Lakes and Water in the Mackenzie Delta

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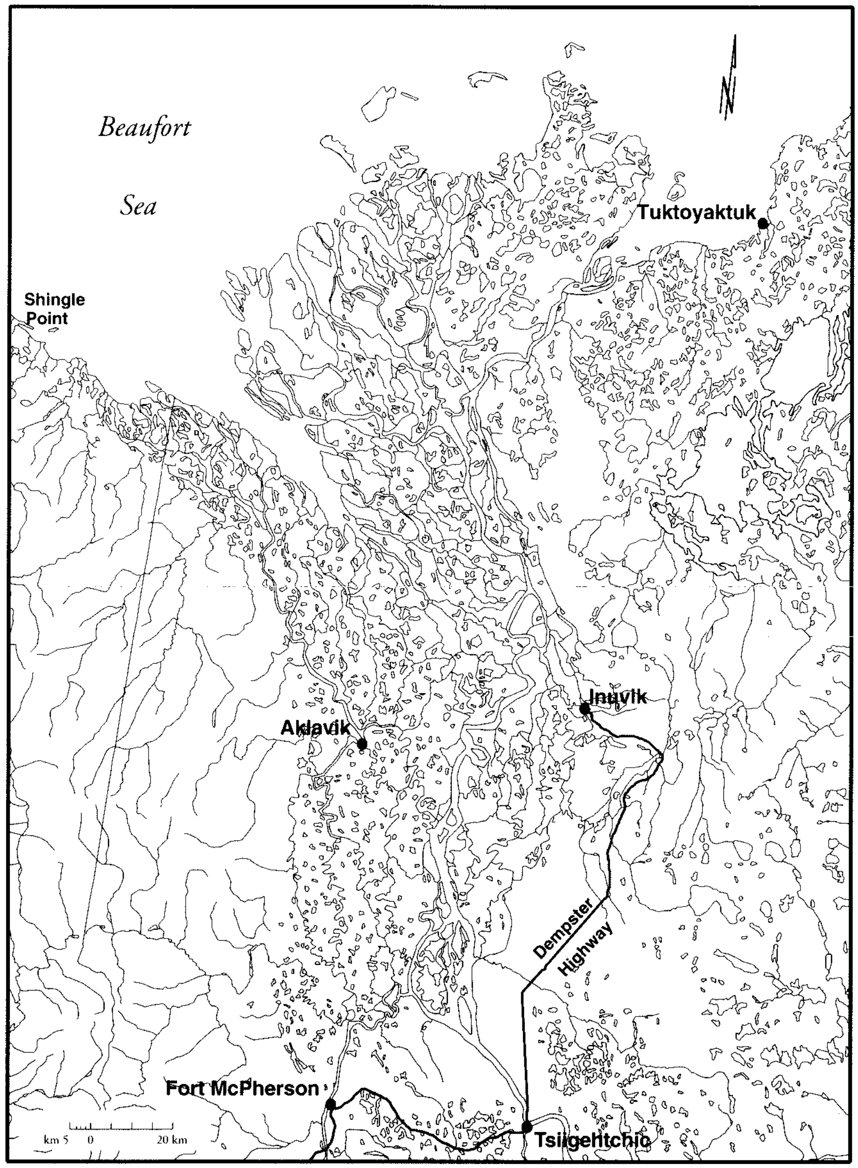

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Glossary

Channel - a natural passageway or water course connecting two bodies of water.

Climate - long term (over 30 years) average in temperature, humidity, and wind for example.

Delta - an accumulation of sediment where a river enters a lake or ocean. The shape and size of a delta are controlled by the climate, the water discharge of the river, the amount of sediment supplied by the river, the size of the waves, the current and the tides in the receiving body of water.

Evaporation - the change of state from liquid to water vapour.

Groundwater - the water beneath the surface of the ground. In northern Canada much of the groundwater is frozen as ice within permafrost. However, since the area beneath the channels and lakes in the Mackenzie Delta are not frozen, groundwater movement may occur through these zones.

Hydrology - the scientific study of the portion of the earth that is water, in liquid, frozen, or vapour form, as it moves or is distributed on the earth's surface, under the ground, or in the atmosphere.

Ice Jams - occur in river channels when floating ice is blocked at a constriction in the channel. The resulting partial blockage of the channel can lead to very high water levels upstream of the jam (see text box for further details).

Lake sill elevation - the elevation that a lake is perched above the main channels of the delta.

Mean sea level - the average elevation of the sea surface (see text box for further details).

Negative water balance - water flows out of the lake or evaporates from the lake faster than it is replaced by rainfall or runoff into the lake. As a result, the lake water level declines.

Net radiation - the difference between the incoming and outgoing electromagnetic radiation received by a surface. The incoming radiation includes the visible radiation from the sun as well as the infrared radiation emitted by the atmosphere and clouds. The outgoing radiation includes the visible radiation reflected by the surface and the infrared radiation emitted by the surface.

Permafrost - ground that has a temperature of below 0°C for more than two years. The ground may or may not contain ice. The Mackenzie Delta is located within the Continuous Permafrost zone. However, permafrost often does not occur below the channels or lakes in the delta.

Positive water balance - the opposite of negative water balance, where the amount of water added to the lake is larger than that leaving the lake due to evaporation or runoff. As a result, lake level increases.

Radiation - electromagnetic energy that travels as a wave. Radios and TVs receive programmes by radiation. Visible light is also a type of electromagnetic radiation. All material emits electromagnetic radiation with the wavelength of the emitted radiation dependent on the temperature of the body. In the case of the sun, the wavelength is in the visible range of humans. In the case of most natural surfaces, the radiation has a longer wavelength and is in what is called the infrared range.

Return period - the average time between extreme events. Bridges and culverts often are designed to resist a so-called 1 in 100 year flood event. Over a long period of time, say 500 years, a 1 in 100 year flood would be expected to occur 5 times. However, it is possible to have a number of these events within a fairly short period of time, followed by a long period of time with no events of this size.

Storm surge - short term rise in sea level due to strong offshore winds (see text box for further details).

Talik - an unfrozen zone through the permafrost.

Tides - the periodic rise and fall of the waters of the ocean and its inlets, produced by the attraction of the moon and sun, and occurring about every 12 hours. In the Beaufort Sea the maximum tidal range is approximately 0.37 m.

Transpiration - the passage of liquid water through a plant from the roots through the vascular system to the atmosphere as water vapour.

Weather - day to day variations in temperature, humidity and wind, for example.

Uniqueness and Importance of the Mackenzie Delta

The Mackenzie Delta is an extremely important and unique area. It is the largest delta in Canada and the second largest northern delta in the World, smaller only than the Lena Delta in northern Russia. The Mackenzie Delta is 210 km in length, has an average width of 62 km (Figures 1 and 2), and is 12,995 km^2 in area (over twice as large as Prince Edward Island). It has formed by the slow and still ongoing deposition of sediment into a shallow bay.

To determine how thick the sediment of the Mackenzie Delta is, and to help understand how long it has taken for the delta to form, four drill holes were bored into the ground beneath and beside a small lake about 5 km west of Inuvik. This work was carried out in April 1961 by the National Research Council of Canada. These drill holes revealed that at this location there is about 70 to 80 m of deltaic sediment overlying bedrock. Wood found at a depth of 38 m in one of these holes was dated using radiocarbon techniques at around 6,900 years of age. This is one example of the information used to demonstrate that the delta has formed since the retreat of the continental glaciers from this area between 12,000 to 13,000 years ago.

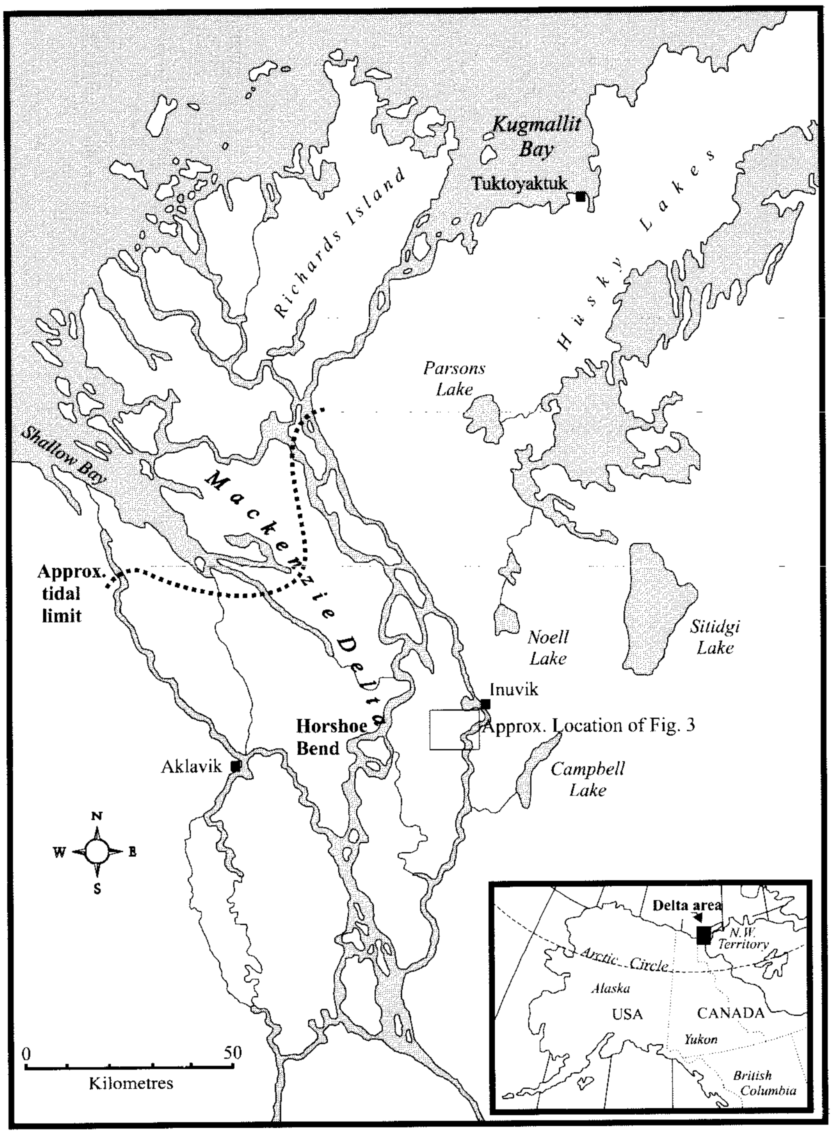

Figure 1: Map of the Mackenzie Delta showing the approximate limit of tidal effects and the location of the air photo shown in Figure 3. The total north south distance is 210 km, the average width is 62 km. The total area of 12,995 km² is over twice that of Prince Edward Island.

The climate of the area is very cold, with mean temperatures of -29.6°C in January and 13.6°C in July at Inuvik. As a result,

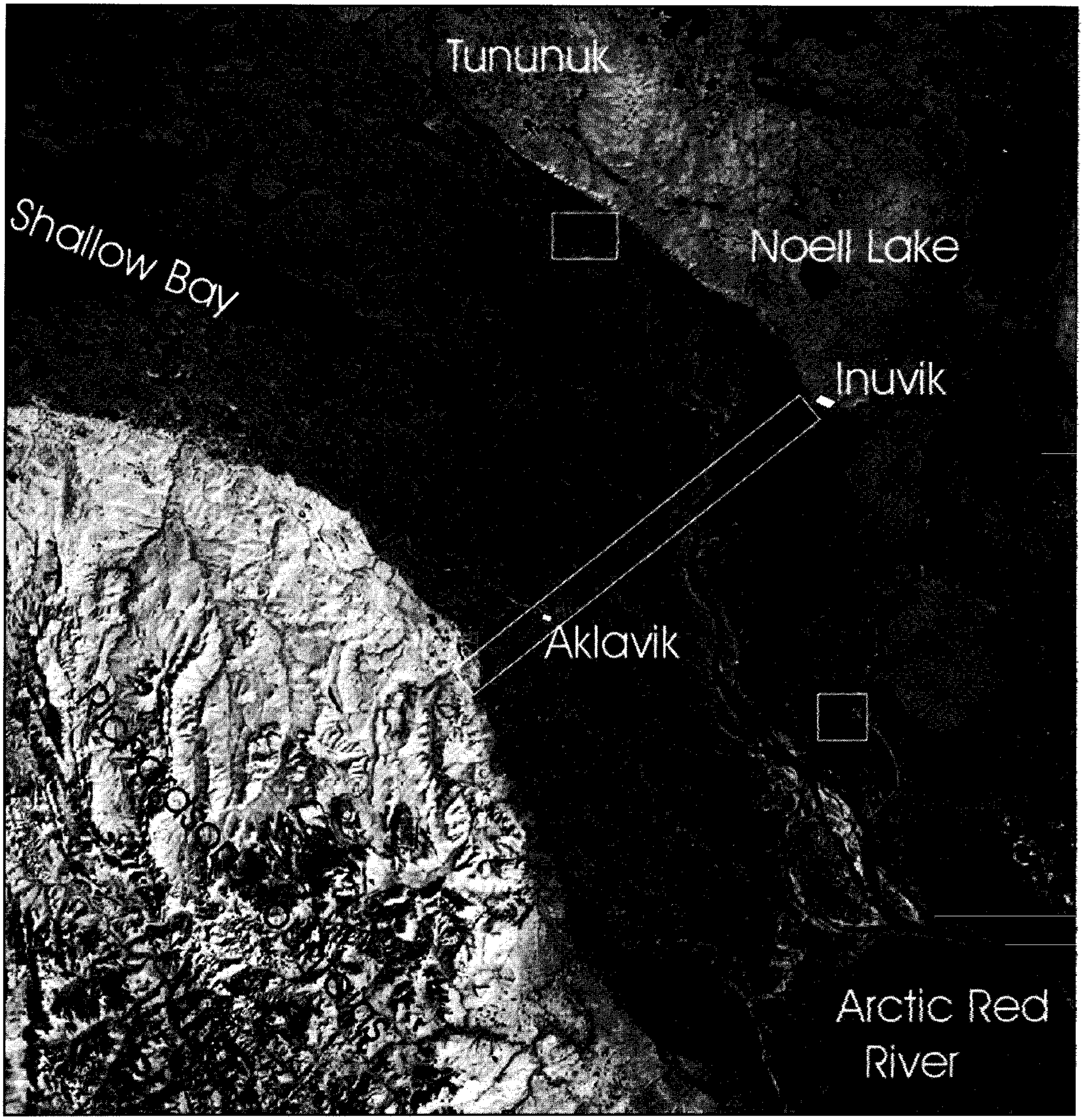

Figure 2: Satellite (Landsat) image of the Mackenzie Delta taken on August 6, 1985 from an altitude of approximately 700 km above the earth's surface. The many large channels of the delta, and the vast number of small lakes are visible. The location of a cross delta transect and study areas near Reindeer Station in the northern delta and towards Point Separation are also shown. At these sites the elevation of over 3,500 lakes have been measured. This allows an estimation of how often lakes are flooded by the Mackenzie River in these areas.

much of the Mackenzie Delta is underlain by permafrost. Below land areas in the delta and well away from river channels or lakes, the permafrost is approximately 100 m in depth. However, beneath main channels and lakes, there is no permafrost. Another result of the cold climate is that the land is snow covered, and the lakes and channels of the Mackenzie Delta are ice covered, for up to 8 months of the year.

Figure 3: Airphoto of delta lakes and channels (location shown on Figure 1). The perched lakes appear dark in this photo since their water is clear. Lower elevation lakes have progressively lighter colours due to the increasing suspended sediments from the water added by the Mackenzie River.

In spite of the cold climate, the occurrence of permafrost and the long snow and ice covered period (in fact these are the main features that distinguish northern deltas from temperate or tropical deltas), the Mackenzie Delta is biologically very productive. This is demonstrated by the fact that the treeline is close to its most northerly location, and that the delta is home to great numbers of fish, mink, lynx, muskrat, moose and bear, and large populations of ducks, geese, and swans either nest or feed in the delta.

It is vital that we protect this valuable resource. Given the possibility of environmental impacts from climate change, hydro-electric development, or contamination from upstream areas, for example, it is essential we have the information needed to make decisions about development proposals and to help design strategies for environmental protection. Since our ability to predict possible changes to the delta ecosystem was very limited, the National Hydrology Research Institute began to study the lakes of the Mackenzie Delta in the early 1980's. This research included detailed observations of two "typical" lakes (Figure 3). The first two, Skidoo and South Lakes, had channels that could be boated most of the open water period (Figure 4). The other, NRC Lake, had only a very small channel that could not be boated, and for much of the year the water level of NRC Lake was higher than East Channel water level. This type of lake is said to be "perched" above the main channels. In addition to these studies, we carried out a

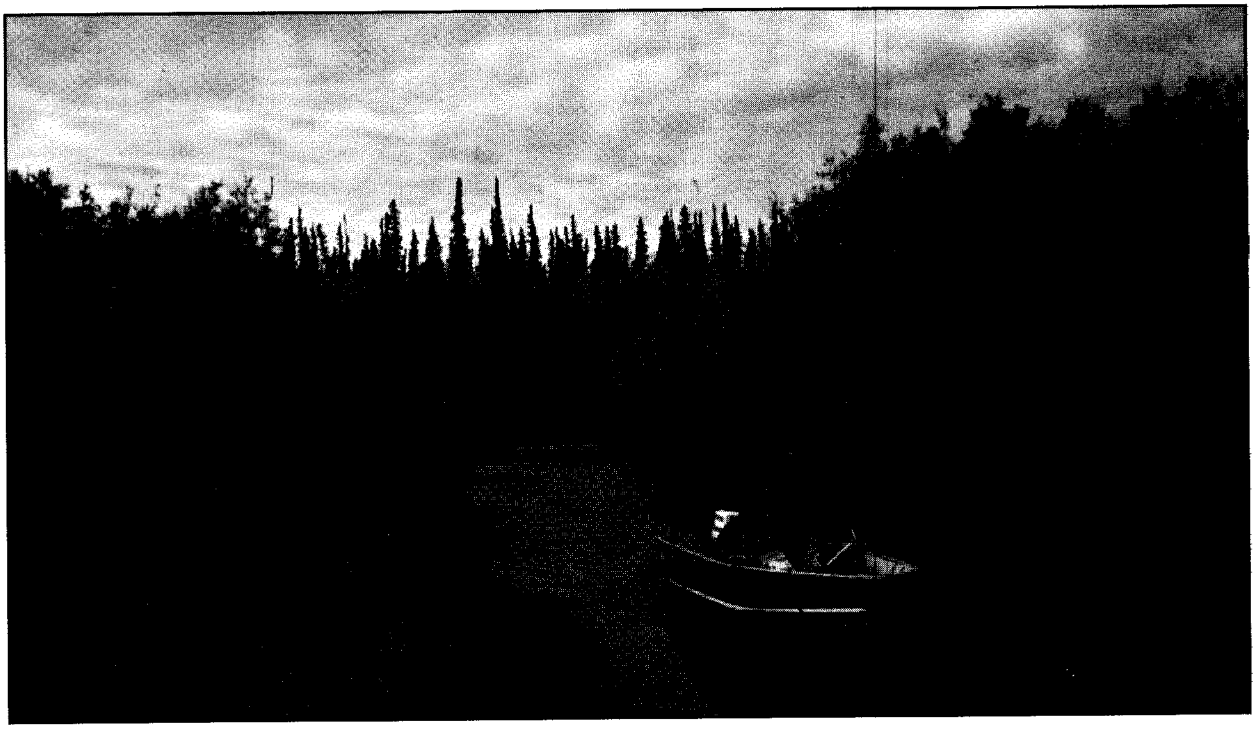

Figure 4: Photo of a typical channel into a low elevation delta lake. This channel is sufficiently low that it can be boated for much of the open water period. Only during periods of very low water level is it not passable by a small boat.

variety of other research at sites shown in Figure 2, to learn more about the wide range of lake conditions in the delta.

Lakes in the Mackenzie Delta

The delta is dominated by approximately 25,000 lakes. These lakes are not static features, but are constantly changing. Changes are caused by the deposition of sediments within the lakes and in the areas surrounding the lakes, the draining of lakes as main river channels cut into the banks separating the channel from the lakes, the division of large lakes into a number of smaller lakes as deltas are formed in these large lakes, the enlarging of lakes due to melting of permafrost in the lake shoreline, and the creation of new lakes as channels are abandoned. It is, in fact, the large number of lakes and the great variety of lake size, shape and hydrology that make the Mackenzie Delta so dynamic and productive. Only northern deltas have such a large number of lakes, as most temperate and tropical deltas have large areas of marshes and swamps, and few lakes.

Given the great diversity and importance of lakes in the Mackenzie Delta there are a number of important questions, including:

(a) Why are there so many lakes in the delta?
(b) Why don't the delta lakes dry up? Why do the lake levels change over time?
(c) How often are lakes flooded by the Mackenzie River?
(d) What would happen if lakes were not flooded by the Mackenzie River?
(e) What causes changes in the water level in the channels of the Mackenzie River? Do storm surges affect channel or lake levels all through the delta?
(f) What controls the thickness of lake ice?

In the following sections we will try to briefly answer these questions. Other questions we could ask include:

(a) Are there different types of lakes?
(b) How often does the water level fall low enough so that the channels connecting the lakes to the Mackenzie River dry up?
(c) How much sediment accumulates in a lake each year?
(d) How long would it take for a lake to fill up with sediment?

Why are there so many lakes in the delta?

Unfortunately, we really cannot answer this question to any great degree of certainty. However, since most temperate and tropical deltas do not have large numbers of lakes we expect that their occurrence in the Mackenzie Delta is somehow related to the cold conditions of this area. One hypothesis is that the small number of lakes in temperate areas is the result of the rapid infilling of lake basins with organic material (primarily plant remains) due to the high productivity of these areas. For example, in the Mississippi and Fraser Deltas, there are over 5 m of peat accumulation in many areas. Such peat accumulations do not occur in the Mackenzie Delta. It seems likely then that the continued existence of lakes in the Mackenzie Delta is due to the slow accumulation of organic material within the lakes.

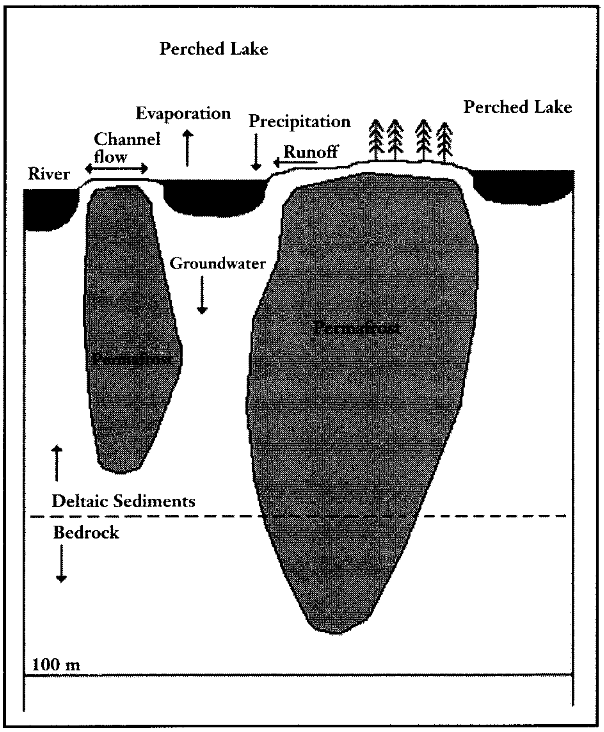

Figure 5: Diagram of water cycle for a delta lake showing all of the components of the water balance, and the location of permafrost in the area around the lake.

Why don't the delta lakes dry up?

A delta lake receives water from a number of sources (Figure 5), including rainfall and snowfall directly onto the lake surface, floodwater from the Mackenzie River, and runoff from the land surrounding the lake. A delta lake may lose water by evaporation from the lake surface, groundwater flow out of the bottom of the lake, or as flow out of the lake through a channel. Although groundwater may either enter or leave a delta lake through the unfrozen area beneath the lake (called a talik), it is usually a very small amount since the lakes are underlain by silts and clays that have a low permeability to water. The addition of all of these sources and losses of water is called the water balance. If the water balance is positive, the lake is gaining more water than it is losing and the lake level will rise. If the balance is negative, the level will fall. Lakes typically undergo periods when the balance is positive and periods when it is negative. If the balance is negative for a long period of time, the lake will eventually disappear.

Measurements at the study lakes (Figure 6) have allowed us to determine the magnitude of all of the water balance components mentioned above. Briefly, these measurements were conducted as follows: snow added directly to the lake over the winter is estimated by measuring the depth and density of snow on the lake ice, while rainfall onto the lake during the summer is measured by a tipping bucket recorder. Runoff into the lake is determined by measuring water flow in small rills draining the land area around the lake, and by measuring groundwater flow through the thin unfrozen layer overlying the permafrost. Evaporation from the lake is estimated by standard equations that use air temperature, net radiation, and lake water and bed temperature. Groundwater flow beneath the lake is measured using narrow pipes installed down to various depths in the lake bed. Water flowing into or out of the lake through the lake channel is determined using a device that measures the water depth, velocity and flow direction (either into or out of the lake) within the lake channel.

This research has shown that for Skidoo and South Lakes the channel flow in and out of the lake is the largest part of the water balance. For NRC Lake, however, the channel flow is only important during the spring since it is dry during the summer. Since there is usually little runoff from the lake basin to the lake and evaporation is usually greater than summer rainfall, the lake level falls over the summer period. If flooding by the Mackenzie River does not occur, lake level will continue to decline over a number of years. This suggests that without flooding by the Mackenzie River, lakes would disappear within about 10 years.

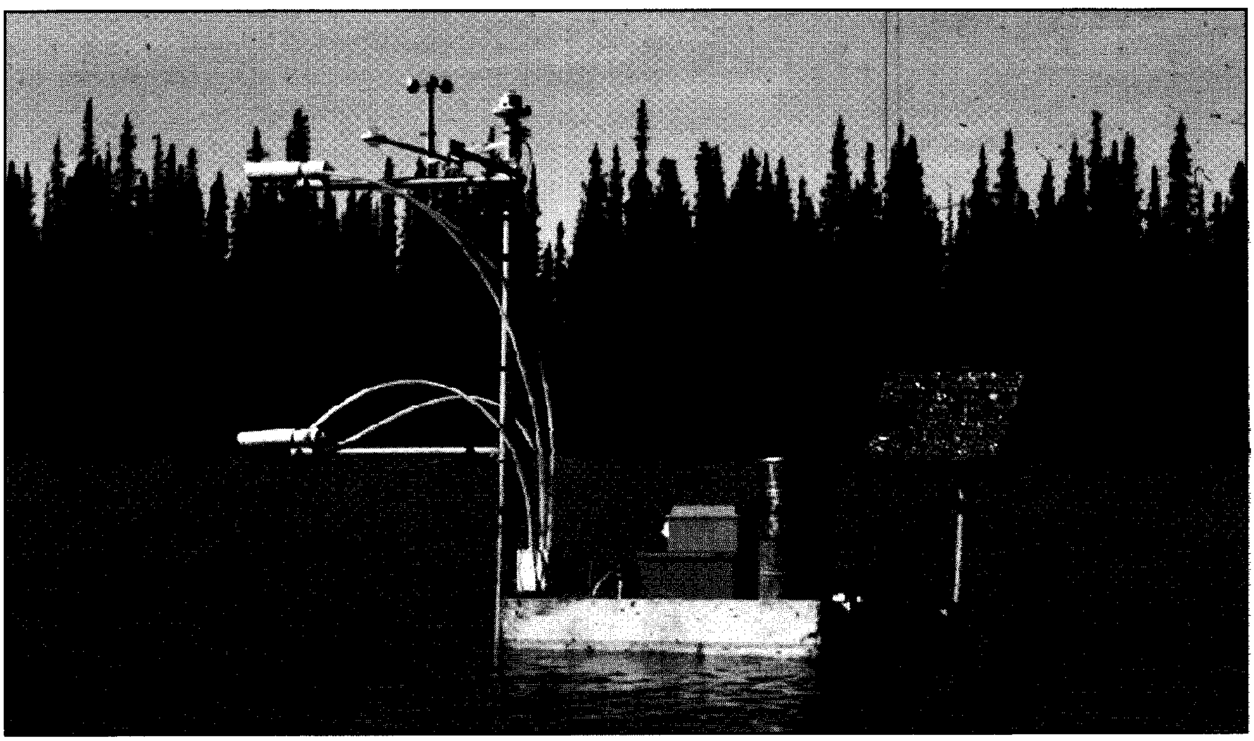

Figure 6: Photo of field measurements at NRC Lake, showing a tipping bucket rain gauge, an anemometer, and instruments for measuring air temperature, relative humidity, solar and net radiation. Also visible is a solar panel for recharging the batteries required to run the scientific equipment.

How often are lakes flooded by the Mackenzie River?

How often a lake is flooded by the Mackenzie River depends on where the lake is located in the delta, and how high the lake is perched above the channel. NHRI has measured how high lakes are perched at three locations down the east side of the delta, and at locations between Inuvik and Aklavik (see Figure 2 for locations). In all, we have measured approximately 3,500 lakes. In the upper delta towards Point Separation, the lakes are perched up to 7 m above the normal late winter main channel levels, while in the lower delta near Reindeer Station, the highest lakes are only perched up to 3 m above the normal late winter levels. Near Horseshoe Bend, lakes are perched higher than on either side of the delta (Figure 7).

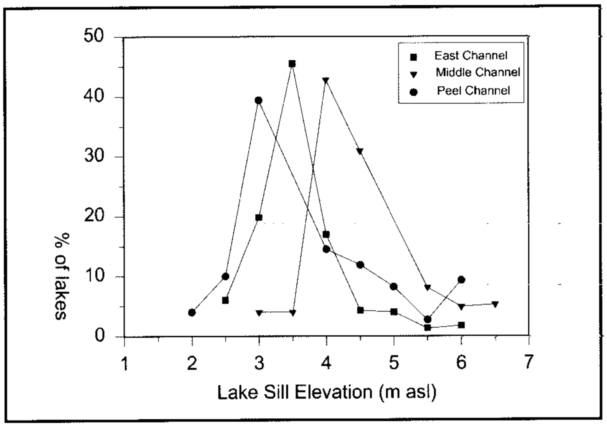

Figure 7: Changes in sill elevation for lakes in the East, Middle, and Peel Channel areas along the cross delta transect shown in Figure 2. This diagram shows that, although there are low and high elevation lakes in all areas, there are more high elevation lakes in the area of Middle Channel than in the areas on the east or west side of the delta. A similar diagram for areas in the upper and lower delta, would show that the number of high elevation lakes decreases as you go from near Point Separation to the Beaufort Sea.

For one of the study areas near Inuvik, the elevation of the perched lakes was compared to the records of water level in East Channel. Through this comparison, one is able to see how often during the last twenty years various lakes have been flooded. In the Inuvik area the largest flood since 1964 occurred in 1972, and during that year all lakes in the study area were flooded. The lowest flooding occurred in 1984 when only the lowest 2/3 of lakes were flooded in the area near Inuvik. This work has shown that 2/3 of lakes are flooded every year in the spring, while the remaining 1/3 of lakes are flooded between every two and five years. In the upper portion of the delta, many lakes are perched higher, and they therefore flood less frequently. In the highest lakes in this area, flooding may only occur every 10 years on average. Some of these lakes undergo large declines in water level and in fact may nearly dry up before being flooded again.

What would happen if lakes were not flooded by the Mackenzie River?

As discussed previously, one third of lakes in the Inuvik area may not be flooded during the spring period, and they are not flooded during the summer period. What would happen to these lakes if spring flooding no longer happened? Although it may seem unlikely that this could occur, it must be remembered that after many extensive floods over the period prior to 1972, the Peace-Athabasca Delta underwent a period of over 20 years (1972 to 1996) when flooding did not occur and many lakes dried up. This had a major impact on the wildlife of the delta and on the people who use the delta. Recent research has shown that the reasons for this decline in flooding are probably related to both the construction of a dam on the Peace River, and decreased snowfall and snowmelt runoff to the Peace River.

Mackenzie Delta studies have clearly shown that there is very little snowmelt runoff from the land area surrounding the lakes. This is because most of the water is absorbed by the frozen soil and subsequently evaporates or transpires from these soils. Moreover, evaporation from the lake surface is usually larger than the total of summer rainfall and winter snowfall. The result is that in most years, the lake water balance is negative and therefore the lake level declines. This was observed for a lake in the upper delta that was flooded in 1982, but not flooded in the following years, and as a result the lake level gradually declined.

These results seem to suggest that many of the perched lakes would disappear without frequent flooding from the Mackenzie River. In addition, since lake ice is usually 0.6 to 1.5 m in thickness, and the high perched lakes are often only 1 to 2 m in depth, even a small change in lake depth would result in the lakes freezing to the bed over their entire area, making it unsuitable for muskrats over the winter period.

What causes changes in the water level in the channels of the Mackenzie River?

As those who boat in the Mackenzie Delta know, the water levels in these channels are constantly changing (Figure 8). In autumn, water levels gradually decline due to reduced runoff from the upstream areas of the Mackenzie River basin. However, when the channels begin to freeze in October, water moves more slowly through the channel because of the formation of ice. As a result, the water level in the channel rises. This causes an increase in the amount of water stored in the channel and the channel discharge actually decreases for a brief period of time, after which it increases and then stabilizes for much of the winter. This is often the period with the lowest discharge of the year. For the remainder of the winter, the channel water levels continue at a low level. In the small

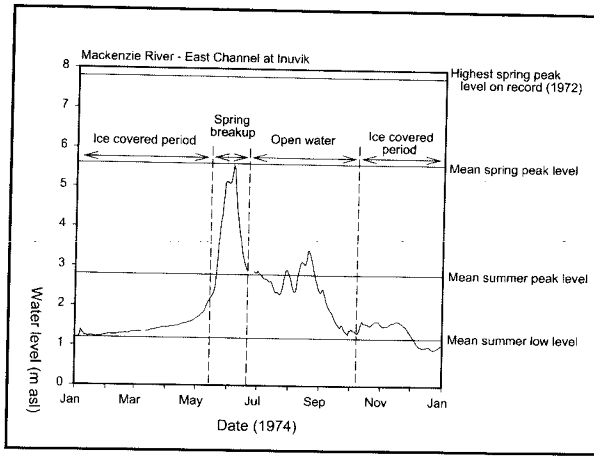

Figure 8: Example of water level for East Channel at Inuvik for a typical year (in this case 1974). The highest water level for the year occurred during the spring breakup in late May and early June, and lower water levels occurred during the summer period. Note, however, that there was a period of high water levels during August due to a rain storm upstream in the Mackenzie River basin. Also shown for comparison are four important water levels: the highest water level on record, the mean spring peak, the mean summer peak, and the mean summer low.

channels of the delta, discharge may cease as the channels freeze to the bed and as a result, the discharge of the large channels may increase as flow is diverted from these smaller channels. The rising water levels in these larger channels, may overflow into low lying lakes during this period.

In late April and early May, the water level in the channels begins to rise as the first snowmelt runoff from the southern portions of the Mackenzie Basin reaches the delta. The first sign of the arrival of this water is the occurrence of overflow water on the ice of the channels. Water levels continue to rise as the crest of the flood-wave approaches the delta. As discharge and water levels increase, ice jams may form in the larger channels, especially in Middle Channel, causing the water level to rise dramatically. Two locations that are very prone to the formation of major ice jams are Middle Channel just downstream of Point Separation and the Horseshoe Bend area. Other channels are prone to the development of smaller ice jams (see text box).

Ice Jams

Ice Jams occur in river channels when floating ice is blocked at a constriction in the channel. The resulting partial blockage of the channel can lead to very high water levels upstream of the jam. Although ice jams occur during both freeze-up and breakup, the breakup jams are typically the largest and most important. There is no doubt that they are the most dramatic events that occur during ice breakup, causing water levels that far exceed even the largest summer floods. For example on the East Channel at Inuvik, the highest ice jam flood has a water level over 4 m higher than the largest summer flood. There are two basic types of breakup ice jams. During years when the river discharge is small and the weather is warm, the ice cover weakens and only small ice jams occur. During these years, water levels are also low. In years when the discharge is large and the weather remains cool, the ice remains strong and very large ice jams occur. It is during these types of breakups that the highest water levels occur. In the Mackenzie Delta, it is during these types of events that the highest floods occur and most lakes are flooded.

In the summer, water levels may rise in response to rainstorms upstream of the Mackenzie Delta. The largest summer floods occur due to rain in the Mackenzie Mountains and in the headwaters of the Liard River. During the highest summer floods, only two thirds of lakes in the Inuvik area of the Mackenzie Delta are flooded.

In the summer, water levels in the delta are also affected by changes in sea level in the Beaufort Sea. Since the maximum tidal range of the Beaufort Sea is only about 0.37 m, channel water levels are only affected by tidal activity in the area seaward from a line approximately from Tununuk to 10 km south of Shallow Bay and then west to the western edge of the delta (Figure 1). This area affected by tidal activity covers about 30% of the entire delta. In addition to this tidal activity, when there are periods with high winds from the north and north-west, sea level of the Beaufort Sea may rise by up to 2.4 m. These events are called storm surges (see text box).

Even with a storm surge of about 1.5 m, water level in the Delta channels rises in response as far upstream as Tsiigehtchic.

Storm surges

A storm surge is a short term rise or fall in sea level due to strong winds. The actual size of the surge is often accentuated in shallow water or along shorelines and is also affected by both wave size and tide height. Due to the fact that surges that result in a rise in sea level have the greatest impact on human activities, these types of surges are typically of most interest. In the Mackenzie Delta area, surges that increase sea level are the result of strong offshore winds from the Beaufort Sea. Although they may occur when the Beaufort Sea is ice covered, typically they are largest during the ice free period. In the Tuktoyaktuk area the estimated maximum storm surge elevation with an approximate 100-year return period is 2.4 m. Such storm surges flood large areas along the Beaufort coast, flood much of the lower Mackenzie Delta, and result in a rise in water levels as far upstream as Tsiigehtchic (formerly Arctic Red River).

Sea Level

The level of the ocean changes over both short and long time periods. On a daily basis it changes due to both tides and waves. On a more infrequent basis it is affected by storm surges. Over very long periods of time it changes due to both variations in the global sea level and rising or falling of the land surface. For example: sea level may rise or fall with the increase and decrease in the world wide area of glaciers. During the last ice age the huge increase in glacier size removed water from the oceans and as a result sea level fell. At the same time, however, the great weight of the continental glaciers depressed the land beneath the glaciers and it has been slowly rebounding ever since. In addition, in the Mackenzie Delta area the land has been sinking due to the great weight of the sediment deposited in the delta. In the Mackenzie Delta region the combined effect of these various factors has been a relative rise in sea level of approximately 60 m over the last 10,000 years. The result of this is that although the Mackenzie Delta has been growing by the addition of sediment, it has also been gradually flooded by the slow rise in relative sea level. The result is the relatively rapid erosion along the Beaufort Sea coast of the Mackenzie Delta.

What controls the thickness of lake ice?

The thickness of ice on the lakes of the Mackenzie Delta is very important in determining the suitability of lakes as muskrat habitat and in deciding if the ice is safe to travel on. Ice thickness is controlled by both the air temperature and the snow depth, with the ice being thickest with colder temperatures and thinner snow depths. In fact, snow depth is usually as important as air temperature in controlling ice thickness! In years where there is little snow, or on lakes which are windswept, the ice will be thicker.

Observations suggest that if water depth below the ice cover is less than approximately 0.5 m, the lakes are not used by muskrats. Such conditions may occur in very shallow lakes, during winters when the lake level is low, or during years when the ice is thicker than normal. Therefore to determine the impact of climate change on the delta lakes, measurements of both lake level and ice thickness are required.

Research on the Mackenzie Delta by the National Hydrology Research Institute

The National Hydrology Research Institute (NHRI) and its forerunner agencies (including the Geographical Branch of Energy Mines and Resources, and Glaciology Division of Environment Canada) have been collecting data in the Mackenzie Delta region since the early 1960's. This work has been funded and supported by a number of agencies, including: Environment Canada, Energy Mines and Resources, the Aurora Research Institute, Polar Continental Shelf Project, and Northern Oil and Gas Action Program (NOGAP).

The main goal of this work has been to obtain a sound scientific understanding of the hydrology of the lakes in the Mackenzie Delta. By this we mean being able to answer questions such as those posed earlier in this report. Why is it important to understand these things? By understanding how a natural system works, it is possible to predict the effects of natural or man-made changes to the environment. Being able to predict changes before they happen allows us to either change our way of doing things so that we do not have an impact on natural areas, or to adapt to the changes as they happen. In the Mackenzie Delta we want to be able to predict possible changes in the delta lakes that could occur because of local climate change in the delta itself, changes in runoff and ice jamming in the Mackenzie River due to changes in climate upstream in the Mackenzie River basin, or to the development of new hydro-electric dams, or changes in sea level.

Such an understanding is essential in order for groups with a management role (federal, territorial and municipal governments, Inuvialuit, Gwich'in) to make informed decisions when assessing the potential environmental impact of hydro-electric dams or oil and gas production. In the 1960's and 1970's, NHRI's work in the Mackenzie Delta produced an historical record of conditions such as flow, water level, water temperature, ice thickness, and suspended sediment conditions. During the 1980's and 1990's our work has aimed at developing computer models for predicting changes in lake conditions.

Conclusion

The Mackenzie Delta is a very complex region, greatly influenced by the interactions of the hydrology of the Mackenzie River, changes in the sea level of the Beaufort Sea, and the local climate. The many lakes within the delta play an important role in the ecology of the delta. The large number of lakes is due primarily to the cold conditions. The water levels of these lakes are controlled by flooding by the Mackenzie River, the precipitation onto the lakes, and the evaporation from the lakes. It appears that the higher elevation lakes are very sensitive to changes in these factors and without flooding by the Mackenzie River they would rapidly disappear.

Acknowledgements

I would like to thank the National Hydrology Research Institute (Environment Canada), Polar Continental Shelf Project, the Aurora Research Institute, and the Northern Oil and Gas Program for supporting our research in the Mackenzie Delta over the years. I thank Alan Fehr, Katarin Baskin, Les Kutny, Mike Muller and Leah Watson for assistance in the preparation of this paper.

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Experiment

How to Make a Delta

Equipment needed:

- shallow pan with water (i.e. cookie tray)
  [represents the ocean]
- eaves trough (or similar)
  [represents the river]
- sand - place along the river channel
  [sediment]
- bucket with water
  [stream flow]

Method:

1. Gently pore water onto sand covered eaves trough, which rests on the cookie tray.
2. Experiment with various angles, volumes of water, and changes in 'sea level'.
3. Watch different types of deltas form in the 'Ocean'.

Explanation:

This experiment demonstrates exactly what has been happening in the Mackenzie Delta over the last 10,000 years, as sediment from the Mackenzie and Peel Rivers have accumulated in a large bay. The formation of the Mackenzie Delta has been complicated by rising sea level, erosion of the outer edge of the delta, and the 'sinking' of the entire coastal area as the great weight of the delta sediment has depressed the coastline.

About the Author

Philip Marsh is a Research Scientist at the National Hydrology Research Institute (Environment Canada) in Saskatoon, and also an Adjunct Professor at the University of Saskatchewan. He received his Ph.D. from McMaster University in 1982. He has been conducting research on the hydrology of northern Canada since 1975, with a particular focus on snow, ice, permafrost and runoff. His earlier work concentrated on the hydrology of the High Arctic Islands, but since 1984 much of his research has been carried out in the Mackenzie Delta region. This has included the study of lakes within the delta and of snowmelt runoff in both boreal forest and tundra areas to the east of the delta.

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