ICE JAMMING CHARACTERISTICS OF THE MACKENZIE DELTA, N.W.T.

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ABSTRACT

Break-up in the Mackenzie Delta N.W.T. was monitored from 1981 to 1987. The purpose of this research was to identify and quantify processes involved in ice break-up and jamming, and to assess their importance to the hydrological regime of the Mackenzie Delta. Two types of break-up, thermal and mechanical, were observed. Thermal break-ups occurred in six of the seven years; a mechanical break-up occurred in 1982. This paper describes the break-up patterns, prevailing climatic conditions, and characteristic ice jams associated with each type of break-up. The paper documents the location of frequent ice jams in the Delta as well as their formation, composition, growth, and describes the backwater build-up and flow diversion patterns which result.

INTRODUCTION

Research on the hydrologic regime of the Mackenzie River has been sporadic. Remoteness and the inclement weather conditions make the logistics of conducting detailed research both difficult and expensive. Although observations of spring break-up on the Mackenzie have been recorded as early as the 1890's (Mackay, 1963a), very little was known about the hydrological regime of the river until Brown (1957) collected data in the 1950's. The importance of break-up to the hydrological regime of the Mackenzie River and the Mackenzie Delta (Figure 1), was not recognized until Mackay (1963a) and MacKay (1965, 1966) followed the progress of break-up down the river. In later studies, they also documented the location of frequent ice jam sites, and investigated the effects of break-up on the hydrological regime of the Delta (MacKay and Mackay, 1973a, 1973b).

Detailed studies of the northern ecosystem were undertaken in the late 1970's when a series of northern mega-projects including hydroelectric installations, pipeline construction, and facilities for the exploration and extraction of hydrocarbons, were proposed. As part of the response to these proposals, the National Hydrology Research Institute played a leading role in the investigation of the hydrological regime of the Mackenzie River and Delta.

This paper consolidates and interprets the information collected from 1981 to 1987 on break-up and ice jamming in the Mackenzie Delta and more specifically a 100 km reach of the main flow channel. The purpose of the paper is to describe the break-up processes affecting ice jamming, the location, formation, and growth of ice jams, and the backwater flooding and flow diversion caused by these jams. Because ice jamming is an important part of the hydrological regime of the lakes and channels in the Delta, understanding the factors controlling the formation of ice jams is essential to proper water management in the region.

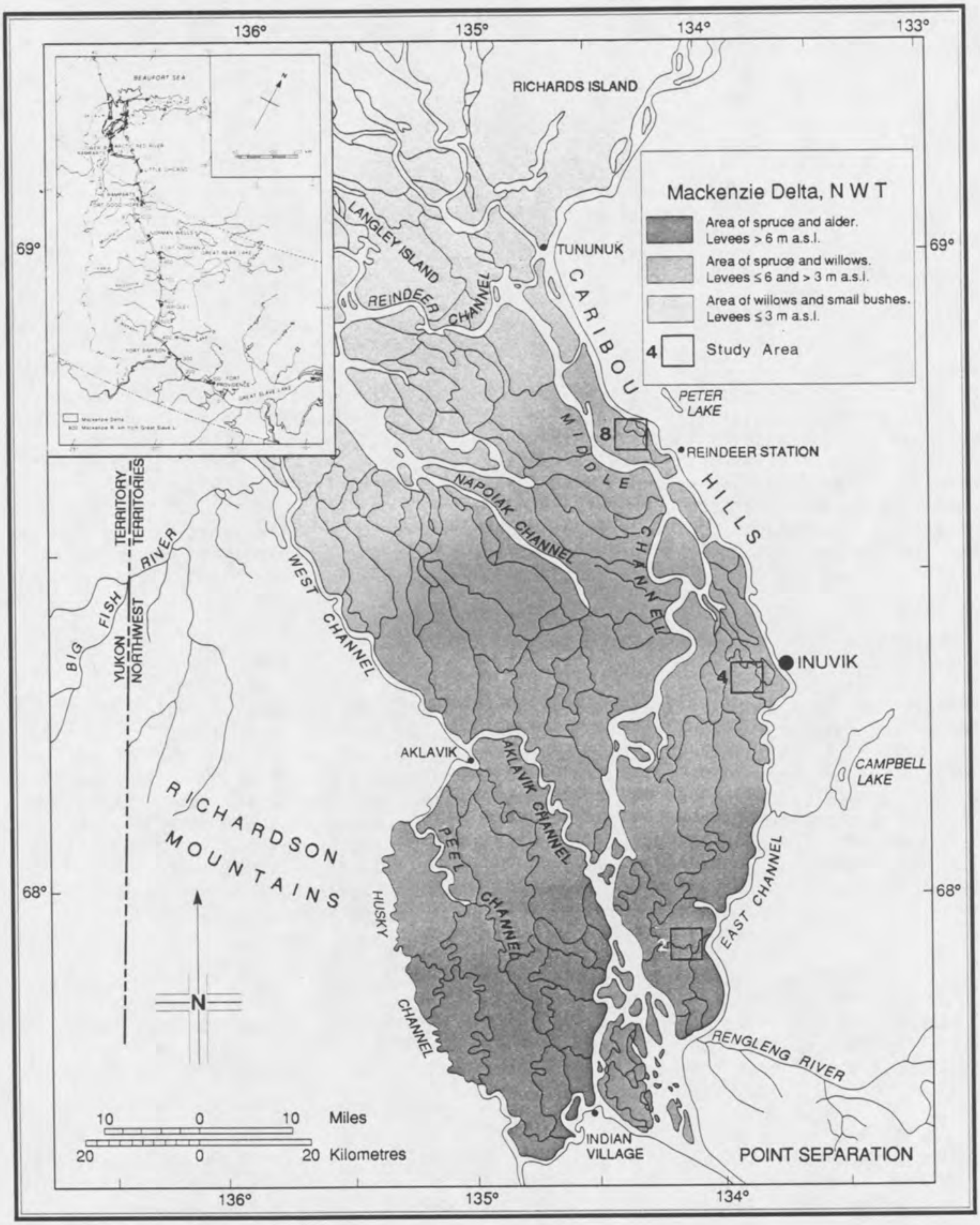


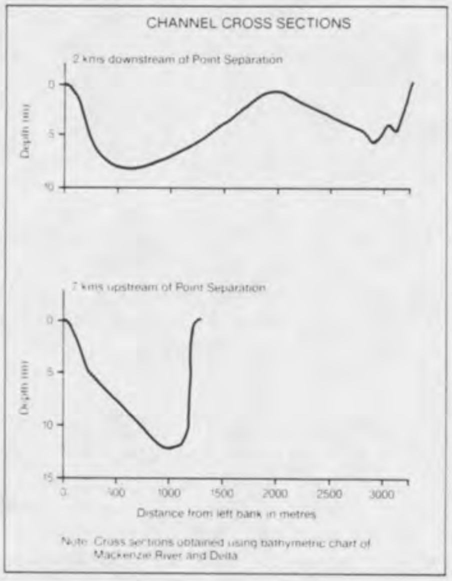
Figure 1: Map of the Mackenzie Delta regions and study areas. Also shown is a location map of the Mackenzie River and Delta.

MACKENZIE DELTA

The Mackenzie Delta covers an area of approximately 12,000 km^2 comprised of a maze of channels and shallow lakes which are frozen for up to eight months of the year. During the open water season (June to October), it is an active delta that continues to extend into the Beaufort Sea. The Delta has a very gentle slope varying only 3 to 4 metres over its 200-km length. It has numerous lakes, ponds and channels, but also contains land ranging in type from stable forested areas in the south to tidal flats in the north. Permafrost underlies most of the Delta land mass and during the summer months, the active layer can extend a metre or more into the soil. The lakes and channels are underlain by large talik zones, extending many metres in depth (Johnston and Brown, 1964). The Delta consists of three regions (Figure 1), which may be distinguished by levee height (Mackay, 1963b) and vegetation type (Gill, 1978). Levee heights decline from about 10 m a.s.l. in the southern Delta to less than 2 m a.s.l. in the northern Delta (Figure 1).

The Mackenzie River enters the Delta via Middle Channel at Point Separation, where it is transformed from a well-incised river 1.25 km in width to a channel 3.25 km wide (Figure 2). Middle Channel is the largest of the channels in the Delta with an average width of 2.5 km. It is the main link in the Delta channel system, and carries up to 80% of the flow. Middle Channel is also shallow, averaging less than 5 metres in depth at mid-summer. A cluster of islands and shoals occupy up to 80% of Middle Channel at its widest point, only a few kilometres downstream from Point Separation (Figure 1).

Break-up on the Mackenzie Delta is a complex event. The southwestern region is controlled by the break-up of the Peel River and other mountain rivers along the western side of the Delta, while the middle and eastern portions are controlled by the Mackenzie River. The western mountain tributaries are early break-up rivers (Mackay, 1963a). Forty-seven years of records in the period 1895 - 1960 show that the Arctic Red River at the confluence with the Mackenzie River broke up on average 4.5 days before the Mackenzie, and that the Peel River at Fort MacPherson broke up on average 8 days earlier than break-up on the Mackenzie River (Mackay, 1963a). Unlike rivers such as the Liard where break-up on the tributary acts as a trigger mechanism by initiating break-up on the main channel (MacKay and Mackay 1973a; Anderson 1982; Prowse 1984), break-up on these rivers does not initiate break-up on the Mackenzie Delta. Complete ice break-up and removal in the Mackenzie Delta is dependent to a large extent on flow from the Mackenzie River main stem. According to MacKay (1965), the mean break-up date for the Mackenzie River at Arctic Red River is May 24.



Note: Cross sections obtained using bathymetric chart of Mackenzie River and Delta

Figure 2: Middle Channel cross sections.

Although this report reviews some general break-up characteristics of the Mackenzie Delta, more specific data are provided for the main study site, a 100 km reach of Middle Channel from km 1440 to km 1540 (Figure 3). This site was chosen because ice jams have frequently been observed in the area, because it is close to a water level monitoring site, and because there are several consecutive years of good aerial photography of the reach.

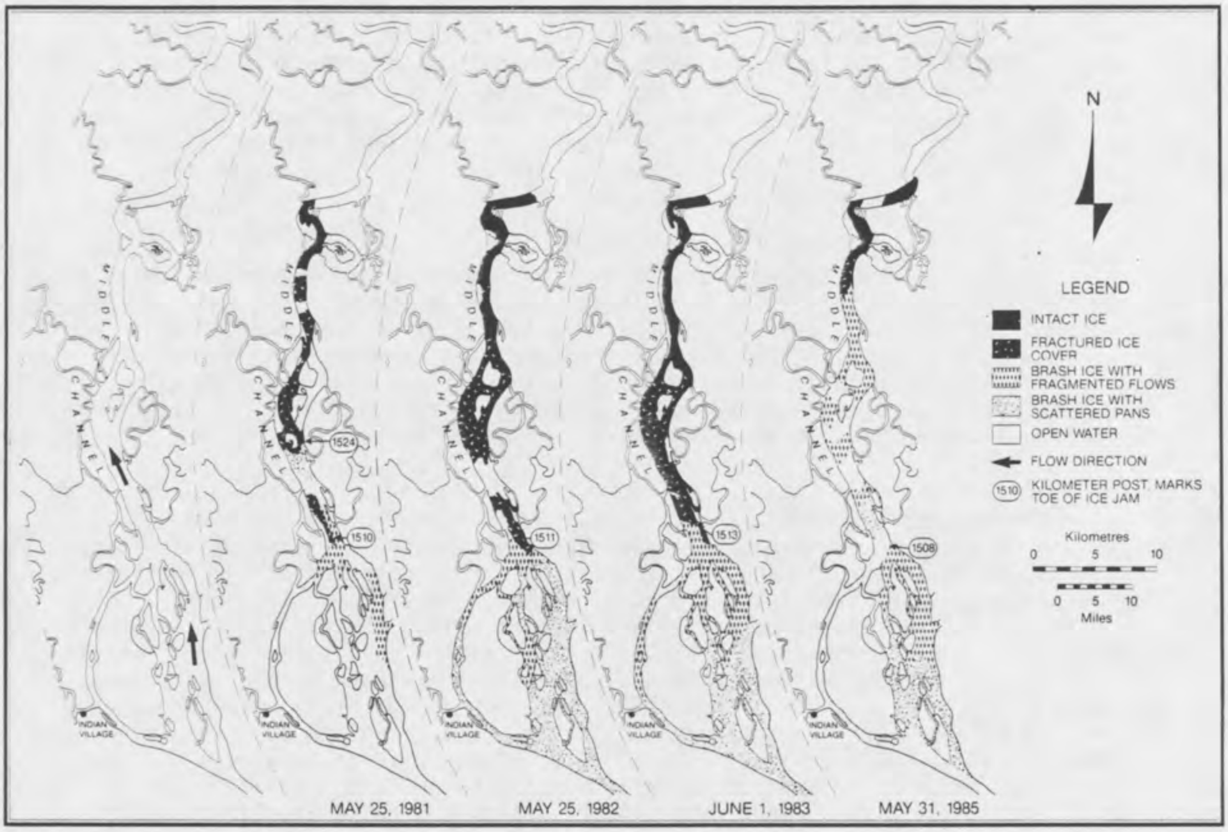


Figure 3: Location and composition of ice jams on Middle Channel, Mackenzie Delta, N.W.T., 1981-1985.

STUDY METHODS

From 1981 to 1985, break-up in the Mackenzie Delta was monitored using aerial photography to obtain information on the timing, progression, locations, dimensions, and composition of ice jams and on the extent of backwater flooding. Supplemental information was acquired between 1981 and 1987 from 35 mm hand-held oblique photography and videos, during fixed-wing and helicopter reconnaissance flights.

Since 1981 a serious effort has also been made to obtain a continuous record of water levels during break-up in the Mackenzie Delta. Until recently, attempts to measure peak events using conventional techniques (e.g. stilling well and bubbler system) were frustrated by ice shove and scour along channel banks. To overcome this problem, 16 mm time lapse camera systems developed by Banner and van Everdingen (1979) were aimed at a series of staggered staffs along channel banks. This system provided a photographic record of peak water levels during spring break-up (Bigras, 1987). Water levels were also measured using conventional survey techniques at various settlements throughout the Delta.

RESULTS and DISCUSSION

Break-up

Between 1981 and 1987 two distinct kinds of break-up have been observed in the Mackenzie Delta. Each produces different ice jamming patterns. In a thermal break-up, short-lived ice jams regularly cause flooding in the northern and central region of the Delta. Mechanical break-ups, on the other hand, produce ice jams which last much longer and flood much larger areas, usually including the southern region of the Delta.

Thermal break-ups occurred in six of the seven years. This kind of break-up is characterized by extensive melting of the ice cover and irregular progression of the ice front downstream. In general, conditions which prevail during a thermal break-up include warm air temperatures, high solar insolation, reduced albedo, low water flow, and an extremely weakened ice cover. Early in May, the cold Pacific highs which dominate the Delta during the winter months are broken down by a series of intruding weather systems which bring increased radiation and warmer air temperatures. Increased solar radiation combined with the advected heat soon melts the winter snow-pack. Snow-melt ponds on the ice surface, while snow-melt run-off from the surrounding land mass causes shore leads to develop between the ice cover and the channel bank which weaken and finally free the shore-fast ice sheet. By this time warm water from the Mackenzie River enters the Delta system and melts the ice cover from underneath. Consequently, it is not long before the ice cover candles and loses its competency. At this stage a low energy flood wave is all that is required to clear the ice downstream.

Although thermal break-ups appear to be the rule in the Mackenzie Delta, mechanical break-up of the ice cover on northward flowing rivers is a frequent occurrence. A mechanical break-up is dynamic in its movement downstream. Large ice floes are keyed out and broken up into smaller diameter floes as the front advances (Antonov et al. 1970; Burdykina 1970; Fountain 1984; and Prowse 1986). In years when the break-up is mechanical, air temperatures are low, and, because much of the winter snow pack remains on the ice surface, albedo is high. When these conditions persist during the spring break-up period, the ice cover remains competent and break-up depends on the arrival of a high magnitude, high velocity spring flood wave. In the spring of 1982, for example, the mean daily temperatures in May was 2.0°C colder than the 23-year mean of -0.8°C. High discharge and accompanying record high water levels broke up the ice cover at the confluence of the Arctic Red River on May 23 while the ice was snow-covered and still quite competent.

Ice jams; location, composition, dimensions, and backwaters

The strength or competency of the ice cover, then, is a central factor controlling the formation of ice jams. The more competent an ice cover, the more likely the resultant jam will remain static for longer periods of time and cause greater backwater build-up. In thermal years, when the ice cover is less competent, ice jams tend to release or decay much earlier and produce lower upstream water levels. The other main variables controlling ice jam formation along Middle Channel are the morphology of the channel bed and the magnitude and velocity of the spring flood wave. These three factors have been shown to control the formation of ice jams on rivers by many researchers, among them Gerard (1975); Beltaos (1978); Kamphuis and Moir (1983); Bigras and Anderson (1984); Andres and Doyle (1984); and Prowse (1986).

In the Mackenzie Delta, the morphology of the channel is perhaps the most important factor affecting the formation and the hydrological effects of ice jams. Morphology partly controls the velocity of the spring flood wave once it enters the Delta and determines the location at which ice jams occur. The spring flood wave loses much of its kinetic energy when it leaves the well-incised, 1265-m wide channel of the Lower Ramparts and enters the

3225-m expanse of Middle Channel with its gentle slope of 0.00002. No sooner has the flood wave lost this momentum than it encounters a cluster of islands obstructing up to 80% of Middle Channel. The advancing ice front will make its way in and around the islands through the numerous channels until it finally stalls a few kilometres beyond a point where the channel is extremely shallow (2 - 3 metres). During the years of the study, the ice regularly became grounded there, and ice jams have been observed and recorded at this location as early as 1954 (Brown, 1957).

Figure 3 shows the extent and composition of the ice jam when its toe is at this location. No illustrations appear for 1984, 1986 and 1987 because the ice cover was extremely candled and offered very little resistance as the ice front advanced downstream. Small ice jams did form in those years, but they remained static for only a few hours with no appreciable backwater build-up. Table 1 shows the areal dimensions of these jams at this location from 1981 to 1987.

Table 1. Ice jam characteristics

Year	Date	Length (km)	Area (km2)
1981	May 25	20	22
1982	May 25	73	249
1983	June 1	53	176
1984*	May 28	26	29
1985	May 31	33	64
1986#			
1987*	June 2	9	12

* Ice jam did not remain static for more than a few hours.
\# No jam formation on Middle Channel at first cluster of islands.

Although the toe of the ice jam formed in roughly the same location each year, the composition of the toe varies markedly with the type of break-up. Brash ice interspered with large fragmented floes are typical of an ice jam toe formed during a thermal break-up. During a mechanical break-up, however, the toe of a jam usually consists of small diameter brash ice abutting the downstream, possibly fractured ice cover (Prowse, 1986). This was the case in 1982 (Figure 3) when heavily fragmented brash ice abutted an 8 km^2 section of downstream fractured ice.

In 1982 the advancing ice front encountered a competent ice cover on Middle Channel and the ice began to pile up. A large section of the winter ice cover was wedged across the channel at km 1511, and was grounded at the downstream end, resulting in an extensive ice jam (Figure 3; Table 1). From May 23 to 29 the ice jam remained static, with its toe located at km 1511. There was considerable movement, however, within and at the edges of the jam. The head of the jam moved downstream several times from May 25 to 29 as a result of melt, compaction, and finally entrainment of the brash ice underneath the large ice floe (Figure 4). Warm water entering the system was a major factor in the decay of the jam. A vertical water temperature profile at the head of a small jam in 1987 yielded an average of 2.0°C, while several kilometres downstream just beyond the toe it was 0.01°C. In 1980 Terroux et al. measured the water temperatures at the head and toe of an ice jam in Middle Channel, and found them to be 8.5°C and 0.05°C respectively.

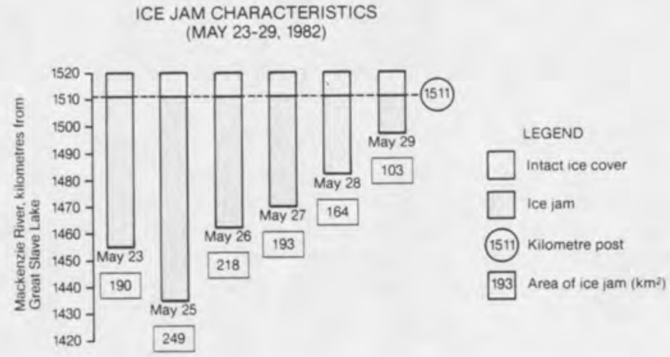


Figure 4: Ice jam characteristics, Middle Channel, Mackenzie Delta, N.W.T., May 23 - 29, 1982.

The morphology of the Mackenzie Delta ensures that water levels behind the ice jams remain low. In any year, high enough energy gradients to break the ice in front of the jam do not develop, and the ice jam can only begin to move when the ice cover becomes thermally weakened. In most years water levels remain low because backwaters are diverted through secondary channels which are open because of thermal decay. In the exceptional year when break-up is mechanical, backwaters overtop even the highest levees and as a result can not build up high enough to move the ice cover. This type of ice jam situation has been examined for the general case of shallow rivers with floodplain flow by Calkins (1983).

So much ice had entered the Delta in 1982 that all the secondary and distributary channels located around the island cluster in Middle Channel were plugged by brash ice, and no alternate routes were available for the water to flow through. Consequently, record high backwater levels were recorded upstream of the jam at the confluence of Arctic Red and the Mackenzie rivers, 22.79 m a.s.l. (Figure 5). Meanwhile, at the toe of the ice jam, the water level had also increased considerably since the jam formation. The hydrograph in Figure 5 is a daily water level record obtained at a study area not far from the toe of the jam in 1982. The water level rose steadily up to its peak of 9.53 m a.s.l., and remained there for 2 days before receding. Backwater had increased sufficiently to overtop the levees behind and around the jam so that the flood wave was reduced to a flood sheet covering the central and southern Delta regions. Despite the dampening effect of the lateral flow, backwater did build up enough to lift the downstream 8 km^2 of ice thereby allowing a substantial portion of the brash ice to be entrained downstream. This accounts for the huge reduction in the area of the ice jam between May 28 and 29 (Figure 4.)

Backwater levels on the Mackenzie Delta do not reach the levels recorded on well incised rivers because of lateral flow across channels. Nevertheless, ground surveys and aerial observations of hydrologic conditions have demonstrated that energy gradients are higher during a mechanical break-up than during a thermal break-up.

Backwater Flooding and Diversion

Fluctuations in the water level of Delta channels associated with spring break-up and ice jamming are an integral part of the Delta's hydrologic regime. Without the high water level peaks caused by ice jams at break-up, the ecological nature of the Delta would undergo drastic changes (e.g. Mackenzie River Basin Committee, 1981; Marsh and Bigras, 1988).

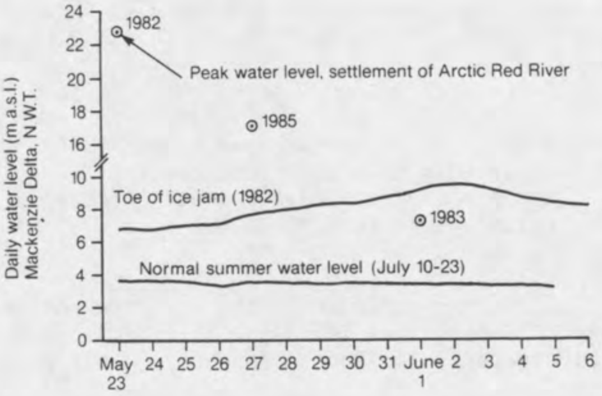


Figure 5: Water levels during break-up, Mackenzie Delta, N.W.T.

Table 2 contains peak water levels recorded at the confluence of the Mackenzie and Arctic Red rivers, and at three study areas representative of the three Delta regions (Figure 1). Flooding and flow diversion in the southern and the south-central regions of the Delta are controlled by ice jams which form at the island cluster downstream of Point Seperation. This is not the only site where ice jams form on Middle Channel, even though the largest and longest lasting ice jams in the Delta occur here. Two other sites of frequent ice jams on Middle Channel also have an important role in flooding and flow diversion in the central region, and to a lesser extent in the northern region of the Delta.

Table 2. Peak water levels (in metres a.s.l.)

Year	Date	Mackenzie River*	Date	Area 2	Date	Area 4	Date	Area 8
1981	08/06	8.28#	NA		NA		28/05	3.54
1982	25/05	22.79	30/05	9.53	NA		04/06	5.19
1983	01/06	7.30	01/05	8.27	05/06	5.76	05/06	4.18
1984	24/05	9.66#	30/05	6.76	27/05	4.65	31/05	2.72
1985	27/05	16.95	01/06	7.60	30/05	6.49	30/05	4.32
1986	02/06	14.08#	NA		04/06	5.74	NA	
1987	03/06	6.98	02/06	7.74	NA		NA	

* Confluence of the Mackenzie and Arctic Red rivers
NA Not Available
\# Water Survey of Canada, water level gauge located on Mackenzie River just above Arctic Red River, (unpublished data)

The ice jams which occur regularly in the area of the large island cluster in Middle Channel (Figure 1) cause flooding in the southern region of the Delta. However, many of the lakes perched atop the levees in the southern region are not flooded annually because water levels are usually well below the top of the levees, which average 10 m a.s.l. (Table 2; Area 2).

Farther downstream where Middle Channel begins to narrow, two islands obstruct the passage of the advancing ice front (Figure 1). Ice jams that form at this site cause flooding over a vast expanse, encompassing the transition zone between the southern and central Delta. By the time the ice front reaches this site, much of the ice cover on the secondary channels is either mostly candled or absent. Because levees are much lower here, averaging approximately 6 m a.s.l., backwaters are not contained, and many of the lakes and channels in the area are flooded. The community of Aklavik (Figure 1) is also within this flooding sphere, although it is not flooded annually because it is situated at the upper end of the central Delta.

At km 1555 Middle Channel has a large oxbow known as Horseshoe Bend (Figure 1). Backwaters from jams that form at this site can flood the entire central Delta. Here levees average 4.5 m a.s.l. and are over-topped frequently (Table 2; Area 4). Most of the lakes and channels in this region are flooded annually.

Once the ice front has passed Horseshoe Bend, the northern region of the Delta is usually completely submerged. Because the levees in this region are less than 3 m a.s.l. (Figure 1), the entire northern Delta is flooded annually (Table 2; Area 8).

CONCLUSIONS

Ice jams produce peak water levels which would not ordinarily be recorded in the Mackenzie Delta as a result of the spring run-off wave alone, and which exceed summer peaks. From 1981 to 1987, ice jams which formed at the study site on Middle Channel ranged in length from 9 to 73 km, and the toe of the ice jam formed in roughly the same location each year.

Different kinds of break-up in the Delta produce different kinds of ice jams. Thermal break-up dominated from 1981 to 1987, occurring in six of the seven years; a mechanical type break-up occurring only once in 1982. The mechanical break-up produced a larger, longer-lasting ice jam with a high backwater build-up.

The energy gradient associated with a large ice jam and backwater build up on controlled rivers (e.g. well incised rivers) is not to be found in the Mackenzie Delta. Once water levels reach the height of the surrounding levees, the water overtops the levees and flows like a sheet over the Delta.

Delta geomorphology determines the extent of flooding in each region. The area flooded increases as levee heights decrease. The northern and outer portions of the central Delta are flooded annually, even when run-off is low and break-up is thermal. Only in exceptional circumstances, such as those that occurred in 1982, is the southern region of the Delta flooded.

Although recent studies have contributed new information about the processes involved in the formation of ice jams during spring break-up, and about the importance of ice jams to the hydrological regime of lakes and channels in the Mackenzie Delta, more needs to be done. More cost effective methods for monitoring the progress of break-up, as well as the development of a reliable stage flood relationship are required for successful water management in the Delta. A good flow distribution model which would allow the simulation of the effects of flow diversion in the Mackenzie Delta during spring break-up is also a necessity. Such a model could be used to predict the extent of flooding in the various regions of the Delta. More importantly the results of this kind of research could be used to integrate future regional development with the effective management and preservation of Canada's northern waters.

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