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Hydroelectric Power Development and the Ice Regime of Inland Waters: A Northern Community Perspective

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Hydroelectric Power Development and the Ice Regime of Inland Waters: A Northern Community Perspective

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ABSTRACT

Inland waters play a vital role in the life of the many small communities that dot Canada's north and which depend in large measure on the provisions of the natural environment for their sustenance. Despite their relatively small population, these communities and their activities often represent the only habitation and industry in the region and therefore have a significance beyond that suggested by their small population.

Because of the nature of their livelihood, the residents of these communities are attuned to the rhythms of the natural world, especially that of the ice covers that form on inland waters in winter, and on which they depend for transport to fishing, hunting and trapping grounds, and to and from other communities for supplies and services. These communities are therefore particularly vulnerable to changes in the ice regime of these waters, especially changes that are irregular.

However, the north is also the site of much of Canada's hydroelectric power development and potential, developments that can have a major influence on the ice regime of effected waters. It is therefore important that the residents of communities that are, or will be, influenced by such developments are aware of the possible changes that can take place, and of the nature of hydroelectric operations, so that they can ensure their interests are considered in the planning and operation of a project, and to assist them in their adaptation if if goes ahead. It is also important that the agencies responsible for these developments and their operation are aware of the changes to the ice regime that will be wrought and the consequences for the residents.

As a contribution to the background information required for the necessary discussions and negotiations associated with such developments, in

this report the various aspects of the natural ice regime, and the possible effects of hydroelectric development and operation on this regime, and its consequences, are briefly reviewed. The emphasis has been placed on changes that will likely be of most significance to northern communities in the bedrock-controlled country of the western Canadian Shield.

The major direct, and in some circumstances life-threatening, impact of changes to the ice regime is on trafficability of the iceways that play such a vital role in the life of the communities. Hence particular emphasis has been placed on this aspect and on the formation of the slush and thin ice conditions that are the bane of over-ice travel and that are subject to unexpected changes by hydroelectric development and operation.

To place these changes and their effects in some perspective, the nature of a hydroelectric development is also briefly described and an effort made to indicate the large costs incurred if these developments are restrained in their operation to avoid or mitigate some of the effects on the ice regime.

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ACKNOWLEDGEMENTS

Dr. T. Prowse of the National Hydrology Research Institute initiated and coordinated this project, and provided much of the background material on which the report is based. His assistance and encouragement is gratefully acknowledged. Martin Jasek assisted in collecting further background information on the interaction of hydroelectric power plants and the ice regime. Toni-Lynne Jacobson prepared a draft background document on the effects on wildlife of changes to the ice regime of inland waters.

DISCLAIMER

This report was prepared as part of the Federal Ecological Monitoring Program. Any conclusions, recommendations or opinions expressed herein are those of the author and are not necessarily the same as those of the sponsoring departments.

1. INTRODUCTION

It is in the north that Canada's greatest hydroelectric potential lies, and the north is replete with examples of rivers that have been developed for their power: 5.2 GW* at Churchill Falls in Newfoundland; 10 GW from the first phase of the James Bay project in Quebec; 3.1 GW from the Peace River development in British Columbia; and 3.9 GW from the Churchill-Nelson development in Manitoba when the Limestone plant begins operation. Some 67% of Canada's electrical power needs is currently supplied by hydroelectric power. The economic significance of this power is therefore immense, both in its monetary value and in the pollution saved from power production by thermal power plants. But it has its own environmental price, particularly for the northern communities influenced by the development.

Construction of a large hydroelectric development on a river can have an enormous influence on the ecology of the waters that it influences. Indeed, the large reservoirs that are part of these developments have as their purpose the total change of the flow regime of the river. This is particularly so for a northern river. Under the natural regime, the flow in a northern river typically falls gradually over the winter, reaching a minimum in late winter, prior to a sudden increase in spring as snowmelt begins and the river casts off its mantle of ice. Yet the maximum power demand on a hydroelectric plant occurs in winter. Hence the plant must pass the maximum amount of water through its turbines in winter to meet this demand. The result is an almost complete reversal of the natural winter cycle in the river downstream. On the

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*Gigawatt, or 1,000,000,000 watts, enough power to supply electricity for about 1 million residences.

other hand, downstream of a major diversion for power development, such as the Churchill River diversion in Manitoba, there is a drastic reduction in flow in winter below the minimum that already occurs.

The interaction between hydroelectric power operations and the ice regimes of inland waters has an impact on two parties: the utility company which operates the plants and, through them, particularly in those Provinces where the utilities are Crown Agencies, the people of the province; and the residents of the local communities effected by the development. It is the latter that are of prime concern herein.

The influence of a changed ice regime on the activities of local communities can be immediate, obvious and demonstrably detrimental - to the point of loss of life. This impact must be acknowledged by the organizations responsible for the hydroelectric development and considered in the evaluation of the project, and in its subsequent operation. The local residents should also be aware of this impact, both to allow them to judge the likely significance for them and, if the project proceeds, to aid them in their adaptation to the new reality.

The influence of a changed ice regime on wildlife, on which northern communities depend for much of their sustenance, remains largely undocumented.* Under the blanket of snow and ice that covers the water bodies of northern Canada for much of the year, life continues, albeit unseen and unheard. But it is life under stress and presumably is particularly sensitive to variations from the norm that has been established over the millenia. It is therefore most unlikely that the dramatic changes wrought by hydroelectric

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* It is a remarkable fact that, despite the enormous amount of research on the natural environment in Canada, remarkably little is known of life in the winter. This is particularly true for aquatic and semi-aquatic fauna.

development in the regime of the influenced inland waters will not cause significant changes to this delicately poised existence, particularly during the period of adjustment to the new regime. This adjustment can take decades even with the rather rapid adaptation of which man is capable but, because of its much slower adaptive capacity, can take very much longer for the northern environment.

The development of the Churchill-Nelson River system by the Province of Manitoba provides a major example of the interaction of hydroelectric power development and the environment in western Canada. The present system is shown in Figure 1. The configuration of the scheme is most clearly evident in the perspective diagram of Figure 2, which also shows the extent of planned future developments.

Development of this system began in 1960 when the plant at Kelsey on the Nelson River was commissioned to begin to take advantage of the power potential of the 2,300 m^3/s mean flow in this river, the 216 m fall from Lake Winnipeg to Hudson Bay, and the plethora of dam sites afforded by the geology and topography of the Canadian Shield. Kelsey was followed by construction of plants at Jenpeg, Kettle and Long Spruce. The plant at Limestone is expected to be complete by the early 1990's. In 1976 a diversion structure was completed on the Churchill River at Missi Falls, at the outlet of Southern Indian Lake. Its purpose is to divert an average of some 75% of the 1,011 m^3/s mean Churchill River flow at Missi Falls through the Rat-Burntwood River system to the Nelson River at Split Lake, to augment the power production capacity of the plants on the Nelson River system downstream of this location. At the design diversion of 710 m^3/s, the mean flow in the Burntwood waterway will be some 100 times the recorded minimum winter flow of this waterway and several times the historical mean of 113 m^3/s(13).

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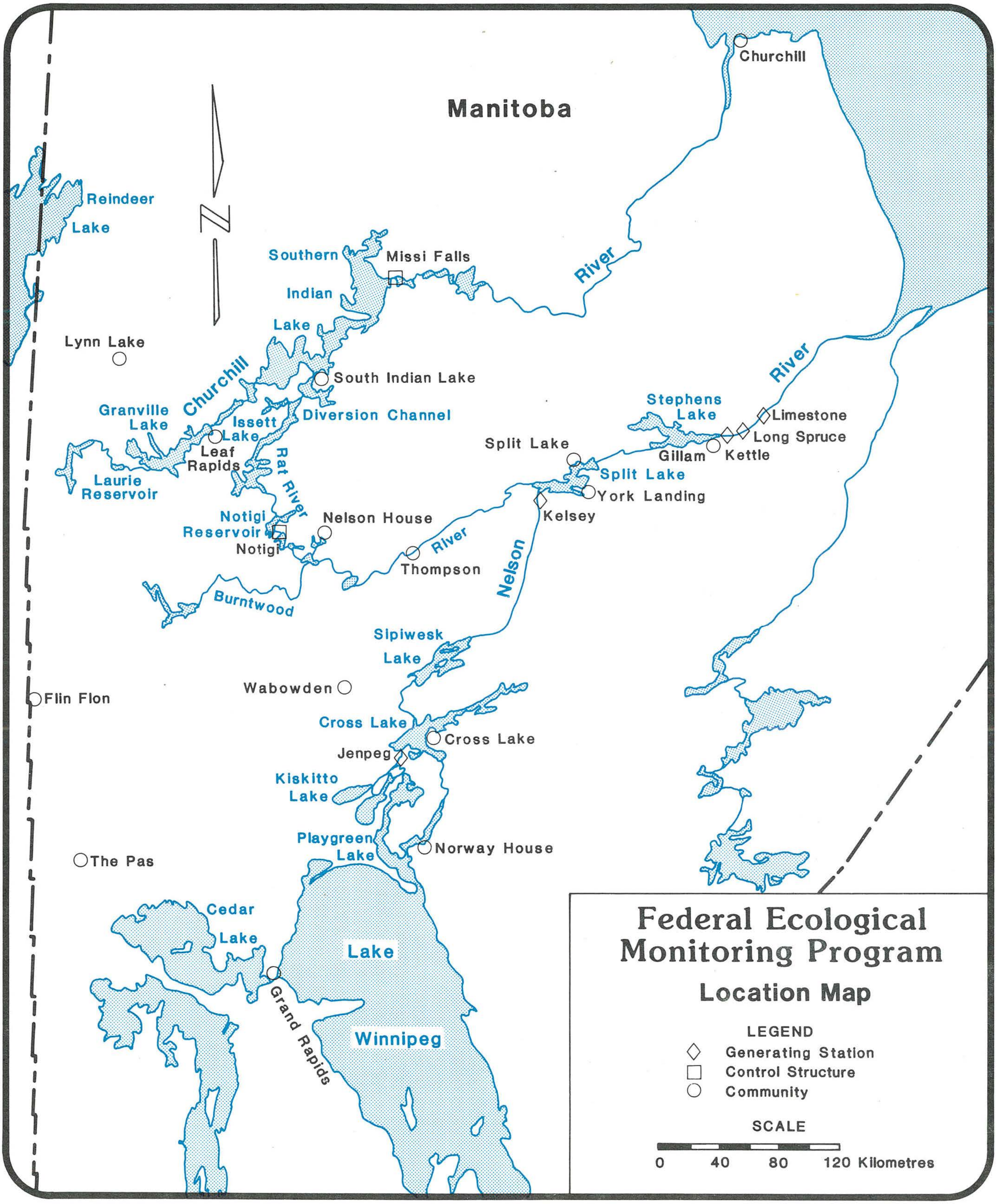
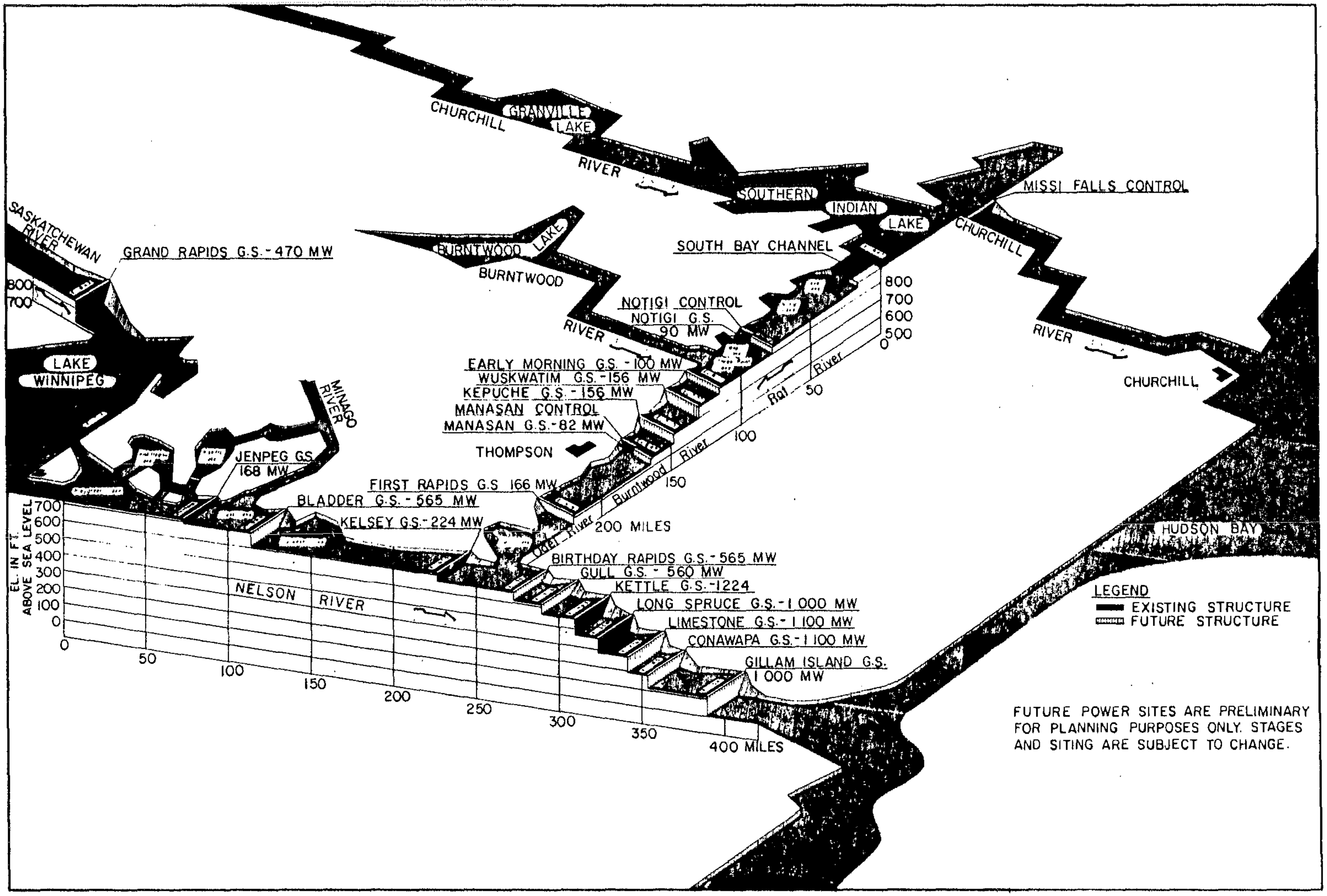
* See the following page.



Federal Ecological Monitoring Program

Location Map



FUTURE POWER SITES ARE PRELIMINARY FOR PLANNING PURPOSES ONLY. STAGES AND SITING ARE SUBJECT TO CHANGE.

Figure 2. The Churchill-Nelson development in perspective (13).

Changes wrought by the Churchill-Nelson development include dramatic reductions in the discharge of the Churchill River below Missi Falls; increases in winter discharge through other lakes and rivers of the system, particularly the Rat and Burntwood Rivers; changes in the thermal regime of all these water bodies; and substantial fluctuations in water levels throughout the winter as the system is operated to optimize power production. Such changes will obviously have a significant influence on the ice regime of these rivers and lakes.

The objective of this report is to provide an outline of the processes, possibilities and problems associated with the interaction of hydroelectric development and the ice regime of inland waters, with particlar emphasis on the influence of the changed ice regime on nearby communities, and on the situation as it is likely to exist in the Shield country of northern Canada, with its unique mixture of rivers and lakes, rapids and pools. While the Churchill-Nelson development provides particularly dramatic examples of such changes, they are by no means unique in Canada.

In the following the natural ice regime of lakes and rivers is reviewed; the nature, objectives and restraints of hydroelectric development are discussed; and changes likely to occur in the ice regime as a result of such development, and their social and environmental significance, are considered.

To understand the various ice processes, it is first necessary to understand something of the hydraulic and thermal characteristics of lakes and rivers, and how these are influenced by the presence of an ice cover.

2. HYDRAULIC AND THERMAL REGIME OF ICE-COVERED INLAND WATERS

2.1 BEHAVIOUR OF A FLOATING ICE COVER

2.1.1 Draft of a floating ice cover

To understand the influence of an ice cover on rivers and lakes it is necessary to understand the behaviour of a floating ice cover. When an ice sheet is free of restraint, it floats to a depth such that the buoyancy of the ice below the water line is sufficient to support the weight of the portion of the ice cover above the water line. This occurs when the draft of the ice cover - the portion of the ice cover below the water level - is about 92% of its thickness, as shown in Figure 3(a). This rule applies even if the ice cover consists of fragmented ice, as shown in Figure 3(b).

If the ice carries a snow cover, or is supporting some other applied load, it will sink into the water like a raft until the additional buoyancy so mobilized is sufficient to support the load. The problem is that with only 8% of the ice cover as freeboard (i.e. above water) this additional buoyancy is very limited. Indeed, a snow cover of only about half the ice cover thickness is usually sufficient to 'sink' the ice cover and allow water to flood through cracks and out over the ice, saturating the lower layers of the snow, as shown in Figure 3(c), and forming the slush or overflow that is the bane of oversnow travel on lakes and rivers. The thickness of this saturated layer will depend on the ice thickness and the depth and density of the snow. Between snowfalls the snow depth can be undergoing change due to drifting.

As discussed later, it is possible to get accumulations of slush ice under the ice, sometimes extremely thick accumulations. The situation is then reversed, and the freeboard of the ice is increased as shown in Figure 3(d).

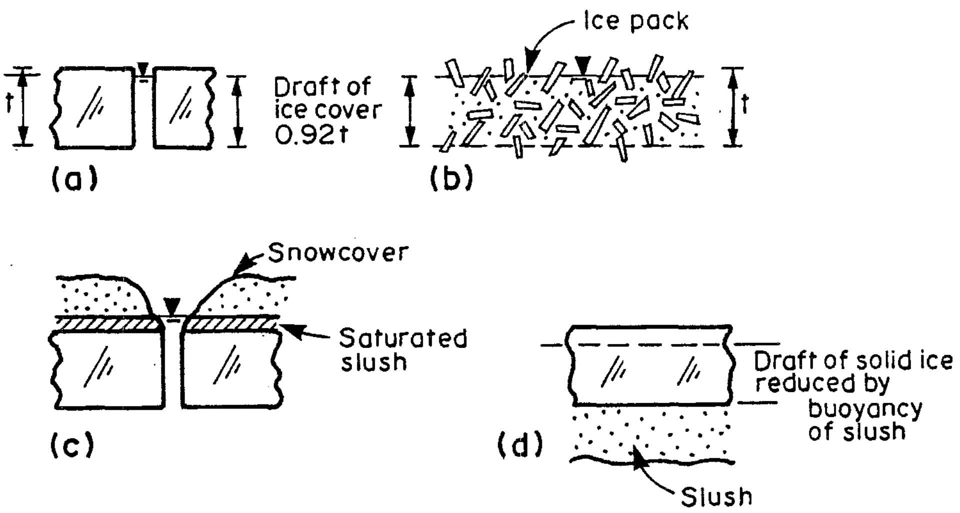


Figure 3. The draft of a floating ice cover

In the above situations the ice cover is free to follow water level changes. However, near the shore or other restraint the ice cover is not free to follow water level changes. For example, it can be shown that, for a sudden change in water level, the portion of the ice cover within about 40 thicknesses from shore, or from a tree or pile to which the ice is adhering, will be restrained to some degree by the attachment, as shown in Figure 4. Then, if there is sufficient increase in water level, flooding of the ice cover will occur to again form overflow or slush, the depth of which depends on the magnitude of the change in water level.

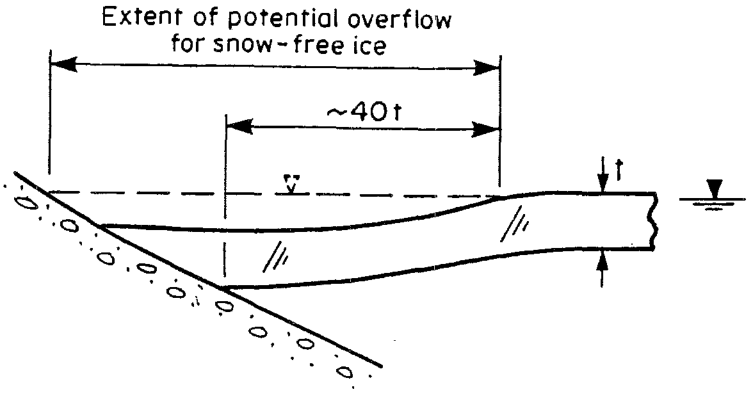


Figure 4. Edge restraint on an ice cover at the shore or around a pile or tree

2.1.2 Load bearing capacity of an ice cover

Despite its limited buoyancy, a thick ice cover is capable of supporting large loads, a feature taken advantage of for ice roads and ice bridges. As this feature of a floating ice cover plays a crucial role in transport and communication in northern communities, and is subject to disruption by the impact of hydroelectric development on the ice cover, important features of the load bearing capacity of an ice cover are briefly discussed below.

2.1.2.1 Slowly moving load

For a locally applied load, such as a vehicle, the ice cover forms a deflection bowl around the load. This deflection bowl has the shape and dimensions shown in Figure 5 if the load is well away from shore, cracks and other discontinuities in the ice cover. The magnitude of the deflection is such that the buoyancy generated over the deflection bowl is equal to the weight of the vehicle.

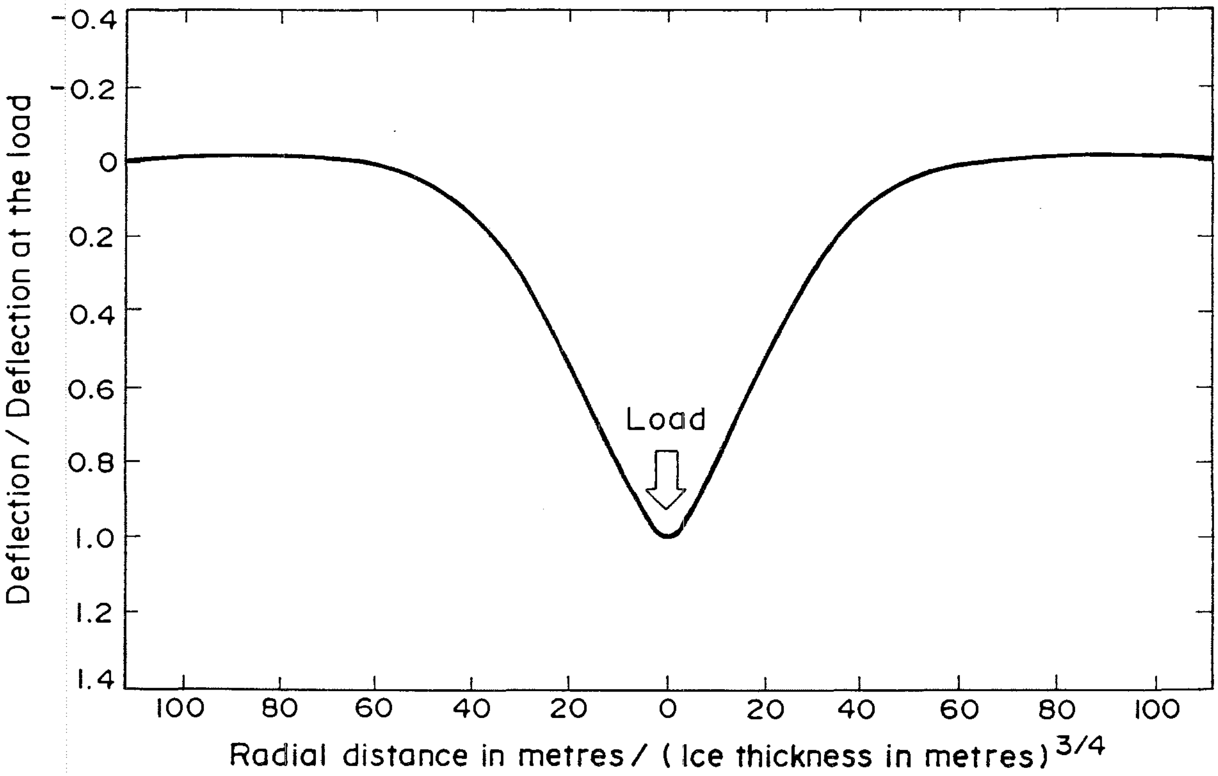


Figure 5. Deflection bowl around a concentrated load on ice (adapted from 20)

In other words, the deflection bowl acts much like an ice raft, with the size of the raft, and the strength of the 'floor', governed by the thickness, strength and stiffness of the ice sheet. If the load is too large the stresses generated in the ice cover will exceed its strength and the vehicle will break through the ice - the floor of the raft. Experience has indicated that this is unlikely to happen for a slowly moving load (i.e. say between 1 and 10 km/h) on good quality fresh water ice if the load is less than that shown in Figure 6. However the load bearing capacity is reduced if the load is stationary, or if it is travelling near the critical speed for the ice cover, as described below.

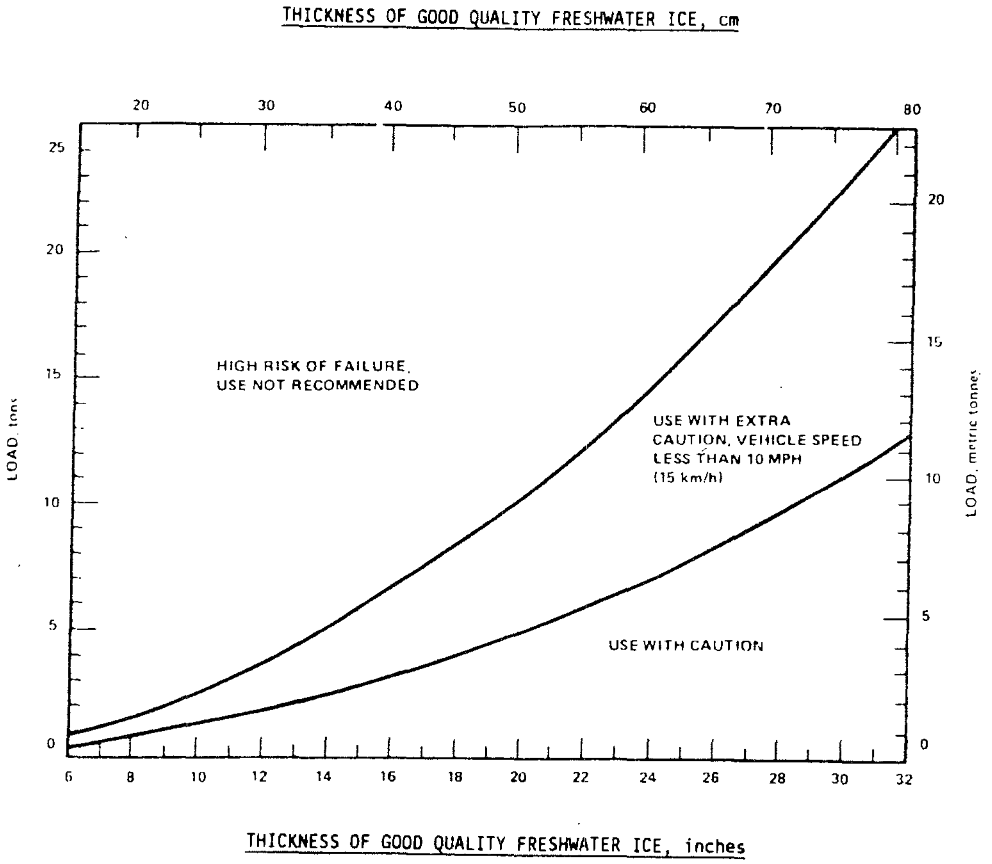


Figure 6. Recommended maximum load for good quality fresh water ice (from 30).

2.1.2.2 Stationary load

Ice is a crystalline material that in nature exists very close to its melting point. Any other crystalline material so close to its melting point, such as a metal like steel or copper, would display a marked softening, if not actually be semi-liquid. It is one of the remarkable features of water that its solid state - ice - remains as stiff and brittle as it does so close to its melting point. Nevertheless it does display some softening, and ice will continue to deform over time under the action of a constant load, as shown in Figure 7, and can eventually fail, even though the load was supported initially. This process of continued deflection under constant load is called creep. As would be expected, it increases markedly as the ice temperature approaches 0°C.

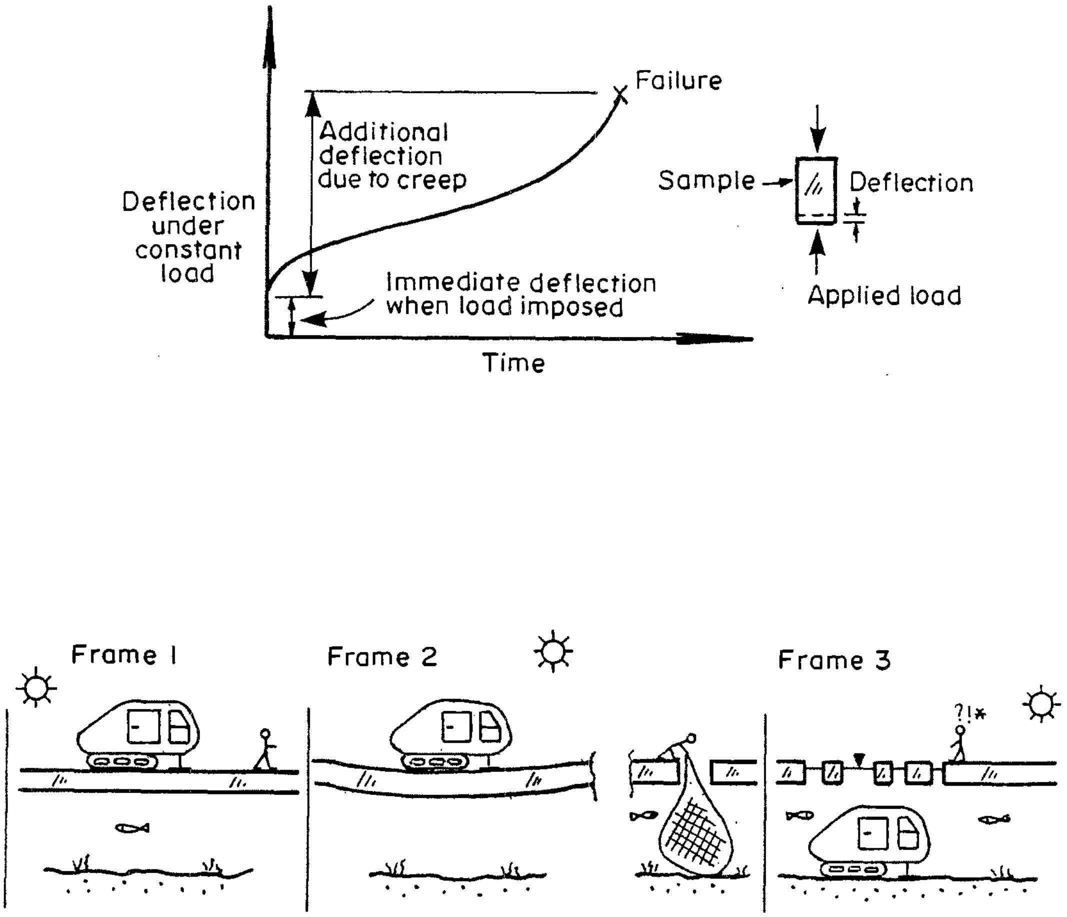


Figure 7. Creep of ice under a constant applied load. The cartoon illustrates a practical aspect of this behaviour.

The implications of this process for parked loads can be as shown in Figure 7. Hence if a parked load is anywhere near the limit given by Figure 6, the situation should be at least visually checked at frequent intervals for signs of distress in the ice cover. These signs include development of a marked sagging or flooding of the ice cover around the load. If such signs develop the load should be moved: failure can occur within minutes of such distress becoming apparent.

2.1.2.3 Moving load

When a load moves over the ice, the action of the deflection bowl on the water underneath is akin to that of a shallow-draft boat or ferry. It generates a wave in the water. This wave travels at a speed that depends primarily on water depth and ice cover thickness, as shown in Figure 8. If the load is moving at about the same speed as the wave, stresses in the ice induced by the vehicle are compounded by those induced by the wave.

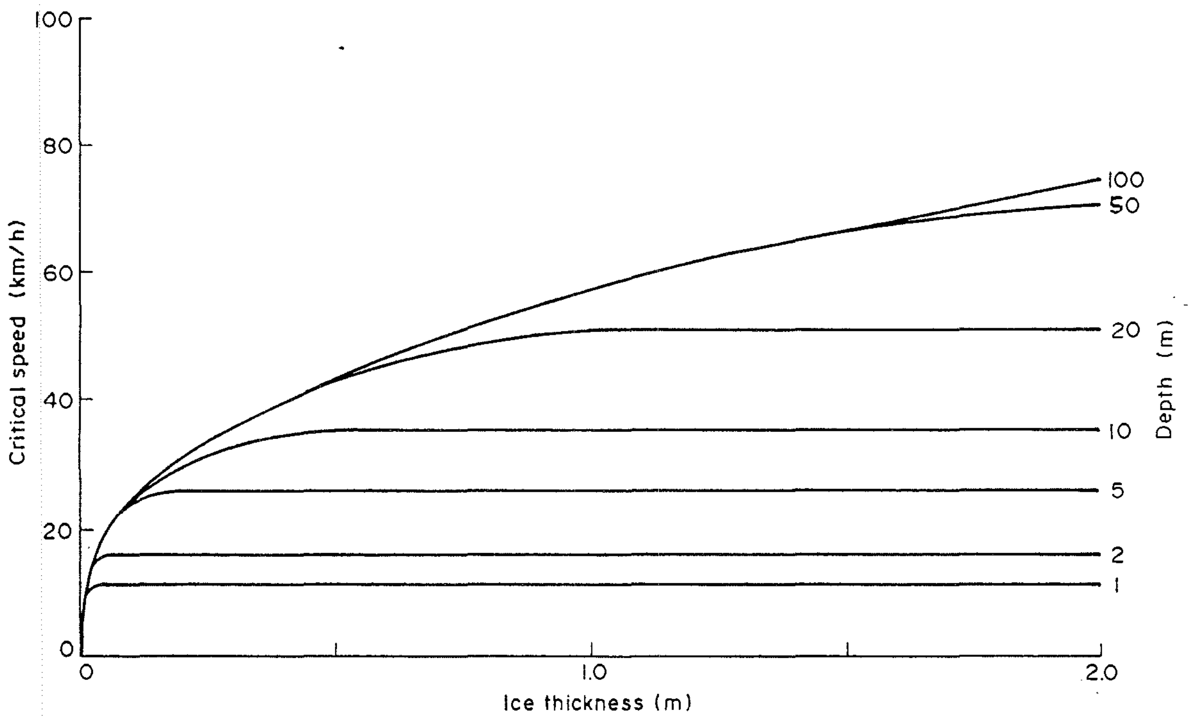
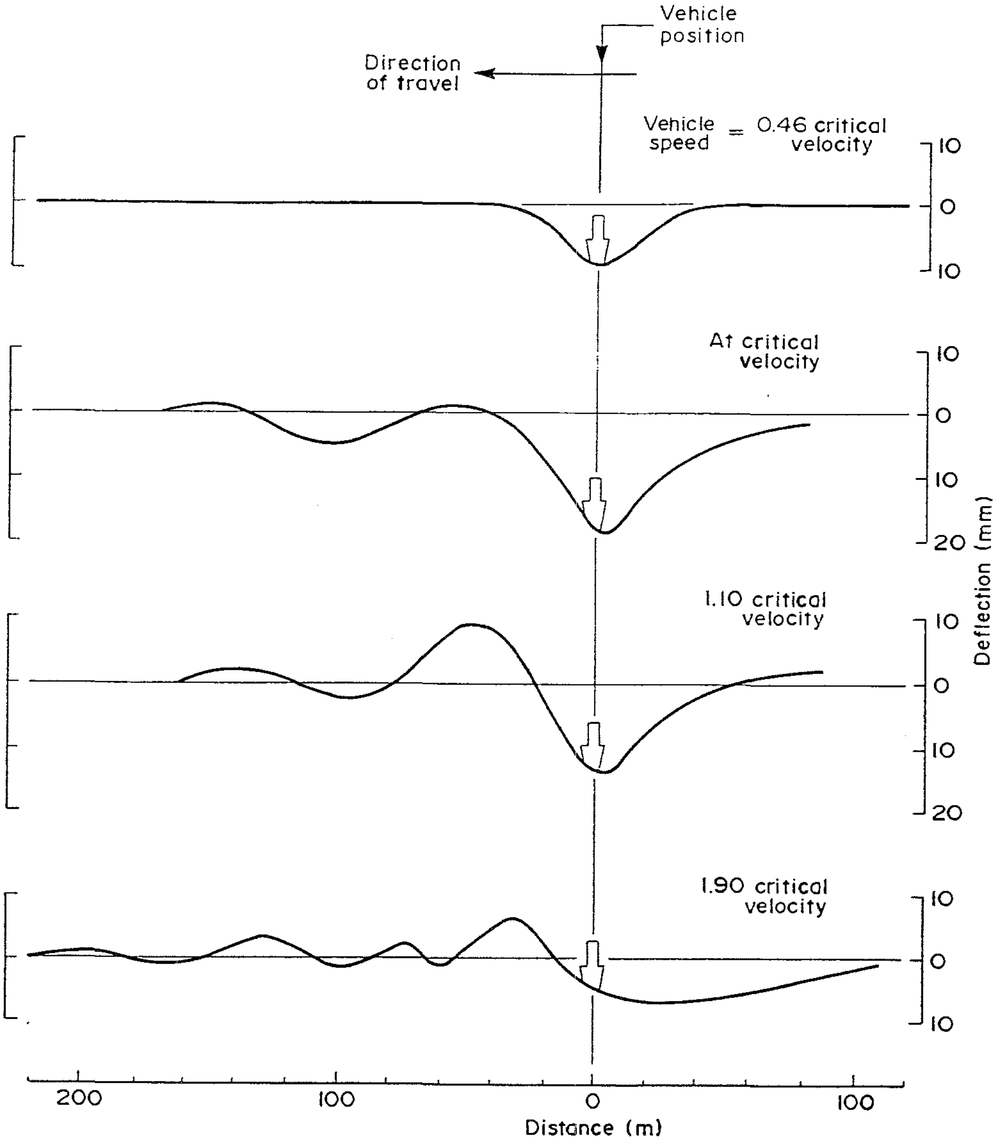


Figure 8. Critical speeds for moving loads on floating ice covers (adapted from 21)

Significant additional stressing of the ice cover can be expected for a speed between about one half and two and a half times that indicated by Figure 8 for a particular situation.

The distortion of the ice cover induced by the wave is clearly evident in Figure 9. Of particular note is that the vehicle has obviously begun to move



Notes: Ice thickness 0.59 m
Water depth 4.3 m
Critical velocity 26.3 km/h (7.3 m/s)

Figure 9 Deflections of an ice cover near a moving load (adapted from 4)

out of the deflection bowl when its speed is about twice the critical velocity, and would appear to be 'running over the wave'. The latter is a common observation at the time of breakthrough.

It is evident from Figure 8 that for speeds less than about 10 km/h to be near critical, the depths are shallow enough that a breakthrough is likely to be inconvenient rather than catastrophic, unless the traveller is alone in an isolated location - then it can be fatal. At speeds substantially above the critical speed, the deflection bowl and wave do not have time to form, being 'left behind' the vehicle, so that the situation is akin to that of a water skier. Then the deflections can be less than for a slowly moving load. However the induced stresses may be more. Hence, while a rapidly moving vehicle may not break through the ice, it can leave a trail of seriously weakened ice that will be catastrophic for any following load. Indeed, it is a common observation that it is the following load that breaks through the ice.

Near shore the wave will be reflected and thereby impose additional stresses on the ice cover. This latter effect may be reduced somewhat if the shoreline is approached at an angle. Likewise, if vehicles travel, or pass, too close the waves and deflection bowls interact, so increasing the stresses in the ice cover. To avoid this the deflections shown in Figure 9 suggest the spacing between vehicles should not be less than about 300 to 400 times the ice thickness in metres.

With reasonable care and attention to the above considerations, a breakthrough on good quality ice of known thickness is unlikely. The problem almost invariably lies in the unknown and unsuspected aberrations in thickness and strength that can occur in a natural ice cover.

2.1.2.4 Some effects of aberrations

2.1.2.4.1 Cracks: As described in more detail in Section 3.2.2, any natural ice cover is crazed with fine cracks generated by thermal movements of the cover. However, these do not necessarily indicate a reduction in load bearing capacity of the cover. The problem comes with large cracks, particularly wet cracks. A wet crack indicates that the crack penetrates the full thickness of the cover and can significantly effect the load bearing capacity. In the case of a single wet crack it should be assumed the bearing capacity has been reduced by half and, for two intersecting cracks, by one quarter of that for a good cover. A special and dangerous situation arises with wet cracks that intersect in such a fashion as to isolate a slab of ice. This has the effect of literally reducing the size of the ice 'raft' to that defined by the pattern of the cracks. Vehicles have been known to fall through ice more than two metres thick when they have inadvertently moved onto such slabs. Unfortunately a little snow drifting and some slight refreezing can do much to disguise the presence of such cracks.

Cracks are particularly likely to form or open up after a sudden and substantial drop in temperature. In addition to this, the drop in temperature generates additional stresses in the ice cover, and the cold makes the ice much more brittle. For this reason, if operations cannot reasonably be suspended entirely, loads should be reduced and especial care taken for a day or more after such a change in temperature to allow time for some refreezing of the cracks and for the stresses in the cover to be relieved by creep. While a sudden warming does not have the same implications with regard to opening up cracks and increasing brittleness of the ice, it also generates additional stresses in the cover so that extra care is advisable.

The removal of a snow cover, either by snow ploughing or by drifting, has the same effect as a sudden drop in air temperature, and has the same consequences with regard to the load bearing capacity of the ice.

If ploughed snow is left in a windrow along the side of an iceway, it not only loads the ice along the windrow, causing it to creep and crack, but also insulates it and prevents it thickening with the rest of the ice cover. For this reason the ice under and near such a windrow is particularly treacherous and should be avoided. A similar situation exists at pressure ridges. These are not only usually accompanied by wet cracks, but often also by snow drifts that insulate the ice and prevent it thickening and healing.

2.1.2.4.2 Thin ice: With cracks there is always the chance that they will be noticed and avoided. This is rarely the case with sections of thin ice. There are many natural reasons for an ice cover thickness to vary, particularly early in the season. In a lake, the first among these is the combination of currents and warm water: such currents can be difficult to anticipate. Groundwater inflow to a lake or river has a similar effect. Polynyas - areas of open water - left in the freeze-up pack on a river or lake will remain thinner than surrounding ice. They can be particularly treacherous early in the season when they carry only a very thin ice cover and enough snow to disguise them, while the surrounding ice is thick enough to support a load safely. Likewise ice under an early drift will remain thinner.

So, even in the absence of currents in a lake, or warm groundwater inflows in a lake or river, significant and natural variations of ice thickness are to be expected in any ice cover. These variations have a much larger significance for thin ice than for thick ice: for example, a 1 cm reduction in ice thickness reduces the load bearing capacity of a 1 m thick ice cover by only 2%, but it reduces that of a 10 cm thick cover by 20%. Hence light loads, such as snowmobiles, that theoretically only require a relatively thin ice cover to support them, are far more prone to be victims of variations in ice cover thickness. It is for this reason that when determining the required ice thickness from diagrams like Figure 6, it is prudent to add to this thickness an amount sufficient to allow for expected variations in ice cover thickness, and that special care be taken with light loads early in the season.

2.1.2.4.3 Shell ice: This is thin ice attached to or supported by the shore, banks, rocks, trees or docks, that is left behind when the water level falls. As illustrated in Figure 10 the decrease in water level over the winter for a large river can be substantial. If the water falls away from the bottom of supported ice early in the season it cannot then thicken further and will remain a trap for passers-by for the remainder of the winter. Any water under this ice will be insulated by the ice and air gap and may not freeze again.

Figure 10. Sagging ice left along shore near the mouth of a tributary following the fall in water level of the mainstream over the winter.

Another type of shell ice is that formed as overflow begins to refreeze after an increase in water level. Unlike the shell ice left behind by a fall in water level, the overflow can eventually refreeze entirely. Until it does though, it remains a hazard to over-ice operation. Furthermore, just as two beams are not as strong as one of the same total thickness, even a very thin layer of unfrozen slush within an ice sheet can significantly reduce its load bearing capacity.

2.2 HYDRAULICS OF ICE-COVERED RIVERS

2.2.1 Uniform flow

As mentioned above, the ice cover on most streams of reasonable size floats freely on the water over most of its width, so that the draft of a snow-free ice cover is simply that required to support the ice cover, some 92% of its thickness. For a given discharge from upstream, this means that, in a long, reasonably uniform river carrying an ice cover, the water level must be at least this amount above the open water level to provide sufficient remaining waterway to convey the discharge.

But this is not the only effect of the ice cover. The ice cover represents another stationary solid surface that resists the flow. The average flow velocity under an ice cover will therefore be less than under open water conditions and the water level must be even higher - at least 30% of the open water average depth - to convey the discharge from upstream. The situation is illustrated in Figure 11. If the ice cover is rougher than the stream bed - an ice jam for example - the required increase in water level will be even greater.

Hence the total increase in water level caused by the presence of an ice cover is at least 30% of the open water depth plus 92% of the ice cover thickness, whether the ice cover is an ice sheet or the pack of an ice jam.

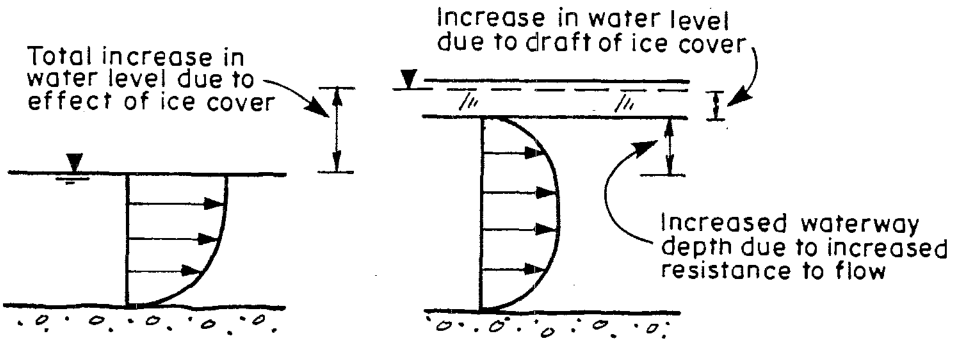


Figure 11. Influence of an ice cover on the water level required to provide sufficient waterway to convey a given discharge

2.2.2 Non-uniform flow

In the above situation there was no significant change in channel geometry along the channel so that the flow was more or less uniform - that is, it didn't change along the channel. Such a situation is common for the alluvial streams of the Prairies and for man-made channels, but it is usually not the case for the bedrock-controlled streams of the Canadian Shield. In this environment the frequent succession of rapids and pools, rivers and lakes, makes non-uniform flow quite common. These features will be seen to play an important role in the development of the ice cover.

The secret to understanding the sometimes unexpected behaviour of non-uniform flow is to appreciate that effects of a disturbance to the flow in a channel can only be felt upstream if small waves transmitting the effects of the change can move upstream over the flow. If the flow velocity is so high as to sweep these small waves downstream, the effect of the disturbance cannot be communicated upstream and the disturbance cannot influence the upstream flow. When the flow velocity is equal to the wave velocity, the flow is called critical flow. If the flow velocity is greater than critical it is called supercritical, or shooting flow; if it is less than critical it is called subcritical or tranquil flow. (The situation is directly analogous to supersonic and subsonic velocities of aircraft. In this case disturbances generated by the aircraft move at the speed of sound through the air so the behaviour of the air is quite different depending on whether the aircraft has a speed higher or lower than the speed of sound.)

The average flow in most streams of reasonable size is usually subcritical. However, consider the flow in a river approaching the brink of a waterfall or rapids as shown in Figure 12(a). As it does so its velocity increases markedly due to the increased water surface slope caused by the drawdown at the brink, reaching its maximum velocity at the brink. This maximum velocity can be no higher than the critical velocity because, when it reaches that velocity, no further disturbance can be transmitted upstream and there is therefore no incentive for the flow depth upstream to be lower.

Hence at rapids of reasonable height there will be subcritical flow upstream and supercritical flow downstream, as shown. If there is a reasonable distance downstream to the next disturbance, the flow some distance downstream of the rapids will be at the uniform flow depth and, as has been mentioned, this will usually be subcritical and deeper than for the supercritical flow. Therefore at some point just below the rapids the flow depth must increase. Unlike the drawdown to critical depth at the brink of the rapids, this expansion occurs suddenly in a phenomenon called a hydraulic jump, as shown in Figure 12(a). In a very real sense, this hydraulic jump is a large wave that results from the higher water level downstream being held back by the supercritical flow.

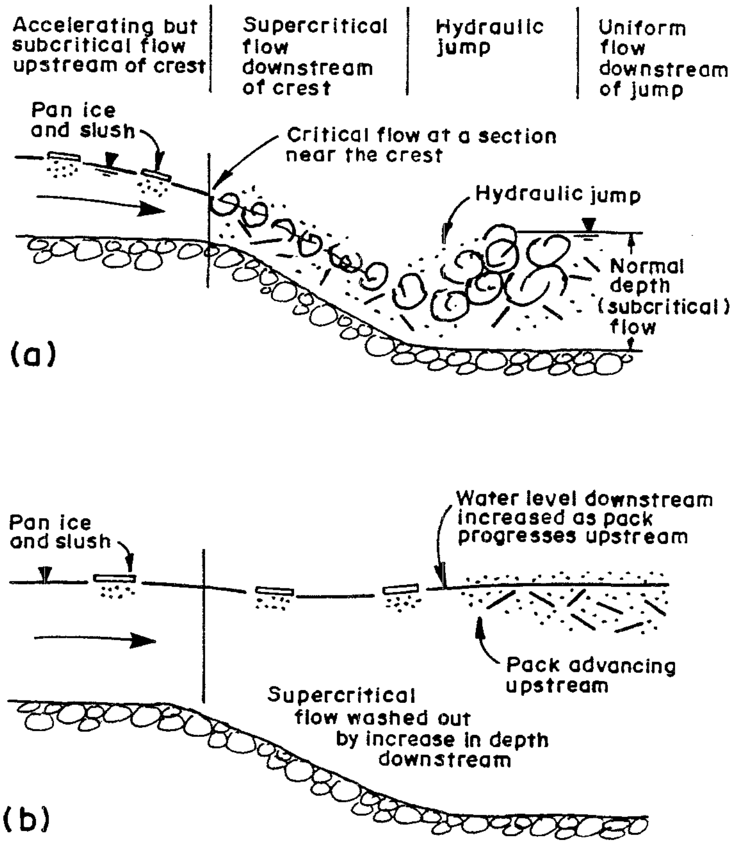


Figure 12. Details of flow at rapids

While the depth downstream is low enough to be held back in this manner by the supercritical flow, any change in the water level downstream of the rapids will not effect the situation upstream of the rapids. However, if the water level downstream becomes high enough, due to development of an ice cover for example, the hydraulic jump can advance upstream over the supercritical flow until it drowns out the critical flow control at the brink of the rapids and the flow is subcritical throughout. Then the two channel sections cease to be isolated and disturbances to the flow downstream can move across the rapids as shown in Figure 12(b).

Being a rapid expansion in the flow, it is a characteristic of a hydraulic jump that the flow is exceedingly turbulent in the jump. This rough water entrains so much air that the effective density of the water is decreased, with the result that it is much less buoyant. These features, together with the reverse roller on the top of the jump, can make it a deadly threat to boaters that inadvertently get caught in the flow. Figure 13 shows

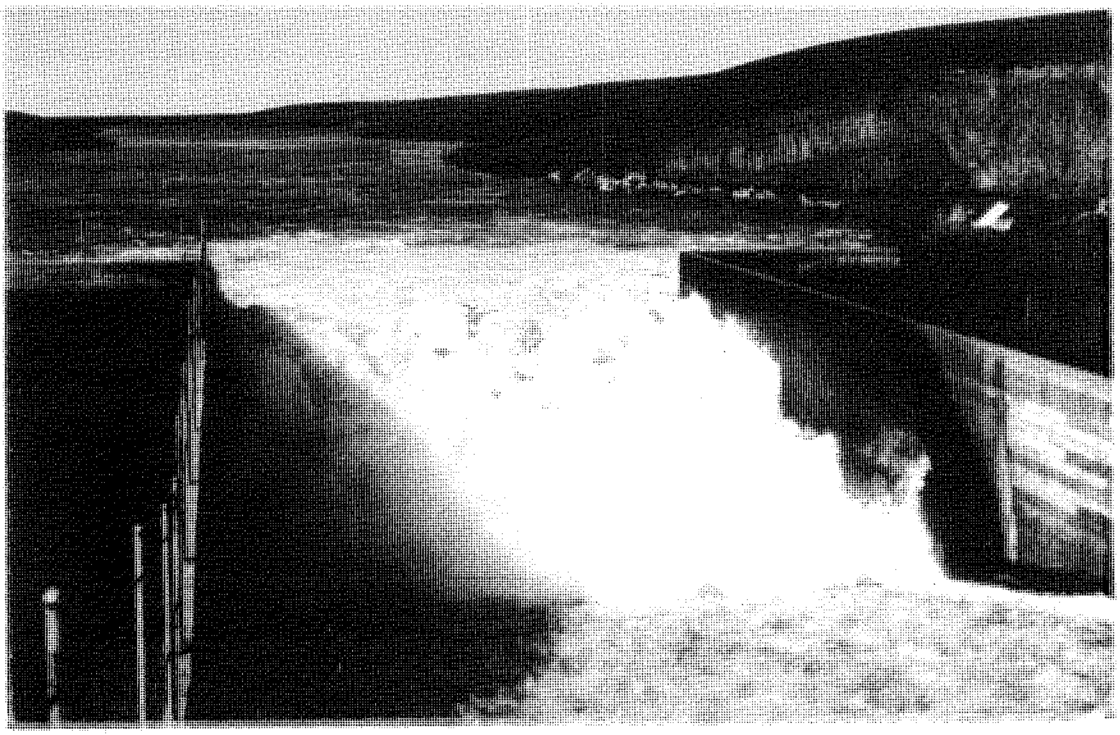


Figure 13. Hydraulic jump at the base of a chute drop structure, illustrating the violent turbulence and air entrainment characteristic of these features.

an example of a hydraulic jump formed at the bottom of a steep chute in an irrigation canal in southern Alberta. In a river they are rarely as well defined as this, but their character and influence on the flow is similar.

Now consider the response of river flow to a forced increase in depth, such as would occur at a dam or weir. The situation will then be as shown in Figure 14. Well upstream of the dam the flow must again be at the uniform flow depth and, in a river, this will likely be subcritical. The disturbance from the dam can now be transmitted upstream and so the flow begins to adjust to the presence of the dam before it reaches it, forming a very gradual 'backwater' curve, as shown in the figure. Such backwater curves typically extend for many kilometres upstream of the disturbance.

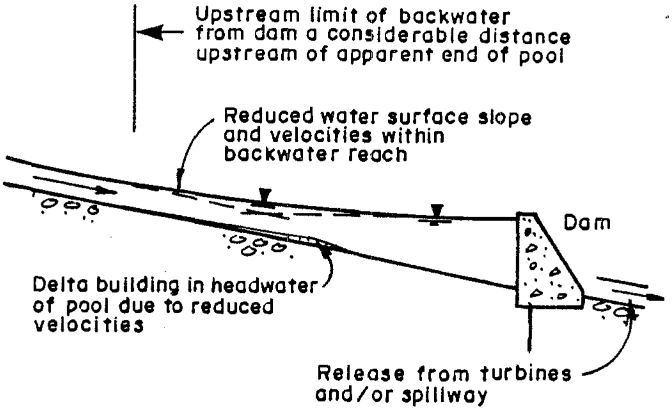


Figure 14. Water surface profile for subcritical flow upstream of a dam or other flow obstruction.

2.2.3 Unsteady flow

The flow situations discussed above have been steady flows - flows that do not change substantially in a short time. However, sudden changes in gate settings of a control structure, or of turbine settings in a hydroelectric plant, can generate rapid changes in flow. To illustrate the consequences of such rapid changes, consider the control gate in a canal shown in Figure 15. If this gate is suddenly opened a relatively sharp-fronted surge will move rapidly down the channel, leaving behind on increased depth and discharge as it passes. A somewhat more gradual depression wave moves rapidly upstream through the pool behind the gate.

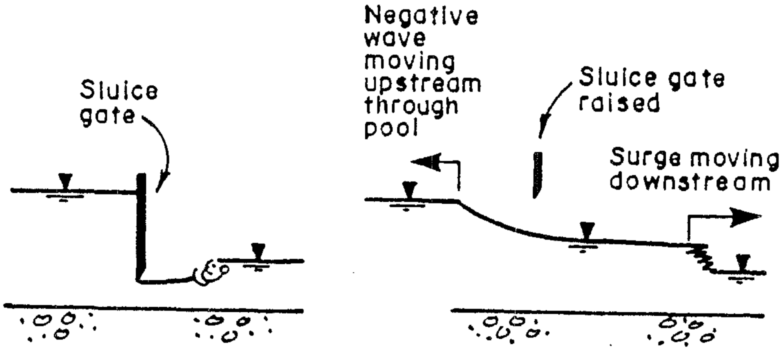


Figure 15. Surge generated by a sudden increase in discharge or water level.

If the channel is ice-covered, the passage of such waves will put the ice cover under stress, particularly along the banks. If large enough the surge downstream will cause the cover to crack and cause flooding of the shorefast ice. Indeed it may trigger general breakup of the ice cover. A similar surge is released by sudden ice jam failure and will be seen to play a pivotal role in break-up of the ice cover on a river.

2.3 WINTER THERMAL REGIME OF RIVERS

As anyone who has watched the surface of a river with any attention will have observed, the flow is usually quite turbulent. Turbulence in a river has the same influence as the turbulence generated by stirring a cup of coffee - any contaminant, including heat, is uniformly mixed throughout the flow. Hence normally the water temperature in a river is remarkably uniform over the depth, being usually within a few hundredths of a degree of the surface temperature, as shown in Figure 16.

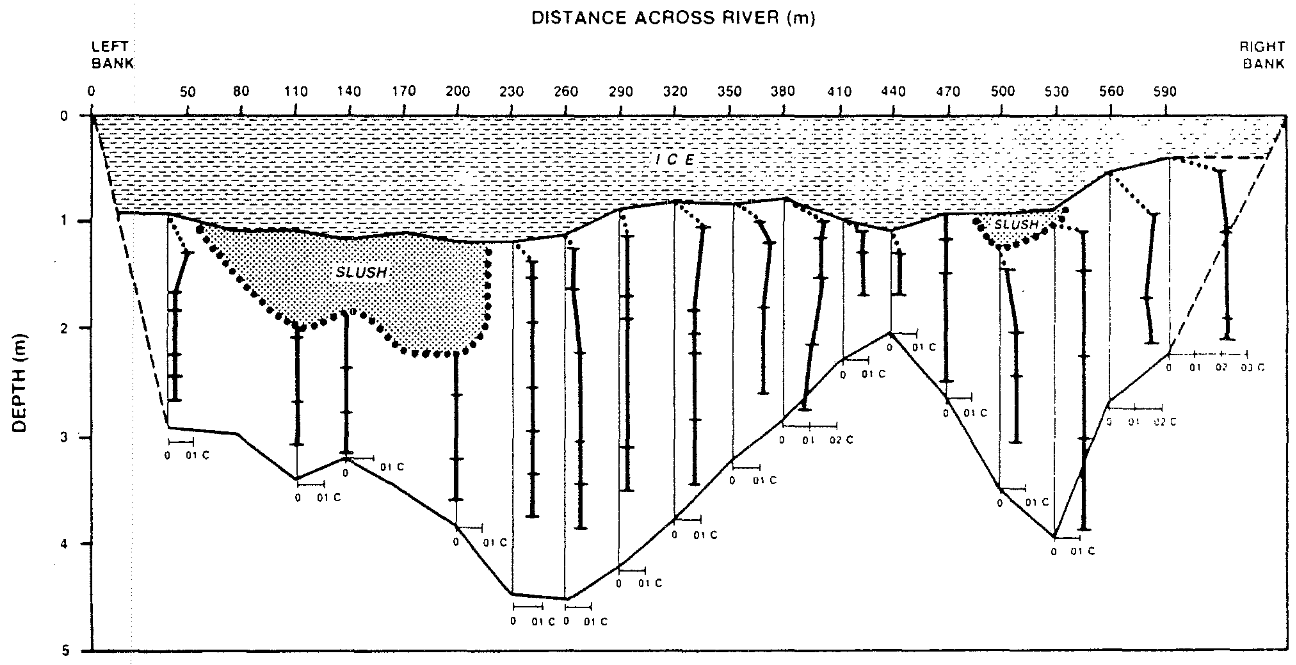


Figure 16. Measured variation in temperature over the depths of the Liard River, an alluvial stream in the N.W.T. (27)

As will be discussed further below, even in the depths of winter the water issuing from a lake, or released from a hydroelectric plant, will normally be above 0°C and it will take some distance - sometimes hundreds of kilometres - before it cools sufficiently for ice to form on it. This distance will depend primarily on the lake or reservoir water temperature, meteorological conditions, the heat balance at the river water surface, the discharge, and the depth of flow in the stream. An example of the winter temperature variation along a river downstream of a reservoir is shown in Figure 17.

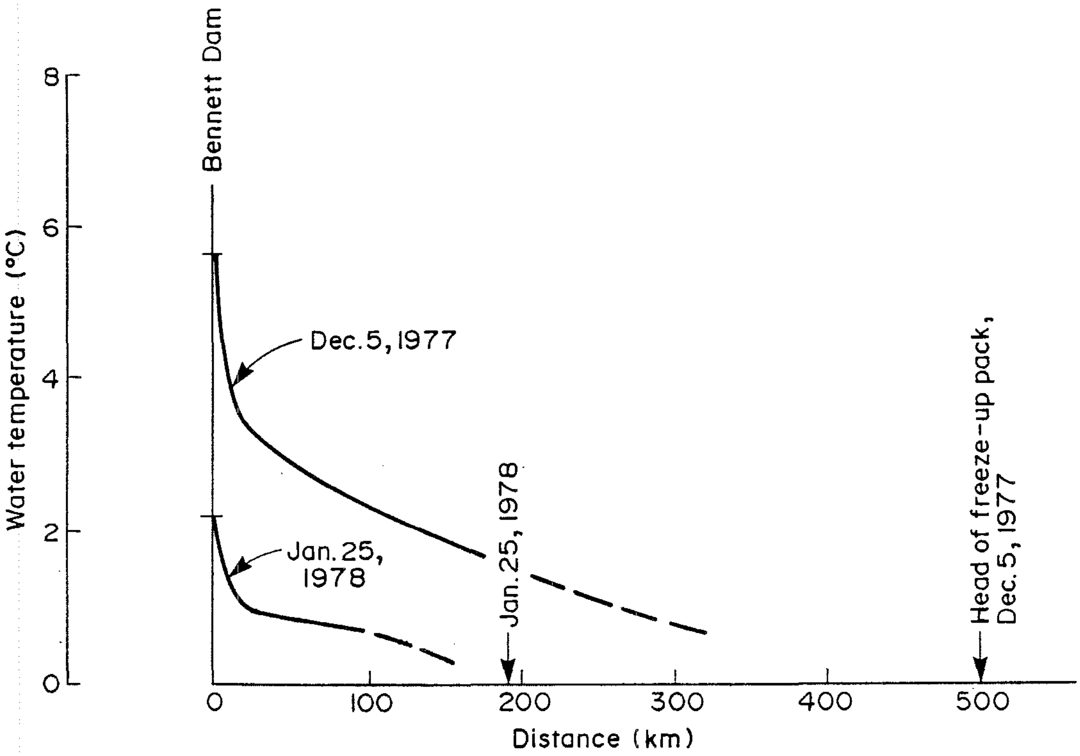


Figure 17. Temperature variation in winter along a stream downstream of a hydroelectric plant (adapted from 1).

The above situation is typical of an alluvial stream. However, the bedrock control of Shield rivers means that in many reaches the flow is more akin to that in a lake than a regular river. The hydraulics and thermal regime are then closely linked.

2.4 WINTER HYDRAULIC AND THERMAL REGIME OF LAKES AND RESERVOIRS

2.4.1 Water levels

The water level in a lake is directly governed by the water level in the stream at its outlet. If the stream becomes ice covered at or near the outlet, the water levels at the outlet will begin to rise. However for this to happen the lake storage must be filled from the discharge entering from upstream. This reduces the discharge downstream. The reverse happens if water levels at the outlet fall.

The rate of rise or fall of the lake water level, and the magnitude of the discharge change downstream, are a sensitive function of outlet conditions, and these can change with the weather as the ice cover melts and reforms, or as anchor ice deposits grow on the bed.* In a reservoir the situation is more well-defined because the outlet is usually submerged. However, here water level fluctuations can be caused by plant operation.

The water level in a lake can also be disturbed by wind. The wind exerts a shear on the surface of the water and, to balance it, the lake surface sets up, rising at the downwind end and falling upwind. The longer the fetch (the reach of exposed open water in the wind direction), the shallower the lake, and the stronger the wind, the larger the set-up. Typical wind-generated water level profile fluctuations on Lake Winnipeg are shown in Figure 18. Such water level variations can be expected to occur until the lake or reservoir is entirely ice-covered.

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* Anchor ice formation is described in Chapter 3. Also see the Glossary.

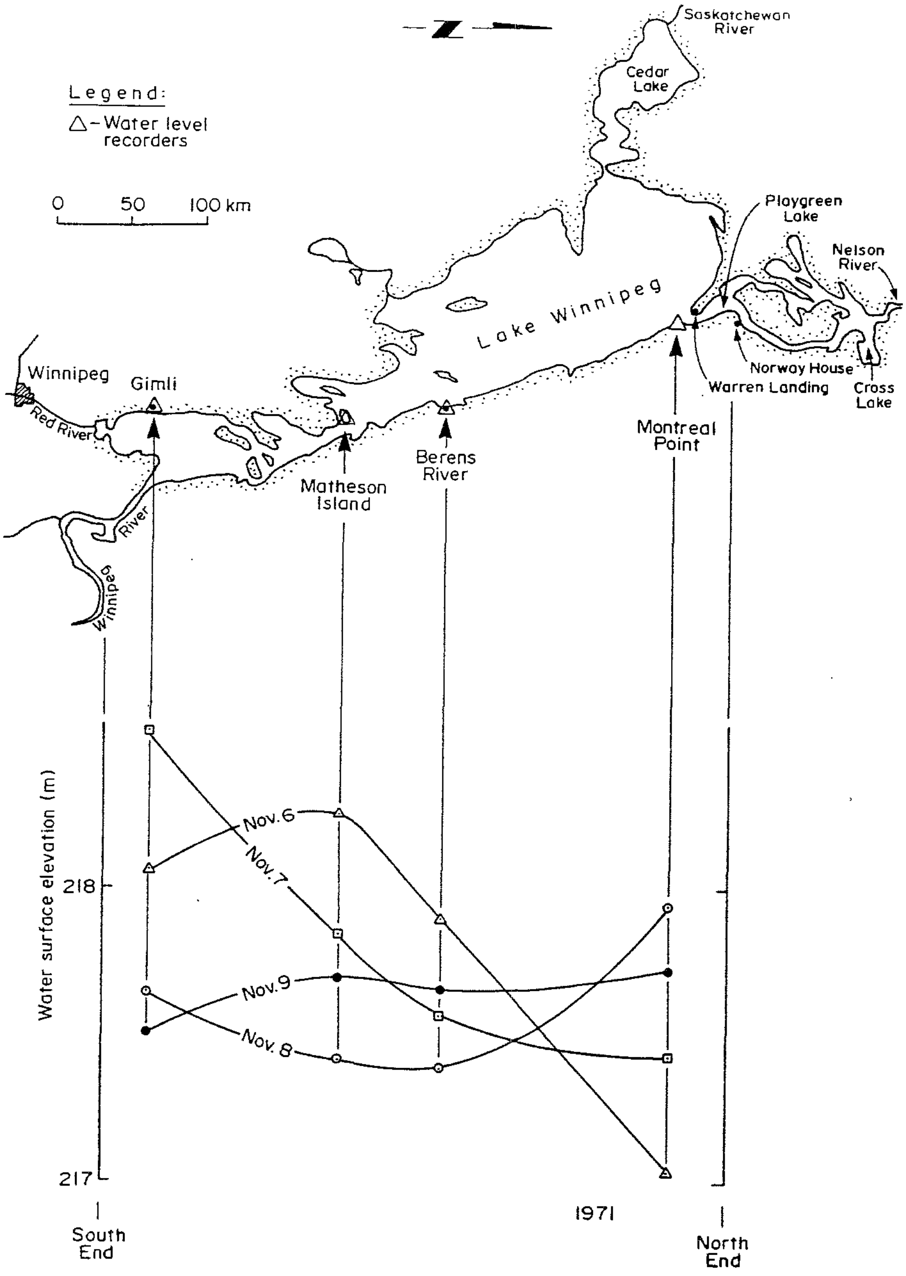

Figure 18. Wind-generated water level variations on Lake Winnipeg (adapted from 16).

2.4.2 Temperatures

Wind shear also generates turbulence in the lake or reservoir. If the lake is shallow this turbulence will penetrate to the bottom, so that the lake is turbulent over its full depth, as in a river, while the wind is blowing. However, the shear at the surface of a lake depends only on the wind velocity and is independent of the depth. Hence, if the lake is deep enough, the turbulence at the surface cannot penetrate over the full depth of the lake and the bottom waters will remain calm even in the presence of a storm at the surface.

However, unlike a river that always flows and is therefore always turbulent, the wind can diminish and calm return. There is then little mixing in the lake and the waters at the surface become warm in the sun. This increase in temperature renders the surface water less dense, so that it tends to 'float' and remain at the surface, setting up a stable density gradient through the depth.* It is then much more difficult for the mixing action of wind-generated turbulence to penetrate the lake depths. A result of this is that in summer there can be a pronounced change in temperature at the base of the layer that can be mixed by the wind, as shown in Figure 19, with the water

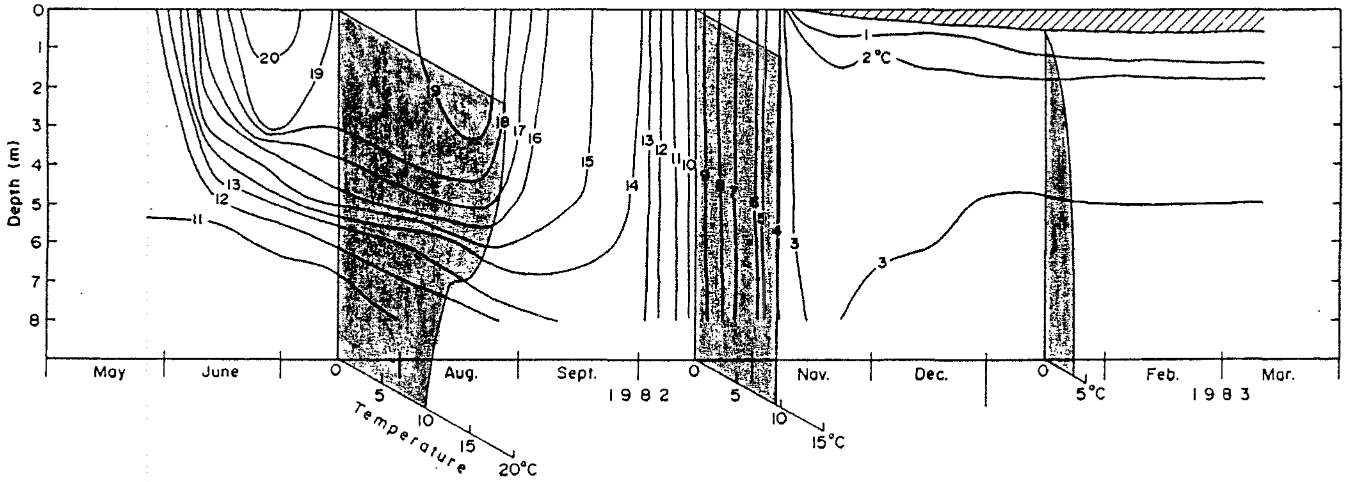

Figure 19. Typical annual variation in the temperature profile through a lake: Halfmoon Lake, Alberta (adapted from 26).

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* For water temperatues above 4°C, warm water over cold water is stable and will resist mixing; cold water over warm water is unstable and will mix of its own accord.

at larger depths only warming slowly. The location of this pronounced change in temperature is called the thermocline. The depth of this thermocline will primarily depend on the severity of turbulence generated by the wind, and thereby on the fetch.

The situation in winter is quite different. As another of its many unusual characteristics, water has a maximum density at 4°C. In the fall the surface waters will cool fastest, just as they warmed fastest in the spring, and will reach this maximum density temperature of 4°C first. Unlike in the summer, the water at the surface will then be denser than the water beneath it and it will 'sink'. As it does it displaces warmer bottom waters to the surface. This thermally-driven mixing process, aided by wind-driven turbulence when it occurs, will continue until the whole lake is at a temperature of 4°C, as shown in Figure 19. This is the well-known fall overturn that is so important to the health of a lake in that it allows a mixing of nutrients throughout the lake depths.

However, as the lake surface continues to cool below 4°C the surface waters will become **less** dense and, as in summer, will tend to float and remain at the surface, so that a stable density gradient will again exist, but with a temperature profile that is the reverse of that in summer. This means that only the surface of the lake cools to 0°C and begins to form an ice cover, as shown in Figure 19. The formation of the ice cover insulates the surface and dramatically reduces the rate of heat loss to the atmosphere. This slows the cooling of the lake so that its temperature can remain above 0°C all winter.* Subsequent snow accumulation on the ice reduces this heat loss

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* If it wasn't for the unique characteristic of water that it has its maximum density at 4°C, a lake would not begin to freeze until the whole water body had reached 0°C, leaving the surface exposed to the cold temperature of the air. The lake would then cool to 0°C very much faster.

further.

Figure 20 compares the summer temperature profiles of two lakes in northern Manitoba: Wood Lake, a relatively small lake with an area of 23 m^2, and Southern Indian Lake, a much larger lake with an area of 1,977 km^2 and large expanses exposed to the wind. It is evident that while Wood Lake develops a thermocline, Southern Indian Lake tends not to. This is likely because of the much stronger mixing action of the wind on Southern Indian Lake, due to the larger fetches. In winter the smaller lake maintains a warmer temperature, typically reaching an average minimum temperature of 1.9°C while, prior to impoundment as part of the Churchill diversion scheme, Southern Indian Lake fell to below 0.6°C, reaching 0.02°C in some sections. This is presumably because of the delayed formation of an ice cover due to wind action on the larger fetch and the input of 0°C water during the winter by the Churchill River.

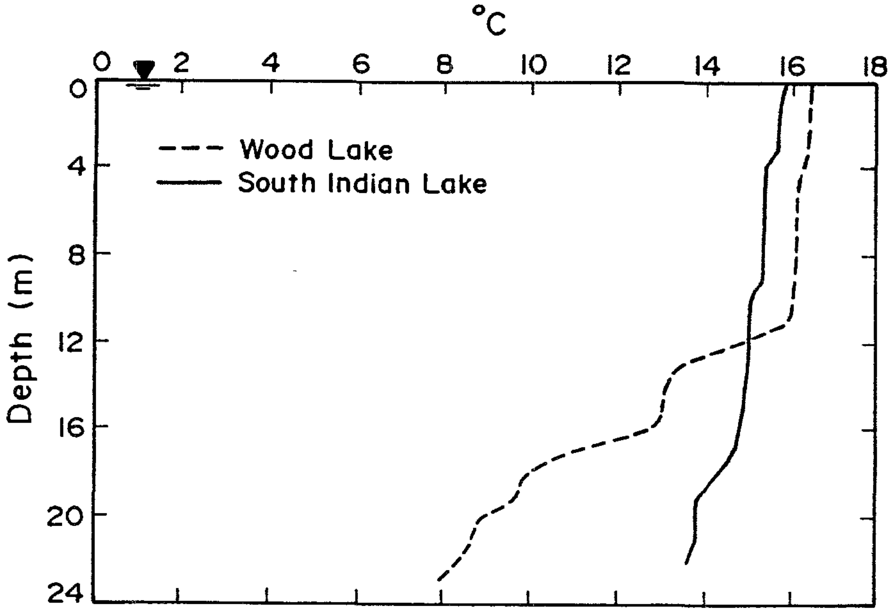

Figure 20. Comparison of summer temperature profiles through two lakes of different size in northern Manitoba (adapted from 12).

2.4.3 Under-ice currents

An important, and possibly deadly, practical consequence of the thermal stratification that exists in a lake in winter is that there is above 0°C water in close proximity to the ice cover. If mixing of this water occurs, warm water will come closer to the ice cover and melting and thinning will begin, unseen by passers-by overhead.

Under an ice cover this mixing can only be accomplished by currents. However, such currents can occur under an ice cover in a lake for a variety of reasons in a variety of places. An obvious location is at the outlet of a lake. Here there is usually a strong current and it is therefore a familiar place for open water or thin ice to be maintained throughout the winter by the 'warm' water leaving the lake. Similar circumstances exist at narrows in lakes that carry significant throughflow, such as those that are a feature of the Churchill-Nelson system. Figure 21 shows the marginal ice locations on Southern Indian Lake that existed before the Churchill River diversion was commissioned. It is evident that they are located at narrows through which the whole flow of the Churchill River passed. However currents generated by throughflow can concentrate at locations other than at the outlet, or at locations that appear as narrows from the surface. They are influenced by the distribution of the depths and shallows in the lake, so it is important to also know the lake bathymetry.

But there are more subtle causes of currents. As is evident from Figure 21, and indeed from any detailed plan of the Canadian Shield, lakes and reservoirs in bedrock country are characterized by many embayments of various shapes and sizes, frequently with only narrow passages between major water bodies. An important result of this which distinguishes them from reservoirs of more regular geometry is that sudden water level changes can cause strong

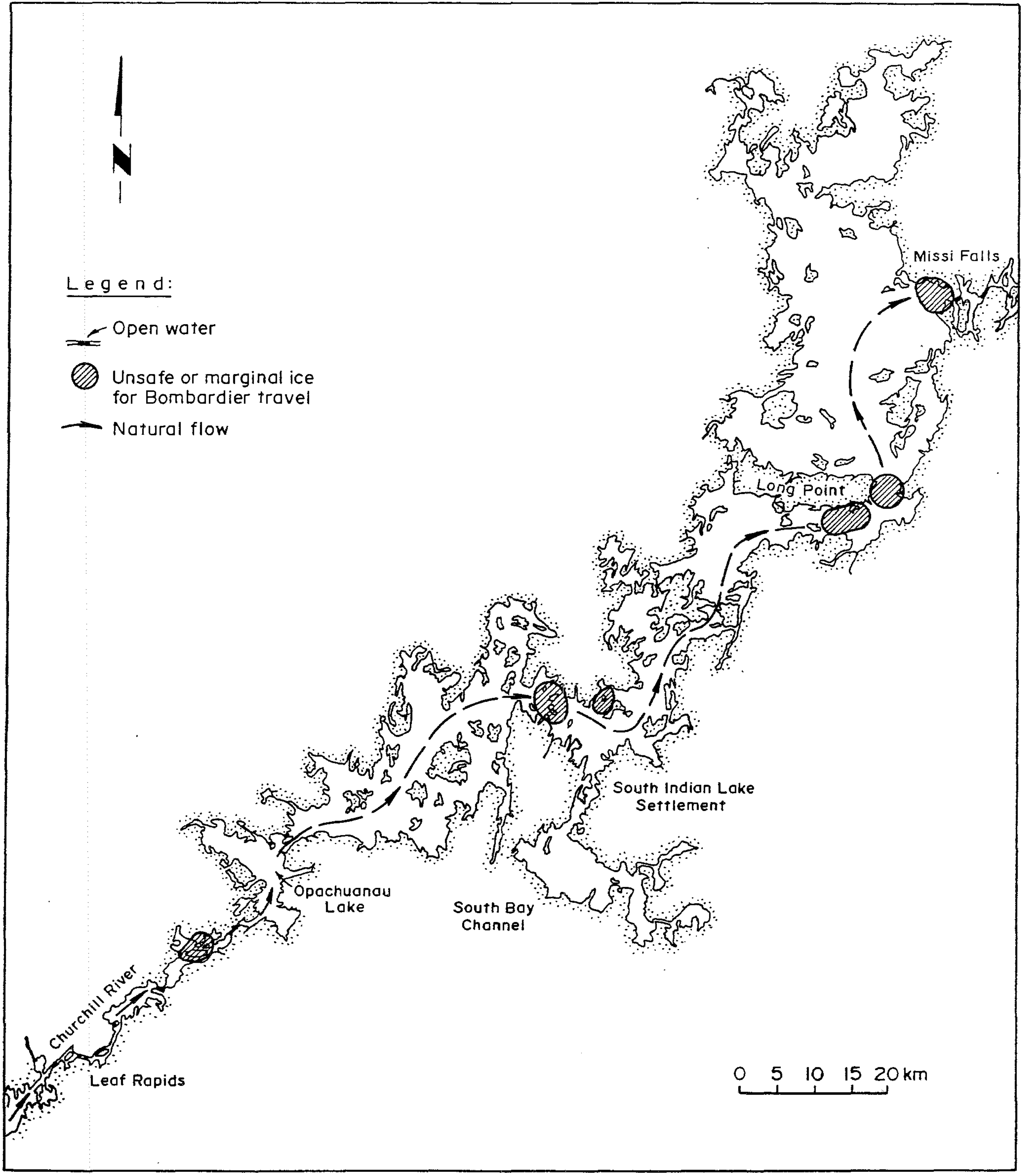

Figure 21. Marginal ice locations in Southern Indian Lake prior to incorporation into the Churchill River Diversion (adapted from 16).

currents through these 'narrows' as the water flows from one section of the water body to the other in an attempt to keep the water levels the same in both, as shown in Figure 22. Such water level changes can be generated naturally, by wind action on the open portion of a partially ice-covered lake, or by changes in the outflow of the lake, perhaps due to changing ice conditions at the outlet. However sudden, and often substantial, unnatural water level changes can also occur throughout the winter on lakes and reservoirs influenced by a hydroelectric development, as the discharge through the turbines is adjusted to follow load demand.

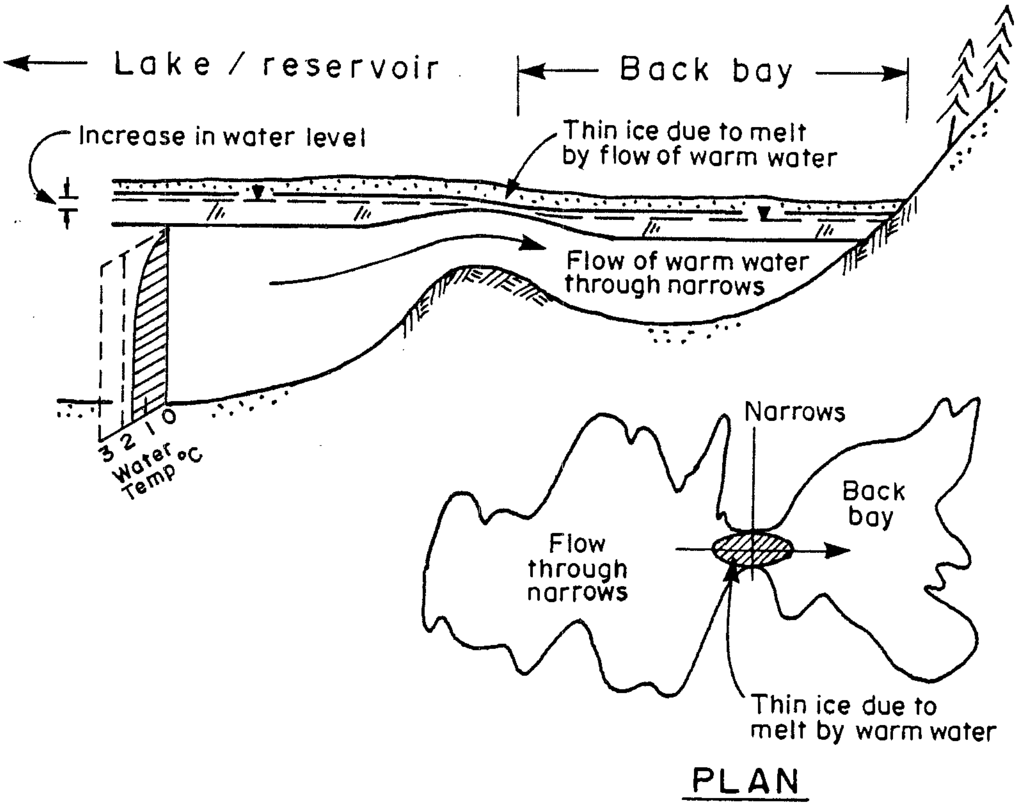

Figure 22. Flow between connected water bodies as they adjust to attain equal water levels.

2.4.4 Effects on ice thickness of under-ice currents and water temperature

Flows under the ice cover destroy the stratification in the water and bring above 0°C water from the body of the lake into closer contact with the ice cover. The rate of heat transfer to the ice cover then increases substantially so that if the ice cover and, particularly, an overlying snow cover, provide sufficient insulation rapid melting and thinning of the ice cover from below can take place.

With normal winter circumstances heat loss to the atmosphere through the ice cover is balanced by heat drawn from the lake and by latent heat released by the freezing water as the ice cover thickens, as shown in Figure 23(a). As the ice cover thickens, the insulation it provides reduces the heat transfer through the ice and thereby the rate at which the ice cover grows. The insulation is increased significantly, and the growth rate decreased, by even a few centimetres of fresh snow cover. Hence as the winter progresses the growth in ice cover thickness slows considerably.

While an ice cover is thin and snow-free, and the air temperature low enough, heat transfer through the cover to the atmosphere can be rapid enough that the ice will continue to thicken even in the presence of mildly warm water. However if, as is illustrated in Figure 23(b), this heat transfer is suddenly curtailed by a snow deposit - either due to a snowfall or drifting - or an increase in air temperature, the heat transfer through the ice cover can be less than that provided to the ice from the water. The difference will then be used to **melt** the ice.

An imbalance between the heat transfer to the bottom of the ice cover and that through the ice cover may also be caused by an increase in the current, as shown in Figure 23(c) - the heat transfer to the ice cover varies almost linearly with the current velocity - or by an increase in water temperature

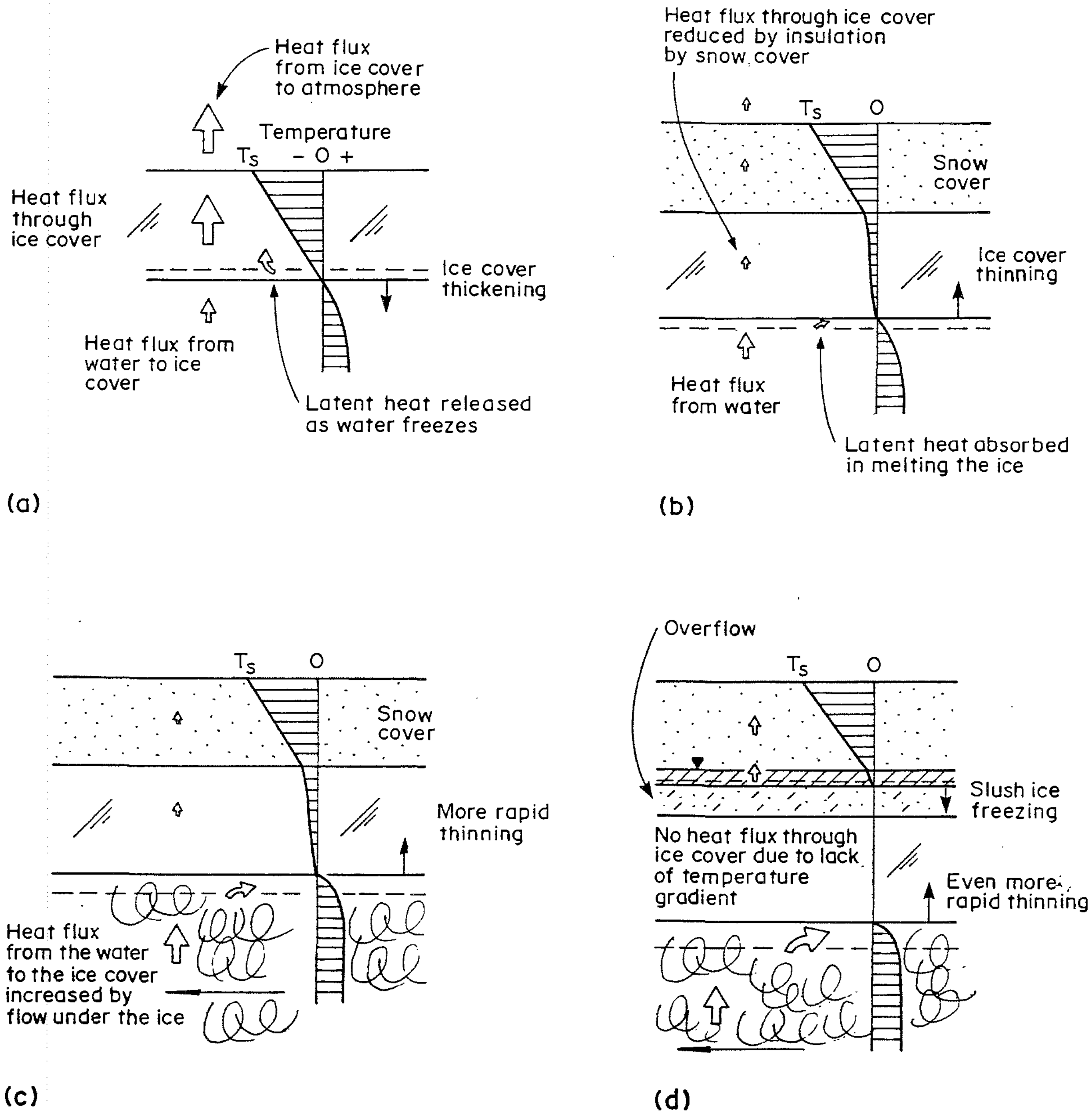

Figure 23. Variation in heat flow from the water through the ice to the atmosphere under different circumstances of water temperature, current velocity, ice thickness and snow depth.

under the ice due to warm water being drawn past the ice from elsewhere in the lake by the current. Analysis indicates that a current with a velocity of only 0.1 m/s and a water temperature as small as 0.1°C can melt about 1 cm in a day if there is no conduction through the ice cover. Such a velocity can be generated through a narrows by a difference in water levels of as little as a few millimetres. The situation will be even worse if snowfall is sufficient to cause flooding of the cover and the formation of slush. This renders the ice cover isothermal, with the same temperature through its thickness. Then there will be no heat transfer through the ice cover and all the heat from the water will be used to melt the ice, even as new ice is being formed at the top as the snow slush freezes, as illustrated in Figure 23(d).

Table 1 lists the circumstances found at the locations of marginal ice in Southern Indian Lake shown in Figure 21. It confirms significant melting can take place under seemingly quite innocuous circumstances.

Table 1. Effect of water current velocity on the condition of the ice cover in Southern Indian Lake (after 16).

Estimated current velocity (m/s)	Condition of ice cover
0 - 0.03	Safe for bombardier
0.03 - 0.06	Marginal for bombardier
0.06 - 0.15	Unsafe for bombardier
0.15 - 0.30	Open leads
0.30 -	Open water

The above discussion has been of the winter hydraulic and thermal regime of rivers, lakes and reservoirs, and the influence of an ice cover on that regime. It remains to discuss the ice regime itself.

3. NATURAL ICE REGIMES OF INLAND WATERS

3.1 RIVERS

3.1.1 Initiation of an ice cover

Consider an alluvial stream of reasonably regular cross-section. As fall approaches the water temperature cools. Because of mixing by the turbulence that is characteristic of rivers, this cooling occurs uniformly over the flow depth. However, in the quiet shallow nooks and crannies along the banks this mixing is not so effective, if it occurs at all, and it is here that the water temperature will first reach 0°C at the surface and a skim of ice will form. Initially this ice is thin, but as the cold weather continues it grows both in thickness and laterally out over the deeper and more turbulent flow, as shown in Figure 24. This ice is called border ice. Its lateral growth rate varies with circumstances but it is slow, being typically about 0.1 m per °C day of frost*.

While border ice grows along the banks and margins of islands and bars, the more turbulent flow in the centre of the stream continues to cool and will eventually reach 0°C. Because of the turbulence an initial skim of ice cannot form. Instead small thin disks of ice - typically about 1 mm in diameter - form throughout the flow when the water temperature falls a little below 0°C, giving rise to something akin to an underwater snowfall. This ice is known as frazil, a Canadian (French) word for cinders, which this ice type resembles in form if not in colour. Being slightly lighter than water, these

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* A °C day represents a mean temperature of 1°C over 1 day. For example, 10°C days of frost will accumulate over a winter day for which the **mean** temperature is -10°C.

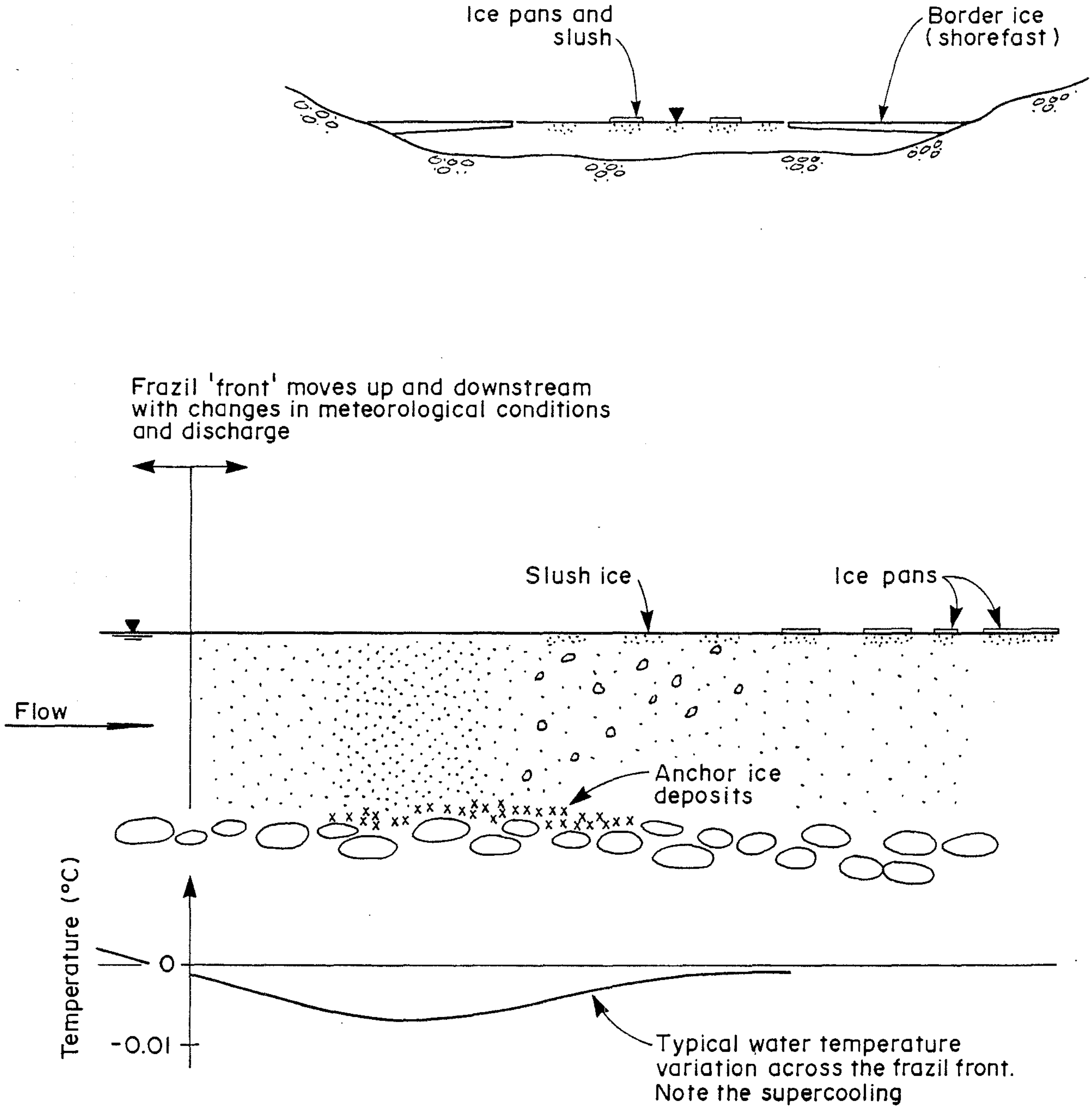


Figure 24. Ice production on a river prior to freeze-up. (Note the horizontal dimensions have been compressed relative to the vertical dimensions in this sketch for the sake of the presention. Typically the events depicted take place over 10's of kilometres).

frazil particles eventually overcome the mixing by the turbulence and reach the surface, to form the familiar slush ice that is so evident on rivers in the fall. A snowfall during freeze-up, or drifting snow off the banks, can contribute significantly to the amount of slush in the river. As the slush ice moves down river it congeals under the action of the cold air temperatures to form ice pans as illustrated in Figure 24. The situation in the river is then much as is shown in Figure 25. In very cold weather these pans will themselves meld together to form large ice floes, as shown in Figure 26, and can develop a reasonable thickness of solid ice at the surface.

When they first form, the frazil particles are actively growing and tend to attach to any object they contact, including the stream bed. If the stream bed material can resist the slight buoyancy of the frazil, a frazil deposit will form on the bed as shown in Figure 24 and 27. This is known as anchor ice. Such deposits can become quite thick and can even grow to protrude through the water surface in reasonably shallow flow. Anchor ice is especially prone to form in and near rapids, where the fast water keeps the flow open and consequently frazil production continues longer than elsewhere.

As cold weather continues the border ice encroaches further out over the flow and the concentration of ice pans and slush ice on the remaining open water increases. Eventually, at some point where the open water between the border ice edges is narrowest, the ice pan concentration is so high as it passes between the border ice that it will lodge, as shown in Figure 28. This represents the beginning of freeze-up in this reach. Thereafter, ice moving down from upstream will accumulate behind this lodgement and the accumulation will build upstream. Little will move on downstream, where the production of slush ice and pans must begin again.

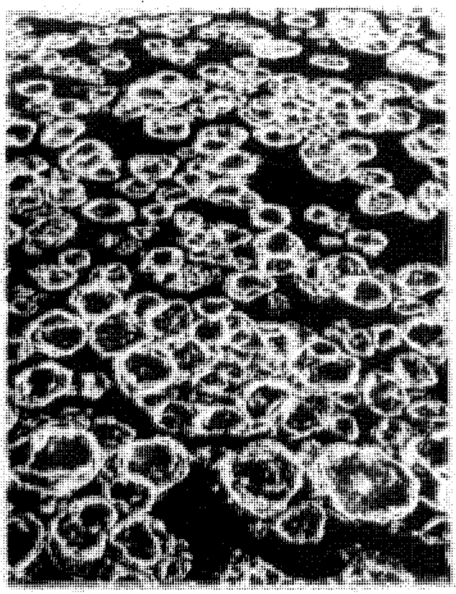
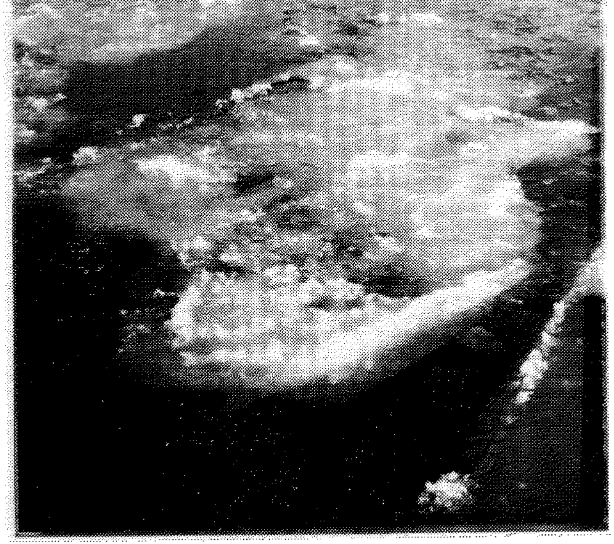


Figure 25. Ice pans, slush and border ice



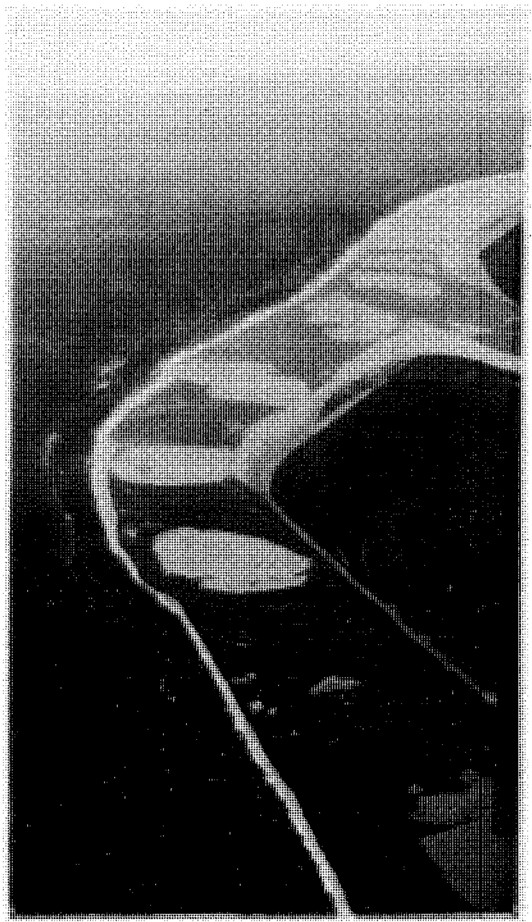


Figure 26.
Large ice floes
formed from ice pans
and slush ice. Note pack
forming in the distance

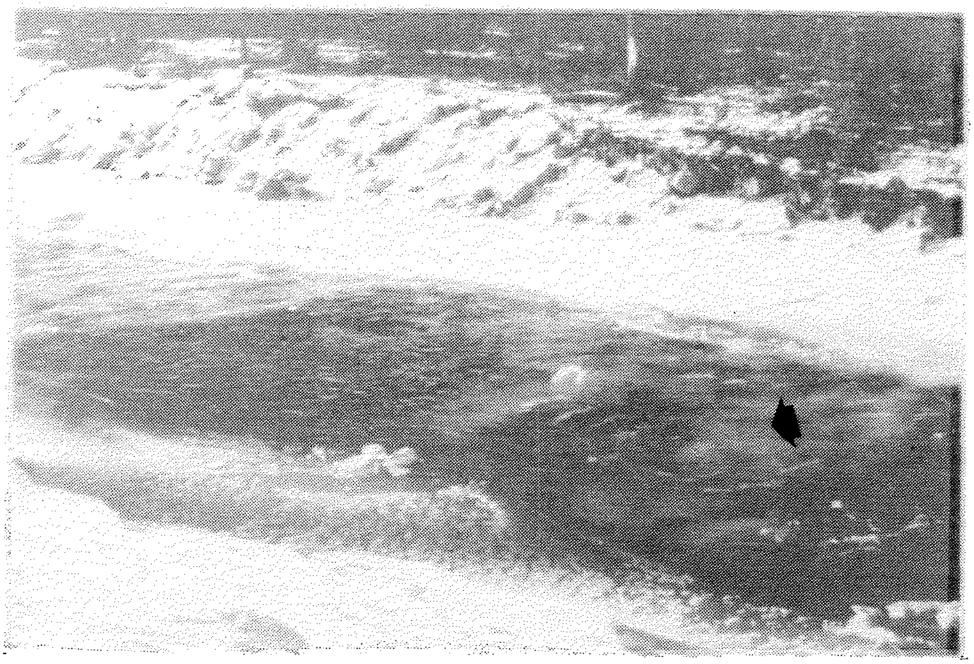


Figure 27. Anchor ice on a stream bed.

Figure 28. Lodgement.

For example, before the developments on the Nelson River such lodgements typically occurred first in mid-November in the vicinity of Deer Island near the mouth and Gull Lake some 150 km upstream (22). It took much of the remainder of the winter for the ice cover to progress between these two locations, despite the severe climate and enormous amount of ice produced. This was because of the unusually thick pack that had to form to be stable on this reach, as described below.

While being reasonably consistent in location from year to year if the flow regime remains reasonably consistent, it is difficult to predict these lodgement locations. They must usually be defined by field observations. If the flow regime is changed significantly, it is likely lodgement locations and timing will also change.

Once lodgement has occurred, the ice pans and slush from upstream accumulate behind the lodgement to form the initial freeze-up pack, causing the water level to rise under the pack and for some distance upstream. As ice continues to arrive, the pack gradually extends upstream at a rate controlled by the quantity of ice arriving from upstream, and by the nature of the pack.

Initially the pans will usually simply stop and float against the head (upstream end) of the pack. However, as the pack extends upstream, the drag of the flow under the pack, and the component of the weight of the pack that acts downstream, increases. For the pack to stay in place, this load must be transmitted to the lodgement point or to the banks. To transmit this load, the pack must be strong enough to sustain it. However the strength of the pack depends on its thickness. Eventually the pack can become long enough that the load on the pack exceeds its strength. The pack then collapses, or shoves, reducing in length but increasing in thickness and raising the water level further. When the thickness becomes sufficient to sustain the load, the shoving will cease and the pack will begin to advance upstream again. On steep streams the required thickness can be substantial: for example, a 2.6 m thick freeze-up pack forms on the Salmon River in Idaho (6). More typically it is about a metre or so on the flatter alluvial streams of the Prairies.

To collapse, the pack must also fail along the banks. It is this action that gives rise to the so-called shear lines that are so characteristic of such ice packs.

The adjustment of the thickness by shoving does not necessarily occur continuously. Rather it usually proceeds in an intermittent fashion. Once begun, some of the shoving events can be quite dramatic. For example, on the Peace River in Alberta the freeze-up pack collapsed over 95 km, almost causing flooding in the Town of Peace River (18). The remarkably thick pack on the Nelson River near the Limestone site collapsed over 12 km in just 3 hours in one instance. Events like this were a major concern in the diversion works design for the Limestone project (5).

An important modification to pack progression can occur during freeze-up. If air temperatures are low enough, sheet ice will begin to form in the interstices in the pack. This can significantly increase the pack strength so that a smaller thickness is required to sustain the loads applied to the pack. Furthermore, in particularly cold weather, the ice can arrive as large congealed floes, as described above. When incorporated into the pack these will also strengthen it. Hence the nature of the pack, and particularly its thickness, can vary along even a uniform reach, from the relatively thin juxtaposed cover shown in Figure 29(a) to the thicker, rougher pack that results from shoving shown in Figure 29(b), depending on the meteorological and discharge conditions during which it was formed. Irregularities in the channel geometry will cause further variations along the pack.

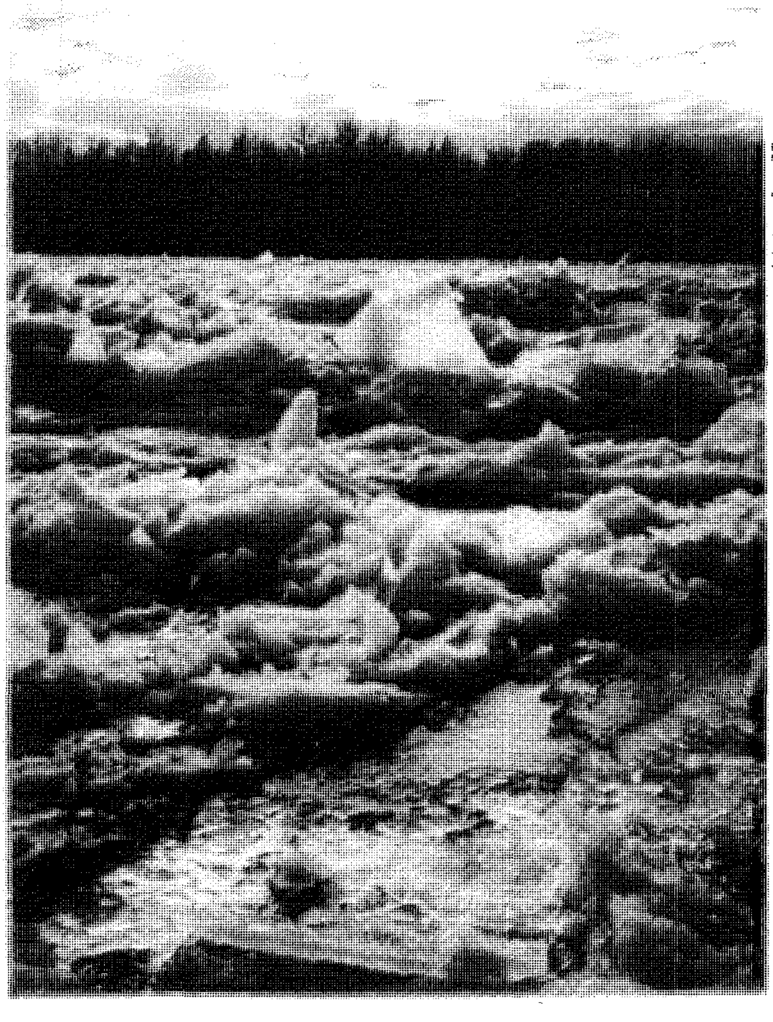


Figure 29.
Contrasts in pack types formed in the same reach (a) thin pack of juxtaposed floes (b) thick rough pack due to collapse and shoving.

With large floes being incorporated into the pack it is not uncommon for large polynyas to form, these being open water areas between the ice floes as shown in Figure 30. These polynyas are isolated from a supply of frazil and therefore must freeze by the growth of border ice from the edges of the opening, a relatively slow process.

Figure 30. A polynya, or area of open water, left in a freeze-up pack.

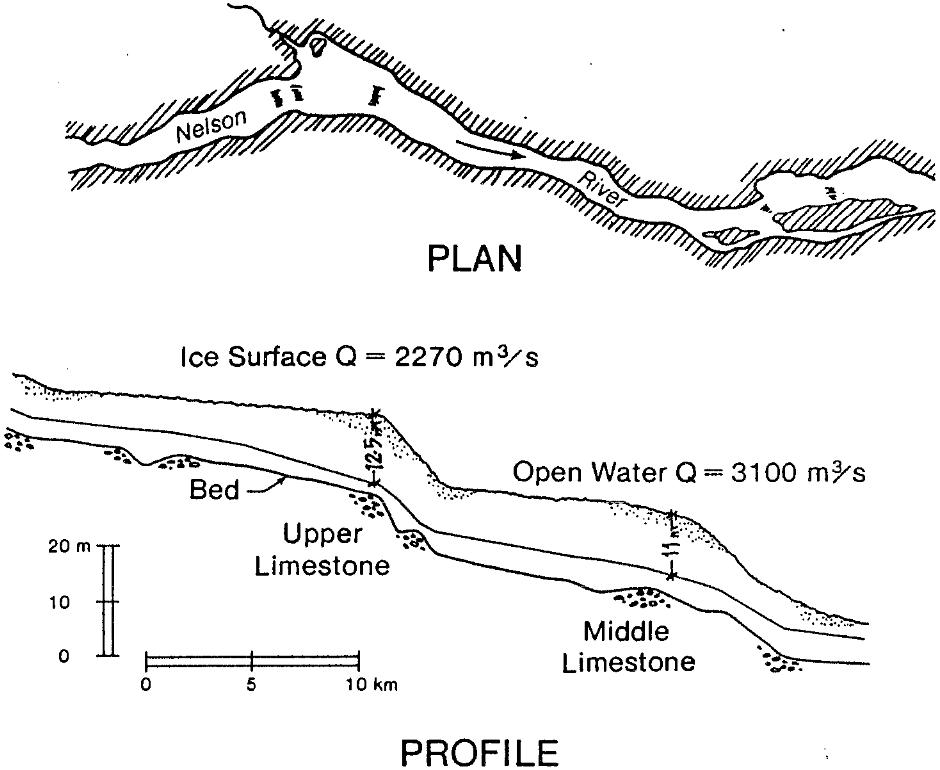
When the advancing pack encounters fast water, such as would exist at rapids, another process will be initiated. Because of the fast water the pans and slush will be unable to remain on the surface and will instead be engulfed and entrained by the flow, as shown in Figure 12, and carried under the pack to be deposited downstream at a lower velocity location, in a reverse sedimentation process. This entrainment, transport and deposition will continue until the thicker pack where the ice is being deposited causes sufficient resistance that the water level at the head of the pack is increased, and the flow velocity decreased, sufficiently for entrainment to cease and pack advance to continue. If rapids are frequent and high, and discharge large, the required pack thickness that must be built up for the pack to advance can be quite remarkable. For example, Figure 31 shows the pack thickness that developed at least partly in this way on the Nelson River near the Limestone site. The water level is some 12 m above the equivalent open water level after the pack had formed. A better sense of the significance of these numbers can be obtained from the photograph shown in Figure 31, taken at another site along the Nelson River.

Generally pack progression will occur through a combination of these various modes, depending on circumstances. The substantial increase in water level that can occur as the head of a freeze-up pack passes a location often catches people working in the river unawares, as shown in Figure 32. It was a major consideration in the design of the coffer dams for the various Nelson River projects.

3.1.2 Ice types and ice cover growth

After the initial pack has formed, interstitial water in the pack freezes. If the pack is rough ice this will result in solid ice with a very irregular internal structure as shown in Figure 33. If it is simply frazil pans and slush, it will result in a regular fine grained ice as described below. In either case, because it is growing through an accumulation that is already mostly ice, the thickening of the solid ice will be faster than if it was growing through just water.

After the freezing front has moved through the pack (if the pack is thick enough, as on the Nelson and Churchill Rivers, this will not be achieved by the end of winter) the solid ice cover thickens by the growth of 'black', or



PLAN

PROFILE

(after Newbury, 1967)

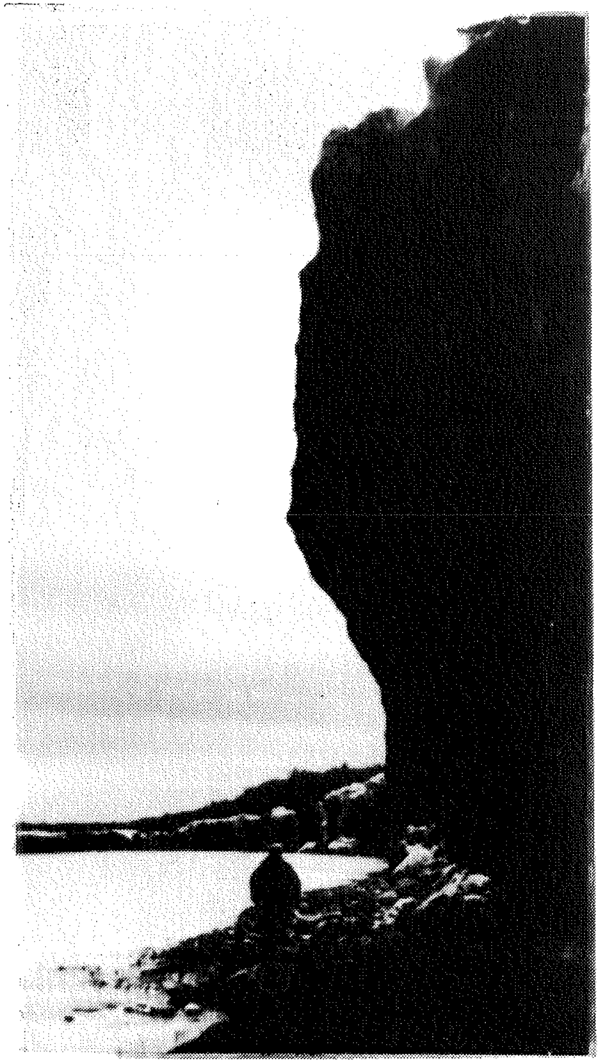


Figure 31.
Thickness and water level profile through the freeze-up pack on the Nelson River near the Limestone site (photograph courtesy of R. Raban, Manitoba Hydro).

Figure 32. Bridge foundation excavation flooded by the increase in water level as the freeze-up pack progressed upstream past the site

Figure 33. The internal character of a piece of refrozen freeze-up pack at break-up.

'clear', ice below the pack. If there is sufficient snow, 'white' ice will grow on top so that a typical late winter ice cover looks as shown in Figure 34(a). The different grain structures of these ice types is evident in Figure 34(b). This grain structure has a significant influence on how the ice decays in the spring.

Freezing of the water under the pack as the solid ice cover thickens is accomplished by the growth of the ice crystals at the bottom of the pack. The ice so formed is almost transparent and so is called clear ice. Because of this transparency it takes on the hue of whatever is under it, which is usually the dark river or lake bed, so it is also called black ice. Ice crystals have a preferred growth direction so, as they grow, those with a more favourable orientation grow at the expense of the others. Hence, as the ice sheet thickens the crystals exposed at the bottom become fewer in number but larger in size, reaching finger size and larger by the end of winter. Hence, the 'clear' ice portion of the ice sheet consists of candle-like crystals that increase in diameter towards the bottom, giving the clear ice a course, distinctly columnar-grained structure, as shown in Figure 34(b). This ice type is therefore also known as columnar ice.

As mentioned before, a snowfall equal to or greater than half the ice thickness is usually sufficient to depress the top of the ice below the water level. Water will then flood up through cracks to run out over the ice sheet and saturate the lower layer of the snow, forming a slush layer. This slush layer will then begin to freeze, forming white ice, the white appearance being due to trapped air bubbles. Because it is frozen saturated snow, this ice is also called snow ice. Unlike the columnar 'clear' ice, it consists of fine grained crystals like the snow it comes from. This is the ice type evident at the top of Figure 34(b).

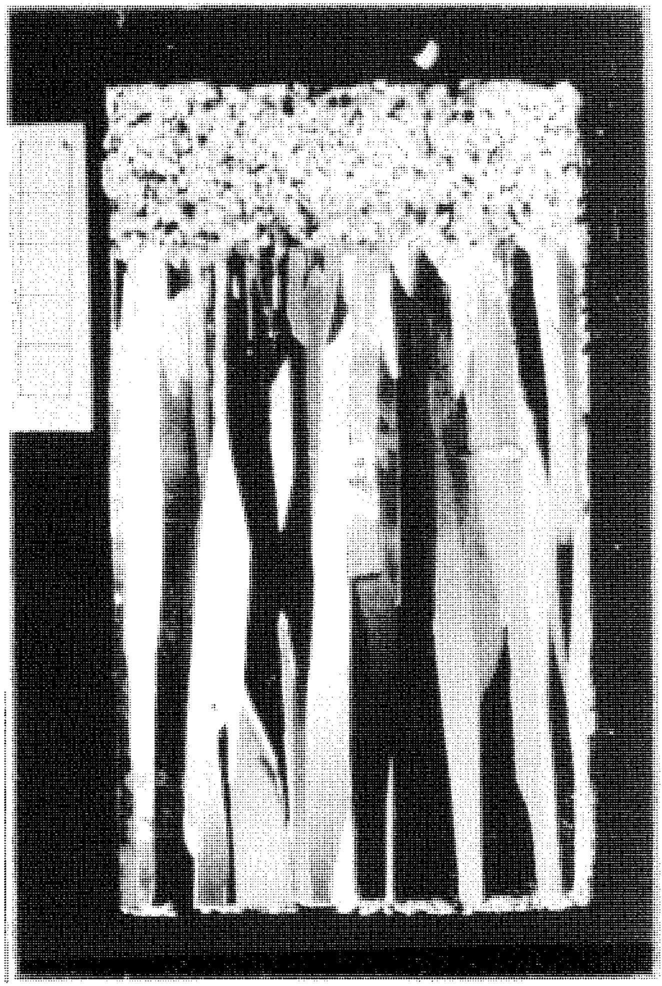


Figure 34. (a) A typical winter ice cover on a small stream. The block has been turned upside down, so that the bottom is up. (b) A thin section from a similar ice cover, showing the grain structure of the black, clear or columnar ice (bottom), and white or snow, ice (top). The squares to the sides are 1 cm x 1 cm. (Photograph of thin section courtesy of A. Gow, USACRREL).

If another snowfall occurs before the freezing of the slush layer is complete, another slush layer will form on top of the first and will begin to freeze. Several layers of slush can be formed in this way over a winter. The continued growth of the ice cover at the bottom, and the freezing of any other slush layers, must await the freezing of the topmost slush layer. Given snowfalls that are frequent and substantial enough, it is therefore possible to find several thin solid ice layers, with unfrozen slush between them overlying the main ice cover. The latter may be thick or thin depending on when the first snowfall occurred and the snowfall since.

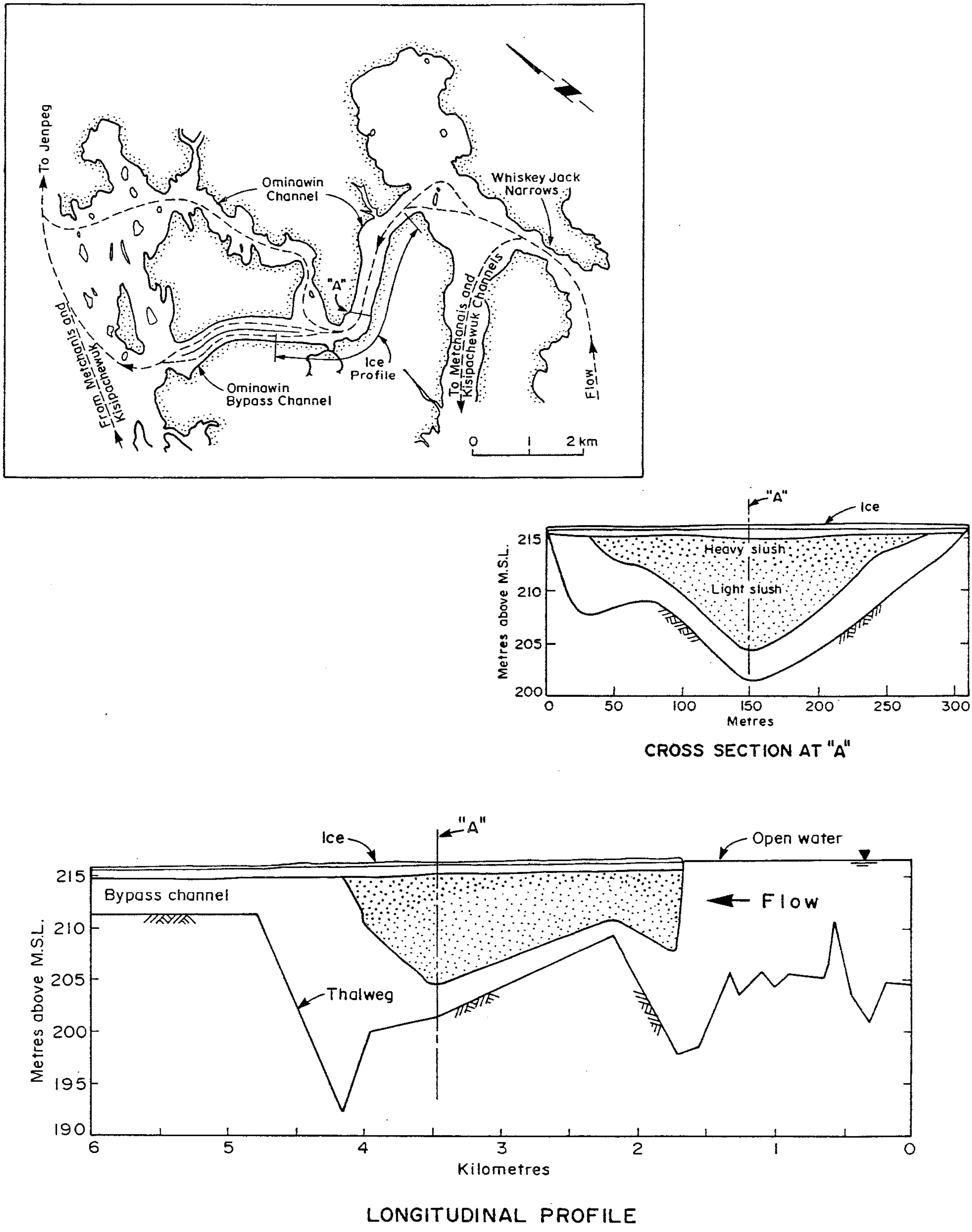
If slush ice has accumulated under the ice sheet, it will be incorporated into the ice cover as it thickens. The ice so formed is called frozen frazil slush and, like the snow ice it resembles, it has a fine-grained structure but is clearer because of much less air inclusion. It often contains noticeable sediment inclusions and has a 'smoky' hue.

The above ice types form generally over large areas of the river or lake. However there are other ice formations and types that have a more localized form.

3.1.3 Localized river ice formations

3.1.3.1 Hanging dam

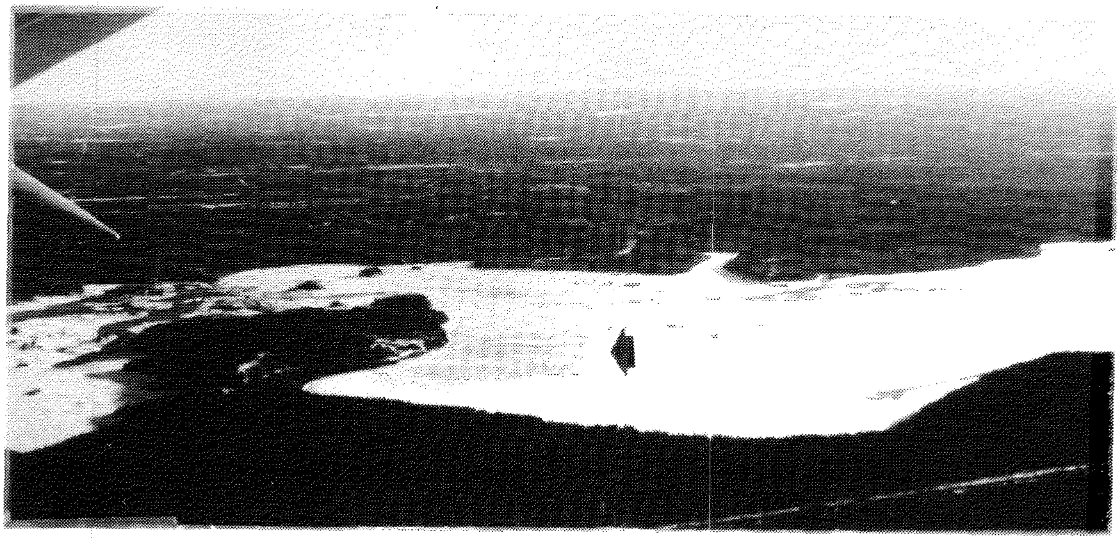
This is a relatively localized accumulation of entrained and deposited ice, as shown in Figure 35(a). Such accumulations typically occur in low velocity areas of the reach, especially below rapids that remain open for a large portion of the winter and which thereby continue to produce frazil to build up the accumulation, as is the case shown in Figure 35(b). In the situation shown in Figure 35(a) it has been formed by frazil from the open lake surface.



CROSS SECTION AT "A"

LONGITUDINAL PROFILE

Figure 35. (a) A hanging dam in the Ominawin Channel below Playgreen Lake, Manitoba (adapted from 28).



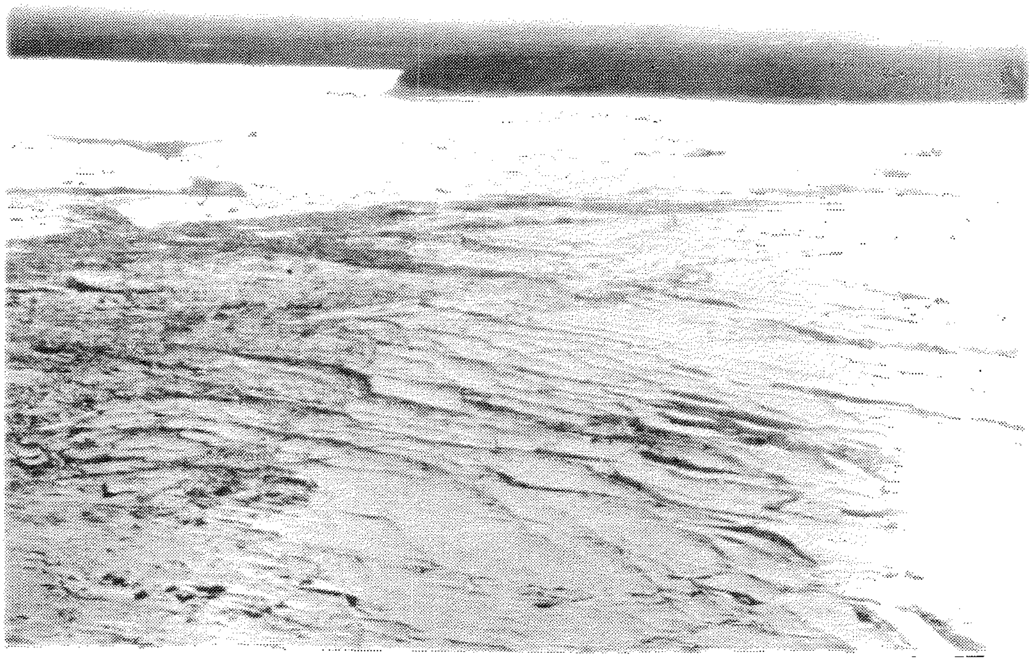


Figure 35. (b) Hanging dam on the Slave River in northern Alberta: the breadcrust appearance of the ice surface, formed as the initial ice cover is lifted out of the water due to the buoyancy of the growing deposit underneath, is indicative of a thick accumulation.

If there are large holes in the channel downstream of the rapids, a common circumstance in bedrock-controlled channels, the frazil deposit will initially have little influence on the water level upstream and the rapids will not be flooded out. The frazil deposit downstream - the hanging dam - will then continue to grow, slowly filling the waterway area until the flow has been constricted so much that the velocity in the remaining waterway is sufficient to prevent the frazil from depositing. The hanging dam then begins to extend downstream. The backwater from the deposit increases as the velocity in the remaining waterway under the hanging dam increases and the hanging dam extends downstream, so that eventually the rapids that are the source of the frazil are flooded out and frozen over. The hanging dam then stops growing, unless frazil continues to be supplied from open water in rapids further upstream. Such deposits can grow to enormous size, given the right conditions. For example, a hanging dam that formed each winter on the Ottawa River was documented to be 90 m thick and 1,200 m long (11).

3.1.3.2 Ice dam

In a shallow stream, the frazil deposited on the bed as anchor ice can grow to form a local accumulation of ice that will impede the flow. This is known as an ice dam and is primarily a characteristic of small steep streams, as shown in Figure 36, although such deposits are also common at the head of rapids in larger streams.

3.1.3.3 Aufeis

This usually occurs when the ice is shore- or bottomfast enough, and the waterway under the ice constricted enough, that water is forced onto the top

Figure 36.
Small anchor ice deposits impeding flow in a small stream.

of the ice sheet through cracks and holes to freeze as shown in Figure 37. The constriction of the waterway under the ice can come about in various ways, such as freezing to the bed at some particularly shallow cross-section, accumulation of ice debris or slush, or depression of the ice cover by snow accumulation. Other causes of aufeis formation are groundwater outflow from the banks and overflow from tributary streams. Small changes in stream environment, such as clearing or snow cover removal, can trigger aufeis formation where none had occurred previously.

Shallow streams, a severe climate, abundant groundwater in high country, and exposed location therefore increase the likelihood of aufeis formation. This is a typical combination of circumstances found in the Canadian

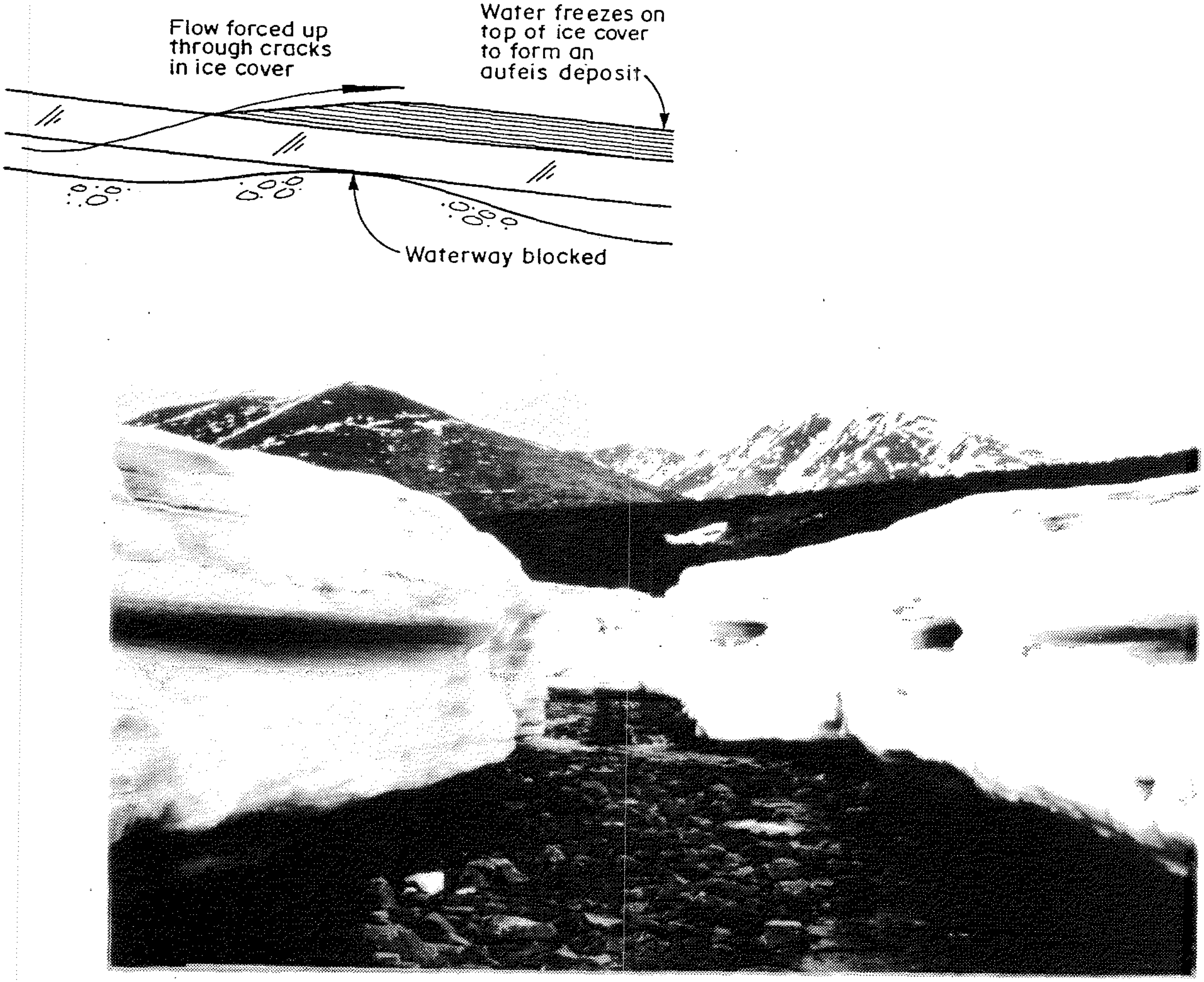


Figure 37. Formation of aufeis, and remnants of an aufeis deposit at a bridge crossing on the Dempster Highway, Yukon.

northwest, and aufeis formation in waterways is a widespread problem there.

A remnant of an aufeis deposit is shown in Figure 37. They represent the storage of all the winter flow, and a small flow over a long winter can create a large volume of ice that can fill the stream channel, culverts, bridge waterways and even encroach on the flood plain, so forcing spring runoff out of the normal channel. If it forms at a culvert or bridge, it can encroach on the roadway, giving rise to very hazardous driving conditions. Such deposits can also block water intakes.

3.1.4 Influence of ice formation processes on stream discharge

As the pack progresses upstream at freeze-up the water level must rise with it. In a manner similar to that described earlier for lakes, to allow this to happen the waterway - the so-called channel storage - and, in alluvial streams, the groundwater storage in the banks - must be filled. The only source of water to do this is that flowing down from upstream. There is then less to move on downstream. This reduction in discharge downstream depends on the rate at which the pack advances, the required increase in water level, the discharge available to fill the channel storage, and the channel storage capacity created by the increase in water level. The latter can be substantial in the bedrock-controlled streams of the Shield that have large lake areas on the stream system. The situation is illustrated in Figure 38.

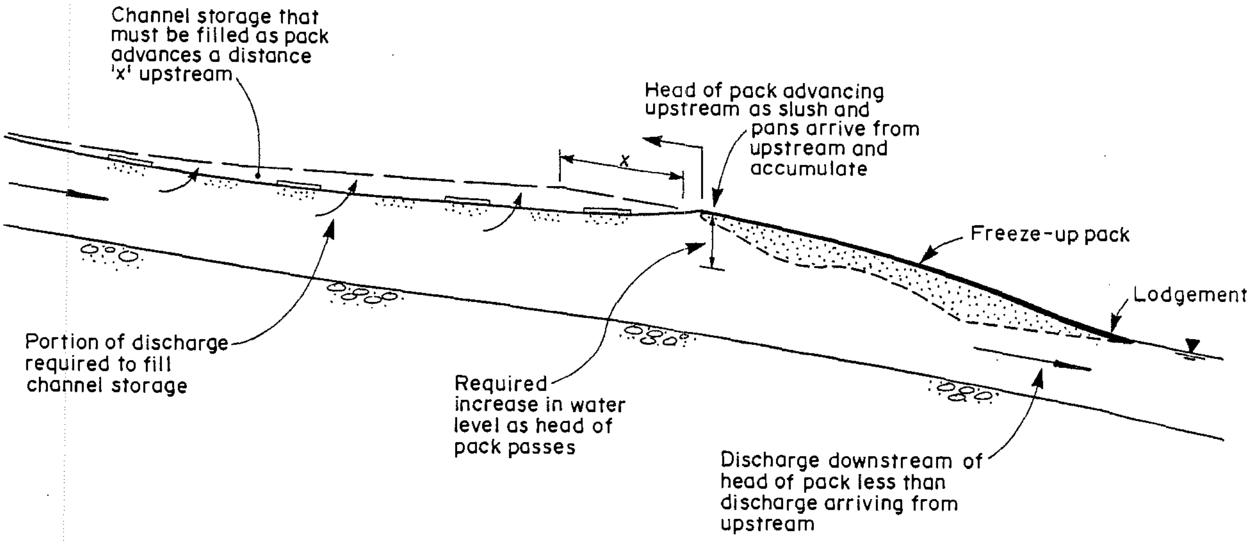


Figure 38. Reduction in discharge downstream of an advancing pack.

Because it depends on the pack advance rate, the discharge reduction varies with the rate at which ice is being produced on the open water upstream of the pack and thereby on the air temperature. Hence, other things being equal, the reduction in discharge can be expected to be larger in cold weather. This reduction in discharge during freeze-up can have serious effects on water intakes and aquatic life downstream.

Of course, the situation is reversed if the pack collapses, retreats or breaks up. Then the water in channel storage is released, with a commensurate sudden increase in discharge downstream. Because such a retreat can occur rapidly, the increase in discharge and water levels downstream can be substantial.

It is not just pack progression that is responsible for a reduction in discharge downstream during the winter. Even after the river is frozen over, the abstraction of flow to form ice continues throughout the winter. On a large river, this is usually a minor portion of the flow, but on small streams it can be significant. This is particularly so if aufeis begins to form. For example, on the Hangingstone River at Ft. McMurray in Alberta this loss represented some 80% of the flow at the end of winter (9).

3.1.5 Other river ice processes

In more temperate regions there can be more than one freeze-up and break-up sequence in a winter, either due to a sustained thaw in mid-winter, or due to winter rain. Winter ice jams can then occur. These subsequently freeze in place and may represent a major obstruction to spring break-up.

Thermal expansion of an ice sheet is usually of most concern on a lake or reservoir, but it can be important in rivers. A troublesome situation is created where tides, hydroelectric plant operation or thermal discharges keep portions of a river open. A bridge pier within the ice on the remainder of the channel may then be subjected to large lateral forces due to the thermal expansion of the ice. In fact, the only known failures in Canada of concrete or masonry bridge piers due to ice forces have been due to this cause: one in Whitehorse in the Yukon, because of open water maintained by the hydroelectric plant there; the other in Quebec due to tidal action keeping the central portion of the St. Lawrence River open.

Thick ice deposits can also be created along banks and bars, and around piers, by repeated flooding of the ice cover by such water level fluctuations downstream of hydroelectric plants or in tidal reaches.

3.1.6 Ice decay and melt

Weakening of an ice cover in spring cannot really begin until the snow cover on the ice has melted. The ice then becomes directly exposed to sunshine and warm temperatures.

It is the sunshine - solar radiation - rather than warm temperatures that is mainly responsible for the subsequent weakening of the ice cover. While a warm air temperature will raise the ice temperature to 0°C, and begin to melt the ice at the surface, causing it to thin, this is a relatively slow process. More importantly melting can occur **within** the ice cover. When the ice forms at freeze-up, any impurities in the water are excluded to the grain boundaries within the ice. As with salt on the road, the presence of these impurities lowers the melting point of the ice. The ice at the grain boundaries is therefore the first to melt as the ice temperature approaches 0°C within the cover. For this melt to take place latent heat must be provided. Little of this can come from the surface by conduction because the ice is isothermal at this stage and there are no temperature gradients.

However solar radiation can penetrate the ice cover and be absorbed. This provides most of the necessary latent heat for the internal melt. When well advanced, in columnar ice this internal melt results in the columnar grains separating from each other as shown in Figure 39. Because of the candle-like nature of the separate columnar grains, this internal melt process is known as candling. One result of candling is a dramatic weakening of the ice cover, even though it may still be quite thick.

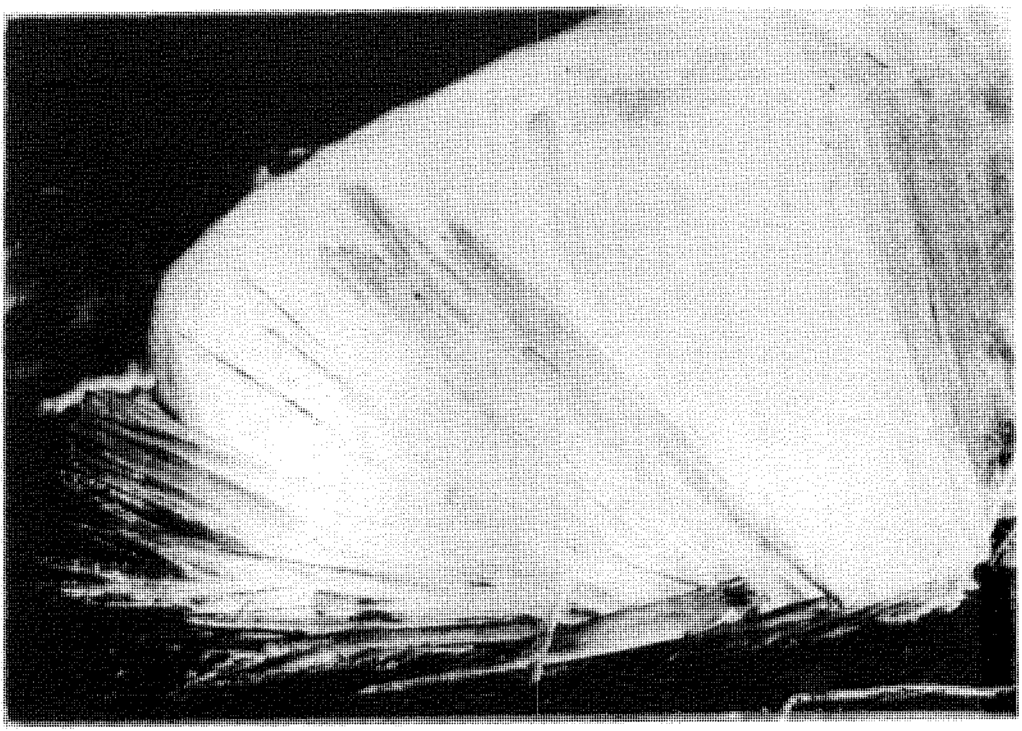


Figure 39. Candled ice (photo courtesy of F. Parkinson, La Salle Hydraulics Laboratory).

With grain boundary melt in columnar ice, channels are formed through the ice which allow any snowmelt on the surface to drain and water from below to move up into the ice. This gives the ice the unhealthy gray tone that is characteristic of decaying columnar ice.

Because of its transparency and vertical columnar structure, even when the candling process is well advanced solar radiation can penetrate a sheet of columnar ice and continue the decay process. This is not the case with snow ice, or with frozen frazil slush. These are fine grained ice types, with no columnar structure. Consequently when melt begins at the grain boundaries the ice crazes near the surface and becomes even more opaque than in its frozen state, so substantially reducing solar radiation penetration. As a result only the surface decays to any extent, becoming like old snow. So, while such fine-grained ice **melts** from the surface at more or less the same rate as the coarse-grained columnar ice, it takes very much longer to **decay.** Hence an overlying layer of snow ice will protect the underlying columnar ice from decay, as is evident in Figure 40.

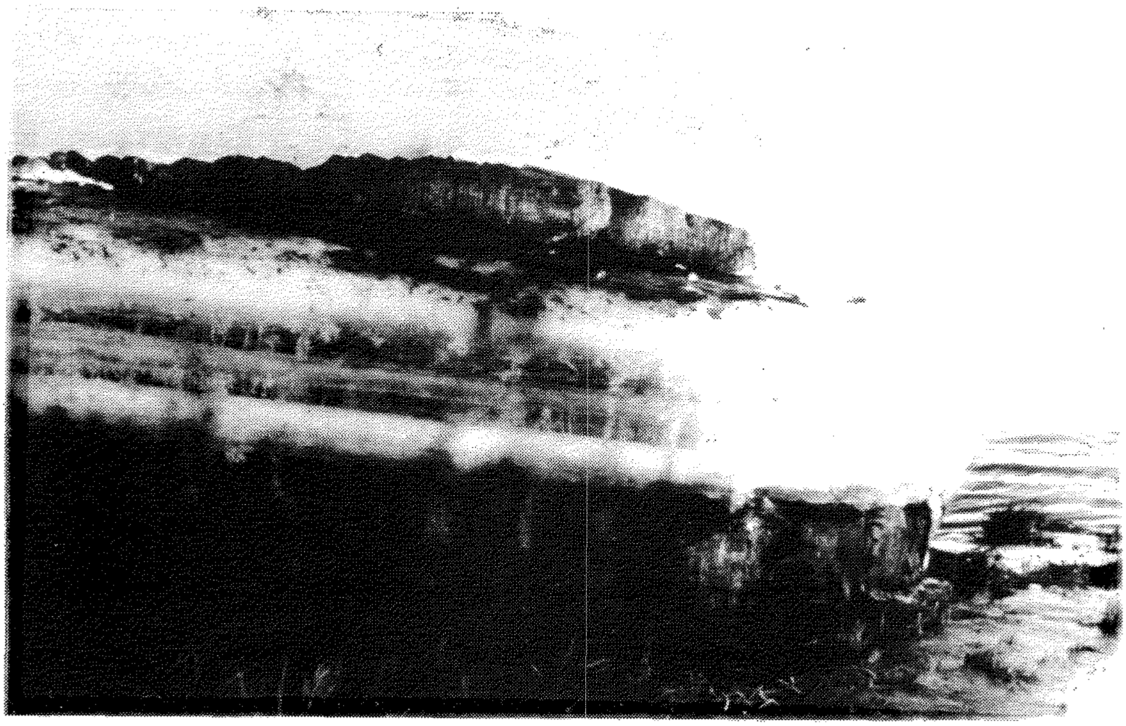


Figure 40. River ice along the shore after break-up. The still solid columnar or clear ice on the bottom has been protected from candling by the snow ice layer on top.

It is evident then that a sheet of predominantly columnar ice will weaken much faster than one with a substantial portion of snow ice or frozen frazil slush. This means that, while the thickness of an ice cover may not vary substantially from place to place in spring, its strength can. For example, a polynya that did not freeze over until late winter will be predominantly columnar ice, snow ice having had little chance to form. Hence, as well as likely being thinner, it will weaken much faster than adjacent ice carrying a reasonable surface layer of snow ice and frozen frazil slush.

3.1.7 Break-up

The moment of break-up of an ice cover at a site depends on events along a whole reach of the river, not just circumstances in the immediate vicinity of the site.

If flow velocities during break-up remain low and steady, due to little snowmelt, or due to control by hydroelectric plant operation, the ice cover will more-or-less melt in place, resulting in only minor ice runs and what is called a thermal break-up. Because of the pack thickness and the extent of bottomfast ice, this is the type of breakup which usually occurs along the Nelson River.

However, in other circumstances the breakup can be dramatically different. As spring advances open water leads begin to develop in the ice cover at locations where late ice formed, such as in a polynya, or where the ice is thin, albeit bottomfast, along shore, and is flooded by the rising water levels. Open water can also be formed in the mainstream off the mouths of tributaries that have become open first, or in which the flow is moving over bottomfast ice, so that the water is exposed to the warming of the sun. As the ice on the mainstream decays, fragments of the sheet break off from the edges of these open water leads and accumulate at the downstream end, forming small ice jams that begin to apply a force to the decaying solid ice cover.

Eventually at some location such an accumulation will become big enough, the restraining ice sheet weak enough, or the flow velocity underneath high enough due to an increase in flow, that one or other of these ice jams will fail and begin to move downstream. As it moves, it releases water from channel storage, forming a surge. This increases the velocity and water levels downstream even further, so contributing to keeping the breakup moving and thereby triggering a general ice run. This is called a dynamic break-up.

At some point the ice run will stall, such as at a stronger-than-usual portion of ice sheet, perhaps where it is more bottomfast than elsewhere, or where it is locked into a sharp bend; at a sudden enlargement of the flow cross section which reduces the effect of the surge, as at the headwaters of a reservoir or lake; or simply when the ice run and surge have been so attenuated in their passage along the river that they are incapable of breaking the normal ice cover.

When the ice run does come to a halt, the pack that forms is an ice jam. An example is shown in Figure 41. The higher and more rapid the increase in discharge that triggered the ice run, and the stronger the ice at the time of the run, the more extensive will be the resulting jam when the ice run stalls, and the higher the water levels caused by the jam. The jam will remain in place until circumstances develop that again allow it to fail and repeat the process. This sequence is repeated until the river is open.

3.1.8 Ice jams

It is evident that ice jams are a natural and common part of both the freeze-up and break-up processes of a river. The configuration ice jams are

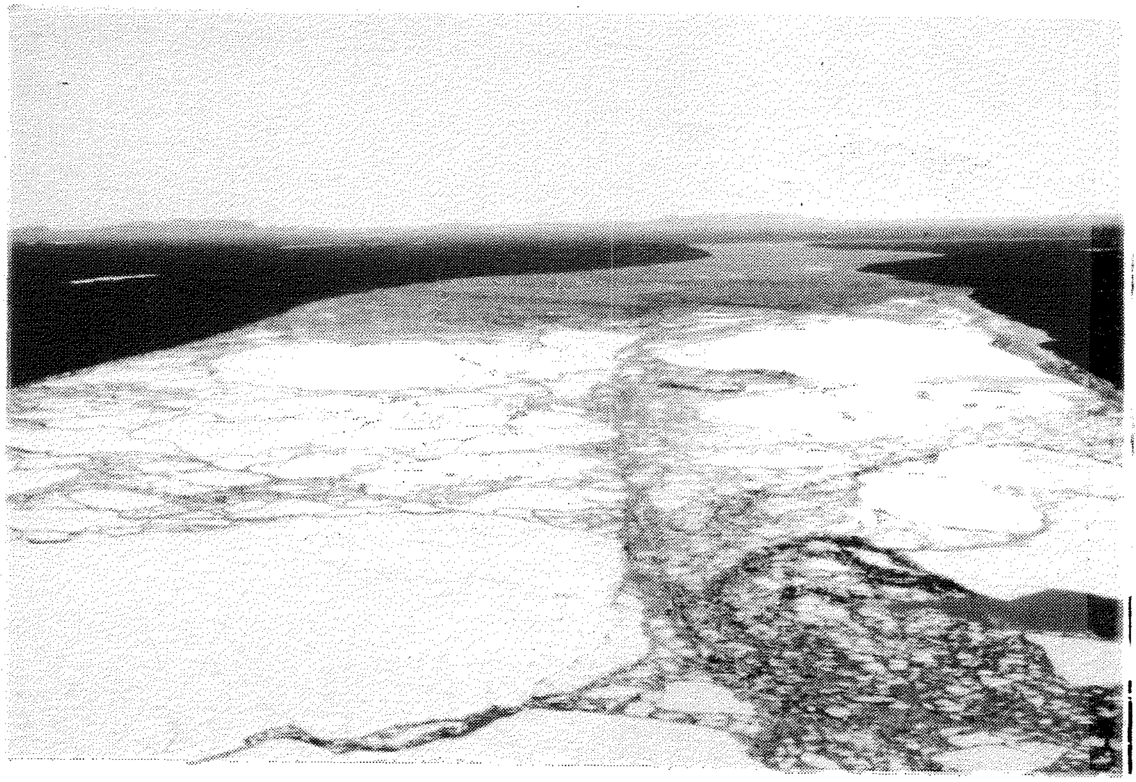


Figure 41. Ice jam on the Mackenzie River at Fort Norman, looking upstream.

believed to have is illustrated in Figure 42. At the toe, or downstream end, the fragmented ice is carried under the ice sheet for some distance, with the thickness of this deposit being limited when the velocity in the remaining waterway under the accumulation is large enough to prevent the ice from depositing, as was the case for a hanging dam. It therefore seems the true downstream end of an ice jam will lie somewhat further downstream than the apparent toe at the upstream end of the ice sheet.

Upstream of the ice sheet the pack configuration is a result of an interaction between the flow and its drag on the ice pack, and the 'geotechnical' properties of the pack. This interaction is such that the

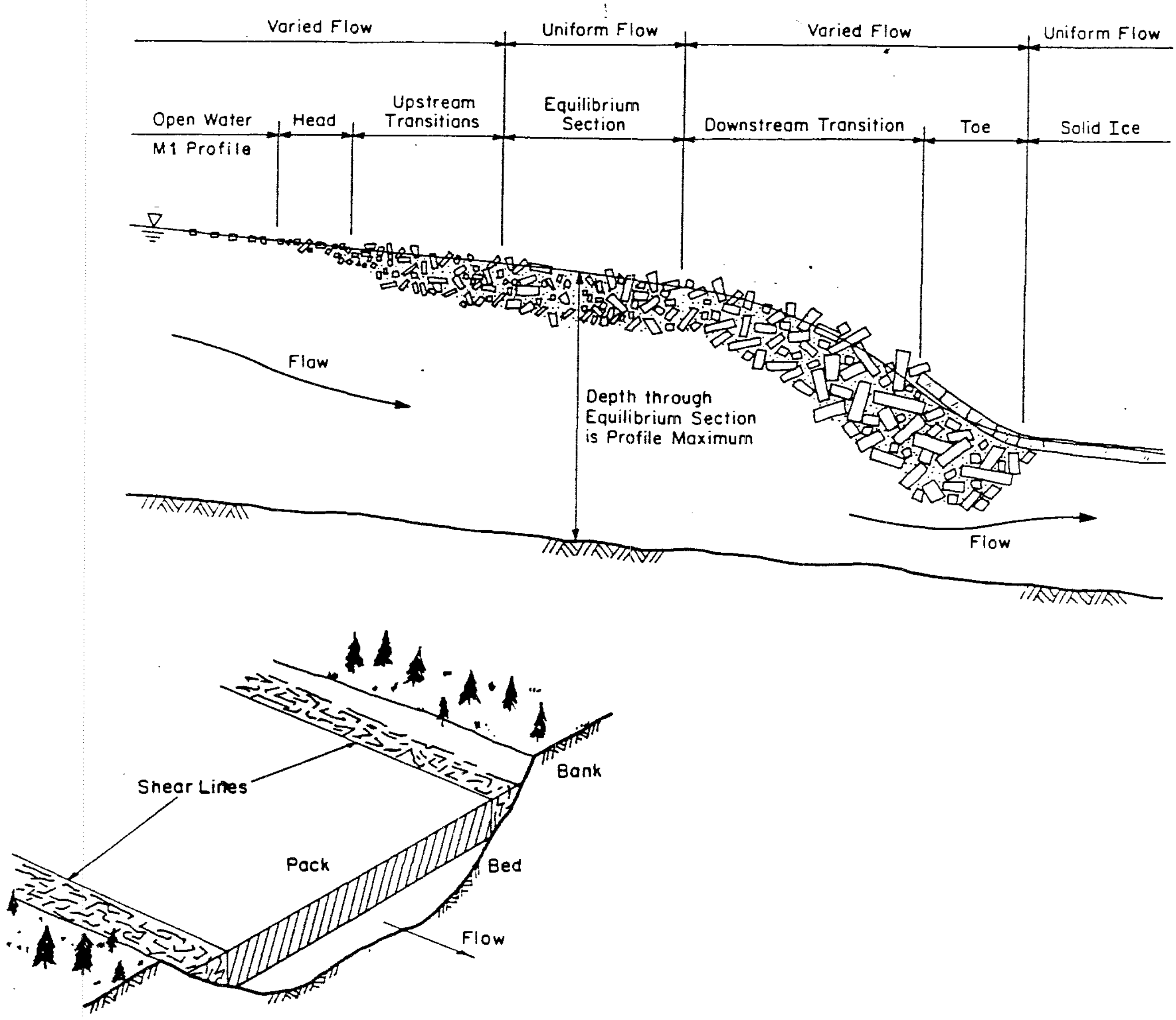


Figure 42. Configuration of an ice jam.

water level increases with distance upstream of the pack, and the pack thickness decreases, until a balance is reached, after which the waterway depth and pack thickness remain constant until just downstream of the upstream end of the pack. The section of the jam with uniform waterway depth and pack thickness is called the equilibrium section. An ice jam that is long enough to have developed such a section is called fully-developed.

It is evident from Figure 42 that the maximum water depth occurs within the equilibrium section. An analysis for determining this depth was developed in Canada some two decades ago and has since been applied with success in predicting ice jam water levels in streams and rivers in many different circumstances, including that of the thick freeze-up pack that forms on the Nelson River in Manitoba shown in Figure 31. In steep rivers the main cause of the water level increase is the pack thickness; in flatter rivers it is the pack roughness. In either case the water level increase can be dramatic and far exceed the water level caused by even a rare open water flood.

When an ice jam such as that illustrated in Figure 41 and 42 fails, it can do so suddenly. This then is akin to a dam break, or the sudden opening of a sluice gate in a canal as described earlier. A surge is released to move down river. The speed at which such a surge moves along the river can be 20 km/h and higher, with a comparable flow velocity behind the surge. As mentioned, it is the release of such surges by ice jam failure that is responsible for an ice run. The rapid passage of such a surge means the water level increase that accompanies it occurs rapidly, with little warning and considerable danger if the water levels are high enough to cause flooding.

3.2 LAKES AND RESERVOIRS

3.2.1 Initiation of an ice cover

Freeze-up on small shallow lakes, or in bays and inlets of larger lakes, proceeds much as for border ice in a river. However, unlike for river ice, under quiet windless conditions the initial skim of ice can form across the whole surface of a lake overnight. An example is shown in Figure 43. This then thickens through the growth of black ice. If snow accumulates, due either to snowfall or drifting, the formation of snow ice may be added.

Figure 43.
New ice cover on a small lake.

On larger lakes the situation is more complex. The larger body of water takes longer to cool to a point where ice can begin to form on the surface. The large fetch exposed to the wind allows waves to develop in even a mild breeze, which makes it difficult for an ice cover to form anywhere other than along shores and in bays. The result is that, as on a river, frazil and pan ice form on the lake away from shore. Because the stabilizing density stratification that limits the depth penetration of turbulence in the lake in summer is absent after the fall turnover, the only slightly-buoyant frazil ice can be carried to surprisingly large depths by the turbulence generated by the wind, and has been known to clog water intakes at depths of 10 m and more.

Sometimes large expanses of shore ice can break away under the action of waves and wind to join the ice debris moving about the lake, as shown in

Figure 44. This conglomeration of ice will drift around the lake under the action of the wind, sometimes piling up at the edge of the shorefast ice sheet to be coated and augmented by frozen wave wash and spray. An accumulation on the shore of Lake Huron formed in this way extended 14 m out of the water, and 'ice islands' have been observed in the centre of Lake Erie that had a freeboard of 9 m (7).

Figure 44. Ice on a large lake during freeze-up: Great Slave Lake off Hay River, N.W.T.

Eventually the quantity of ice on the surface of the lake, and the damping of the waves that it affords, together with steady growth of shore ice out over the lake, may allow a solid ice cover to develop. However, if the lake is large enough, or the winter temperatures mild enough, the lake may not freeze over entirely. This is a common circumstance on the larger of the Great Lakes, for example.

Once formed, the ice cover will gradually thicken through the winter by the growth of black ice and snow ice as on rivers. However, the proportions of these ice types, and the growth rate, is a strong function of snow drifting on the lake. On large lakes where the snow may drift off large portions of the cover, little snow ice will form. The more exposed ice cover also thickens somewhat more rapidly. This is particularly so in regions of low snowfall. Hence lakes carrying large expanses of almost pure black ice are common in the north.

On the other hand, in regions of heavier snowfall, and near shore and other locations where drifts can accumulate early, the ice cover can have a significant portion of snow ice. The snow cover insulation also reduces the growth rate in these areas.

As described in Section 2.4.4, the warm water that exists just below the ice cover in a lake can also have a significant influence on ice cover thickness. This is especially so if the water is disturbed by currents. Similarly, ice on a saline lake, or near the outflow of saline groundwater, will be thinner due to the lower freezing temperatures of such solutions.

3.2.2. Expansion, contraction and pressure ridges

A familiar site on lakes of any extent is the network of pressure ridges generated over the winter by the thermal expansion and contraction of the ice cover. An example of the distribution of such pressure ridges on a large lake is shown in Figure 45.

As soon as an ice cover forms, it begins to be worked thermally. The temperature of the ice surface remains close to that of the air temperature but, being always in contact with water, that at the bottom of the ice cover remains at 0°C. Air temperature fluctuations therefore generate thermal

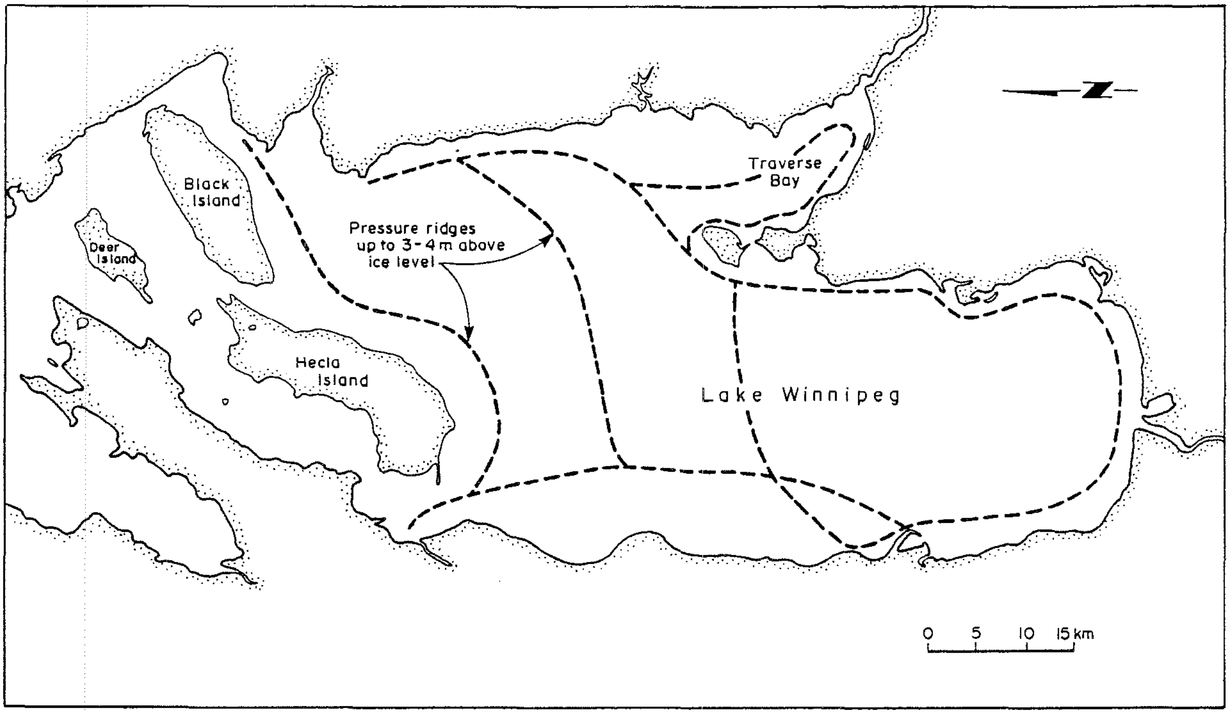


Figure 45. The pattern of pressure ridges formed on Lake Winnipeg (adapted from 16).

stresses in the ice cover. As the air temperature falls, the ice surface tries to contract but is restrained by the ice at the bottom which is at 0°C. Tension is therefore generated at the surface and compression at the bottom. A host of fine cracks occur at the surface as the brittle ice fails in tension. However, because the bottom of the ice is in compression, these cracks do not penetrate through the whole ice cover and therefore remain dry.

The compression induced in the bottom of the ice cover causes a commensurate shrinking of the ice cover as a whole. If the cover is not restrained this is accomplished without further distress. However, if it is restrained, such as at the shore, or within the 'keys' of bays and inlets, this overall contraction will result in the formation of cracks through the full depth of the cover in the vicinity of the points of restraint. Water moves into these cracks and they are therefore known as 'wet' cracks. An initial pattern of these cracks is often observed after the first snowfall in fall, as water moves through the thin ice and saturates the snow, as is evident in Figure 46(a). They can be quite numerous then. Generally though, as the ice cover thickens they become fewer and represent the accumulated contraction of a larger portion of the ice cover, and so can be quite wide, as shown in Figure 46(b).

As is evident in Figure 46(b), these wet cracks can refreeze, with the result that the ice sheet becomes progressively larger over the winter, a process known as 'jacking'. Typically this expansion is as much as 0.1% of the width of the lake (31). For a lake 10 km wide, for example, this represents an enlargement of 10 m that must be accommodated.

At some time during the winter the air temperature will increase and the ice sheet expand again. The wet cracks will then try to close. However, the refrozen portion of the crack, and the mismatch between the edges of the crack as it closes, places localized and eccentric loads on the ice sheet such that, if it is thin enough, and the expansion large enough, the ice sheet will fail at the crack and a pressure ridge will be initiated. Examples are shown in Figure 47. It is in such locations that much of the gradual enlargement of the ice sheet described above is taken up.

If the movement of the ice sheet is sufficient for the pressure ridge to become fully developed it will take up a profile much like that shown in Figure 48, which is a pressure ridge in the Baltic. The notable feature is

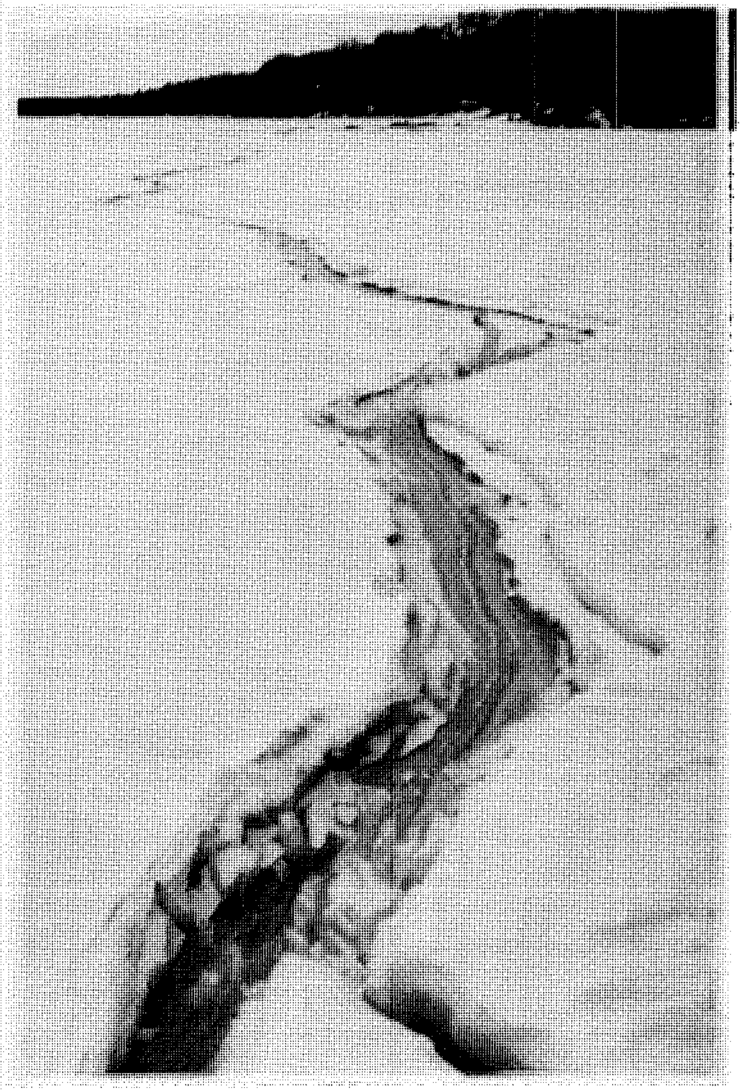


Figure 46.
'Wet' cracks formed by the thermal contraction of an ice cover: (a) the pattern of wet cracks on a small lake in early fall; (b) a refrozen wet crack in late winter.

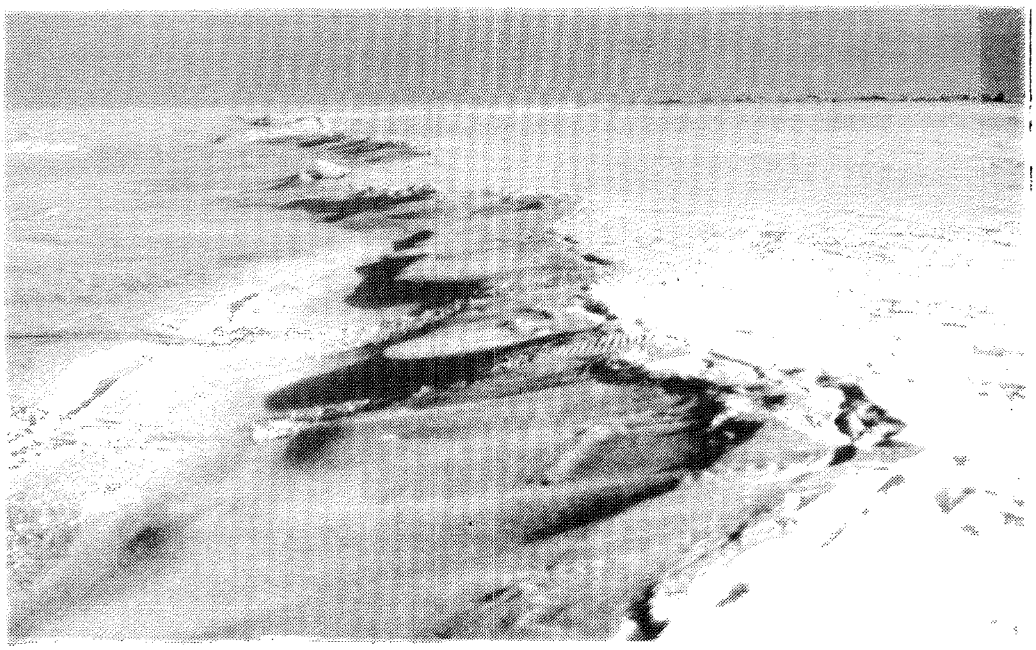


Figure 47.
Pressure ridges in lake ice: (a) a still-active pressure ridge in thick ice in late winter; (b) the thickness of the ice when this pressure ridge was initiated is evident, as is the slow expansion that has resulted in the plastic curving of the ice.

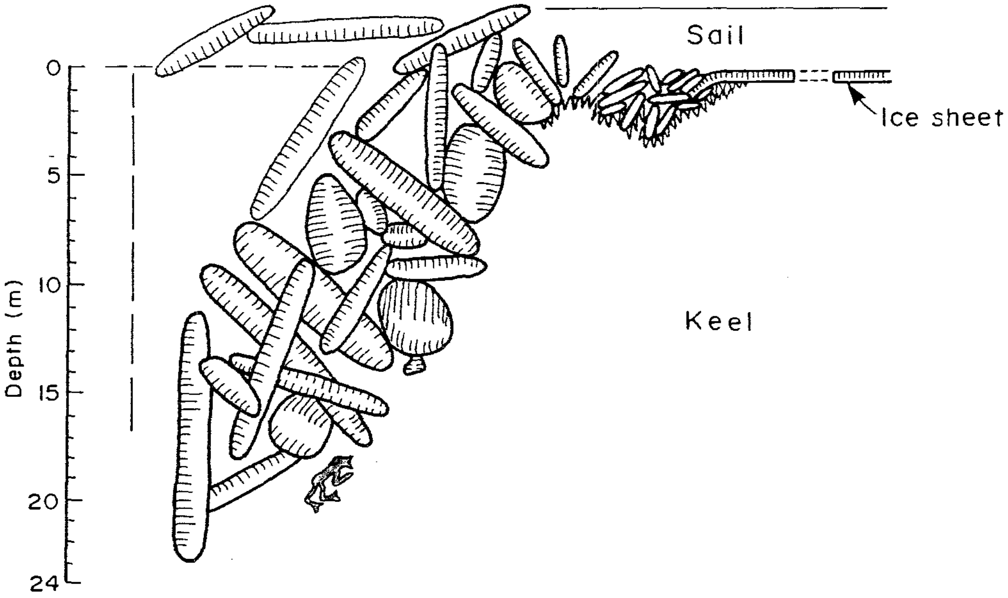


Figure 48. Typical cross-section of a pressure ridge (adapted from 24).

that the keel - the portion below the water line - is very much deeper than the sail - the portion above the water line - is high. The keel/sail height ratio is typically about 4 to 5:1, but values as high as 6 to 10:1 have been noted, particularly where pressure ridges intersect (24). However, on small lakes with thick ice the pressure ridges will likely be much less than fully-developed and the ratio of keel depth to sail height much less consistent. This is certainly the case for both situations shown in Figure 47(a) and presumably also those in Figure 45. Being near shore, that in Figure 47(b) is likely grounded.

If the ice cover does not develop a pressure ridge to relieve the stresses in the ice cover, the expansion of the ice can result in failure of the shoreline attachment and the subsequent slow ride-up of the ice as shown in Figure 49.

Figure 49. Slow ride-up of an ice sheet at a shoreline due to thermal expansion: Pigeon Lake, Alberta.

3.2.3 Break-up

Away from shore the snow cover melts and pools on the ice cover, or drains through cracks. Once exposed to the sun's radiation, the top few centimetres of snow ice become porous and white. As described earlier for river ice, this then reflects much of the incoming radiation and absorbs the remainder within a short distance of the surface, and so protects the underlying ice. However, if the ice cover is predominantly black ice, this protective layer does not form and the ice will candle and decay much more quickly. Once the ice cover is candled the ice becomes saturated with water internally, water that is itself warmed by absorbed radiation. This increases the rate of decay and weakens the ice markedly. The columnar grains of ice eventually become almost literally separate candles of ice waiting for the first breeze to pull them apart. Once candling is well established, what is apparently a thick ice cover is very weak and can disappear almost overnight.

Near shore the ice cover is typically thinner due to the insulation afforded by snow drifts. If there is any increase in lake level due to inflowing streams, the bottomfast shore ice will also be flooded. Snowmelt from the shore, which tends to also carry sediment, also ponds on the ice near shore. This water and sediment absorbs the solar radiation and warms, so encouraging the rapid melt of the nearshore ice.

Hence it is usual for the nearshore ice to melt first. This frees what is still a quite strong central ice sheet to be moved about the lake by wind. If this ice sheet contains pressure ridges, these are carried with it and the keels can cause gouges in the lake bed and destruction of installations thereon if they are dragged over them (23). For example, gouges 2 m deep in the stiff clay bed of Great Slave Lake have been documented and are apparent in airphotos of the shallows (17).

The terminal velocity of a wind-blown floe is about 1/30 of the wind velocity. A large, thick ice sheet can therefore develop considerable momentum under a steady wind. If it strikes the shore, or another ice sheet, a large ice pile can develop in a short time and threaten cottages and other structures along the shoreline as shown in Figure 50(a). This has occurred on the shores of Lake Winnipeg, as shown in Figure 50(b), but is apparently not frequent there (15). The horizontal extent of the ice pile is obviously of concern. This depends on the shore profile. If it is low and flat the ice can move up it as a single sheet as shown in Figure 50(a); the inland encroachment will then be a maximum. However this onshore progression can be interrupted by a slight break in the shoreline profile and an ice pile initiated. Encroachment will then be much less.

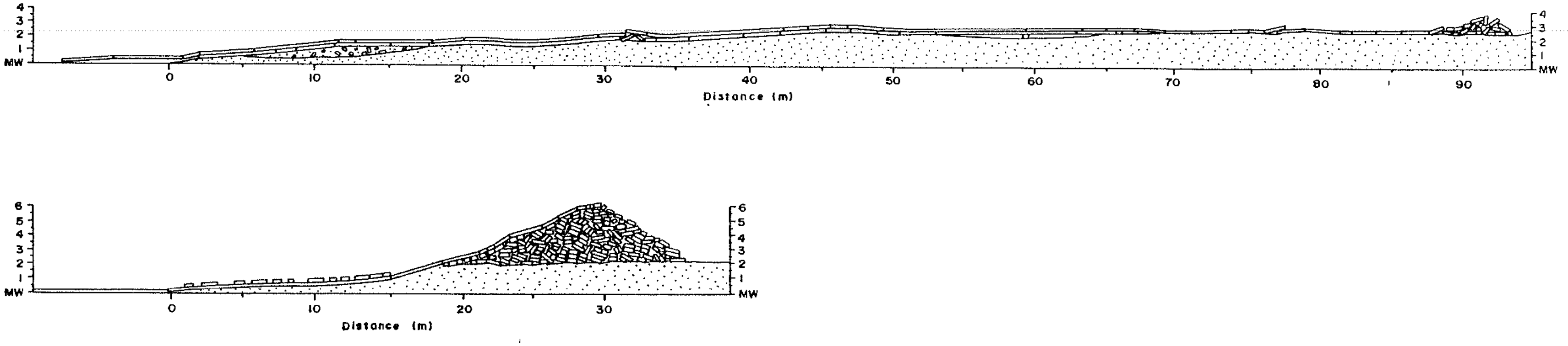


Figure 50.
(a) Profiles of various ice pile-up events on the Baltic coast (adapted from 24) (b) Ice pile-up on the shore of Lake Winnipeg (17)

4. THE NATURE OF HYDROELECTRIC POWER DEVELOPMENT AND ITS INFLUENCE ON THE ICE REGIME OF INLAND WATERS

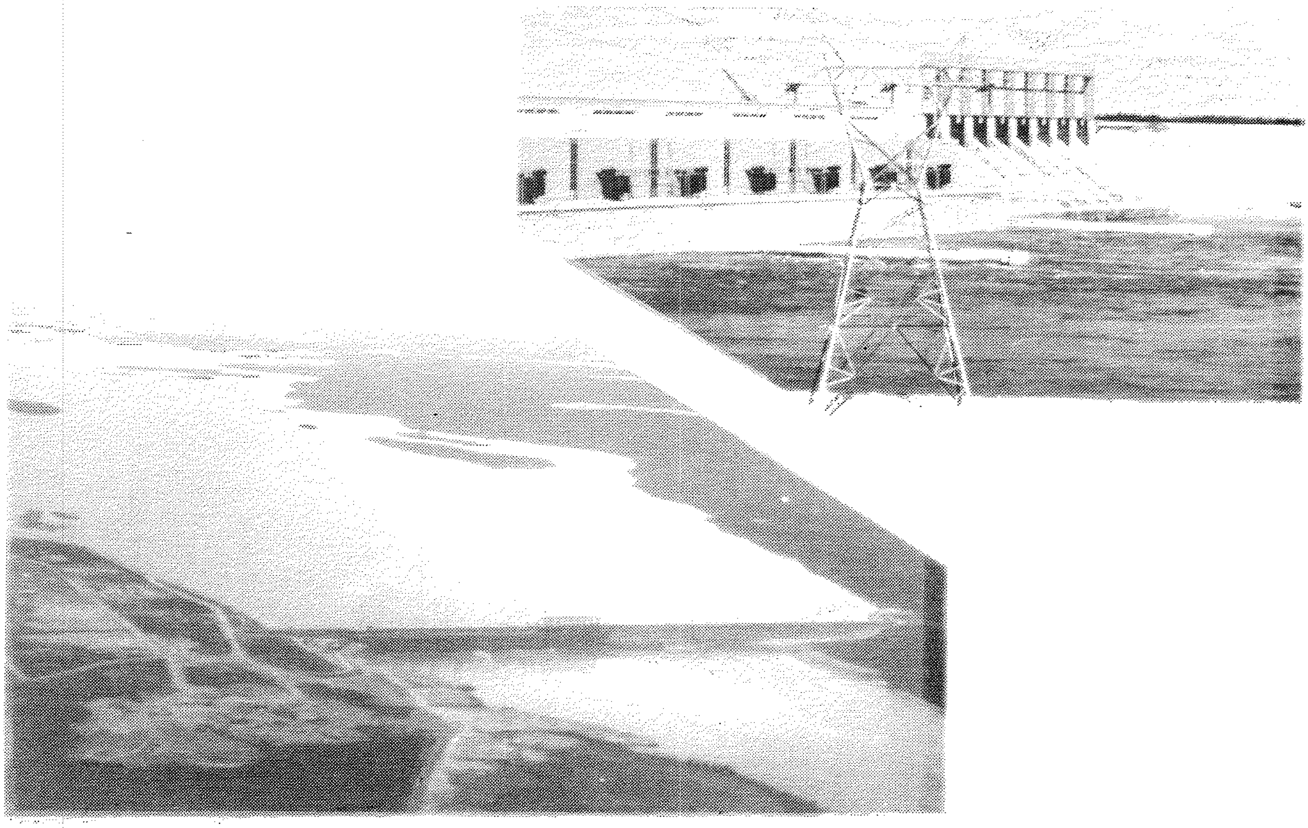
4.1 HYDROELECTRIC POWER DEVELOPMENT AND OPERATION

One of the prime advantages of hydroelectric power is its economy. This is particularly so in a province like Manitoba that has limited fossil fuels to fire thermal power plants. Another advantage of hydroelectric power is its ability to respond rapidly and economically to changes in demand, a characteristic not shared by thermal power plants. Hence, in a system that has both thermal and hydroelectric power plants, it is usual to use the hydroelectric plants to respond to the so-called peak power demands. For the same reason, hydroelectric plants are used to respond to sudden demands imposed by emergency conditions in the system. Hydroelectric power is therefore premium power. However, because the only way a hydroelectric plant can generate power is to run water through the turbines, this means the discharge downstream will vary accordingly as the plant operation is adjusted to follow these sometimes rapidly changing demands.

The dam of a hydroelectric power installation typically has two purposes: first to increase the 'head', or difference in water level across the power plant, and thereby its power generating capacity; and, second, to provide storage so that there is water to run through the plant in times of low discharge in the river upstream. In some circumstances only the first aspect is important. The installation is then known as a run-of-the-river plant and storage is a secondary consideration. This is typically the case for power plants downstream of a large reservoir or lake, or for small private mini-hydro operations. For example the Bennet Dam in British Columbia holds back the enormous Williston Lake. With this large storage in the system, power plants further down the system do not have to be provided with much storage, simply enough to provide some balancing of the flows and to develop the necessary head across the plant. A similar situation applies on the Nelson River system, with the several plants along this river being almost run-of-the-river plants and depending on the storage provided by Lake Winnipeg and the other natural lakes in the system.

The cross-section of a typical hydroelectric power plant installation is shown in Figure 51. The water from the reservoir moves through the penstocks - in this case quite short ones - to the scroll casing which guides the flow around to the adjustable wicket gates that line the inside circumference of the scroll casing. These gates in turn direct the flow at an optimum angle onto the rotating runner. As the flow passes over the runner blades it exerts a tangential force on the runner. This produces a torque which turns the runner and, through their common shaft, the generator above. It is the generator that produces the electrical power. After leaving the runner blades the flow passes through the draft tube into the tailrace and back into the river. The power produced by such a hydroelectric plant varies directly with the product of the discharge through the turbines and the head on the plant (for the type of turbine used in Manitoba this head is the difference in water level between that in the tailrace immediately downstream of the plant and that in the forebay upstream of the intake).

It is difficult to appreciate the size of some of these installations from a diagram: to walk into the enormous scroll casing of the plant shown in Figure 51 is not unlike walking into a cathedral. However, for all their size, they are the most efficient means of producing power, with efficiencies typically well above 90% when operated at optimum. Such efficiencies far exceed those of thermal power plants.



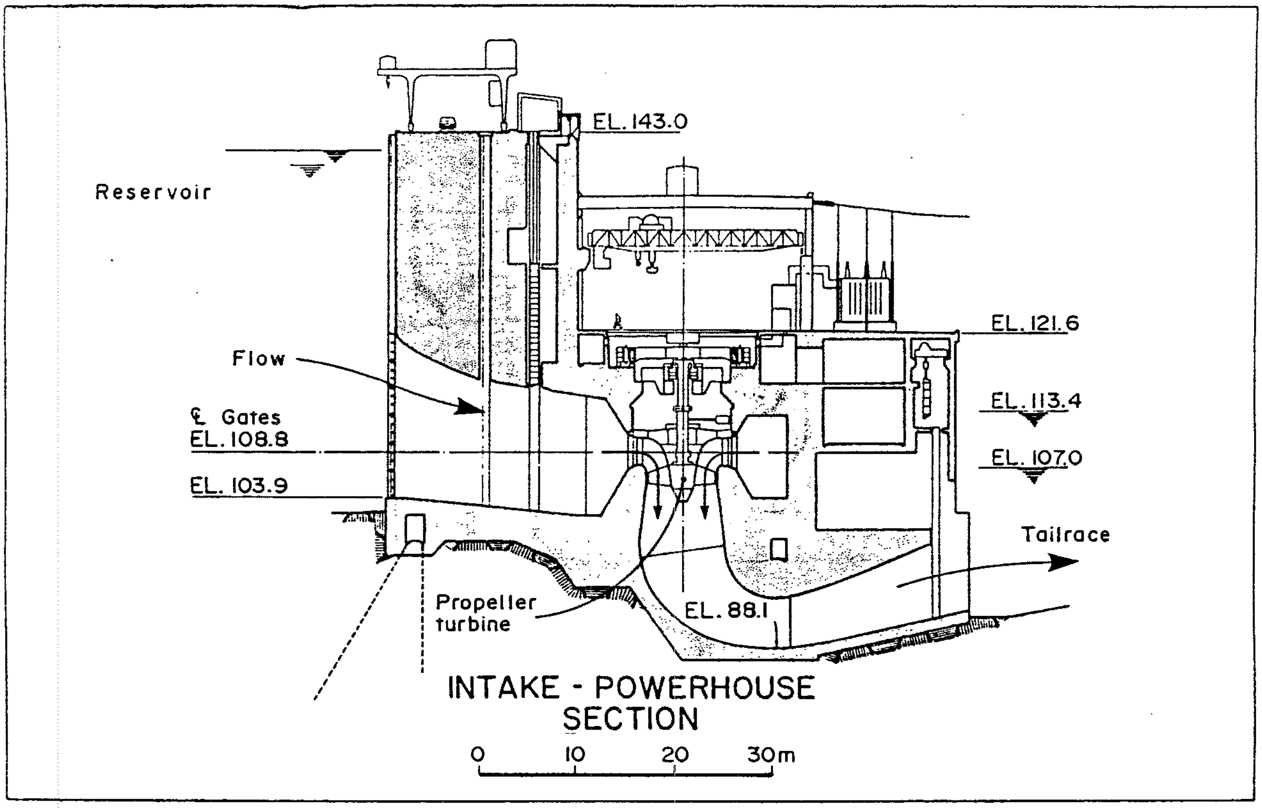


Figure 51. The Manitoba Hydro Kettle Hydroelectric Generation installation on the Nelson River (diagram adapted from 14).

Once installed there is tremendous economic incentive to operate such large hydroelectric plants at optimum. Conversely, any restrictions placed on the operation of the plant, such as might be required to avoid an environmental impact, can be very expensive. For a plant on the Nelson River the loss of just 1 m of head, say due to ice effects downstream or upstream, can represent the loss of more than 700,000 kWh of energy each day which, at the consumer end of the system, is worth about $35,000 to the people of Manitoba.

Because of the nature of the power demand, daily fluctuations in discharge through a plant can be expected, with somewhat larger and more sudden variations if the plant is suddenly called upon to pick up an emergency load due to trouble elsewhere in the system. Once released, these sudden variations progress down the river, usually only slowly becoming smaller due to attenuation and due to 'dilution' by inflow from tributary streams along the downstream reach. An example of such releases and their transformation in passage down a river is shown in Figure 52. While the effects of daily fluctuations are still apparent 100 km downstream, only fluctuations that extend over several days are still evident 380 km downstream. Evidently the effects of short term fluctuations in releases from the power plant are lost reasonably quickly, whereas those of the longer term changes remain. If there are lakes in the river system downstream the fluctuations will be damped out sooner.

These effects of the discharge variation required to meet changing demands on the plant do not only occur downstream of a plant. The pool upstream of a run-of-the-river plant is usually small and remains largely within the confines of the river. Because of its small size relative to the flow that can be passed through the turbines, the pool level of these plants

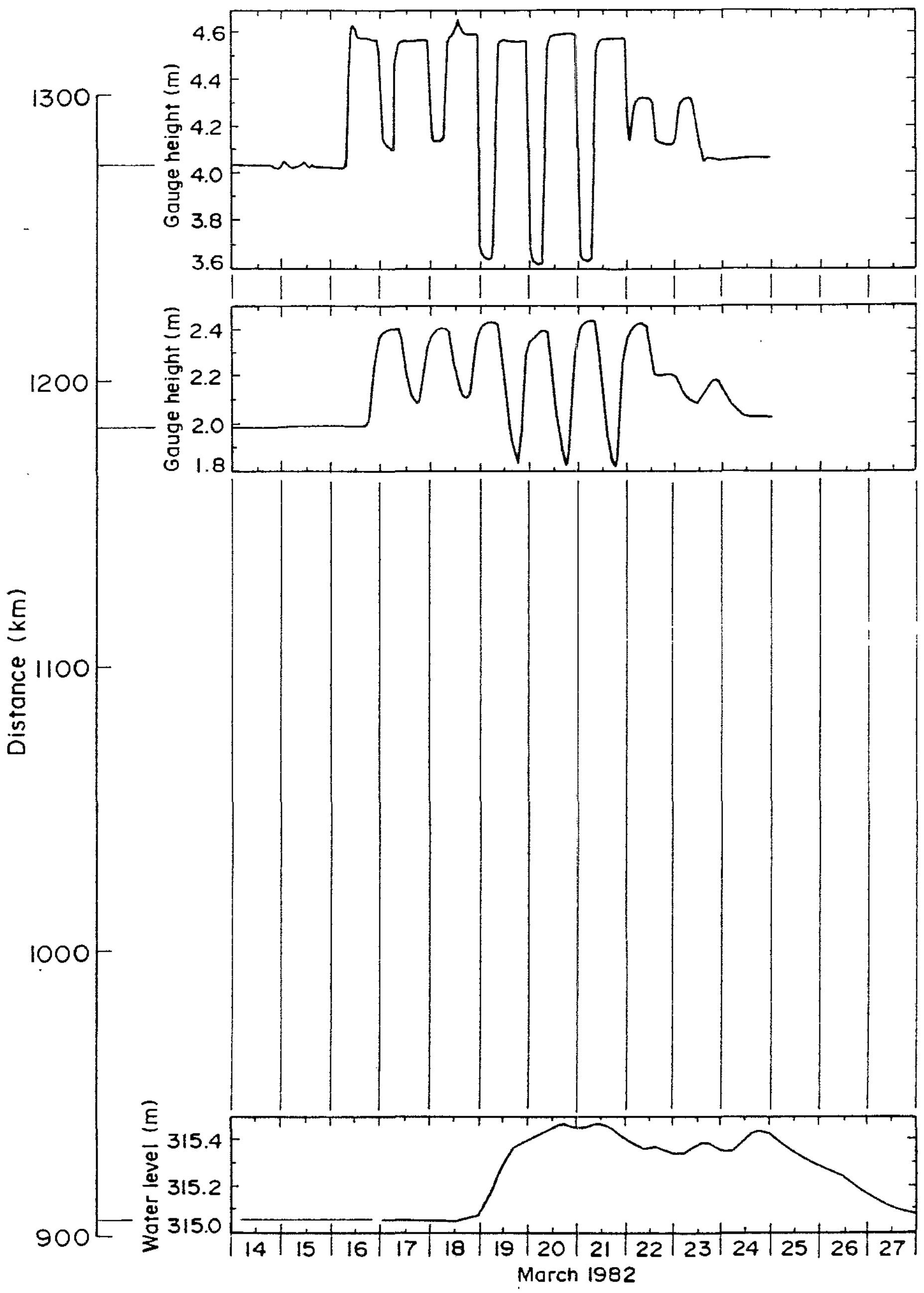


Figure 52. The transformation during passage downstream of discharge surges released by hydroelectric plant operation: the Peace River downstream of the Peace Canyon Dam (adapted from 2).

is also particularly sensitive to load flucutations. This can also apply to plants with large storage reservoirs if the forebay is relatively small. The fluctuations in withdrawal will then again cause significant water level fluctuations in the forebay area. This is the situation at the Jenpeg power plant downstream of Lake Winnipeg. However the effects of short-term fluctuations are not usually felt to any degree upstream of the forebay, being lost in the expanse of the reservoir.

Because demand for power is a maximum in winter and a minimum in summer, whereas the natural discharge in the river is a minimum in winter and a maximum in summer, reservoirs for hydroelectric plants are specifically designed to have sufficient storage to be able to reverse the natural discharge sequence. There is therefore almost complete reversal of the natural monthly mean discharge variation downstream. This also applies to the levels of the reservoir, and of any lake incorporated into the system. This is illustrated in Figure 53, which shows the expected change to the Nelson River flows downstream of Split Lake following development, and the changes to the variation in Lake Winnipeg levels upstream, and Cross Lake downstream, of the Jenpeg plant.

However such plots of mean monthly discharges and levels, which are common in environmental impact statements, must be viewed with some reservation as far as the ice regime is concerned. What is as important then are short term, sometimes even hourly, fluctuations. While there are well-defined average trends in hydroelectric plant operation, it is also true that it is difficult, if not impossible, to maintain scheduled operations at all times when the plant is large and forms part of a grid with other large components that can go off line at any time for a variety of reasons. The problem is illustrated in Figure 54, which shows the variation in releases from the Bennet Dam over the Christmas-New Year period of 1981-82. Discharge was almost doubled, and then halved again, all within a period of about 6 days.

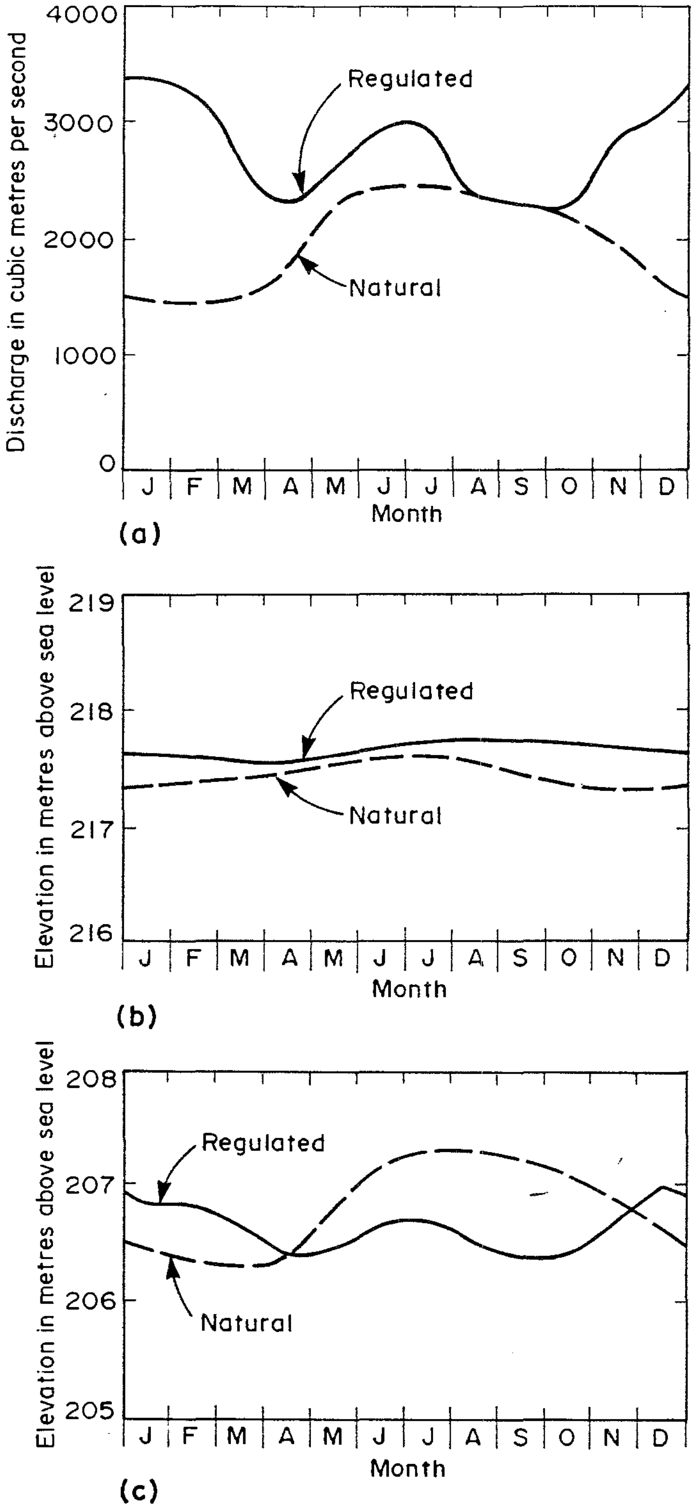


Figure 53. Expected changes in (a) mean monthly discharge in the Nelson River below Split Lake (b) water levels of Lake Winnipeg and (c) water levels of Cross Lake, after regulation (adapted from 15).

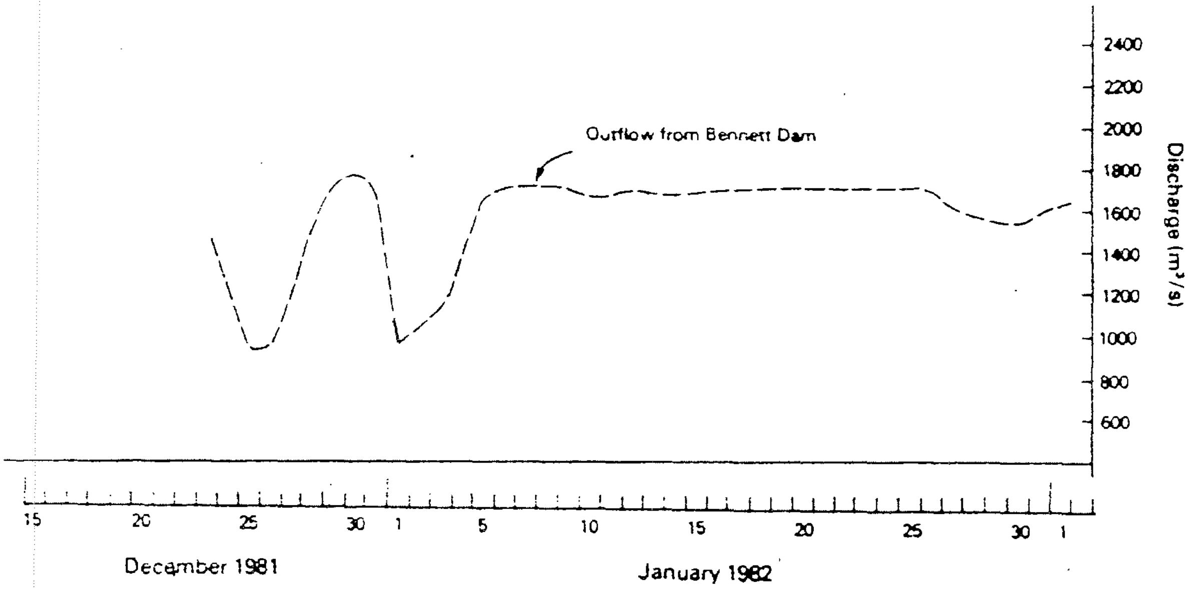


Figure 54. Discharge variation at the Bennet Dam on the Peace River over the Christmas-New Year period, 1982-82 (from 18).

Frequent short-term fluctuations from the average trend are therefore a characteristic of hydroelectric plant operation unless restrained by environmental and other considerations. Even when such restraints are applied, human nature being what it is, the restraints have a marked tendency to soften as the years pass under the increasing economic pressure to relax them, and the generally decreasing environmental pressure to maintain them. This almost inevitable trend must be recognized when assessing the social and environmental response to the planned development.

Downstream of a diversion for hydroelectric power development, the changes will be reversed and the winter discharges will be substantially reduced. This is the situation for the Churchill River downstream of Southern Indian Lake, as illustrated in Figure 55. Also shown in Figure 55 is the major increase in water level of Southern Indian Lake as a result of

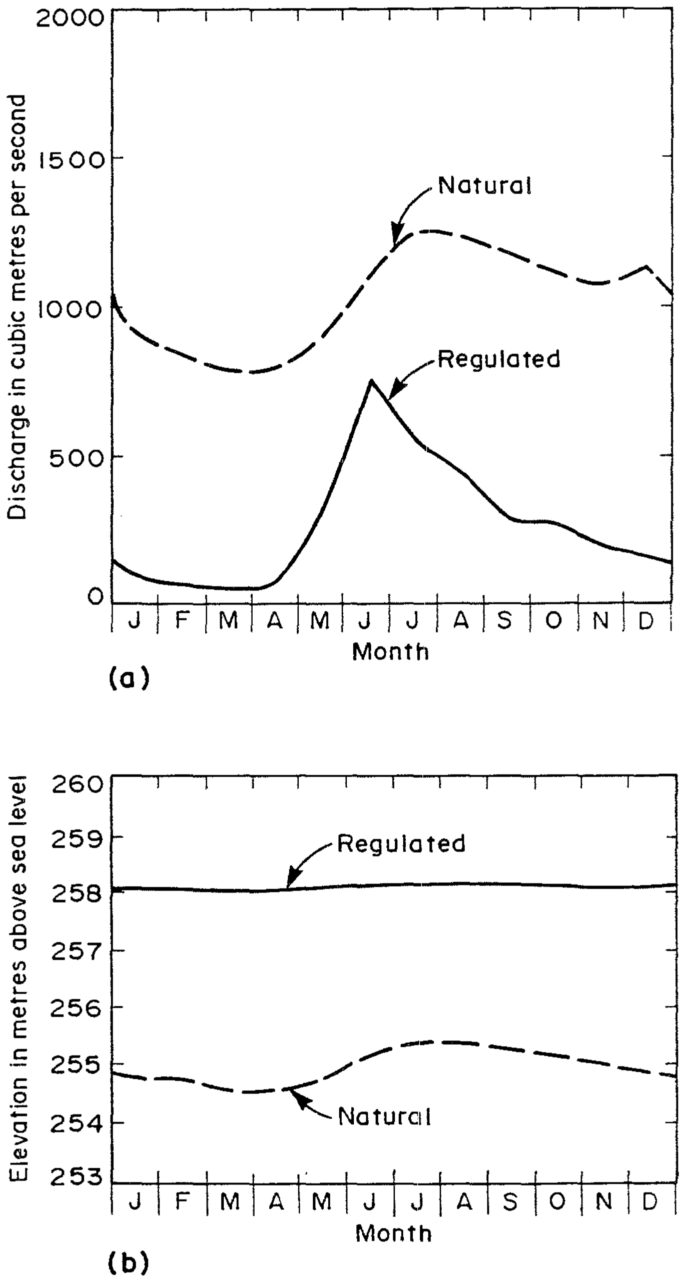


Figure 55. Expected changes in (a) the mean monthly discharge in the Churchill River downstream of Southern Indian Lake and (b) the water levels of Southern Indian Lake, after regulation (adapted from 15).

regulation. However, because it is not directly influenced by a hydroelectric plant, the variation in water level, while unnatural, will be gradual.

The influence of changes in water levels is not confined to the main channels. They also influence tributary streams over long distances downstream. For example, until remedial works were undertaken, there was a major impact of the Williston Reservoir of the Peace River development in British Columbia on the Peace-Athabasca delta over 1,200 km downstream in Alberta. The reduction in the mean water level of the Peace River at the outlet of Lake Athabasca, due to the changed flow regime in the Peace River, resulted in a significant reduction in the level of Lake Athabasca, and thereby a significant environmental impact on Wood Buffalo National Park (25). Even with the remedial measures there is the possibility that the reduced frequency of spring ice jams in the Peace River near the delta may change the frequency of flooding and refreshing of the perched lakes that are an important element of the delta ecology. For similar reasons, a major concern with regard to the proposed Liard River development in northern British Columbia is its possible influence on break-up of the Mackenzie River, and consequently on the Mackenzie Delta 2,100 km downstream.

The above discussion has concerned the obvious influence of hydroelectric development on discharges and water levels. However the thermal regime of the effected water bodies may also be changed. Under natural conditions the water temperature in a river is essentially 0°C whereas that in a reservoir or lake can be considerably warmer. Consequently winter releases of water from a reservoir will usually increase the water temperature over its natural value for a considerable distance downstream as illustrated in Figure 17. This can result in open water where none existed before over a substantial reach of the river downstream of the dam.

Upstream the reservoir will obviously totally change the thermal regime of the river it flooded out. However it can also change the thermal regime of a lake if it significantly influences its water levels. For example, on the Churchill River the thermal regime of Southern Indian Lake was significantly altered by the 3 m increase in water level associated with the Churchill diversion, and the resultant larger water volume and changed exposure due to changes in the freeze-up and break-up dates.

The formation of ice on water bodies influenced by a hydroelectric power plant can have a significant influence on the operation of the plant, ranging from blocked trash racks to severe reductions in operating head due to increased tailwater levels downstream, and reduced forebay levels upstream. However, while such effects of the ice regime on hydroelectric plant operation can represent an annual loss of literally millions of dollars in revenue at a single plant, the concern in this presentation is rather with the effects of the hydroelectric development and operation on the ice regime, and the influence of these effects on the activities and lifestyles of nearby communities.

4.2 POTENTIAL INFLUENCE OF HYDROELECTRIC DEVELOPMENT ON THE ICE REGIME OF INLAND WATERS

4.2.1 Downstream

4.2.1.1 Freeze-up

Increased discharge during freeze-up due to hydroelectric plant operations can have a significant influence on the lodgement locations and timing that allow freeze-up to begin on a river. It will also influence the nature of the initial pack that forms, making a thick rough pack more the norm than before regulation. The increased discharge and the thicker, rougher pack result in increased water levels at freeze-up. If there are significant fluctuations in the flow while the pack is developing, the pack will be more prone to collapse repeatedly and so form an even thicker pack and higher water levels than would form in the presence of a steady discharge. This is particularly so if the pack is progressing in temperatures low enough to produce enough ice to allow the pack to advance rapidly, but not low enough to cause sufficient freezing of the pack to resist the added load that would result from an increased discharge. An example of this is provided by the Peace River development. The rapid increase in discharge downstream, shown in Figure 54, as the plant took on an unexpected load caused the developing freeze-up pack to collapse over some 155 km and consolidate into a pack only 60 km long (18).

The increased water temperatures leaving the reservoir will delay progression of the freeze-up pack, this effect becoming more important as the dam is approached. For example, as illustrated in Figure 17, the temperature of water leaving the dams on the Peace River in the winter is usually well above 0°C. As a result the ice front does not advance much closer than about 100 km to the dam. The presence of a dam also cuts off ice that would otherwise move into the downstream reach during freeze-up. This further delays advance of the freeze-up pack.

4.2.1.2 Winter

The major influence of hydroelectric plant operation on the ice cover in winter is the fluctuating water levels. If severe enough these will contribute to the formation of slush ice on the rivers and lakes downstream, particularly along the shorefast ice, as shown in Figure 56. For example,

Figure 56. Overflow along shore ice following an increase in water levels.

during the first years of operation, flow variations through the Jenpeg reservoir, made in an attempt to form a competent ice cover on the fast flowing water upstream, caused considerable problems with the ice cover on Cross Lake downstream. Slush formation along the shore is especially likely to happen if the lake levels increase over freeze-up, a common situation downstream of hydroelectric plants.

If, on a river, fluctuations are large and sudden enough, they can cause premature break-up of the ice cover at any time in the winter. However it seems these fluctuations do have to be severe to cause break-up. For example, field trials have shown that the mid-winter ice cover on the Madawaska River in Ontario downstream of the Stewartville plant remained intact under an increase in water level of as much as 2 m (8).

For river reaches similar to that of the Nelson and Churchill Rivers, which have various combinations of river and lake, the response of the water body to higher winter discharges is a delicate function of the throughflow of the river and the nature of the control at the 'lake' outlet. If the control normally froze over in winter prior to development but, due to the higher and warmer discharges of the water in winters afterwards, it remained open, the water level in the lake could be reduced despite the higher discharge. On the other hand, if the outlet remained frozen for the higher discharge, the lake level would increase.

4.2.1.3 Break-up

The effect of the hydroelectric plant on the river can be beneficial at break-up. The discharge variations from the plant may be mild compared to the rapid increase in discharge normally caused by rapid snowmelt in the catchment upstream. This steadier discharge may result in a quiet thermal break-up whereas previously there would have been a dynamic break-up with the concomitant risk of ice jams and flooding. However, to ensure this, care must be taken with releases as break-up nears to avoid triggering a premature break-up and ice jams. On the other hand, the Peace-Athabasca Delta example discussed earlier provides at least one example where an 'improved' break-up can be detrimental.

A problem can arise at break-up if there is a series of dams along the stream that can spill ice. Under large spring discharges flooding along the stream will likely occur. The extent of this flooding is obviously sensitive to the operation of the dams, particularly the control imposed on the ice run as the ice is passed from dam to dam. Major examples of this problem were provided by the ice problems on the Ohio River in the U.S. in 1978 and the St. John River in New Brunswick in 1987.

Depending on the influence of the development on the freeze-up progression, the river may also become ice-free earlier.

At an estuary the higher winter discharges following hydroelectric development can result in a larger fresh water plume off the estuary and thereby a larger extent of fresh water ice, both due to the larger plume, on which ice forms earlier than on the sea water offshore, and to the likely greater quantity of slush and ice moving into the estuary from upstream. On the contrary, reduced winter discharges would result in less ice forming in and off the estuary.

4.2.2 Upstream

4.2.2.1 Freeze-up

After its construction, a dam will obviously define the 'lodgement' point of freeze-up in that reach of the river. The surface of the pool will likely freeze-over earlier than the river did previously and therefore the progression of freeze-up upstream will be advanced. Hence, while freeze-up will be delayed downstream of a hydroelectric plant, it will usually be advanced for some distance upstream. However, unlike the effect downstream, this upstream influence will be limited to the backwater curve and a little beyond.

For steep reaches in more temperate regions, the presence of the dam may mean that an ice cover will form where none did previously. In other circumstances the smooth ice cover that forms on the pool may be in strong contrast to the thick rough pack that previously formed on the river.

The formation of the freeze-up pack on the already unnaturally high water levels of the backwater upstream of the reservoir will increase these water levels further and may cause flooding. In an alluvial stream the headwater of a reservoir is also the site of sediment deposition and delta formation. This deposition can change the character of the stream along the backwater and, with it, the ice regime. This also applies to any tributary entering the reservoir.

4.2.2.2 Winter

If there are frequent and substantial fluctuations of the pool level as the load on the power plant varies, overflow and cracks can be expected to develop along the edges of the pool and, as winter progresses, for a thick ice foot to develop. Because of the continually changing water level, at any given time the ice near the banks is unlikely to be level and may contain large cracks as shown in Figure 57.

While the average pool level of a run-of-the-river plant remains more or less the same through the winter, that of a storage reservoir will slowly fall. If this fall is substantial it can result in the shores of the lake that are free of trees, or that have been clearcut prior to impoundment, being 'draped' with an ice sheet. An example of such draping is shown in Figure 10, although, in this case the fall in water level was on a tributary of a larger river and was natural.

If the pool area was not clearcut prior to filling, the ice cover can be attached to trees. Then as the reservoir level falls the ice will be held up by its adherance to the trunks, and a very irregular ice cover will result. In places the ice cover may be left propped above the water where it will remain thin and a trap for travellers on the ice. On the other hand, the

Figure 57. Thick ice and cracks developed on the margins of the pool behind a small hydroelectric plant on the Bow River in Alberta.

restraint imposed by trees on the ice cover will also prevent the ice cover following an increase in reservoir level. The ice amongst such stands of trees is then more prone to develop overflow and slush.

Although the water level in a large reservoir is less sensitive to short-term variations in power plant operation, what effects there are are transmitted over a much larger area. As some of these effects can then be well removed from the dam site, their existence can be unexpected. An important example of such hidden effects are the currents set up by reservoir level fluctuations discussed in Section 2.4.3.

4.2.2.3 Break-up

A major influence of the dam on the ice regime upstream is likely to occur at break-up. As the surge of an ice run on the river or a tributary enters the backwater from the reservoir, the waterway area increases and flow velocities decrease. This reduces the impetus of the surge and will cause it to stall, forming an ice jam. This, in combination with high spring discharges, can be the cause of extensive flooding upstream of a reservoir. The events over the last few decades on the St. John River in New Brunswick seem to attest to this. The ice cover on the reservoir will also likely remain longer than the ice cover on the river previously.

5. SOCIAL AND ENVIRONMENTAL SIGNIFICANCE OF CHANGES TO THE ICE REGIME

5.1 PRELIMINARY CONSIDERATIONS

Except possibly for an increased incidence of flooding, the significance of changes to the ice regime increases as the location moves north and the people of the region depend more and more on the natural environment for sustenance. They are then more vulnerable to changes in this environment, **particularly changes that do not follow a natural or consistent rhythm.**

The most extensive industry in the Canadian north is that of harvesting the provisions of the natural world. This is the northern equivalent of the agriculture and ranching that are the mainstay of more southern areas. Through necessity it is a low density occupation, but it is the only one that can reasonably be expected to provide sustainable support for the many and widely scattered northern communities for the foreseeable future.

The low population provides a false impression of its significance and it is important to put this into some perspective. For example, Yellowknife, with its low population, is unlikely to be less important to the Northwest Territories than Toronto, with its vastly larger population, is to Ontario. And in turn, Toronto is no less significant in Canada because of its small population relative to New York, London or Tokyo. It seems it is the relative size of the community that is the best measure of its significance in a region, not its absolute size. From this perspective the significance of disrupting a northern community becomes much more apparent.

In a similar, but perhaps less justifiable way, the same applies to people. The loss of life in an unusual circumstance, such as a plane crash, has a much larger perceived significance than the loss of life in a more familiar situation such as a highway accident. From this point of view, the drowning of a person from a small community by breaking through the ice can represent more than the equivalent, at least in local and political perception, of the regular carnage on the roads and highways of larger communities in the south.

A similar logic also applies to the means of transport in these small communities. In an area devoid of roads, and likely to remain so for a long time, ice covers on lakes and rivers provide natural highways in winter. The disruption of one of these iceways by a change in the ice regime is not dissimilar, in relative significance, to the disruption of a major throughway in a city. Indeed it can be worse - it can be fatal.

5.2 TRANSPORT

In northern areas the inland waterways still play a crucial role in transport and communication. They serve as both roads and airfields. The major use of the ice covers on these waterways is for transport, whether it is for access to trap lines, hunting areas, fishing areas, travel to a local community, communication between communities, or for travel to other regions, to obtain supplies and access to services, such as health and education, not available in the local area. Indeed the availability of this natural road in many cases is a deciding factor in the location of the community. Modification of the ice regime can therefore have serious consequences for a northern community, particularly if it is unexpected.

The primary hazards for transport on an ice cover are thin ice, particularly if camouflaged under an innocuous snow cover, and overflow or slush. Both are a significant threat to life. The former causes breakthroughs, with the associated risk of either drowning or being left isolated in a remote area in freezing temperatures. The latter, slush, seriously impedes the movement of snowmobiles and significantly increases the wear and tear on the machines. More importantly, though, the slush can so increase resistance that the machine will stall and stop, again leaving the operator alone and without transport. The following quote illustrates the problem (19): "On the way to the net we encountered slush twice. Both areas were difficult to travel through...It was in the large patch which we got stuck. There was 6-9 inches of slush overlain by 6-10 inches of snow. We had to disconnect the sled and pull the skidoo out. The sled had to be pried loose with pole branches...It was more difficult to proceed through the slush on the trip back. To turn the machine around after we got to the net, we had to pick the skidoo up and reverse its direction. It would have been impossible to leave the trail". The formation of slush and its influence on accessibility is a common cause for the abandonment of fishing nets.

The creation of open water on a river downstream of a dam, and the delay in freeze-up over a longer reach downstream, is an obvious disruption to the use of the ice cover for transport, especially for a major river around which access can be very difficult. Even where an ice cover does develop, the changed flow regime can change the nature of the ice cover, often from smooth to a far more rough and difficult to travel nature.

Travel on iceways is a risky undertaking at the best of times, and safe travel requires experience developed with the waterway and its ice cover over many years as it goes through its natural cycle. What to the communities are largely unknown and unpredictable man-made fluctuations in the flow regime after hydroelectric development, and the largely unpredictable response of the ice cover to these fluctuations, can render the ice far less reliable. Even if adjustment to the changes can be achieved after years of trial and error, unusual fluctuations in the flow, with concomitant changes in the local ice cover, can be triggered by unexpected developments in the operation of the power plant to meet the varying demands of the power grid.

Even where the ice cover is competent, the combination of the shore attachment of the ice cover and the fluctuations in discharge characteristic of the flow regime below a hydroelectric dam, can lead to increased overflow and slush formation, with the associated risk to winter travel on the ice. The characteristic increase in water levels over freeze-up of a lake or river downstream of a hydroelectric plant is especially prone to develop overflow and slush.

Upstream of the dam the ice cover becomes much more extensive and apparently more amenable to travel. However a problem arises at the shore. As is the case downstream of the dam, the fluctuating levels in the reservoir can result in a much more widespread generation of slush than would occur under natural conditions. This is likely particularly so amongst trees that line a shoreline not cleared prior to impoundment.

If the dam influences an already existing lake, a common circumstance in the Shield country of northern Canada, other changes to the ice regime can take place. As described earlier, the configurations of the shorelines of such lakes are not as uniform as that of reservoirs formed in the more regular valleys of alluvial streams in the south. Rather they are characterized by a multitude of bays and inlets of various sizes, with frequent narrowing of the lake at and below the surface by bedrock outcrops. Water level fluctuations in such circumstances generate currents under the ice as water passes from one section of the waterbody to another, currents that, together with the warm water characteristic of a lake, can cause thin ice. This variation in the current and temperature regime of the lake is difficult to forecast in even the reasonably steady circumstances of the natural regime, and a knowledge of marginal ice areas must usually be determined by experience. Under the irregular operating regime of a hydroelectric plant the situation is very much less well-defined and thereby of greater risk.

Hence there can be many surprises for the over-ice traveller in hydroelectric country. This is particularly so for developments on the Shield where what appears to be a lake far from any unnatural disturbance may in fact be a reservoir in disguise and subject to irregular water level fluctuations throughout the winter.

While the iceways are used for local transport in winter, the waterways are used in summer. A change in the ice regime can mean a change in the timing of the use of these two means of transport. But while movement by water is limited to the waterways, this is not the case with over-ice travel. Hence a change in the timing of the availability of the iceway can mean a major inconvenience in access to trap lines and fishing areas, and to communication with the rest of the country. This is particularly so because the major trapping activity corresponds with freeze-up and break-up, the two aspects of the ice regime subject to most change by development.

Ice bridges over ice influenced by water level fluctuations associated with hydroelectric plant operation are also exposed to sudden change, particularly near the shoreline. The cracks that form here following a water level change can be a threat to traffic. The availability of these crossings may also be changed markedly by a change in ice regime.

5.3 FLOODING

With the increased discharges downstream that usually accompany hydroelectric development, there is an increased risk of fall flooding. To avoid this, operation of the plant is often restricted while the freeze-up pack is building through a sensitive area. The management of this requires continual monitoring of the ice cover, and imposition of the restraints on plant operation can represent a significant financial loss to the utility. For example, it is estimated that such restrictions on the operation of the relatively small Big Horn plant on the North Saskatchewan River costs about $40,000 each day while waiting for the freeze-up pack to move through a critical 90 km reach of the river(8). As this reach is near the upper limit of the pack, this process can be repeated through the winter as the head of the pack retreats and advances in response to changes in the weather. On the Bow River a significant part of the justification for construction of the Bearspaw Dam just upstream of Calgary was to reduce freeze-up flooding in that city due to the operation of other plants further upstream (8).

A river diversion will result in higher discharges in the receiving channel and changes to the ice regime that may cause flooding. The Burntwood River diversion of the Churchill-Nelson scheme, in which the freeze-up discharge in the Burntwood River was increased tremendously, and its influence on water levels at the City of Thompson, provides an extreme example of this. Special control works have been installed at Manasan Falls to try to limit this impact and thereby relax some of the ice-related restraints on the diversion in winter (8).

Discharges from hydroelectric plants have also to be controlled in winter, and particularly during break-up, so that they do not cause a premature break-up of the ice cover and the related risk of ice jam formation. Generally, this steadier discharge at break-up results in a milder event, and can change what is usually a dynamic ice run into a thermal break-up. This is what has happened on the Peace River at the Town of Peace River. However, the change in break-up timing, and the changed discharge in the mainstream at break-up, can have detrimental effects as well. For example, an ice run on a tributary may be more likely to stall at or near the mouth than before and can thereby change the location of ice jam formation and flooding.

As illustrated by the situation on the St. John River in New Brunswick, a dam downstream of a community can cause a significant increase in flood risk. The ice run at break-up will often stall in the headwaters of the reservoir and, in concert with the backwater from the dam and a high spring discharge, cause flooding.

A similar situation exists at freeze-up. Because of the restraint offered by the ice sheet that forms early on the reservoir, the freeze-up front will begin to progress upstream earlier, when discharges are higher. This, together with the raised water levels in the backwater, and possibly sediment deposits and changes to the channel characteristics that follow this, can result in flooding that did not take place previously.

5.4 REDUCED MINIMUM FLOWS

Minimum flows in a river are required to maintain the aquatic environment and, in some locations, to provide sufficient water for water intakes or sufficent dilution of pollutants added to the river. While the average minimum flow in a river is usually increased downstream of a hydroelectric plant, there are times when this may not be true. As discussed earlier, the advance of the freeze-up front entails an increase in channel storage and thereby a reduction in flow moving downstream. For the North Saskatchewan River upstream of Edmonton it is estimated this reduction can be as high as 75% of the flow released from the Big Horn Dam if very low temperatures cause freeze-up to occur rapidly (8).

Diversion of flow from a channel obviously results in a reduction in winter discharge downstream of the diversion. This will change the ice regime, with earlier freeze-up and break-up likely. In the case of a significant diversion, as from the Churchill River, the reduction in discharge and water levels can be very detrimental. Imposed on this is the reduction in discharge that must be expected due to channel and lake storage that must be filled as freeze-up progresses or as the controls on lakes vary through the winter. The need to release sufficient flow to overcome these problems can again impose expensive constraints on the operation of the diversion. For example, the releases from Southern Indian Lake currently judged necessary to prevent the water intake at Churchill freezing up, or being engulfed by salinity intrusion from the estuary, is estimated to cost some $1,000,000 per year (8).

5.5 WILDLIFE

There is little doubt that the major documented impact of ice regime modification is on the harvesting of the wildlife resource, as discussed earlier. However, there are also direct influences on the resource itself. Strangely, though, as for winter aquatic ecology in general, the effects of changes in ice regime on wildlife are largely undocumented and can only be inferred. A few examples are described below.

5.5.1 Fish

The formation of the ice cover in the fall seals the water body. The storage of heat and the essential dissolved oxygen that exists then must last the under-ice organisms until the spring turnover rejuvenates the lake. It can be a long winter under the ice. As recently as the winter of 88-89, the commercial fishery on Utikuma Lake was lost as a result of winter kill in this and many other lakes in northern Alberta, due to reduced dissolved oxygen contents in the lakes near the end of winter.

Fish behaviour is apparently closely linked to water temperature which, in particular, seems to have a major influence on their migration and spawning behaviour, and on their survivability in the egg and juvenile stages. The species most sensitive to changes in thermal regime are fall spawners such as whitefish and lake trout. For example, incubation of whitefish eggs is optimum for water temperatures between about 0.5 and 1°C, with significantly higher mortality rates for temperatures as low as even 4°C (29). In lakes such optimum temperatures usually only occur within reasonably close proximity to an ice cover. An increase in winter water levels, and thereby ice level, means that these optimum temperatures will be associated with newly flooded foreshores, usually a less than desirable substrate for this fish species. This situation will be exacerbated if the water levels increase over the winter. Then eggs laid in the fall in water of suitable temperature are gradually immersed in warmer water as the water level rises. On the other hand, a reduction in water levels over the winter can expose the eggs to temperatures near zero and even result in their being engulfed by the frost front if the water becomes shallow enough to freeze to the bed.

In shallow lakes, a reduction in water level, and thereby volume, can result in a severe deterioration in water quality as a result of the increased concentration of salts in the remaining water as they are rejected during ice formation, and a reduced dissolved oxygen supply for the winter.

Lower water levels will advance freeze-up and likely delay breakup. This will prolong winter underwater, making winter kill more likely. A delay in breakup can also influence spring spawners such as pike and walleye, whose spawning activity is triggered by temperature. In the already short summer, a delay of even a week or so in the onset of the triggering temperature, and thereby in the lifecycle of these fish, will likely have a significant influence.

As discussed earlier, the reach of a river downstream of a hydroelectric plant in winter is characterized by relatively warm open water for many kilometres downstream, increased waterway area, a delayed freeze-up and, if changed at all, an advanced break-up. In as much as all these effects delay the onset of the underwater winter, and shorten it, the effects are likely positive. For example, it is known that otter and mink favour areas in a river or lake kept open under natural conditions by rapids or currents. This suggests that such open water areas are indeed oases in the winter landscape for aquatic and semi-aquatic life.

However, there can be detrimental effects of these conditions. Open water means that frazil will continue to be generated throughout the winter. While in suspension these particles constitute a threat to fish in that high enough concentrations can block the gills. The formation of anchor ice and deposition of slush under the ice can also reduce the available waterway for overwintering fish. This is of most concern in small streams. The deposits of anchor ice and slush can also cut the flow of water to eggs laid in gravel by fall spawning species.

On the Susitna River in Alaska a major concern was the flooding, due to the higher discharges at freeze-up, of sloughs and other off channel pools used as spawning areas. This would cause a sudden influx of much colder water into these pools, with a possible increase in mortality of the incubating fish eggs.

In the bedrock-controlled rivers of Shield country, the increase in water level associated with the higher winter discharges will result in increases in water level in the various quiet waters, the impact of which will be much like that on lakes or reservoirs, except that the downstream water bodies will typically be smaller and therefore more sensitive to fluctuations in the discharge released from the plant.

In a river downstream of a significant flow diversion the situation is quite the reverse. Typically freeze-up is advanced, break-up delayed, and the waterway area reduced. As described earlier, during freeze-up the discharge downstream is typically even less than that released from an upstream control structure due to the abstraction from the flow to fill channel storage. In bedrock-controlled streams this discharge reduction can be unusually large. These features generate a long hard winter for overwintering fish. The lower water level in the mainstream also means that water levels in all connected bodies of water, such as tributaries and lakes, are also low.

5.5.2 Animals

The threat to semi-aquatic animals such as muskrat and beaver is more from fluctuating water levels than ice. Increases in water levels over the winter, a characteristic of lakes downstream of hydroelectric plants, can result in the flooding out of beaver and muskrat houses. On the other hand, the reduction in water levels upstream can result in houses built in the fall being frozen out. Some of these fluctuations can be caused indirectly by ice through the operation of the hydroelectric plant to overcome problems with ice formation near the plant. For example, the initial plan for operation of the Jenpeg plant on the Nelson River was to cut back the discharge in the fall to allow an ice cover to form, and then to subsequently increase the discharge. This procedure was eventually abandoned because of the influence on the water levels of Cross Lake downstream and thereby on the semi-aquatic animals, as well as on the safety of the ice cover for travel.

Beavers and muskrat installed along the backwaters of a river or along tributaries are likely to also be victims of high and variable winter water levels downstream of a power plant, and of the lower water levels downstream of a diversion. A prime example of the impact of low water levels is provided by the Peace-Athabasca delta in northern Alberta described earlier. The lower water levels in the Peace River for the few years while the enormous Williston Reservoir was being filled resulted in the lowering of the water levels of Lake Athabasca and the delta. This ruined so much muskrat habitat that the catch fell from 38,000 to 2,000 pelts over 4 years (25).

There is a possibility that the long reaches of open water typically found downstream of a hydroelectric plant can disrupt migration paths and even the traditional winter territories of moose and other ungulates. For long or large reservoirs, this can also occur upstream, especially during freeze-up and break-up.

5.6 COMMUNITY ACTIVITIES

The effects of changes in the ice regime on activities required to harvest natural resources in the north have been emphasized in the above discussion, and there is little doubt that these are the major general effects of the changed ice regime for communities in this region. However there are other direct effects on the communities.

One is that of high ice levels on the many docks which are a characteristic of communities that depend so heavily on waterways for their existence. On waterbodies such as Split Lake on the Nelson River, that are downstream of hydroelectric plants, the higher ice levels that exist in winter will encompass the docks that have been built on the basis of the lower natural water levels with the result that, during spring break-up on the lake, the docks can be damaged or taken out by the ice, either directly or by the impact of floes driven by the wind over the still-high water. Even though they may not be destroyed, docks built close enough to the summer waterline to have reasonable utility can experience more frequent damage because, although the range of water level fluctuations may not exceed the natural range of the lake, the travel over the full range will likely be more frequent under regulated conditions.

With substantial increases in water levels there may also be a threat to houses and other structures built close to the water from the pile-up of wind-driven floes on shore, either at freeze-up or break-up.

The higher ice will also begin to scour the new shoreline and possibly remove shoreline vegetation. The significance to local residents of such apparently harmless events is revealed by the following quote from a letter written by the Split Lake Indian Band: "Before the project, willows on the shore provided safe docking for canvas canoes. Now, since the willows have been torn out by winter ice canvas canoes cannot be used..".

In contrast, lower lake levels at the end of winter that are characteristic upstream of hydroelectic plants will result in a shoreline draped in thick ice and, if fluctuations in lake level have been substantial, there will likely also be a quite pronounced ice foot along the shore. The result of this is that the open water that forms in spring around the edge of the ice cover near the waterline will now occur well out on the ice cover, making access to this early open water for travel around the lake more difficult.

Another effect, noted for example by the community of Southern Indian Lake (16), can be the creation of weak ice on the portion of a lake or river that separates two sections of a community. This can make communication within the community in winter difficult if not dangerous.

Anyone who has been associated with Local Government in any part of the country is well aware of the significance to individuals of effects like those described above which, while they may seem relatively minor when viewed from the perspective of a distant office, can be a strong source of irritation for local residents.

6. CONCLUSIONS

Inland waters play a vital role in the life of the many small communities that dot Canada's north and which, in many locations, represent the only habitation and industry in the region. These inland waters can undergo profound changes when influenced by hydroelectic development.

Perhaps the most significant feature of this change is that a reasonably consistent and predictable natural cycle is replaced by an unnatural one. This is particularly so in winter. Ice formation in fall and its demise in spring is one of the cycles of nature to which life in and near these waters has been adapted over the millenia. This time of quiet and little change for inland waters in the north country becomes, under hydroelectric development, a time of peak, and sometimes quite erratic, activity as the hydroelectric plants respond to the tremendous and varied demands placed on them by an electrical power grid that covers much of the nation.

This can have a significant, and sometimes even life threatening, influence on the iceways that play such a vital role in the life of northern communities. Recalibration of the empirical understanding of the ice behaviour that is essential to safe utilization of the iceways by residents, and of its influence on the natural environment on which they depend, can take many years. Even then it is subject to sudden and generally unannounced interruptions as the operation of the plants is changed to respond to emergencies that can develop in the electrical power grid.

It is therefore important that residents of these communities be aware of the possible changes that can take place, and of the nature of hydroelectric operations and the demands placed on these developments once they come into service, both so that the residents can ensure their interests are considered in the planning and operation of the project, and to assist them in the necessary adaptation if the project goes ahead and the then inevitable changes take place.

To help provide background for the necessary discussions and negotiations associated with this planning and adjustment, the various aspects of the natural ice regime, and the possible effects of hydroelectric development on this regime, have been briefly reviewed in the above presentation. The emphasis has been placed on changes that will likely be of most significance to the northern communities in the bedrock-controlled country of the western Canadian Shield. To put the significance of these changes into some context, an effort has also been made to indicate the cost incurred by the public if these large hydroelectric developments are restricted in their operation. Once they are commissioned there is enormous economic pressure on the responsible utility to keep their operation near optimum, and to manage the flow and ice regime to this end, a pressure that increases as time goes by. This is usually in strong contrast to the pressure to reduce the environmental impact of the operation, a pressure that tends to decrease with time.

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8. GLOSSARY

Alluvial channel: In the sense used herein, a river or stream eroded into reasonably erodible material.

Anchor ice: An accumulation of frazil particles attached to the bed of a stream. Anchor ice is not found on sand bed streams because of the inability of the bed material to resist the buoyancy of such a deposit.

Aufeis: Ice formed on ice by the freezing of overflow. It is often coloured by chemicals from the groundwater that is usually the source of winter flow.

Backwater: The increase in water level upstream of an obstruction for subcritical flow.

Bathymetry: The distribution of depth in a lake.

Bedrock-controlled channel: A river or stream running over largely inerodible rock country. Such streams are characterized by sequences of lakes, pools and rapids, with infrequent alluvial reaches.

Black ice: See columnar ice.

Border ice: Shorefast ice that forms and grows in the quiet flow near the stream banks and around islands and bars during freeze-up.

Canadian Shield: The wide area of Precambrian rock extending west from the Labrador coast to the Mackenzie basin, and north from the Great Lakes to Hudson Bay and the Arctic.

Candling: Melt at grain boundaries in columnar ice due to absorbed solar radiation. The melt eventually separates the columnar grains which then look like candles. The decay of columnar ice is known as candling.

Channel storage: The volume that must be filled in a channel to generate an increase in water level. In an alluvial channel it will include the water required to raise the water table in the banks.

Clear ice: See columnar ice.

Coffer dam: A temporary embankment constructed around a construction site in a river or lake to allow dewatering of the site.

Columnar ice: Translucent ice formed by freezing water. It has a relatively course columnar crystal structure.

Creep: The characteristic behaviour of ice whereby it will continue to deform with time under the action of a constant load.

Discharge: Volume of flow per unit time. In the SI measurement system it is given as cubic metres per second.

Draft: Distance from water level (e.g. in a hole drilled in the ice cover) to the bottom of the ice sheet or pack.

Dry Crack: A crack that only partially penetrates the ice cover.

Equilibrium section of an ice jam: A section with uniform thickness and waterway that develops in a long ice jam in a more-or-less uniform channel.

Fetch: Unobstructed length of water, in the along-wind direction, exposed to the wind.

Floe: An ice sheet of limited extent.

Forebay: The section of a reservoir or channel immediately upstream of a hydroelectric plant.

Frazil: Small thin discs of ice, typically about 1 mm in diameter.

Frozen frazil slush: Ice formed by the freezing of slush accumulations under water. Like snow ice it is fine grained but more translucent due to the smaller quantity of air inclusions. There are typically sediment inclusions.

Fully-developed ice jam: An ice jam long enough to have developed an equilibrium section.

Hanging dam: A local and often very large accumulation formed by deposition, in a low velocity location under an existing ice cover, of slush and ice fragments entrained by high velocities upstream.

Head: As in 'head across power plant'. To a first approximation, the difference in water level across an object.

Head of an ice jam: The upstream end.

Hydraulic jump: A sudden increase in water level in the downstream direction as the flow converts from supercritical to subcritical flow. It has the nature of a stalled surge.

Ice dam: A local accumulation of anchor ice projecting through the water surface and backing up the flow.

Ice jam: A forced, stationary accumulation of fragmented ice and slush.

Ice pans, or pancake ice: Rounded pans of ice formed by the congealing of frazil slush at the surface after exposure to the cold air. The pans are characterized by a thickening crust of solid ice with an underhang of slush.

Ice pile-up or ride-up: Piles of fragmented ice generated by the collision of moving ice floes with each other or with the shore.

Isothermal: All parts of an object have the same temperature.

Keel of a pressure ridge: The portion below the water line.

Latent heat: Heat energy released or absorbed by a material to allow it to change phase, such as from ice to water (absorbs latent heat) or water to ice (releases latent heat).

Lodgement: The bridging of pan and slush ice between the edges of shorefast ice to begin development of the freeze-up pack.

Moving load: A load moving over the ice with sufficient speed that the inertia of the ice sheet and the water under it have a significant influence on the deflection of the ice cover. This speed depends on the water depth and ice cover thickness but is typically more than 10 km/h.

Non-uniform flow: Flow that changes significantly in waterway geometry or velocity over the reach of interest.

Overflow: Water that moves through cracks out over the ice cover. Other sources of overflow are tributary streams, groundwater discharge from the banks and municipal sewer outfalls.

Penstock: The conduit that delivers flow from the forebay to the turbine. In many hydroelectric installations it is specially reinforced to avoid failure due to the large pressures generated when the turbine operation is adjusted as the power demand varies.

Polynya: An area of open water in an otherwise continuous ice sheet.

Pressure ridge: A raised section of buckled or fragmented ice caused by failure of an ice sheet in compression due to thermal expansion or collision between floes.

Reach: A portion of a river or stream.

Runner: The rotating part on which the blades of a turbine are mounted.

Sail of a pressure ridge: The portion above the water line.

Scroll casing: The snail-shell-like conduit that delivers and distributes flow to the wicket gates of a hydroelectric plant.

Shear lines: Linear features developed along each side of an ice pack when it fails in compression across the channel and in shear along the banks.

Shell ice: Thin ice formed by the water dropping away from under an ice sheet that is otherwise supported by the shore, banks, rocks, trees, etc.

Shorefast ice: An ice sheet that is attached to the shore.

Shoving: Failure in compression of a floating ice pack.

Slush: Unfrozen saturated snow.

Slush ice: Loose accumulations of frazil particles, either on the surface of the water or under an ice cover.

Snow ice: Ice formed by the freezing of saturated snow. It has a fine grained structure and a white appearance due to air inclusions.

Steady flow: Flow that does not change substantially over the duration of the event of interest.

Subcritical flow: Flow in which the water velocity is less than that of a small wave on the surface of the flow.

Supercritical flow: Flow in which the water velocity is higher than that of a small surface wave on the flow.

Surge: A reasonably sharp-fronted wave moving down a channel. Its passage will cause a rapid increase in water level and increase in flow velocity.

Tailrace: The channel immediately downstream of a hydroelectric plant.

Thermocline: Region of rapid change in temperature in a lake.

Toe of an ice jam: The downstream end.

Turbine: The 'windmill' portion of a hydroelectric plant that is turned by the water flowing past it, and which in turn rotates the generator.

Uniform flow: Flow that does not change substantially in waterway geometry or velocity over the reach of interest.

Unsteady flow: Flow that changes significantly with time.

Velocity: Speed in a particular direction.

Wet crack: A crack that penetrates the ice cover to the extent that water can move into the crack from below.

White ice: See snow ice.

Wicket gates: Moveable gates that can be adjusted to maintain the optimum angle of attack of the water flow onto the blades of the runner, and to control the discharge through the turbine.