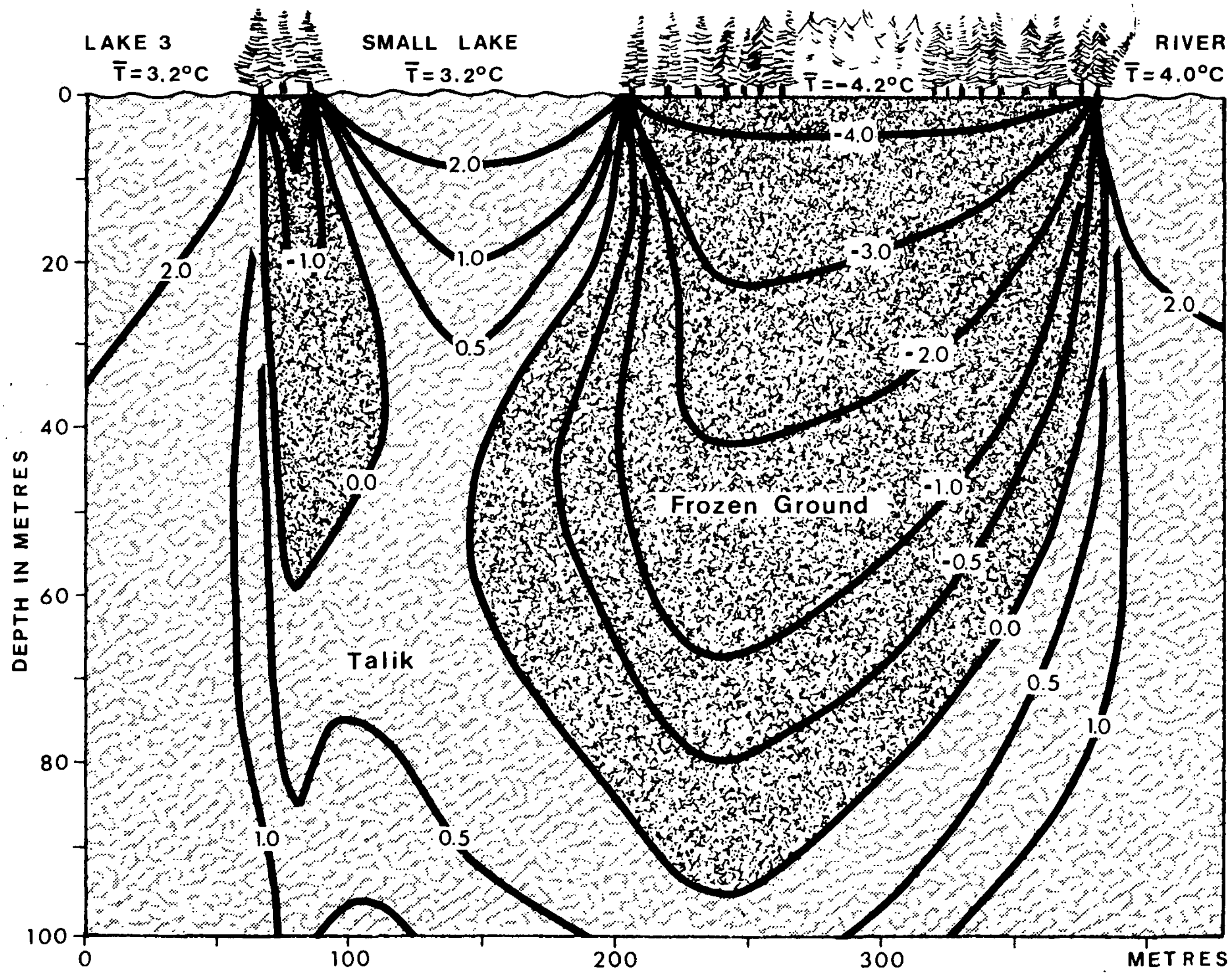

Figure 2. Computed temperatures and permafrost occurrence beneath a lake/land/channel system similar to NRC Lake. Bedrock occurs at a depth of 70 m at NRC Lake. (from Smith, 1975)

Discussion

The above sections have demonstrated two important effects of permafrost on the hydrology of NRC Lake. First, the high infiltration capacity of the frozen soils, in combination with the occurrence of permafrost and high evaporation rates, limit snowmelt and rainfall runoff from NRC Basin. Estimates suggest that less than 10% of annual precipitation is available for runoff. This is considerably lower than for most permafrost basins where rainfall runoff ratios are generally well above 10% (Newbury, 1974). Since runoff is small, the main source of water to NRC Lake between flooding events is precipitation directly onto the lake surface. Second, the thick permafrost, which extends below bedrock around much of NRC Lake, in conjunction with low hydraulic conductivity silts, limits groundwater flow from the lake.

This combination of low basin runoff and low groundwater discharge implies that between flooding events, NRC Lake level is controlled primarily by the balance between precipitation directly onto the lake surface and evaporation from the lake. Since annual precipitation averages only 266 mm/year and summer lake evaporation for NRC Lake is 230 mm/year (Marsh and Bigras, 1989), NRC Lake experiences a relatively stable water level over the 11 month period between flooding events.

Lakes with a higher sill elevation than NRC Lake have flooding return periods of up to 5 years. Assuming that the processes controlling water supply and loss at these lakes are the same as at NRC Lake, their water balances must rely solely on the balance between precipitation and evaporation. These lakes are more sensitive to long term fluctuations in precipitation and evaporation and therefore experience larger variations in lake level (eg. see Marsh and Bigras, 1989).

Without permafrost, the hydrologic regime of the delta lakes would change considerably. Snowmelt runoff from the basins to the lakes may increase due to warmer soil temperatures, but so would the groundwater flow from the lakes. Although it is difficult to calculate the relative magnitude of these two contrasting effects, it is unlikely that the high-closure lakes would retain the present stable water level regime. Instead lake levels would be characterized by rapid infilling during non-annual flooding events, followed by a rapid decline in water level due to large groundwater and evaporative losses. Moderate elevation lakes, like NRC Lake, would become seasonal, filling during the spring flood, but experiencing sharp drops in water level over the summer and winter. Higher elevation lakes would become intermittent, filling only during non-annual floods, then drying up until the next flood.

Conclusions

Permafrost plays an important role in the formation of lake basins in the Mackenzie Delta. During the formation of progradational lakes, the aggradation of permafrost accentuates the height of levees surrounding the lake. Although it has often been assumed that thermokarst lakes are not common in the Mackenzie Delta, recent work by Lewis (1988) suggests that in fact a majority of lakes may be of this origin.

Since thermokarst lakes are generally perched above the surrounding channel system they do not receive flood water from the Mackenzie River on an annual basis. In the delta near Inuvik, the frequency of flooding of these lakes varies from just over one year to five years. Analysis of six years of field data have shown that permafrost has two contrasting effects on the water supply of these lakes between flooding events. First the high infiltration capacity of the soil and the large heat flux into the permafrost limit snowmelt runoff. At NRC Lake, for example snowmelt runoff has only been observed in once in six years. Second, the great thickness of permafrost eliminates groundwater flow from the lakes. As a result, water is available to the lakes and the amount of water required to maintain stable water levels is reduced. Without permafrost these lakes would experience a profoundly different hydrologic regime, and probably would not maintain stable water levels.

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