Hydrologic Response to Freeze-up on Large Northern Rivers (Case Study)

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Ice accumulation on rivers can result in upstream storage effects and downstream decreases in stage and discharge. Ice formation on a river can significantly alter seasonal flow characteristics. Ice-cover formations can result in a shift of the annual low flow occurrence from late winter (when basin catchment and atmospheric inputs are at a minimum) to the freeze-up period. Understanding the hydrologic impact of freeze-up is a prerequisite for assessing the significance of these events within the riverine environment. This paper describes the hydrologic response from major freeze-up and ice accumulation events on the Liard and Mackenzie Rivers during the fall of 1990. Analysis of the 1990 event found that low flows resulting from the freeze-up processes began in late October and were sustained through to the end of November. The freeze-up event resulted in a 33% and 42% flow reduction during November for the Liard and Mackenzie Rivers, respectively. Reasons for these dramatic decreases in flow are explored.

INTRODUCTION

Cold regions rivers have often been considered as having two significant hydrologic regimes: open water and ice-covered. The ice-covered period can be further sub-divided into periods of freeze-up, solid ice cover and breakup. Considering that the open-water period can represent less than 50% of the year for high latitude locations, comparatively little is known about the processes during these ice-covered periods.

Compared to studies related to ice jam flooding, few investigations of low flow events associated with freeze-up processes have been conducted (e.g. Gerard, 1981; Gerard, 1990; Andres and Spitzer, 1990). Prowse and Gridley (1993), in a recent comprehensive review on the environmental effects associated with river ice, emphasize the lack of research in the area of river freeze-up processes. Considering the importance of low flows on, for example, the concentration of pollutants and settling of sediment-borne contaminants, surprisingly little effort has been focused on these events. The impact of backwater storage also has hydro-ecological implications, such as flooding of low lying riparian areas, re-establishing hydraulic connection with perched channels and influencing localized groundwater levels.

Understanding the hydrologic impact of freeze-up is a prerequisite for assessing the significance of these events within the riverine environment. In the fall of 1990, a dramatic low flow event occurred on the Liard and Mackenzie Rivers, NWT, illustrating the significance of freeze-up storage (Gray and Prowse, 1993). This paper further analyzes these particular freeze-up events with respect to assessing their hydrologic response and examining some of the possible freeze-up storage processes.

STUDY AREA

a) Basin Characteristics

The Mackenzie River originates at Great Slave Lake and drains north into the Arctic Ocean. The main stem of the Mackenzie River has a length of approximately 1800 kilometres. The drainage area of the basin is 1,680,000 km^2 just prior to entering the Mackenzie Delta. The Liard River enters the Mackenzie River immediately upstream of Fort Simpson, NWT. It's basin drains an area of 275,000 km^2 and is the largest tributary of the Mackenzie River downstream of Great Slave Lake and is the second largest unregulated river in Canada (Figure 1). Mean annual flow for the Mackenzie River is 6770 m^3s^{-1}, with a mean for January and July of 2830 m^3s^{-1} and 12,600 m^3s^{-1}, respectively. The Liard River has a mean annual flow of 2480 m^3s^{-1} with mean flows of 521 m^3s^{-1} and 5970 m^3s^{-1} for the months of January and July. Ice becomes a factor on these two rivers as early as mid-October, with a solid ice cover forming in November and occasionally, as late as mid-December. The river remains ice covered until late April early May when breakup begins.

Flow in the Mackenzie River upstream of Fort Simpson is primarily controlled by outflows from Great Slave Lake. Smaller lakes, like Beaver Lake and Mills Lake upstream from Fort Simpson, also help to regulate flows in the river. These lakes provide storage for upstream inputs and can also influence the formation and breakup of the river's ice cover. Tributaries between Great Slave Lake and Fort Simpson drain lowland boreal and wetland environments and provide comparatively small contributions. Much of the Liard River Basin originates in the alpine and sub-alpine zones of the Western Cordillera to the west of Fort Simpson and unlike the Mackenzie River, has no direct influence from any lakes. The lower portions of the Liard River basin flow through the relatively flat plains of the Interior Plateau.

b) General River Ice Conditions

Freeze-up on large northern rivers, such as the Liard and Mackenzie, generally progresses in an upstream direction, although this can be intermittent. Unfortunately, few observations have been made on the Mackenzie and Liard rivers to document freeze-up processes. Typically freeze-up of large cold region rivers involves the generation of frazil ice, slush, frazil pans and shore fast border ice (eg. Ashton, 1986; Gerard, 1990).

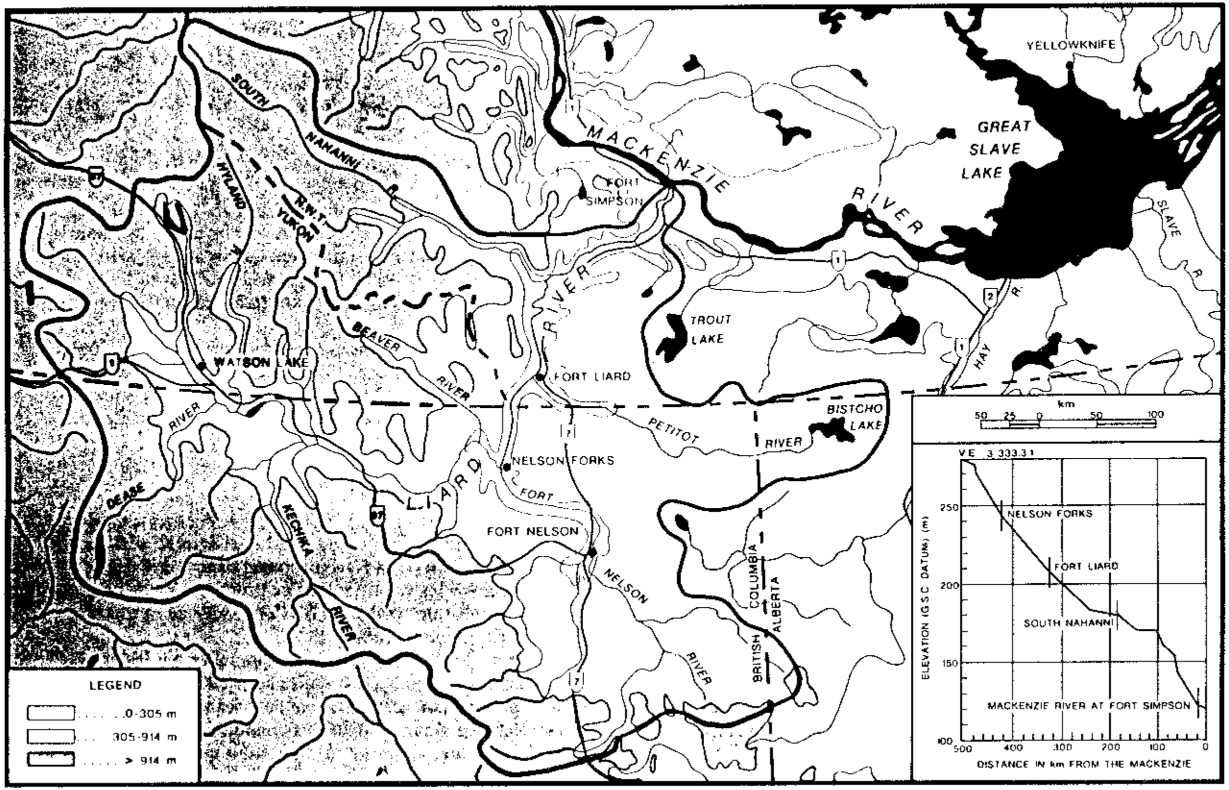


Figure 1: Liard and upper Mackenzie River. Inset shows the slope (after Parkinson and Holder, 1982) of the Liard River from Fort Nelson to Fort Simpson on the Mackenzie River.

Large lakes, such as Great Slave Lake, can also be quite important to the production of ice for the outlet river. As on the river cold temperatures and turbulence (by wind action) promote the growth and agglomeration of slush into frazil pans. Prior to the establishment of a solid ice cover on the lake, there is the potential of introducing a considerable amount of slush and frazil pans to the river system. Depending on the size of the lake, the production of slush and frazil pans and subsequent transfer to the river system can continue long after lodgment and the formation of a solid ice cover in the river.

Eventually, at some point along the river, the combination of border ice growth, channel morphology and hydraulic conditions will restrict the passage of frazil pans. The pans will lodge between the border ice, and additional pans moving down from upstream will begin to accumulate behind the lodgment. The ice cover gradually extends upstream as more frazil pans arrive, and the accumulation then solidifies and

Determining where lodgment may occur is difficult because no theory exists for defining the combination of meteorological and hydraulic conditions required for bridging to occur at specific morphologic locations. The studies that include large scale freeze-up observations (eg., Newbury, 1968; Andres, 1996), and observations from more site specific studies (eg., Anderson et al, 1988; Calkins and Brokett, 1988; Hopper et al, 1978; Keehnan et al, 1980) indicate that channel constrictions, areas of channel shoaling, and sharp channel bends are all locations where lodgment is likely to occur.

Once lodgment occurs there is an increase in the wetted perimeter of the channel due to the imposed ice cover, resulting in an increase in flow resistance. To provide a sufficient waterway to carry incoming discharge, water levels must rise upstream of the jam site. Water is abstracted from incoming flow and used to fill the available storage, thus reducing downstream discharge (Figure 2). It is believed that once the backwater storage potential is accommodated, discharge in the river will recover to a normal winter recession. There are few studies related to the hydrologic effects of freeze-up events (Gerard, 1981: Santeford and Alger, 1984), and because of the logistical difficulties presented during freeze-up, there is little documentation on the magnitude and duration of such events.

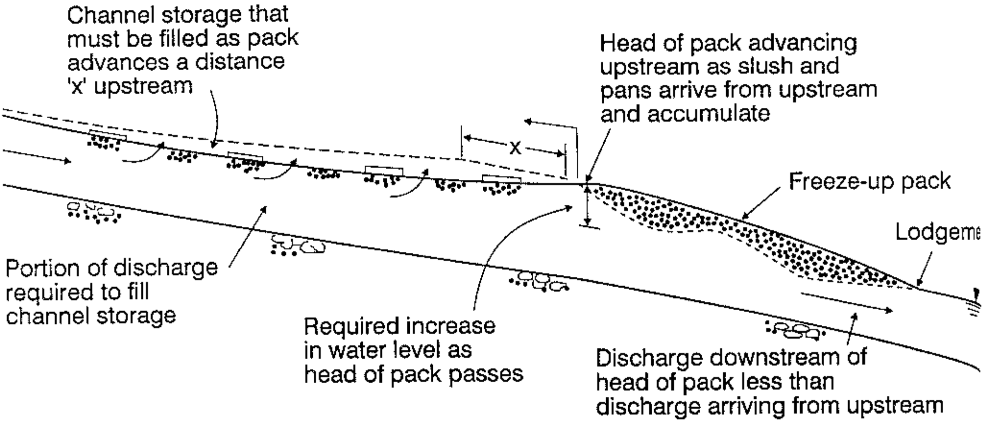


Figure 2: Discharge used to accommodate channel storage during freeze-up (from Gerard, 1990).

CASE STUDY: FREEZE-UP OBSERVATIONS

In the fall of 1990, water levels on the Mackenzie River at the community of Fort Simpson began to drop rapidly under, seemingly, open-water conditions. Although, water levels usually follow a steady recession in the fall, this rapid decline suggested that the river flow was being restricted. Field investigation in November of 1990 revealed the occurrence of freeze-up jams near the mouth of the Liard River and approximately 50 km upstream on the Mackenzie River from the Liard River confluence (Figure 3). Freeze-up jamming on the Liard River occurred in the vicinity of Truesdell Island at the mouth of the Liard River. Ice jamming on the Mackenzie River occurred at a bend in the river where the channel narrows. The mouth of the Liard River has historically been the site of breakup jams, due to the complex of islands and shoals at this location (Anderson, 1982; Prowse, 1986). Local sources indicate that these locations are among several sites along both rivers which are prone to freeze-up jamming (P. Wood, Pers. Comm, 1995).

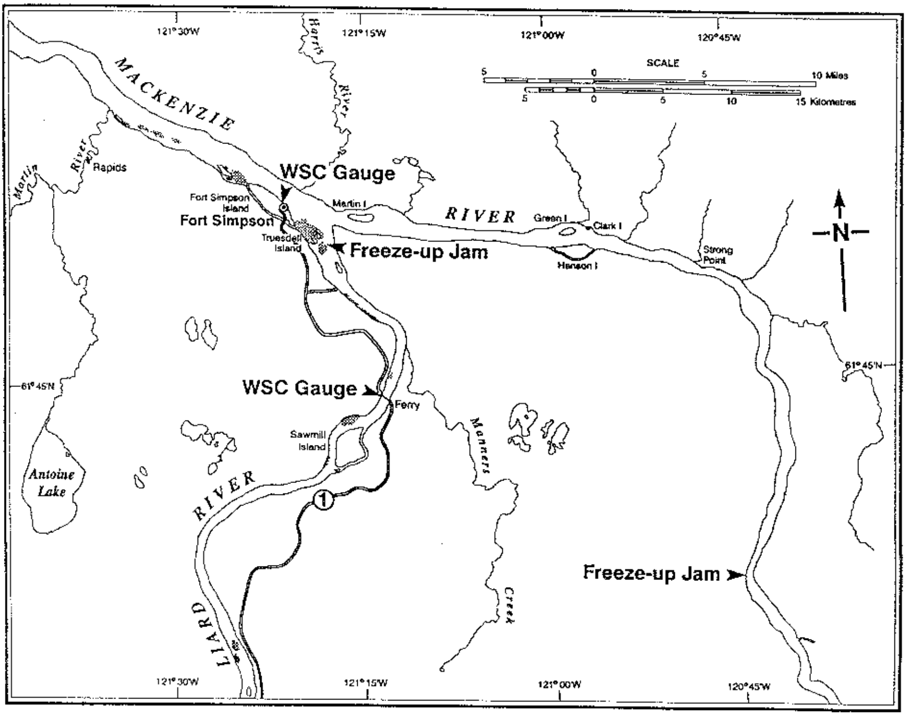


Figure 3 : Location of toes of Freeze-up jams on the Liard and Mackenzie Rivers, 1990.

From the onset of these low water events, continuous water level records were obtained by Water Survey Canada for both the Liard and Mackenzie Rivers. Detailed discharge measurements were also taken throughout the 1990 freeze-up period on the Liard River, including one open-water measurement below the Liard River freeze-up jam. Although no direct flow measurements were made on the Mackenzie River, discharges derived from the open-water level records obtained during the event are considered reliable. This assumes that the open-water reach at Fort Simpson was not under any backwater effect from ice conditions further downstream.

Hydrographs of the Liard and Mackenzie Rivers for the 1990/1991 are presented in Figures 4 and 5. Throughout the months of September and October, both locations were experiencing a gradual recession in flows. At the end of October, discharge at both locations began to decrease rapidly from a constant winter recession rate. According to Water Survey of Canada records, the recession rate started to drop more rapidly on October 29 for the Liard River and October 30 on the Mackenzie River. Minimum flows on the Liard and Mackenzie River of 280 m^3s^{-1} and 1540m^3s^{-1} were reached on November 12 and 13 respectively. These early winter values are 29% and 46% lower than the typical late-winter flow, which normally occurs in March/April when catchment runoff is at a minimum. In addition, they are in striking contrast to the mean winter low flows for the winter hydrologic period (i.e., November 1 - April 1) as illustrated in Figures 4 and 5. Based on the stage record and discharge measurements, the low flow event lasted until November 23 and December 15 on the Liard and Mackenzie Rivers, respectively, at which time flows appeared to return to a normal winter recession.

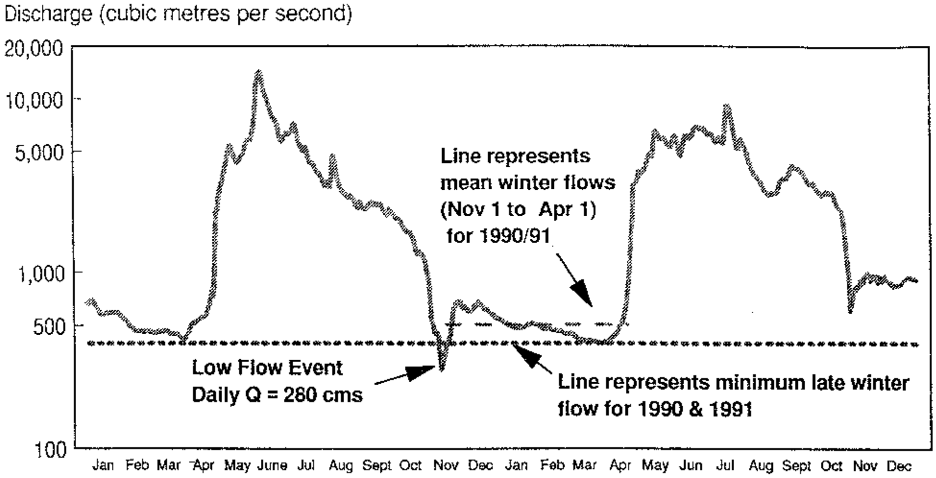


Figure 4: 1990 and 1991 hydrograph for the Liard River.

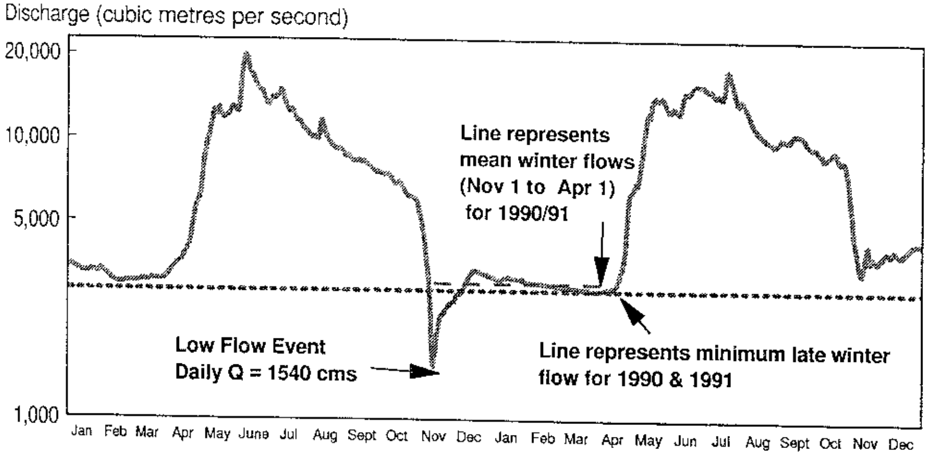


Figure 5: 1990 and 1991 hydrograph for the Mackenzie River.

ANALYSIS

Constant recession hydrographs, with steadily declining rates of discharge between inflection points (i.e., from the start of the abrupt decline in discharge to the return of normal flow recession), were generated to estimate the volume of flow extracted to accommodate storage (Figure 6). The differences in flow volume between the constant recession and actual hydrographs are provided in Table 1. For the 26 day low flow period on the Liard River and the 47 day period on the Mackenzie River, the flow extracted for storage represented 30% and 34%, respectively, of the expected flow for these periods. Monthly hydrograph separation, indicates that 33% and 42% of the anticipated November flows are placed into storage for the Liard and Mackenzie rivers. Estimates, based on constant recession hydrographs, indicate that this storage represents an annual seasonal redistribution of 0.8% and 2.5% for the Liard and Mackenzie river flows, respectively.

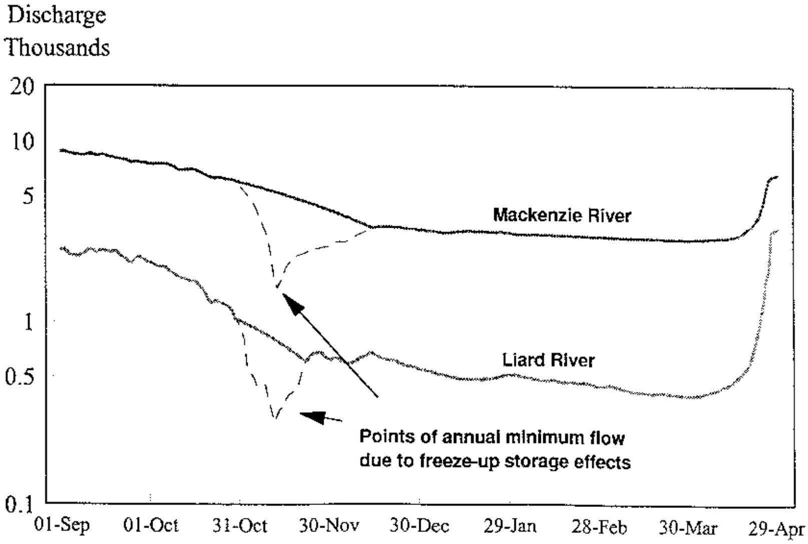


Figure 6: Constant recession hydrographs, showing displacement of minimum flows.

Table 1: Flows for the Liard and Mackenzie rivers. November flows are based on constant recession hydrographs. Bracketed values indicate the actual flows determined for the month.

	Annual Flow ($x10^9$ m^3)	November Flow ($x10^9$ m^3)	Ve Estimated Storage ($x10^9$ m^3)	% Nov. Flow	% Annual Flow
Liard River	78	2.0 (1.3)	0.66	33%	0.8%
Mackenzie River	224	13.0 (7.6)	5.5	42%	2.5%

The main observations required for the analysis of a freeze-up event include: stage, discharge, ice types, concentrations of ice, method of freeze-up, nature of ice cover formed and rate of upstream progression (Prowse, 1990) As this event occurred in a remote region of northern Canada many of these observations could not be obtained. Due to the location of the ice jam on the Mackenzie River (Figure 3) no water level measurements were obtained immediately upstream of this jam location. The Liard River gauge, however, located approximately 15 kilometres upstream of the freeze-up jam location, indicated stage increases approaching 2.5 metres during this event (Figure 7). Applying the 2.5 m increase as a mean backwater depth, utilizing an average slope of 0.00034 and a constant channel width of 800 m, 330 km of channel length would be required to accommodate the flow abstracted for storage in the Liard River. This would suggest that the backwater from this freeze-up jam would extend as far upstream as the town of Fort Liard (see Figure 1).

Another approach in determining the backwater storage is to calculate the water profiles that would develop following flow obstruction by ice lodgment. Unfortunately, insufficient data are available to calculate backwater curves, therefore a more simplistic approach had to be adopted. Water stored in channel, upstream of the freeze-up jam is consider as a wedge (Figure 8). Using the estimated volume (V_e) of water placed into storage in each river, average channel widths (B) and slopes (S) for each site, backwater stage increases (h) and effective backwater distances (x) upstream of freeze-up jam locations were estimated (Table 2). Although, this rudimentary analysis will have errors associated with assuming constant slope and channel width, it does illustrate the magnitude of the freeze-up storage. Calculated backwater stage increases of 24 m for the Liard River are an order of magnitude higher than measured in the fall of 1990 (Figure 7). These estimates of backwater suggest that local in-channel storage cannot fully account for the flow abstracted as a result of freeze-up jamming and ice cover formation. Additional storage processes must be considered in accounting for the dramatic loses of flow in the system. Questions remain, however, as to the type and magnitude of the various storage processes.

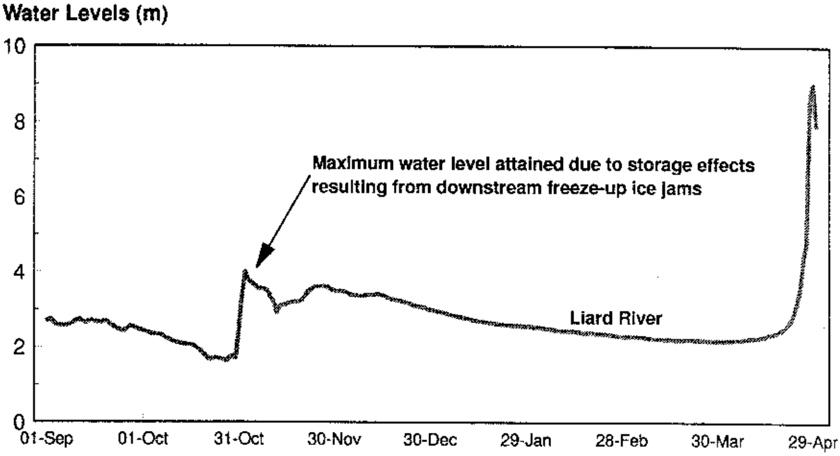
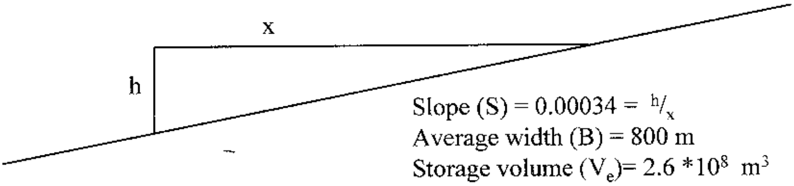


Figure 7: Water level hydrograph for the Liard River near the mouth, fall and winter 1990/91.



Slope (S) = 0.00034 = $^h/_x$

Average width (B) = 800 m

Storage volume (V_e)= 2.6 $*10^8$ m^3

Figure 8: Estimating backwater based on "wedge of water".

Table 2: Backwater estimates, based on average conditions based on "wedge of water" approach.

	V_e $(x10^9 m^3)$	W (m)	S	X (km)	h (m)
Liard River	0.66	800	0.00034	70	24
Mackenzie River	6.5	1000	0.00012	330	40

DISCUSSION

Several storage processes can be considered, and in combination provide some explanation for the total storage. Total storage can be expressed as a function of:

$$S_t = f(S_i + S_j + S_c + S_g + S_o + S_l)$$

where S_i is the volume of water utilized in the formation of ice, S_j is the backwater specifically associated with freeze-up ice jamming, S_c is additional in-channel storage available as stage increases, S_g is the groundwater storage component, S_o is overbank storage associated with perched basins and wetlands, and S_L is the lake storage component.

As ice forms, water is removed from the flow and as ice accumulates it during it creates a linear frozen reservoir of water (S_i). As the ice continues to thicken additional water is abstracted from the flow. The amount of water required will depend on how the ice cover forms (i.e., thick 'consolidated' ice cover vs. thin 'juxtaposed' ice cover). For the Liard River, average ice thickness at the measurement cross-section was 0.24 m on November 7, the first opportunity to safely measure from the ice surface. Based on an average width and a 100 km of reach of river, this represents less than 1% of the total storage. Over a greater distance of the river S_i will be higher, but relative to the S_t it is still a small percentage.

Formation of a solid ice cover, as it progresses upstream, can also result in water being abstracted from the flow for storage (Figure 2). The amount of backwater storage generated by a freeze-up jam (S_j) is dependent on how the ice cover forms. A thin smooth juxtaposed ice cover will not create the same resistance to the flow as a rougher, thicker consolidated ice cover. The greater the resistance to the flow the more flow must be abstracted to storage to raise the ice cover to a level that will accommodate the existing discharge. As S_j increases additional in-channel storage (S_c) becomes a factor. Estimates of backwater were calculated using average conditions and therefore do not take into account all in-channel storage (S_c & S_j) local to the freeze-up jam sites. S_c can include secondary channels behind islands, backwater snyes, and the mouths and channels of tributaries feeding into the river.

Elevated stage can influence Sg by reversing local hydraulic gradients which can lead to groundwater recharge or restrict further groundwater input to the channel. Raised water levels resulting from ice induced backwater resulted in surcharging of groundwater and the mid-winter flooding of basements in the Town of Peace (Andres, 1996). The importance of the S_g by either recharge or restriction of base flow inputs will vary depending on the dominance of the groundwater regime to basin flow characteristics. Unfortunately, knowledge of basin wide groundwater recharge in northern environments is limited (van Evirdingen, 1990) and therefore the extent that S_g contributes to S_t is difficult to assess. Even if the stage increases enough to level or reverse local hydraulic gradients, river systems like the Liard and Mackenzie rivers, which are dominated by large exotic flows, are unlikely to be significantly affected by S_g. Smaller basins with dominant base flow characteristics would likely have a higher S_g component under ice induced backwater conditions.

Local stage increases can also re-establish hydraulic connection to overbank areas (S_o). Studies in the Mackenzie Delta, for example, have found that some overbank basins can be hydraulically re-connected as a result of water level increases associated with ice cover formation on the main channels (Burn, 1991). As water levels rise they eventually surpass a minimum sill elevation, allowing the water to drain into overbank areas or perched basins. Although S_o is not considered significant on the main stem of the Liard and Mackenzie rivers, it may have significant implications in wetland and deltaic environments.

Lakes are natural storage reservoirs and can accommodate large amounts of backwater associated with freeze-up jamming. The Liard River has no significant lakes along the length of it's main stem and therefore S_l is not considered as a factor for this system. The site of the freeze-up jam on the Mackenzie River, however, is approximately 280 km downstream from Great Slave Lake and only 150 km downstream of the outlet of Mills Lake. Considering the magnitude of the S_t, it is possible that Mills Lake may provide storage (S_l), but no data are available to confirm this suspicion. Lake outlets can also have significant control on flows to a river. Outlets on small lakes can freeze to the bottom, reducing the effective catchment area of the basin by cutting off flow to the system. Although heat storage in larger lakes often prevents the outlet from freezing during the winter, large ice pans formed during the early freeze-up process can temporarily restrict the outlet, resulting in S_l. Without direct observations of ice conditions at the outlet of either Mills Lake or Great Slave Lake, it is impossible to determine their effect on the low flow conditions on the Mackenzie River during the fall of 1990.

Several storage components have been considered in the examination of the early winter low flow events on the Mackenzie and Liard rivers, but it may be that this event was a result of a combination of low flow events throughout the basin. Smaller tributaries often form ice covers prior to larger systems. As these smaller basins freeze-up, each will undergo localized storage effects (S_t'), with the dominance of individual storage components dependent on local basin characteristics. The combination of these events occurring with those on a larger system can amplify low flows at downstream locations. Unlike the open water conditions that occurred on the Mackenzie River at Fort Simpson in the fall of 1990, local ice cover formation and backwater can potentially mask the magnitude of low flows.

Although it is generally recognized that north flowing rivers freeze from north to south, the reverse does occur. Gauge records for the Liard River at Fort Liard, for example, indicate that in the fall of 1990 ice induced backwater occurred three days prior to backwater at the Liard River near the mouth. It is therefore conceivable that the entire length of river between these two sites (i.e., approximately 330 km) could have been subject to freeze-up storage effects. Thus the earlier analysis that indicated that backwater would have to extend as far back as Fort Liard to account for the flow abstracted to storage may not be completely unreasonable

Although this low flow event on the Mackenzie River seems unique, it is interesting to note that the historic daily low flow also occurred in the early winter on November 24, 1980 ($Q = 1500\ m^3s^{-1}$). Similarly, the lowest flow on the Liard River, occurred on November 7, 1979 ($Q = 260\ m^3s^{-1}$). The similarity in magnitude and timing of these record low flows, to the 1990 events, suggests that they may also have been a result of freeze-up processes. It may be that early winter low flow events are quite common but due to the logistical difficulties associated with monitoring flows during this period many of these events are overlooked.

SUMMARY

This paper has provided documentation and analysis of early winter low flow events on the Liard and Mackenzie rivers. The low flow events on these two rivers occurred during the freeze-up period and were sustained for more than three weeks. The rapid decrease in flows and subsequent storage of water on the Liard and Mackenzie rivers were quite dramatic considering the magnitude and duration of the events. Analysis of the events suggests that the amount of flow removed to storage cannot be fully accounted for by in-channel storage associated with the formation of the freeze-up jam and ice cover. Various storage components were identified and briefly discussed relative to their affect on these river systems. It is recognized that the dynamics of freeze-up within a basin, the timing and areal extent of these storage components are important considerations. For example, generation and growth of the ice cover may not account for a significant volume of water over a short distance but integrated over the linear basin drainage network, will be more significant. In addition, the formation of freeze-up ice jams and associated backwater can occur at multiple locations within the basin. Therefore the total storage effect measured will be a result of concomitant storage effects throughout the basin. Documenting the hydrologic responses associated with freeze-up and the hydrometeorological conditions that drive the system are necessary steps to understanding these dramatic events.

As identified by Gerard (1990), the interaction between ice, lakes and minimum flows on rivers has largely been neglected. The dynamics of the freeze-up process and the difficulties associated with conducting field programs using conventional methods during this period have often resulted in unreliable flow data. It is apparent, however, from documentation of the hydrologic responses of the Liard and Mackenzie Rivers, NWT that significant storage effects and subsequent low flows can be realized as a result of freeze-up processes. The next steps required to obtain a better understanding of these low flow events and associated storage effects should include: a) compilation and review of Water Survey of Canada data and stage records to provide insight to the frequency of occurrence and the possible influence of basin wide responses to freeze-up processes; b) basin wide freeze-up observations, which are necessary to understand the influence of concomitant storage effects and low flow events, and; c) reach specific investigations to better understand the processes involved with the various freeze-up storage components.

ACKNOWLEDGEMENTS

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Rick Rodman - Klohn Crippen Consulting Engineers

What was the duration of flows/water levels attributed to the ice front formation - a few days or a month?

Reply:

The low flow events extended for 26 days for the Liard River - basically one month and for 47 days for the Mackenzie River - about a month and a half.