

RIVER-ICE ECOLOGY

T.D. Prowse





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RIVER-ICE ECOLOGY

Terry D. Prowse

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National Water Research Institute
Environment Canada
11 Innovation Blvd.
Saskatoon, SK, CANADA
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ABSTRACT

River ice is an integral and important component of the flow regime in cold-regions environments. From a general physical perspective, it is known to produce many hydrologic extremes, such as low-flows and floods, that far exceed those possible under open-water conditions. It can also significantly modify a number of other physical and chemical processes that have important biological implications, such as the erosion and deposition of sediment or the production and transport of oxygen. More generally, it also determines the nature, quality and abundance of various in-stream, deltaic and riparian habitats. This monograph reviews our current state of knowledge about the ecology of river ice, identifies major research gaps, and proposes the incorporation of river-ice processes into some basic theories of river ecology.

RÉSUMÉ

La glace de rivière est une partie intégrante et importante du régime d'écoulement dans les régions froides. Sur le plan physique général, elle engendre de nombreux extrêmes hydrologiques, comme les débits d'étiage et les crues, qui sont nettement plus marqués que ceux enregistrés en eau libre. Elle peut aussi modifier considérablement d'autres processus physiques et chimiques qui ont des répercussions biologiques majeures, comme l'érosion et la sédimentation ou la production et le transport d'oxygène. De façon plus générale, elle détermine également la nature, la qualité et l'abondance des habitats fluviaux, deltaïques et riverains. La présente monographie revoit l'état des connaissances sur l'écologie de la glace de rivière, cerne les principales lacunes en matière de recherche et propose l'incorporation des processus associés aux glaces dans certaines théories de base sur l'écologie fluviale.

ACKNOWLEDGEMENTS

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The author would also like to thank the efforts of M. Hey, H. Popoff and P. Trischuk for their relentless pursuit of the numerous elusive documents that contribute to the voluminous bibliography that accompanies this review. Thanks are also owed those who have permitted the inclusion of their unique photographs. Much credit is due to P. Gregory and S. Gardner whose graphic skills greatly enhanced the value of my original crude illustrations.

The author would also like to express his appreciation to the various reviewers of this monograph, or its relevant sub-sections, including: J. Culp, R. Cunjak, A. Pietroniro, G. Power, L. Watson, and F. Wrona. Their comments have resulted in distinct improvements to this review and ensured that my synthesis of the multiple scientific fields of river ice was accurate.

FOREWORD

Seven years ago, Dr. T.D. Prowse and N.C. Gridley co-edited the *Environmental Aspects of River Ice*. At that time, this volume was the authoritative summary of the state-of-science knowledge on the physical, chemical and biological aspects of river-ice hydrology and ecology.

Since the publication of that monograph, economic development pressures have increased in northern rivers, as has our need to evaluate more fully the importance of associated anthropogenic impacts. For instance, recent research on the fate, distribution and effects of contaminants on aquatic biota, flow regulation and climate change impacts has underlined the importance of river ice processes. Moreover, there is increasing pressure to understand how multiple environmental stressors are affecting northern rivers from a cumulative impacts perspective. Such an assessment in these riverine ecosystems requires a thorough knowledge of river ice processes.

This review paper serves a valuable role in further advancing our knowledge of river ice hydrology and its interactions with riverine ecological processes. In addition, it directly supports the scientific needs of the Water Resources Division of the Department of Indian Affairs and Northern Development with respect to decision making on water resource management.

The work also further advances northern hydrology, thereby supporting the scientific priorities and agendas of international scientific societies such as the International Association for Hydraulic Research (IAHR), Committee on Ice Engineering and Research.

Finally, with the renewed interest in water diversion and export, this paper will help identify crucial aspects of cold regions river hydrology and ecology that should be considered in the development of future policies and R&D activities.

Frederick J. Wrona, Director

*Aquatic Ecosystem Impacts Research Branch
National Water Research Institute, and;
National Hydrology Research Centre
Saskatoon, SK, Canada*

AVANT-PROPOS

Il y a sept ans, les Drs T.D. Prowse et N.C. Gridley collaboraient à la rédaction d'un ouvrage intitulé *Environmental Aspects of River Ice*, alors considéré comme un écrit faisant autorité pour ce qui est des connaissances scientifiques se rapportant aux aspects physiques, chimiques et biologiques de l'hydrologie et de l'écologie des glaces fluviales.

Depuis la publication de la monographie, les pressions relatives au développement économique des rivières du nord se sont accrues, tout comme notre besoin d'évaluer plus en profondeur l'importance des incidences anthropiques connexes. Par exemple, les travaux de recherche récents sur le sort des contaminants, leur distribution et leurs effets sur la biote aquatique soulignent l'importance des processus des glaces fluviales. En outre, on tente de plus en plus de déterminer de quelle manière les agents d'agression environnementaux multiples affectent les rivières du nord sur le plan des incidences cumulatives. Une telle évaluation de ces écosystèmes riverains nécessite une connaissance approfondie des processus des glaces fluviales.

L'article de synthèse joue un rôle non négligeable dans le perfectionnement de nos connaissances de l'hydrologie des glaces fluviales et de ses interactions avec les processus écologiques riverains. En outre, il vient appuyer directement les besoins scientifiques de la Division des ressources hydrauliques du ministère des Affaires indiennes et du Nord canadien pour ce qui est de la prise de décisions concernant la gestion des ressources hydrauliques.

L'ouvrage nous permet de mieux comprendre l'hydrologie du Nord, appuyant ainsi les priorités scientifiques et les échéanciers de sociétés internationales comme l'Association internationale de recherches hydrauliques (IAHR) et le Committee on Ice Engineering and Research.

Enfin, dans le cadre de l'intérêt renouvelé pour la déviation des cours d'eau et l'exportation de l'eau, le présent document permettra d'identifier les aspects critiques de l'hydrologie et de l'écologie des régions froides qui devraient être considérées dans l'élaboration des politiques à venir et des activités de R-D.

*Frederick J. Wrona, Directeur
Direction de la recherche sur l'étude des impacts
sur les écosystèmes aquatiques;
Institut national de recherche sur les eaux;
Centre national de recherche en hydrologie
Saskatoon, SK, Canada*

PREFACE

Ice is an integral component of our northern landscapes and can remain in lakes and rivers of cold regions for over half the year. Northerners have adapted to the prevalence of ice in their environment and have developed a unique understanding of ice processes as they affect their day-to-day activities. As scientists and water managers, we must never lose sight of the role ice plays in shaping and sustaining our northern aquatic ecosystems. Our current knowledge, however, may not yet be complete enough to allow us to understand completely the role of river ice in ecological processes.

This monograph represents the first comprehensive overview and critical analysis and integration of the physical, biological and chemical aspects of river ice ecology. Only seven years have passed since publication of a state-of-science book, *Environmental Aspects of River Ice and Ice Ecology*, revealed what can be achieved by looking beyond single-discipline research and advancing to broader, ecosystem-based, river-ice research. This volume should not be considered an endpoint in our efforts to understand the importance of river ice ecology, but rather as the starting point to conduct multi-disciplinary research into this complex, scientifically challenging, and rewarding field of ecology.

The Water Resources Division, Department of Indian Affairs and Northern Development, is pleased to participate in these areas of scientific endeavour. As day-to-day users of aquatic ecosystem research and knowledge, we recognize the importance of the linkages and interrelationships among a number of ecological processes. But more importantly, advances in our understanding of river ice ecology will benefit resource managers, who must make decisions regularly about northern aquatic resources.

David Milburn

*Manager, Water Resources Division
Renewable Resources and Environment
Yellowknife, NT, Canada*

PRÉFACE

La glace est une partie intégrante de nos paysages septentrionaux et peut subsister dans les lacs et les rivières des régions froides pendant plus de la moitié de l'année. Les habitants du Nord se sont adaptés au phénomène des glaces dans leur milieu et ont acquis des connaissances uniques des processus des glaces puisque celles-ci ont une incidence sur leurs activités quotidiennes. À titre de scientifiques et de gestionnaires des eaux, nous ne devons jamais perdre de vue le rôle que jouent les glaces dans le modelage et le maintien de nos écosystèmes aquatiques. Cependant, nos connaissances actuelles ne sont peut-être pas assez exhaustives pour nous permettre de comprendre tout à fait le rôle des glaces fluviales dans les processus écologiques.

Cette monographie est le premier ouvrage qui comporte un aperçu général, une analyse critique et une intégration des aspects physiques, biologiques et chimiques de l'écologie des glaces fluviales. Seulement sept années se sont écoulées depuis la publication de l'ouvrage sur l'état des connaissances scientifiques intitulé *Environmental Aspects of River Ice and Ice Ecology*; l'ouvrage révèle des perspectives inattendues lorsqu'on embrasse plus d'une discipline et que l'on fait une incursion dans des recherches plus vastes, basées sur les écosystèmes et sur les glaces fluviales. L'ouvrage ne doit pas être considéré comme le point final des efforts visant à comprendre l'importance de l'écologie des glaces fluviales, mais plutôt comme un point de départ pour effectuer des recherches multidisciplinaires dans ce domaine complexe de l'écologie qui présente des défis sur le plan scientifique et qui est enrichissant.

La Division des ressources hydrauliques du ministère des Affaires indiennes et du Nord canadien participe avec plaisir à ces efforts scientifiques. À titre d'utilisateurs de la recherche et des connaissances des écosystèmes aquatiques, nous reconnaissons l'importance des liens et des relations entre les différents processus écologiques. Mais surtout, une meilleure connaissance de l'écologie des glaces fluviales bénéficiera aux gestionnaires des ressources, qui doivent régulièrement prendre des décisions concernant les ressources aquatiques du Nord.

David Milburn

Gestionnaire, Division des ressources - hydrauliques

Ressources renouvelables et environnement

Yellowknife, T.N.-O., Canada

This monograph provides an introduction to the environmental and ecological effects of river ice, topics that have received only minor attention compared to more traditional hydraulic subjects. It should be stressed, however, that most of the biological, chemical and geomorphological functions associated with river-ice ecology are integrally linked with hydraulic processes. In many respects, an understanding of river-ice hydraulics is necessary for identifying, exploring and solving problems in river-ice ecology. In turn, understanding the full scope of the ecological aspects of river ice will enhance the value of existing hydraulic knowledge and highlight the almost limitless potential for further inter-disciplinary study.

The monograph is an expansion and update of earlier papers by Prowse (1996) for the IAHR-Ice, by Prowse (1994) and Scrimgeour *et al.* (1994) for the North American Benthological Society, and a state-of-the-science book (Prowse and Gridley, 1993) produced by the Committee on River Ice Processes and the Environment of the Canadian Geophysical Union, Hydrology Section. It is broken into four major sections each dealing with a specific portion of the winter season, for which there are important ecological consequences of ice in its various stages of formation, freeze-up, growth, ablation and break-up. In general, the ecological focus varies to a large degree from section to section as determined by the available documented body of scientific material. For example, when discussing the initial cooling of water and ice formation most text deals with the biological responses of fish and benthic organisms, whereas when the focus is the main ice-cover and break-up periods, special emphases are placed on oxygen conditions and fluvial geomorphology, respectively. Notably, however, since it is recognized that the ecology of river ice is a nascent science and, as such, many biogeochemical effects of river ice have not yet been evaluated, attempts have also been made to identify undocumented ecological consequences that require further research. Although space limitations preclude full discussion of the relevant theories and numerical formulations of the many biological, physical and chemical processes that are briefly reviewed, this monograph does include an extensive bibliography of relevant literature from which more specific details can be obtained. While not exhaustive, its length attests to the broad scope of literature on this topic, now for the first time assembled and integrated into a single review.

Even prior to the first formation of ice on a river, the biological system begins to adjust to changing thermal and flow regimes. The best documented behavioural responses are those displayed by various fishes, particularly salmonids (*Salmonidae* family including salmon, trout, char and whitefish; (e.g., Bustard and Narver, 1975; Swales *et al.*, 1986). In general, as water temperature declines, their metabolism lowers, food requirements decline, and activity is reduced. To conserve energy, there is often a redistribution of juveniles to new, more desirable overwintering habitat (e.g., Rimmer *et al.*, 1983; 1984). The exact nature of this habitat appears to depend on the nature of the stream or river and its winter hydrology. In coastal rivers, for example, where winter flows often increase, winter refugia may simply be locations such as near rocks or deep holes where energy expenditure in fighting the current is minimized (e.g., Veselov and Shustov, 1991), or in floodplain swamps and backwater areas (e.g., Bustard and Narver, 1975). For rivers located in colder continental climates, the habitat shift appears to be guided more by a desire to avoid the characteristic decline in winter flows and an increasing exposure of in-channel habitat to cold temperatures and ice effects (e.g., Swales *et al.*, 1988; Cooper, 1953; Cunjak and Power, 1986; Cunjak and Randall, 1993; Cunjak, 1996). Preferred winter habitats offer protection from high flow velocities and freezing conditions and can range from in-channel shelters to off-channel locations such as lakes, back channels, and wetlands (Chapman and Bjornn, 1969; Hazzard, 1941; Swales *et al.*, 1986; Swales *et al.*, 1988; Cunjak *et al.*, 1998). The desirability of many winter refugia is enhanced by the inflow of relatively warm groundwater (e.g., Armstrong, 1986; Cunjak and Power, 1986; Swales *et al.*, 1986; Brown and MacKay, 1995; Cunjak, 1996).

The formation of ice can reduce the amount and quality of winter habitat but can also create new refugia. This dichotomic role of ice in river ecology is apparent at the very first stages of freeze-over. For example, border ice develops along the margins and offers a low-velocity refuge (e.g., Power *et al.*, 1993), and a protection from predation similar to that of overhanging banks (e.g., Maciolek and Needham, 1952). Such refugia are especially important on streams that typically begin to clear as the suspended sediment load declines during the fall recession of the hydrograph. At the same time that border ice is ecologically attractive, frazil ice entrained within the main flow can be repellent and purposely avoided by some fish species (Figure 1a). As suggested by Brown *et al.* (1994), such avoidance appears to

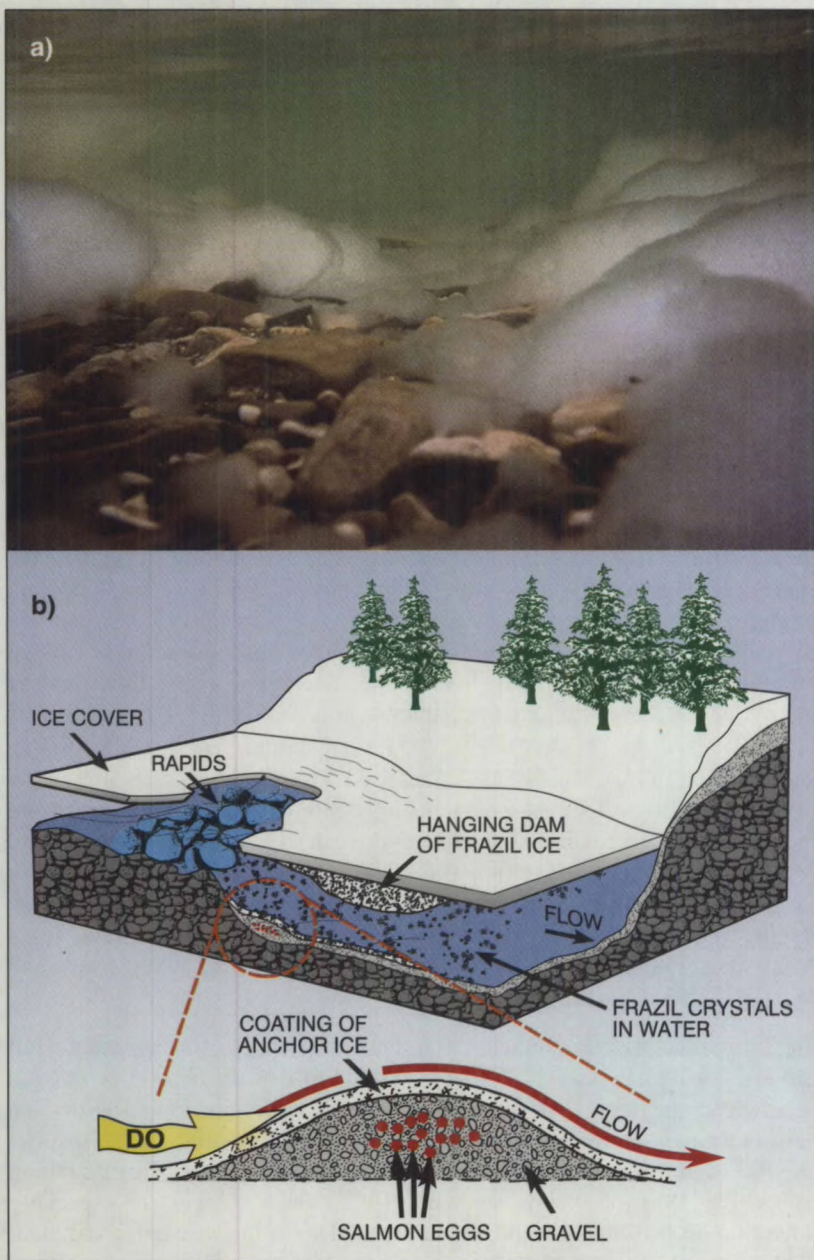


Figure 1: (a) Frazil and anchor ice beneath a floating ice cover, Dutch Creek, AB, Canada (photograph courtesy of R.S. Brown), (b) Frazil deposition below a rapids coating a redd and reducing flow of water and oxygen to eggs.

be related to the ability of small frazil crystals to abrade gills possibly causing hemorrhaging, and to plug gill rakers eventually leading to suffocation. Frazil has been cited in at least one case as being directly responsible for fish mortality (Tack, 1938).

In addition to causing localized avoidance behaviour, the presence of frazil has also been cited as being responsible for the emigration of major fish populations. For example, Armstrong (1986) has suggested that the emigration of grayling from otherwise apparently good winter habitat in spring-fed tributaries is related to the development of extensive frazil. Such behavioural response to frazil may be species specific, however, since other species (silver salmon - *Oncorhynchus kisutch* and slimy sculpin - *Cottus cognatus*) are known to overwinter in the habitat deserted by the grayling.

Where frazil ice and/or the accompanying supercooled water penetrate to the bed, often producing anchor ice, significant mortality can occur in benthic invertebrates and some fishes, particularly in the egg or embryo state. The *in situ* freezing of salmonid eggs is a frequently noted impact (e.g., Neave, 1953; McNeil, 1966; 1968; Bakkala, 1970; Reiser and Wesche, 1979), although later stages, such as fry and parr, may also be affected (Calkins and Brockett, 1988). The development of a coating of anchor ice from the penetrating frazil ice can also promote further ice growth into the spawning areas or "redds" (Walsh and Calkins, 1986). Solid coats of ice are also believed to restrict the essential flow of oxygen-carrying water to the redds (Stuart, 1953; Power *et al.*, 1993) and to prevent the removal of waste products (Bakkala, 1970) produced by the various fish life stages (e.g., eggs and alevins) that inhabit them (Figure 1b). Fry can be particularly vulnerable if emergence from the egg-sac stage occurs during a period of active ice formation (e.g., Benson, 1955).

One of the often cited reasons for freezing impacts on salmonids is winter declines in flow resulting in water levels significantly below those at which the redds were originally constructed (e.g., Calkins, 1989; Chadwick, 1982; Cunjak *et al.*, 1998). Shallower water increases the probability of ice developing on the bed but, importantly, it also appears that freezing-related damage can result from the apparent penetration of supercooled water into the gravel without the formation of frazil or anchor ice (Reiser and Wesche, 1979). Although short-term penetrations of supercooled water are likely to have only a minor biological effect, large mortality to benthic organisms could result from protracted periods of supercooled flow. In the absence of direct physical evidence offered by ice coatings, the prevalence of this phenomenon is unknown. Calkins (1989), however, does report a case where supercooled water that formed in an open lead between two ice sheets and flowed down into the gravel bed persisted for up to 10 hours.

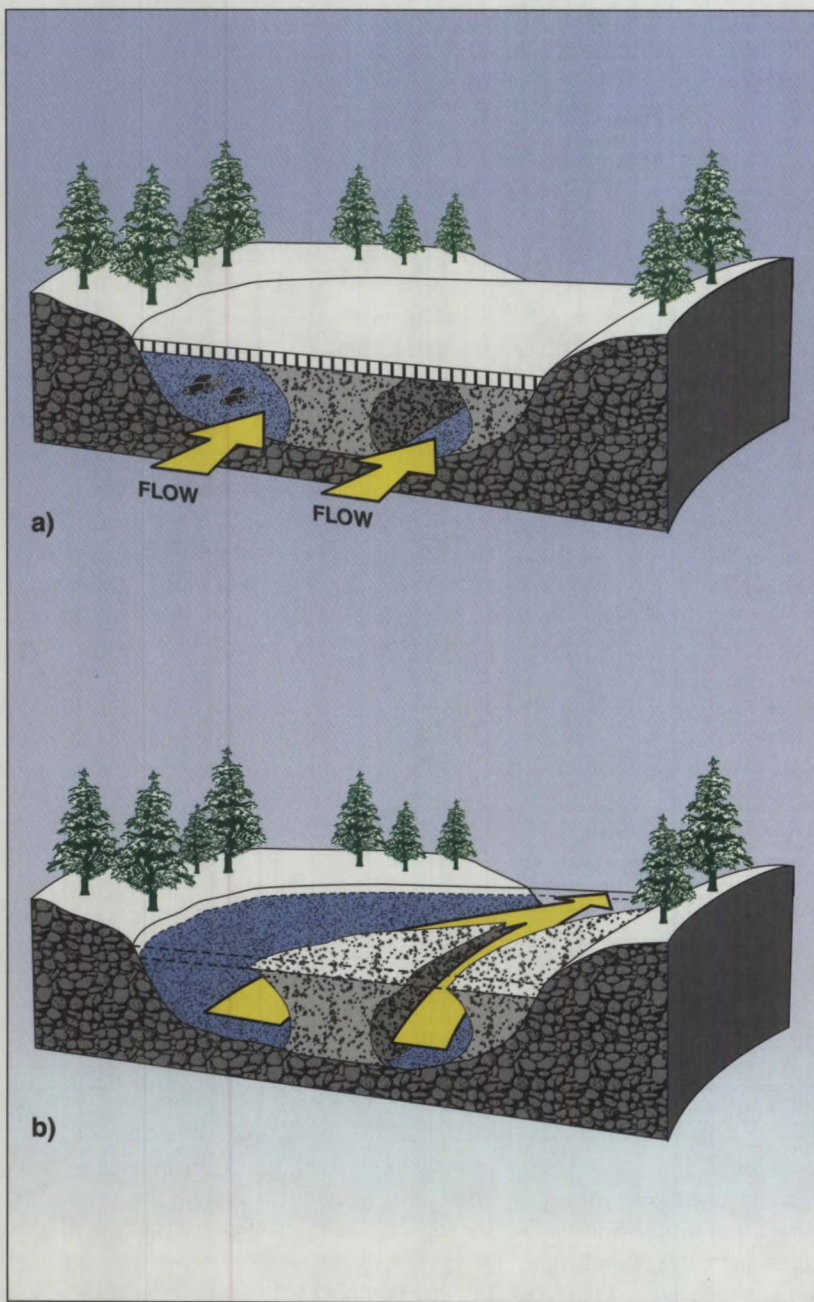


Figure 2: (a) Frazil deposition beneath cover and in low-velocity zones reduces available habitat and, (b) defines new under-ice flow pathways.

Once accumulated into a mass beneath an intact ice cover, frazil ice plays further roles, both positive and negative, in modifying habitat. One of the best examples of the former is frazil accumulations that act as the incubating medium for Atlantic tomcod (*Microgadus tomcod*) (Fortin *et al.*, 1992; Power *et al.*, 1993). More commonly, however, the documented biological effect is one of habitat reduction. Large accumulations of frazil beneath the primary ice cover can eliminate or modify significant areas of preferred winter habitat and can even be disorienting for some fish (e.g., Butler and Hawthorne, 1979). This is especially important since it has also been suggested that the availability of winter rather than summer rearing habitat is the major factor controlling, for example, salmonid abundance (Swales *et al.*, 1986). While frazil accumulations are frequently observed to obliterate large quantities of underwater habitat, they can be ecologically important even when only small zones are congested. This is because frazil tends to deposit most readily in low-velocity zones, including pools - the same areas preferred by fish species attempting to reduce their energy expenditure throughout the winter period (e.g., Brown and Mackay, 1995; Cunjak and Caissie, 1994). As a result, fish can be forced to move into more demanding environmental conditions and away from their preferred specific velocity habitat. Changing ice conditions have been cited as a major reason for in-stream movement of some fish species throughout the winter (e.g., Cunjak and Randall, 1993).

The accumulation of anchor ice can also indirectly alter riverine habitat through alterations in the flow regime (Figure 2). A common habitat modification is in the depth of pools resulting from the elevation of water levels caused by the accumulation of thick (relative to the normal flow depth) anchor-ice at the downstream lips of pools or in riffles (e.g., Maciolek and Needham, 1952; Needham and Jones, 1959). Within shallow streams, anchor ice can also result in the diversion of flow within the channel or floodplain. This can lead to the exclusion of some habitat and, coupled with declining flow and stage, cause the stranding and suffocation (Needham and Jones, 1959) or aggregation of stream biota (Brown and Mackay, 1995), depending on their mobility.

Although anchor ice may form on almost any underwater object, it is most commonly found attached to aquatic vegetation, boulders, and even large areas of gravel and coarse sand. Once released it is known to carry these materials as well as various benthic organisms, thereby increasing the local number of drift organisms (Maciolek and Needham, 1952; Miller and Stout, 1989; O'Donnell and Churchill, 1954; Reimers, 1957). While this causes downstream dispersion of such aquatic life and creates a readily available food source, it does not seem to cause any significant overall depletion of organisms (Benson, 1955; Brown *et al.*, 1953), probably because of rapid recolonization.

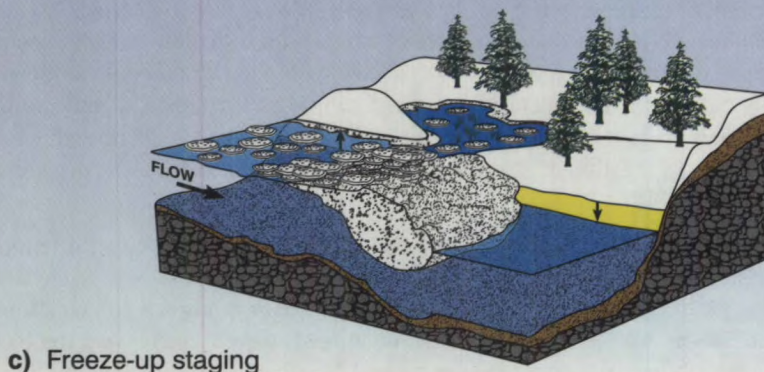
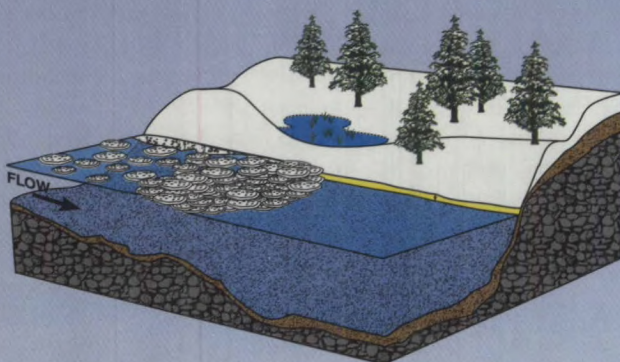
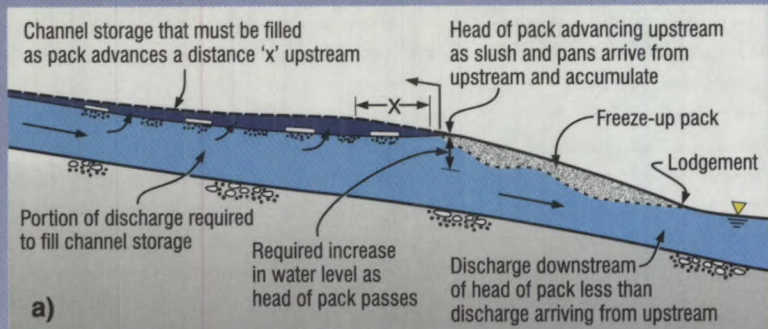


Figure 3: (a) Loss of discharge to channel storage behind advancing freeze-up front; (b) Freeze-up staging of water eventually leading to (c) backwater flooding of riparian zones.

Following the initial growth of border ice and various frazil-ice forms, the next major change to the winter ecology of a stream or river results from the final congestion and complete freeze-up of the water surface. These, in turn, cause some major changes in channel flow, most of which are related to the hydraulic storage of water (Figure 3a). Rises in water level are often quite dramatic, and occur much more rapidly than is possible under open-water conditions. They are especially important for supplying water to the extensive aquatic habitats located along channel margins and the floodplain (Figure 3b and c). During the autumn recession in flow, many side-tributaries, sloughs, and delta lakes can become isolated from the main channel. Elevated water levels at freeze-up can replenish water in these riparian areas, either by direct inundation or indirectly through the augmentation of lateral groundwater flow (e.g., Burn, 1993; Paschke and Coleman, 1986). Notably, the riparian zone is often considered to be the most productive habitat on many river systems. Moreover, it has been shown for some fish species and strongly suspected for others that side-channels and off-channel ponds - areas directly influenced by the level of freeze-up staging - provide preferred habitat for the entire winter period (e.g., Komadina-Douthwright *et al.*, 1997).

A negative aspect of freeze-up backwater relates to the development of low flow (Figure 3d). During the period that water is abstracted from flow for ice

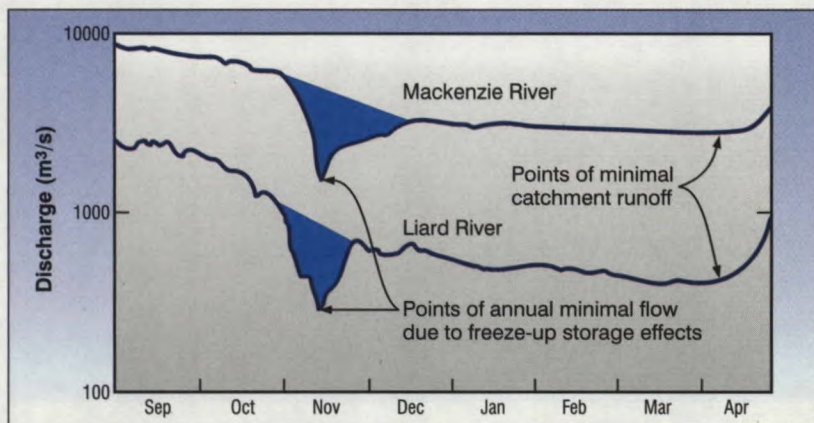


Figure 3d: Effect of freeze-up staging on downstream discharge and creation of winter low-flow.

growth and placed into hydraulic storage behind the accumulating ice cover, discharge decreases downstream. In extreme cases, this period becomes the time of the minimum winter low flow - lower than that commonly thought to occur in late winter when landscape runoff is least (Gerard, 1990; Gray and Prowse, 1993) - and the downstream flow can be reduced to a relative trickle. Eythorsson and Sigtryggsson (1971), for example, note that flow in the lowland reaches of one river in Iceland was reduced to only 6% of normal by the rapid formation and damming effects of anchor and frazil ice in its headwaters. Although relatively short-lived, such low flow can produce a myriad of environmental impacts ranging from modification of aquatic habitat, as through dewatering of shallows or enhanced anchor ice growth, to problems of access to water supply or the effective dilution of effluent. As noted by Prowse (1994), however, rarely are freeze-up low-flow events recorded in conventional hydrometric data bases. Most records depend on methods of discharge measurement and calculation that are notoriously unreliable during this highly dynamic freeze-up period and, as a result, flow records are often linearly interpolated completely ignoring the transient low-flow phase. Where sufficient data have been collected about this phenomenon to produce long-term frequency curves, the probability of the lowest flows falls below those for conditions or streams where abstraction for ice growth/storage is not a significant factor (e.g., Gerard, 1981a).

Once a winter ice cover has developed, the ecology of a river is rapidly transformed. Changes occur in numerous biogeochemical processes, some quite dramatically. Few remain static and continue to adjust throughout the winter period, often as a result of growth and ablation of the ice cover.

4.1 FLOW EFFECTS

As ice growth continues during winter, an increasing portion of river-channel margins (and other shallow locations) becomes frozen to the bed. In shallow streams, during severe winters, and/or under low-flow conditions, such growth can lead to the concentration of flow within only the deepest and/or highest-velocity portions of the channel. Extensive accumulations of frazil beneath the static ice cover can lead to the development of "inner channels" (Figure 2) and further accentuate the flow-concentration process (e.g., Lapointe, 1984).

Under extreme conditions, complete freezing of small streams can occur unless there is enough winter flow from lakes and ponds or the groundwater system. Where the channel flow system is spatially interwoven, as in deltas and braided streams, flow can divert from one channel to another (e.g. Anderson and MacKay, 1973). Where bottomfast (frozen to the bed) or exceptionally thick ice develops at lake outlets, winter outflow to river systems can be blocked. Subsequent loss of flow to downstream lotic systems could prove detrimental, but such blockage could be considered beneficial to lentic systems since it can keep lakes from draining during the low-flow winter period (e.g., Card, 1973; Peterson *et al.*, 1981).

4.2 FREEZING-AVOIDANCE BEHAVIOUR

As the ice grows down into the littoral zone, it can also influence the distribution of certain benthic invertebrates. In general, organisms can either migrate to deeper water or stay in a dormant state (diapause) to be trapped by the growing ice (e.g., Oswood *et al.*, 1991; Olsson, 1981; 1983). Those that remain suffer the greatest mortality from the mechanical effects of freezing unless the habitat temperature falls well below their hemolymphatic freezing point. Invertebrates trapped in anchor ice, for example, are treated

to a relatively warm benign environment and many (e.g., gastropods, pisids, trichopterans and chironomids) are able to overwinter enclosed in the ice. By contrast, mortality of invertebrates can result when an ice sheet grows directly into the littoral zone and, through direct conduction to the atmosphere, exposes them to severe sub-freezing temperatures (e.g., Brown *et al.*, 1953; Olsson, 1981). As summarized by Oswood *et al.* (1991), the major factors affecting freezing mortality include the minimum temperature and duration of freezing, the seasonal variations in cold hardiness of organisms, effects of dehydration, and mechanical damage. Interestingly, it has also been noted that where freezing within the littoral zone produces only partial loss to invertebrate communities, losses due to predation can be greater for organisms that have moved into the adjacent unfrozen sub-littoral zone (Olsson, 1988).

In addition to eliciting invertebrate migration response during the main winter growth period, ice appears to have another effect at break-up. Some organisms have been noted to emigrate purposely from their winter habitat to locations where the effects of break-up are minimized (see Section 5.2.2), such as in the uppermost littoral or into smaller tributaries where increases in spring flow are less dramatic and habitat conditions more suitable for survival (e.g., Hayden and Clifford, 1974; Neave, 1930; Olsson, 1983; Olsson and Söderström, 1978).

4.3 ISOLATED-POOL HABITAT

In very northern climates and/or in years of extreme cold combined with low flow, ice may freeze to the bed across middle portions of river and stream channels creating numerous disruptions to the riverine ecology, the best documented cases being for fishes. In many northern rivers, only isolated pools remain unfrozen over the winter period. For arctic coastal rivers, where alternative freshwater habitat such as deep lakes is generally unavailable, such pools provide the only overwintering and/or spawning zones for some fish species (Craig, 1973; 1989; Craig and Poulin, 1975; Schmidt *et al.*, 1989; West and Smith, 1992). Although some deep holes exist, the most common winter habitat is provided by groundwater springs - sites known by their local name as "fish holes" because of their importance in traditional subsistence lifestyles (e.g., West and Smith, 1992). Spring-fed sites offer ideal winter fish habitat because they preclude the freezing of eggs (e.g., Harper, 1981; McCart and Craig, 1973; Craig and McCart, 1974) and support large populations of invertebrates for winter feed (e.g., Loftus and Lenon, 1977; McKinnon *et al.*, 1978). Within a single winter fish hole, all life-history stages from eggs to adults can be isolated for periods of up to 8 months or more - their survival heavily dependent on the degree of

disturbance affecting the pools over these lengthy periods. Given the importance of such winter habitat, their quality and prevalence are probably a primary regulator of some anadromous fish populations. The preference of fish for spring-fed or groundwater recharge zones under ice has also been documented for more temperate zones where significant streamflow continues throughout the winter (e.g., Cunjak and Power, 1986). Where spring-fed areas remain open, however, predation possibilities are enhanced and can place an indirect pressure on fish populations. For example, migrating species of fish-eating birds (mergansers) have been noted to concentrate their feeding on fishes within upstream spring-fed locations when their normal feeding areas in downstream bays and rivers are completely frozen over (e.g., Hazzard, 1941; Salyer and Lagler, 1940). More generally, the presence/absence of an ice cover influences numerous predator-prey dynamics associated with avian and mammalian predators (e.g., Power *et al.*, 1993).

4.4 ICE-CAVITY HABITAT

Once an ice cover has established on a river, its gradual modification induced by falling water levels produces some unique, and very important, winter habitat (Figure 4). Where the rate of the winter recession in flow (and water levels) exceeds the rate of ice growth, the ice sheet begins to lose the support provided by the underlying water. On all but very narrow creeks, or where the ice cover may be supported at a number of points (e.g., boulders) across the channel, the ice sheet gradually sags with the lowering water surface. This continued lowering eventually leads to a vertical failure (breakage) of the ice sheet along the banks. Along these failure or shear lines, portions of the shore ice become suspended. The open spaces beneath such ice are known to provide access for many aquatic mammals such as muskrat, mink, otter and beaver that forage bank vegetation and aquatic biota (Geddes, 1980; Calkins, 1993).

In streams where large boulders and cobbles protrude into the flow, rapid winter flow recession can leave large portions of the ice sheet totally suspended above the water surface (e.g., Calkins and Brockett, 1988). Protected by the overlying ice, such cavities become well insulated from the extremes of winter weather, especially where they are warmed by incoming solar radiation. They also offer access and breathing space for mammals that feed on aquatic organisms (e.g., Power *et al.*, 1993).

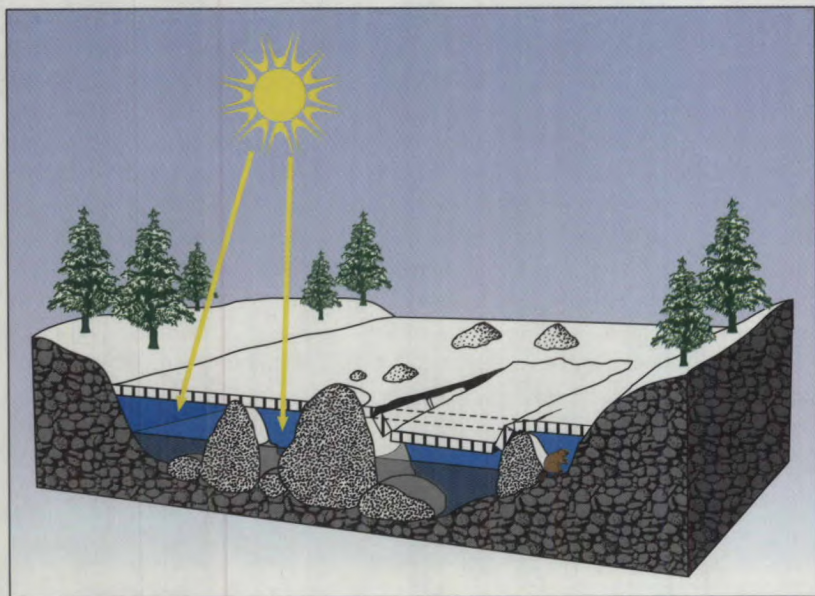


Figure 4: Suspension of ice cover creates unique under-ice habitat over both water and bank surfaces.

4.5 IMPACTS ON VEGETATION

With the gradual decline in winter water levels an increasing area of the littoral zone becomes frozen and in direct contact with the overlying ice cover. This is believed to be a principal factor controlling the distribution of large aquatic plants or macrophytes. Renman (1989), for example, found the position and abundance of several plant species to parallel inter-annual spatial changes in bottom freezing. It was noted to act as a major source of disturbance through the destruction of plant biomass, and as a stress through restriction of growth conditions. Both are maximized in the upper portions of the bed where temperatures are coldest, with the greatest impact on subsequent productivity occurring when plants are totally encased in ice (Olien and Smith, 1981). Even if there is severe mechanical damage, some plants are specially adapted to regenerate and, in fact, to profit from ice damage. Some thin rhizomes, for example, are able to regenerate individual new plants each spring from the separate pieces resulting from ice-induced breakage (e.g., Renman, 1989). Other species that can be referred to as "cool weather strategists" (Nichols and Shaw, 1986) use the ice-cover period to ready themselves for the spring period and to out-compete other species. Living under or encased in ice (e.g., most evidence from off-channel and pond locations: Boylen and Sheldon, 1976; Moeller, 1978; Stuckey *et al.*,

1978; Erixon, 1979), such plants are photosynthetically active when ice melt begins and are able to colonize areas before annuals or species perennating from rhizomes have developed (Renman, 1989). On the other hand, many species are not well adapted and ice cover can directly retard growth. Reimers (1957) noted that prolonged ice cover resulted in a reduction of periphytic algae which in turn reduced the number of grazing invertebrates that are important as fish prey.

4.6 OXYGEN EXCHANGE

4.6.1 Temporal Changes

Once fully developed, an ice cover eliminates direct gaseous exchange between the water column and the overlying atmosphere (Figure 5a). For many streams and rivers, this can lead to significant lowering of dissolved-oxygen (DO) levels, the effect being most pronounced on colder systems where cover completeness and duration are greatest, and less important on more temperate streams where the cover may be intermittent in time and space. Although photosynthetic production of oxygen can continue beneath an ice cover during daylight, it too is reduced because of ice-induced attenuation of solar radiation. This effect is most pronounced in shallow, low-velocity streams of temperate climates where the large plant biomass is capable of photosynthesizing significant quantities of oxygen. It is relatively insignificant on large and deep northern rivers where cold-climate conditions and the scouring effects of break-up minimize plant growth.

In general, DO concentrations are usually quite high in the autumn owing to the increasing solubility of oxygen with falling water temperatures. Often showing a late-season peak just prior to the river freezing over at 0°C, concentrations then generally decline, sometimes quite dramatically within a few days of freeze-up (e.g., Whitfield and McNaughton, 1986; Brunskill *et al.*, 1973). The nature and rate of this decline depend on a number of factors including the quality and origin of source water comprising the flow, and various bio-chemical processes (respiration and decomposition) operating within the water column and channel bed. Rapid declines in dissolved oxygen levels immediately after freeze-up often occur because autumn flows are comprised largely of poorly-oxygenated groundwater (e.g., Babin and Trew, 1985). Thus, once surface reaeration is eliminated by the ice cover, dissolved oxygen levels rapidly assume that of the source groundwater. Where highly oxygenated surface waters dominate the flow, the post-freeze-up decline is much less dramatic.

In some instances, the major winter decline in DO occurs immediately after freeze-up. Whitfield and McNaughton (1986) found that 80% of the total

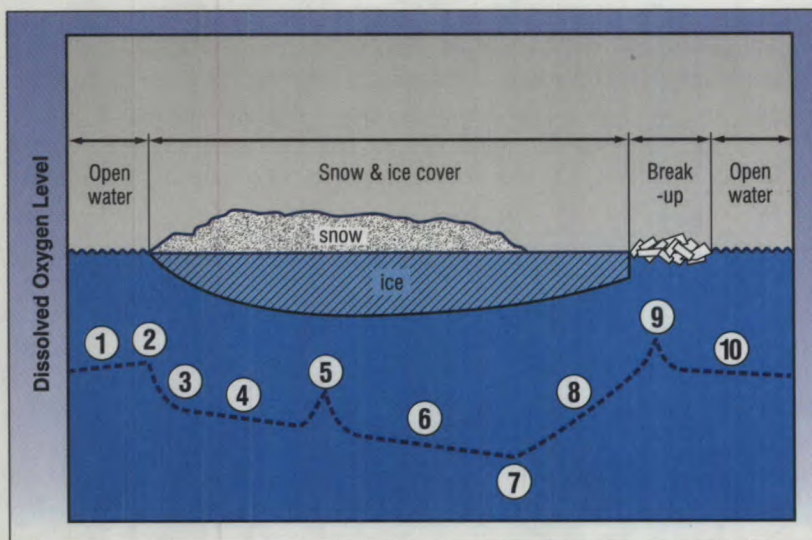


Figure 5: (a) Examples of winter changes in DO including 1) slight increase in autumn levels as water continues to cool because of temperature dependency of oxygen saturation; 2) peak prior to freeze-over; 3) rapid decline at complete freeze-over that can result when main flow is comprised largely of poorly oxygenated water and the related elimination of reaeration; 4) and 6) steady decline as increasing proportion of flow is derived from groundwater; 5) mid-winter increases from runoff events or increased regulated inflow; 7) seasonal minimum late in winter but could also occur at other times, even after break-up when large inputs of organic material consume available DO; 8) rise in oxygen production resulting from increased photosynthetic activity as solar radiation increases with spring and loss of reflective snow cover; 9) brief supersaturation created by turbulence at break-up; 10) return to open-water levels.

winter depression occurred within the first week of ice-cover formation. Subsequent winter declines are usually much more gradual and usually reflect the increasing proportion of flow contributed by poorly-oxygenated groundwater (e.g., Babin and Trew, 1985; Schreier *et al.*, 1980). Importantly, although many winter ice-covered conditions (e.g., low flow and reduced reaeration) tend to favour low DO values, they are not necessarily the annual minimum, particularly in streams with higher summer organic loadings and water temperatures. On the Speed River in Canada, for example, Kelso and MacCrimmon (1969) observed a minimum DO of 2.0 mg/L during July at 22.2°C but a seasonal maximum of 14.5 mg/L under ice.

On rivers that tend to show a winter decline in DO, there can also be a rise in values prior to break-up. As shown also for lakes (Prowse and Stephenson, 1986), this is believed to be due to a rise in photosynthetic activity caused by increasing light levels in the spring (Hynes, 1970; Whitfield and

McNaughton, 1986; Cheng *et al.*, 1993) resulting from a seasonal increase in solar radiation and a reduction in the albedo with the melt of highly reflective snow and white ice layers (see Section 4.7). For other rivers, rich in natural or effluent-induced organic material, the annual DO minimum may occur at or soon following ice break-up, as a result of the spring flood resuspending significant amounts of particulate material and higher water temperatures accelerating their metabolism (Hynes, 1970; Brunskill *et al.*, 1973; Hou and Li, 1987). The high turbulence at ice break-up can, however, produce the opposite effect and increase DO concentrations (e.g., Tilsworth and Bateman, 1982) even to the point of brief supersaturation (Milburn and Prowse, 2000).

4.6.2 Longitudinal Gradients

In the absence of significant oxygen production or reaeration, dissolved oxygen concentrations will decline with distance downstream. This trend, however, is frequently interrupted by the input of oxygen-rich water from tributaries, particularly those fed by lakes, and/or by rapid reaeration that can occur within open-water reaches, especially at turbulent rapids (Figure 5b). Importantly, not all open-water areas can be expected to have high DO, particularly those kept open by large inputs of spring water. The DO in such sites probably closely reflects that of the groundwater aquifer from which they originate (e.g., Schreier *et al.*, 1980).

Many streams and rivers display a pronounced streamwise gradient in DO from upstream to downstream, often remarkably linear in form (e.g., Babin and Trew, 1985; Schallcock and Lotspeich, 1974). Varying hydrologic conditions on many other rivers, however, can create much different streamwise gradients. Large localized inputs of well-oxygenated lake water, for example, can rapidly increase DO levels and obliterate any general declining trend (e.g., Schreier *et al.*, 1980). The opposite effect is seen where there are large localized inputs of poorly-oxygenated water, such as from extensive bogs or groundwater. Rivers in the West Siberian plain are the best examples of this situation. Here, the River Irtysh drains large quantities of de-oxygenated water from vast peatlands into the River Ob' resulting in DO levels of only about 5% of saturation (Hynes, 1970; Harper, 1981). In addition to poorly oxygenated water, the input of organic carbon from such organically rich zones and its subsequent oxidation in the receiving river can further enhance the depression of DO (e.g., Whitfield and McNaughton, 1986; Schreier *et al.*, 1980). The same is true for oxygen-consuming material fed by effluent from industrial, municipal and pulp mill sources (e.g., Bouthillier and Simpson, 1972; Schallcock and Lotspeich, 1974; Brekhovskikh and Volpian, 1991; Hou and Li, 1987). Because 0°C water

temperature slows the decomposition of such pollutants and winter low flows reduce their dilution, BOD can also be the highest during the ice-covered period.

For many river systems, nutrient loadings can be the dominant local (near effluent source) and downstream control on DO concentrations (Figure 5c). Based on a study of six rivers with effluent concentrations >1%, Chambers *et al.* (1997) found that DO was linearly related to river distance and that the

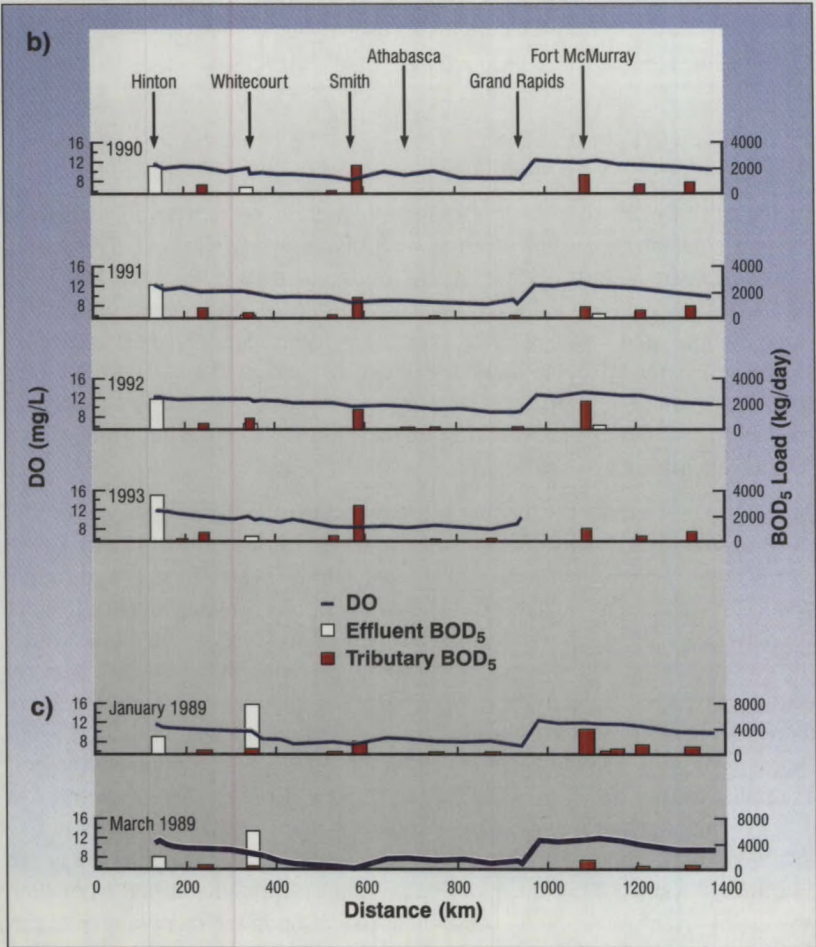


Figure 5: (b) Streamwise decreases in DO measured along the Athabasca River, Canada, 1989-1993. Consistent rise at 950 km point is due to extensive reaeration at large open rapids (after Chambers *et al.*, 1997) **(c)** Streamwise declines in DO measured for different rivers with effluent concentrations >1%.

greatest decline occurred on the river with the greatest effluent concentration (29% on the TuMen River, China; Hou and Li, 1987). Specific observations from the Athabasca River also suggested that short-term loadings have only limited temporal and spatial effects on DO concentrations (Chambers *et al.*, 1997). By contrast, long-term changes over several years can affect winter DO over much larger spatial scales (i.e., hundreds of kilometres). The delayed effect is most probably related to the long-term degradation of settled particulate and/or adsorbed organic matter. Although there is a residual effect of long-term loadings, effluent reductions will also eventually permit DO recovery. Chambers *et al.* (1997), for example, found that a six-fold reduction in BOD₅ (5-day bio-chemical oxygen demand) increased late-winter DO by 1/3 over 200 km downstream.

Interestingly, based on data from another set of nine ice-covered rivers without point-source effluent loadings, Chambers *et al.* (1997) found seven to show no significant changes in DO along their lengths. While this particular selection of rivers shows the importance of effluent loadings, the importance of natural organic loadings, as described above, was also stressed and even noted to be the dominant DO control on one river (Beaver River; Babin and Trew, 1985).

In general, longitudinal gradients are rarely simple and reflect a complex mixture of climatic, hydrologic, hydraulic, geo-chemical, and anthropogenic chemical conditions. Numerous attempts have been made to model this complicated array of factors, the success of the effort being partly a function of the multi-variate quality of the model and the simplicity of the studied system. As a result of the models being derived from open-water conditions, however, there remain some fundamental problems to be addressed to ensure their applicability for under-ice conditions. For example, many of the important chemical rate factors such as BOD, deoxygenation and reaeration that are temperature variant have not been fully validated for low-temperature conditions (e.g., Cheng *et al.*, 1993). The hydraulics of the models also tend not to consider the important modifications induced by an ice cover, such as increasing flow depth and decreasing velocity. As discussed by Ferrick and Calkins (1996), this can have a significant effect on the residence time of flow (e.g., in the simplest case, a 1/3 increase compared to equivalent open-water flow conditions), a variable critical in the calculation of reaeration or oxygen-consuming processes.

4.6.3 Biological response

Similar to the effects of water temperature and food supply, the concentration of dissolved oxygen beneath an ice cover controls the biological

productivity, diversity and even robustness of the entire aquatic community (Barton and Taylor, 1994; 1996). Unfortunately, the sensitivity, tolerance and response of most aquatic species to low DO are poorly understood. Fish have been studied most extensively and appear to experience increased susceptibility to stress, predation, contaminants and disease with lowering DO. It is particularly important for fall spawners because their eggs undergo development under the winter ice cover.

As summarized by Barton and Taylor (1996), sublethal responses of various fishes range from changes in cardiac and metabolic functions to reduced growth and swimming capacity. Behavioural responses are usually manifested in deliberate movements to habitat with higher DO conditions (e.g., Jensen *et al.*, 1993; Klinger *et al.*, 1982). Hynes (1970), for example, describes a situation on some Russian rivers in which there has been observed a gradual outmigration to adjacent brackish waters by low-DO tolerant fish species as saturation levels decline. The emigration begins with the least tolerant salmonids at around 50% saturation and ends with the more tolerant pike and carp at <20%. Hence, by the time very low DO levels develop beneath the ice cover, fish have abandoned most reaches of the rivers and congregated into a few preferred zones where they remain relatively inactive throughout the remaining winter period.

Congregation of fish can also lead to major mortalities as has been noted on coastal plain rivers in Alaska. Here, in an effort to avoid tissue damage associated with freezing effects in marine waters, arctic anadromous fish migrate into the less saline delta regions of rivers. Subsequent growth of river ice isolates upstream areas from further intrusion of brackish water and results in the concentration of fish in selected winter pools. Overcrowding in such shrinking habitat and the associated rise in consumption of oxygen per unit volume have apparently led to extremely low DO levels (reported as low as <0.2 mg/L; Bendock and Burr, 1984) and resulted in localized winterkill (e.g., Schmidt *et al.*, 1989). In some areas, low DO may cause related chemical stresses since it can also promote the accumulation of other toxic substances, such as un-ionized ammonia and hydrogen sulphide (Babin and Trew, 1985).

Overall, it is early life stages rather than adult fish that are most impacted by low DO because of their higher sensitivity. There may be no changes in survivorship but there can be in development rates. Although much less information exists about DO impacts on benthic invertebrate communities, some have been shown to be more sensitive to reduced DO levels than low DO-intolerant fishes such as salmonids (Barton and Taylor, 1996). As with fish, sensitivity to low DO varies by benthic species and by stage of development, and behavioural response is often characterized by migration. For rivers that regularly experience low winter DO, the benthos has been

noted to be composed mainly of low-DO resistant forms (Harper, 1981) while less tolerant types congregate in more favourable conditions near the mouths of tributaries where more oxygen-rich water joins the main flow (e.g., Yukhneva, 1971).

4.7 RADIATION REGIME

One of the primary reasons for the reduced photosynthetic production experienced by plant species during the winter period is the reduction and spectral filtering of solar radiation by an ice cover. During the main winter period, initial reflective losses of solar radiation are determined by the surface snow, which in a newly fallen state can have an albedo as high as 0.95 but decreases to the 0.4 - 0.6 range as the snow ages and ripens (e.g., Gray and Prowse, 1993). Given the seasonal ebb in radiation input, such large reflective losses can severely reduce the total amount of light reaching the water column.

In late winter, after the snow has ablated, the albedo of the underlying ice surface controls reflective losses (Figure 6a and b). If surface ice is a form of snow-ice or white-ice, reflection will remain high, with typical albedo values being in the range 0.3 - 0.4. If black or blue-ice prevails at the surface, reflective losses can be much lower. Once a black-ice surface begins to melt, however, its albedo can rapidly rise to a value comparable to or even greater than that of white-ice surfaces which, in contrast, remain relatively constant during melt (e.g., Prowse and Marsh, 1989). The potential for a late-season rise in the albedo of covers overlain by black ice contradicts the common assumption that inputs of solar radiation to a river column simply increase in the spring after the ablation of surface snow. This has biological significance because of the apparent dependence of the initiation of enhanced productivity on increased light levels in spring (e.g., Prowse and Stephenson, 1986).

Ice cover also alters the spectral regime of radiation reaching the water column. Due to the spectral selectivity of ice and the normal spectral distribution of solar energy, the spectrum from approximately 400 to 850 nm forms the majority of radiation absorbed within relatively thin ice sheets. Although the magnitude of such filtering is small relative to the overall reduction in light quantity, spectral selectivity becomes increasingly important for biological activity, especially at low light levels. This is particularly true for the 450- and 660-nm wavelengths that favour photosynthesis. The range and degree of spectral filtering depend on physical characteristics such as the shape, size and orientation of ice grains, and ice pores (e.g., see Grenfell and Maykut, 1977; Grenfell and Perovich, 1984).

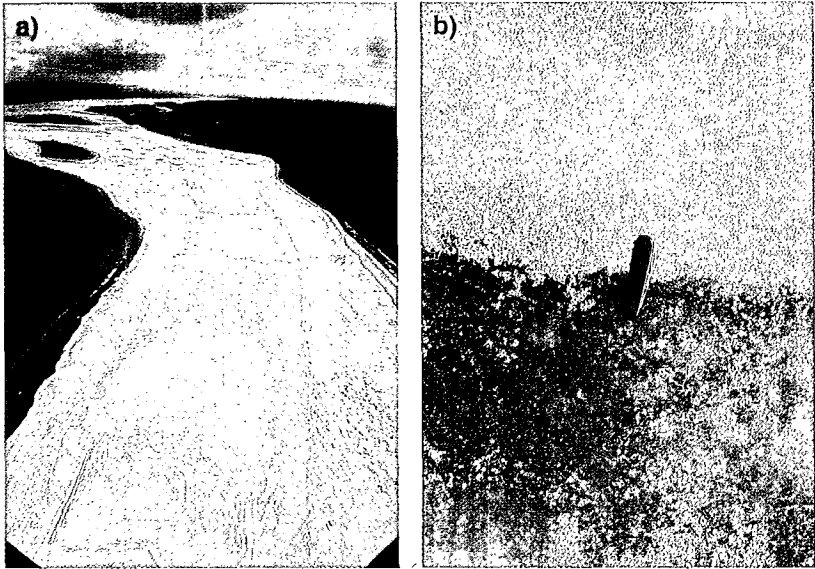


Figure 6: (a) Different freeze-up ice surfaces formed by accumulation of frazil (white zones) and freeze-over of water surface (darker zones). Also shown along margins are rough frazil accumulations. (Mackenzie River, NWT, Canada; photograph: T.D. Prowse). (b) Close up of surface of frazil ice (white) contrasted with darker congelation ice formed by simple freezing of water surface as typically occurs on lakes. (Liard River; NWT, Canada; photograph: T.D. Prowse).

4.8 MIXING PROCESSES AND SEDIMENT TRANSPORT

The presence of an ice cover alters a number of hydraulic parameters that directly influence the ability of a river to mix and transport dissolved and suspended substances, thereby affecting numerous water quality parameters. A general assumption is that an ice cover, as an additional flow boundary, will lead to a parabola-shaped velocity distribution: one characterized by zero velocity at the channel bed and base of the ice cover, and maximum velocity somewhere between them, the exact point depending on the relative roughness of the two surfaces. Similarly, shear stresses linearly increase from the point of maximum velocity towards the two boundaries (e.g., see Larsen, 1973; Lau, 1982; Sayre and Song, 1979; Shen and Harden, 1978).

Concomitant with changes to velocity and shear-stress parameters, are alterations to mixing parameters such as vertical diffusivity, transverse mixing and longitudinal dispersion. Vertical diffusion, controlled largely by flow turbulence, is the main mechanism for vertical spreading of dissolved and suspended substances. Although some theoretical inconsistencies exist in defining the distributions of kinematic velocity with a two-layer flow

model (e.g., Lau and Krishnappan, 1981; Shen and Harden, 1978), in general, it can be expected that the vertical diffusive capacity is reduced by a river-ice cover (Beltaos, 1993).

Similar to its effects on vertical velocity profiles, an ice cover also alters the distribution of radial velocities in channels (e.g., Zufelt, 1988; Urroz and Ettema, 1992). Its ultimate effect on transverse mixing, however, has not been adequately defined, most of the available data suggesting that similar values of the dimensionless (relative to total flow depth, not hydraulic radius) mixing coefficient can be used for ice and open-water conditions (e.g., see Lau, 1985; Beltaos, 1980). Although there is a similar dearth of information about longitudinal dispersion, a review of existing data by Beltaos (1994) indicates that the rate of temporal spread or growth of residence time as the material travels downstream is somewhat higher than that for open-water conditions when respective friction factors are comparable. However, the overall longitudinal dispersion capability, defined as the rate of spatial spread, is expected to be smaller under ice because of the generally slower velocity for equivalent flow depth.

One of the major consequences of ice-induced reductions in flow velocity, vertical diffusivity and shear stresses is a lowering of the transport capacity for suspended and bed material. Although not well quantified, changes in velocity and shear stress distribution should also cause a change in the vertical distribution of suspended material and the ratio of suspended to bed load (e.g., Sayre and Song, 1979; Lau and Krishnappan, 1985). Reduced sediment-transport capacity during the winter months is evident in standard sediment survey data. For example, Tywoniuk and Fowler (1973) found for 14 northern prairie rivers that an average 13% of the annual suspended load was transported by 25% of the annual flow that occurred during the winter ice-covered months. Noting that the period of record was short and probably contained some data from break-up conditions (see discussion below), they revised their figures to 10 and 20% respectively, although the ratio remains approximately the same. Similarly, from a multi-year record for a large northern river, Milburn and Prowse (1996a) found that the under-ice sediment rating curve at low discharge was characterized by lower sediment concentrations than would be expected from a linear extension of the normal open-water sediment rating curve. A much different sediment-flow relationship was found for the ice-break-up period, as discussed in later sections.

In addition to its indirect effect on sediment-transport capacity, ice can also act as a direct agent of sediment transport. For example, frazil ice is known to be a natural scavenging agent of material (e.g., Reimnitz *et al.*, 1990) and an agent of sediment transport once it has buoyed it from the bed (e.g., Kempema *et al.*, 1993; Chacho *et al.*, 1986; Arden and Wigle, 1972;

Osterkamp and Gosink, 1983). Its greatest transport potential is as a large anchor ice deposit that detaches from the bed carrying with it various sizes of bed material and transporting them downstream including, in one case, boulders as large as 30 kg (Larsen and Billfalk, 1978). Frazil ice can also have an indirect effect on sediment transport when it grows to large hanging dams (e.g., Tsang, 1982) and causes a concentration of flow at the bed, thereby creating localized scour holes in alluvial beds (Newbury, 1968; Kellerhals and Church, 1980).

In general, as a result of a decreased sediment transport capacity during the ice-covered period, there is also a greater tendency of fine material to deposit onto the bed. Moreover, since the winter period on most cold-regions rivers is characterized by steady flow recession, and rarely interrupted by episodic mid-winter rises in discharge, the end of winter can be the time of maximum annual fine-grain deposition (Milburn and Prowse, 1998a). This can have important ecological effects since there is a strong correlation between increasing trace-element and pollutant concentrations and decreasing particle size (e.g., Horowitz, 1991; Bero and Gibbs, 1990). Furthermore, major deposition zones on large rivers are commonly also riparian areas where biological productivity and diversity are maximized (e.g., Johnson *et al.*, 1995; Bayley, 1995). An obvious example of such zones are river delta distributaries, areas where Milburn and Prowse (1998b) have found under-ice sediment deposition to be responsible for retention of sediment-bound contaminants.

Following the minima of the winter flow recession, flow begins to rise as meltwater enters the system. This causes an increase in sediment transport capacity and a resuspension of bed material, the first removed being the fine-grained material noted above. As a result, rivers experience a gradual increase in turbidity or the formation of an under-ice sediment plume well before break-up occurs. In view of the chemical affinity of fine-grained material, the pre-break-up sediment plume can represent a significant seasonal pulse in the water quality of some river systems (e.g., Milburn and Prowse, 1996b). It is important to note that because of logistic and safety concerns associated with conventional sediment-sampling programs, these types of data are rarely collected.

The next major change to the winter ecology of a stream or river occurs at the time of break-up. From a purely physical perspective, break-up is known often to be a catastrophic event capable of producing breaking fronts on large rivers that have been often reported careening downstream at velocities in excess of 5 m/s and increasing water levels at over 1m/min (Figure 7). The potential ecological effect of such a physical disturbance far surpasses anything that is possible except under rare and extreme open-water flow conditions. The following discussions summarize some of the ice-induced changes resulting from break-up, including its effect on fluvial geomorphology, in-channel and riparian biological systems, and even climate.

5.1 FLUVIAL GEOMORPHOLOGY

5.1.1. Erosion and Deposition

Break-up ice runs are an important agent of erosional and depositional change. While the economic damage they inflict on engineering structures can be substantial (e.g., Doyle, 1988; Van Der Vinne *et al.*, 1991), they are also important to the general geomorphological structure of many cold-regions rivers. Evidence of ice erosion abounds on alluvial rivers including, for example, erosional features such as high-level benches (Smith, 1980), undercut banks (e.g., Marusenko, 1956; Code, 1973) and, in permafrost regions, thermoerosional niches (e.g., Lawson, 1983). Although permafrost can, in some cases, limit the initial amount of erosion of banks at break-up (e.g., Eardley, 1938; Gill, 1972; Outhet, 1974a; 1974b), where scour exposes ground ice or ice lenses significant melt can follow, eventually leading to much greater bank destabilization and slumping (Newbury and McCullough, 1983; Scott, 1978; Walker and Arnborg, 1966; Walker, 1969). Slope failures can also result from water level rises that reduce effective (intergranular) pressures in soils, or from the rapid drawdown of water associated with the formation and release of ice jams. Oversteepening of river banks by ice undercutting is also considered a major contributing factor in the initiation of landslides (Code, 1973). More generally, it has been proposed that the regular action of ice break-up plays a major role in channel enlargement (Smith, 1980; Martinson, 1980) but this remains a point of debate (Kellerhals and Church, 1980; Church and Miles, 1982; Koutaniemi, 1984).

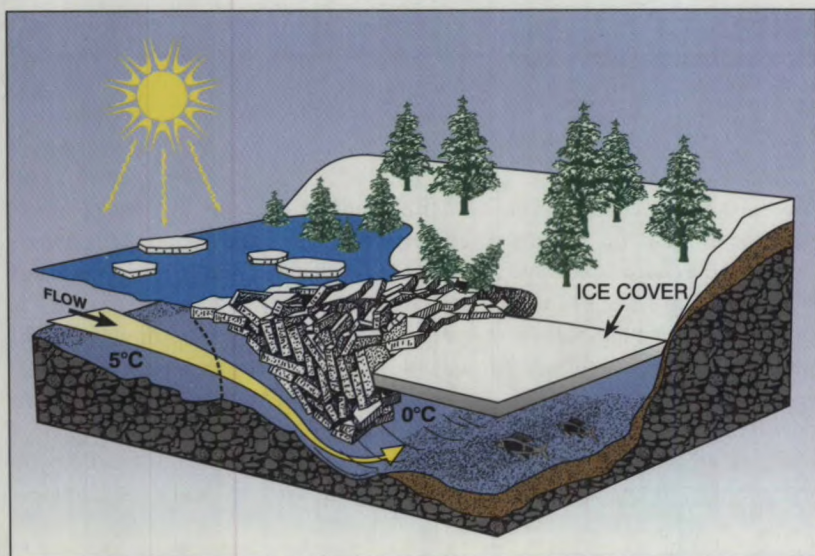


Figure 7: Dynamic transition in processes and habitat created by rapidly moving break-up front.

The diversion of flow by ice jams at meander bends can also produce erosion at the inside of bends (e.g., Martinson, 1980), a sediment deposition zone under normal open-water flow conditions (Figure 8a and b). In extreme cases, such flow diversions could cut off meanders and reduce river sinuosity (Williams and MacKay, 1973) or completely redirect flow into ancillary channels (MacKay *et al.*, 1974). Effects are most pronounced in river deltas, where ice jam floods are often responsible for the shifting of distributaries through channel avulsion (e.g., Dupre and Thompson, 1979). Although most scour effects are evident on fluvial rivers, ice is also known to accelerate erosion of banks comprised of soft rocks such as shale and limestone (Dionne, 1974; Danilov, 1972).

While most erosion features have been observed along the banks and floodplains, break-up activity is also believed to promote scour of river beds by direct ice action (e.g., Danilov, 1972; Collinson, 1971; King and Martini, 1984), especially if underlain by permafrost (McKenzie and Walker, 1974), and through accelerated water velocities, such as found beneath ice jams or produced by ice-jam surges (e.g., Mercer and Cooper, 1977; Wuebben, 1988). The effects are most pronounced if the scour cuts through into more readily erodible underlying strata. Within channel bends, the presence of an ice cover and its effect on transverse velocities are also suspected to decrease transverse bed slopes, as observed in laboratory experiments (Tsai and Ettema, 1994).



Figure 8: (a) Development of a secondary flow channel on the inside of a tributary bend. Main channel is jammed with ice and forces backwater overbank and along route of least hydraulic resistance. (Liard River, NWT, Canada; photograph: T.D. Prowse). (b) Similar diversion of ice-jam backwater along with the shallow margins of a river and on the inside of a meander bend. (Peace River, AB, Canada; photograph: L. Uunila).

Depositional evidence of ice action on rivers varies from thick sediment layers to major boulder accumulations. Most sediment deposits remaining after break-up can be found on floodplain areas within backwater zones of ice jams. They are commonly only a thin veneer but have been reported to be as much as 1 m deep in localized areas from single break-up flood events (Eardley, 1938). Moreover, the backwater flooding produced by ice in river

deltas has been noted to be responsible for the initial development of levees (Henoeh, 1960) and the buildup of land between channels (Hollingshead and Rundquist, 1977; King and Martini, 1984; Ritchie and Walker, 1974). Eardley (1938) suggests that floodplain areas of the lower portions of the Yukon River are some 6 metres above the ordinary river surface because of repetitive deposition during break-up events. This type of deposition combined with scour at lower levels can accentuate the form of the previously mentioned high-level benches that characterize some ice-covered river reaches. So prominent are some of these ridge or bench features, particularly those repetitively worked by ice push, that they have been specifically named as *bechevniks* on Russian rivers (Hamelin, 1979). The word stems from *becheva* meaning a towrope; the *bechevnik* being that portion of a river bank that can be used for towing river craft.

Ice-push produces a number of other large-scale depositional features, most notably at the upstream ends of islands and at the outside of channel bends (Figure 9). At such sites, layers of light alluvial material can be bulldozed each year into obvious ramparts but are then usually washed down by later runoff and flow (e.g., Bird, 1974). If, however, the bank material is comprised of heavier till, the banks may be gradually protected by the

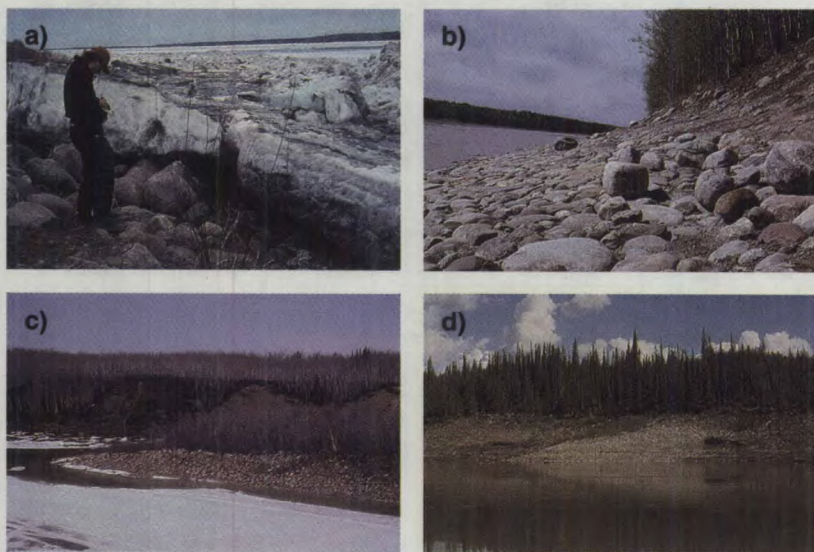


Figure 9: (a) Redistribution and sorting of boulders by ice gliding during break-up. (Liard River, NWT, Canada. (b) Boulder pavement. (Mackenzie River, NWT, Canada; photograph: D.K. MacKay). (c) Boulder barricade. (Mackenzie River, NWT, Canada; photograph: T.D. Prowse). (d) Boulder buttress. (Mackenzie River, NWT, Canada; photograph: T.D. Prowse).

formation of distinct boulder/cobble accumulations. Boulder pavements, for example, are formed by the overriding action of rock-shod ice which tends to align boulders with their long axis parallel to the river bank and to size sort them so that size decreases downstream (Mackay and MacKay, 1977). On large northern rivers, such as the Mackenzie and Yukon, wide (7-30 m) stretches can cover hundreds of kilometres of river bank (Kindle, 1918; Wentworth, 1932). Common to lake and marine environments, river ice also produces other boulder features including buttresses or barricades, common at the upstream ends of islands, and boulder ridges that develop perpendicular to the river and usually terminate in a hook pointing downstream, similar to that of a sandspit (e.g., Rosen, 1979; Barnes, 1982; Brooks, 1993).

5.1.2 Sediment Transport

For many high-latitude rivers, ice break-up occurs concurrently with spring freshet, often the major hydrologic event of the year (Church, 1974; Prowse, 1994). As such, this is usually the major period of sediment transport (Figure 10a and b). For example, Walker (1969) notes for the Colville River in Alaska that almost 1/2 of its discharge and some 3/4 of its sediment load are carried within a three- to four-week period accompanying and immediately following break-up. The greatest concentrations, however, occur during the main period of dynamic break-up. On the Liard River (Northwest Territories, Canada) and upper St. John River (eastern Canada), for example, field studies have shown that although break-up is preceded by relatively low concentrations (<10 mg/L), these usually rise by an order of magnitude just prior to break-up and peak in the several hundred mg/L range to even over 1000 mg/L during active break-up (Figure 11a and b) (Prowse, 1993; Beltaos *et al.*, 1994; Milburn and Prowse, 1996a). The peak values are probably indicative of surge events during which hydraulic conditions maximize sediment transport capacity and high-velocity flow and ice scour maximize sediment input. Prowse (1993) notes that the peak concentrations can be several times that which would occur under open-water conditions for equivalent discharge. Although total load transport during break-up is difficult to assess because of the transient nature of hydraulic and sediment conditions, break-up events on at least these two studied rivers are believed to transport a significant portion of their annual sediment load. Notably, both sets of studies on these rivers also found the material to be very fine with a median size of approximately 10 μm . Again, this could have implications for contaminant transport given the previously mentioned affinity of many chemicals for fine-grained material and the great distances that this largely wash-load material can be transported during the break-up period.

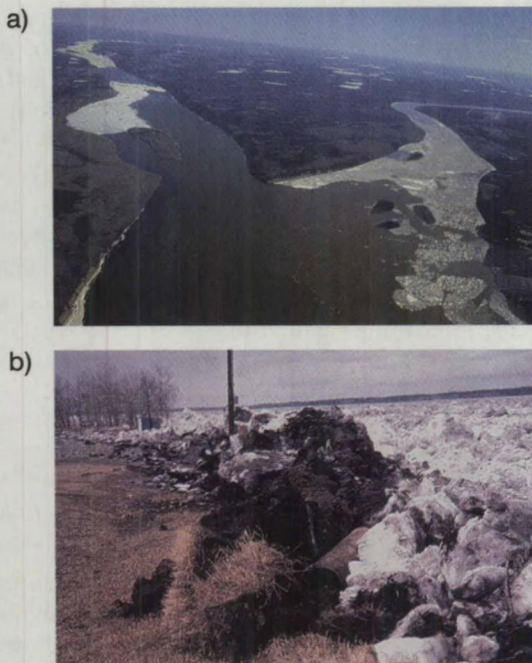


Figure 10: (a) Contrast in sediment dynamics and ice break-up. Both rivers are flowing towards the front of the photograph. Liard River on the right is in active break-up and laden with sediment. Mackenzie River on the left is a lower slope river experiencing a thermal break-up; water is relatively clear. (NWT, Canada; photograph: T.D. Prowse). (b) Erosion of upper bank of Mackenzie River during break-up. Note inundation of hydrometric station in the background. (NWT, Canada; photograph: T.D. Prowse).

Surges during break-up are also likely to be effective transporters of bed load material. Although no direct field measurements have been made, Beltaos (1993) has estimated that sufficient shear stress could be produced by break-up surges (i.e., 5 m/s) to move bed material particles as large as 20 cm in diameter.

5.2 BIOLOGICAL EFFECTS

In addition to modifying the morphological template of streams and rivers, ice is an important modifier of the vegetation and organisms that use the in-channel and riparian areas affected by break-up (Figure 12a and b). Overall, for many cold regions rivers and streams, break-up processes probably establish the annual set-point for biological activity.

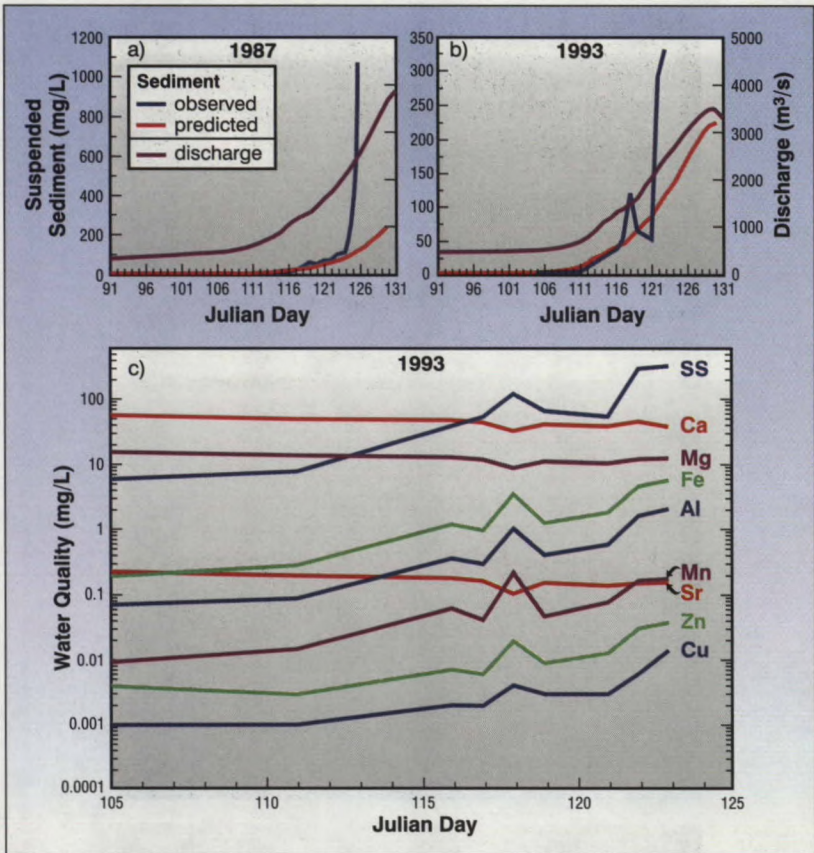


Figure 11: (a) Recorded suspended sediment during break-up of the Liard River, NWT, Canada during a dynamic event in 1987, and (b) a less severe event in 1993. (c) Sediment-water chemistry recorded during the 1993 event.

5.2.1 Vegetation Regimes

Just as break-up can alter the geomorphology of river channels, it can also affect the associated vegetation regime. In general, it is the severity and frequency of break-up activity that determine the floristic composition of riverine vegetation. Although little data exist about the effect of ice and water scour on algal communities, it is reasonable to assume from open-water studies of major floods that such communities would rapidly recover from such impacts. Break-up intensity, however, is likely to affect the timing of peak algal biomass, species abundance, and community composition (e.g., Scrimgeour *et al.*, 1994). Dynamic break-ups, for example, are most likely to deplete severely algal biomass, whereas

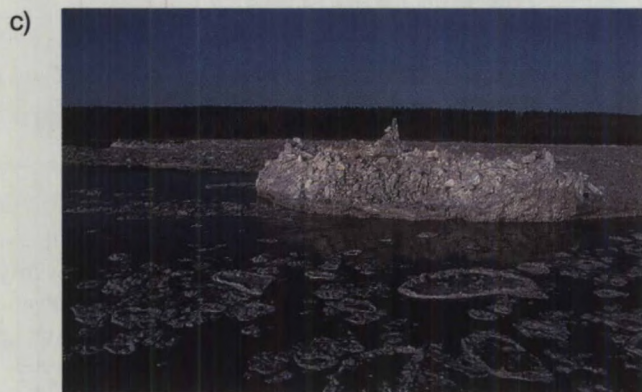


Figure 12: (a) Caribou stranded on ice floes during break-up of the Porcupine River, YK, Canada. (Photograph: M. Jasek). (b) Formation and (c) remnants of an ice island grounded on a shoal during break-up. Elevation of island above water surface is approximately 6 to 8 m. (Mackenzie River, NWT, Canada; photographs: T.D. Prowse).

less-intense thermal break-ups would tend to leave the communities largely undisturbed and able to grow rapidly in the post-break-up period.

Similar relationships exist for break-up effects on submerged macrophytes and riparian vegetation. Again, there is some evidence that vegetation may well respond favourably, below certain limits, to break-up disturbance. For example, Nichols *et al.* (1989) note that although the growth of approximately 20 taxa of submerged macrophytes was impaired by the effects of a severe break-up ice jam, by the autumn of the same year, there was an abundance of taxa equal to or greater than that found after years of less severe break-up. The same holds true for riparian vegetation which exhibits a floristic composition that varies by exposure gradient (Figure 13a; (e.g., Cameron and Lambert, 1971; Uunila, 1997). The most affected communities are those directly exposed to the scour and eroding action of break-up fronts - examples being the heads of islands and outside of bends (Figure 13b and c). A gradual succession to more mesic species in such areas requires a suitable soil structure to develop but this is unlikely if most organic material is removed by the break-up flood.

Often, it is the upper limit of ice action that determines the lower limit of tree growth along river banks. Below this line there is usually a gradient of woody to herbaceous plants. Although severe break-up can largely denude some banks of vegetation (Figure 13d and e), these are often rapidly recolonized by fast-growing, highly productive pioneer species. Willows (*Salix spp.*), for example, have a widespread root structure and despite extensive surface scour are capable of sprouting again soon after break-up has passed. In general, recolonization of herbaceous plants depends on the number of perennating organs remaining after the disturbance and the ease by which plants can be re-introduced from adjacent undisturbed areas. An absence of scour activity, as is characteristic of thermal break-ups, would permit the advance of seral vegetation and the gradual progradation of vegetation down the banks. Over the long term, this would tend to reduce species diversity and overall biological productivity of the riparian zone.

Damage to vegetation along banks has been frequently used as a chronological record of ice break-up activity (e.g., Egginton, 1980; Gerard, 1981b; Gerard and Karpuk, 1979; Henoch, 1973; Parker and Jozsa, 1973; Smith and Reynolds, 1983). When using this type of dating approach, however, an important distinction must be made between ice scars produced by ice-shove (Figure 13f) and those by floating ice: only the latter being a reliable indicator of water level. Separation of annual records of tree scars into ice-shove and floating ice damage is usually possible given that the scars produced by ice shove are normally very localized whereas the abrasion produced by floating ice should be apparent at similar levels along a river reach.



Figure 13: (a) Vegetation galleries resulting from ice scour of banks. (Peace River, AB, Canada; photograph: L. Uunila). (b) Ice push along island and formation of vegetation galleries. (Liard River, NWT, Canada; photograph: T.D. Prowse). (c) Ice push into mature forest. (Mackenzie River, NWT, Canada; photograph: T.D. Prowse). (d) Ice scour grooves in bank vegetation. (Peace River, AB, Canada; photograph: L. Uunila). (e) Forest wreckage cone comprised of accumulation of mature tree trunks. (Liard River, NWT, Canada; photograph: T.D. Prowse). (f) Typical scar on mature tree providing evidence of height of break-up ice action. (Little Southwest Miramichi River, NB, Canada; photograph: T.D. Prowse).

Although largely unaffected by the action of ice scour, vegetation communities within perched basins of river deltas (Figure 14a and b) have also been shown to be dependent on the severity of break-up flooding (Pearce, 1991; Prowse and Conly, 1996; Timoney, 1996). These cases are related to the magnitude and frequency of overbank flooding. Without flooding, the basins begin to dry and highly productive wetland vegetation is gradually succeeded by meadow communities and ultimately by the invasion of more persistent woody species (Figure 14c).

5.2.2 Fish and Benthic Organisms

Similar to the observations concerning submerged macrophytes, the few observations about break-up effects on benthic organisms suggest that the effects of break-up, although not quantified by severity, are relatively short-lived. Bradt and Wieland (1981), for example, noted that following a severe ice year (Bushkill Creek, Pennsylvania, USA) there were changes in total numbers, biomass and dominant taxa but there were not significant changes in the total number of taxa and the diversity index. In general, despite varying environmental conditions, the macroinvertebrate community was relatively stable.

Evidence also suggests that particular invertebrates display specific behavioural responses to ice break-up. Clifford (1969), for example, notes nymphs that congregate in pools beneath the ice cover at low water (Bigoray River, Alberta, Canada) begin to move out as break-up begins and migrate along the shoreline into safer conditions within the tributaries. Another apparent avoidance strategy involves stoneflies that after emerging from a stream drop their eggs in an upstream lake, where they hatch and spend the winter before drifting back into the stream in the spring, thereby escaping the effects of river ice break-up (Harper, 1981; Müller *et al.*, 1976).

Again, although sparsely documented, it appears that some fish exhibit forms of avoidance behaviour to ice break-up. Swales *et al.* (1986), for example, believe that part of the reason juvenile steelhead trout (*Salmo gairdneri*) shelter at considerable depth beneath large rocks and rubble in winter is to avoid the physical damage that could be induced by ice scour. The selective advantage of such avoidance behaviour is clear considering the results of Cunjak *et al.* (1998) who found that the disturbance created by a mid-winter dynamic break-up in a Miramichi tributary (New Brunswick, Canada) was responsible for major declines in that year's survival of various life stages of Atlantic salmon, especially those in the immobile egg stage at the time of the disturbance (Figure 15). Moreover, this particular case study also illustrates the ecological significance of the timing of break-up events relative to

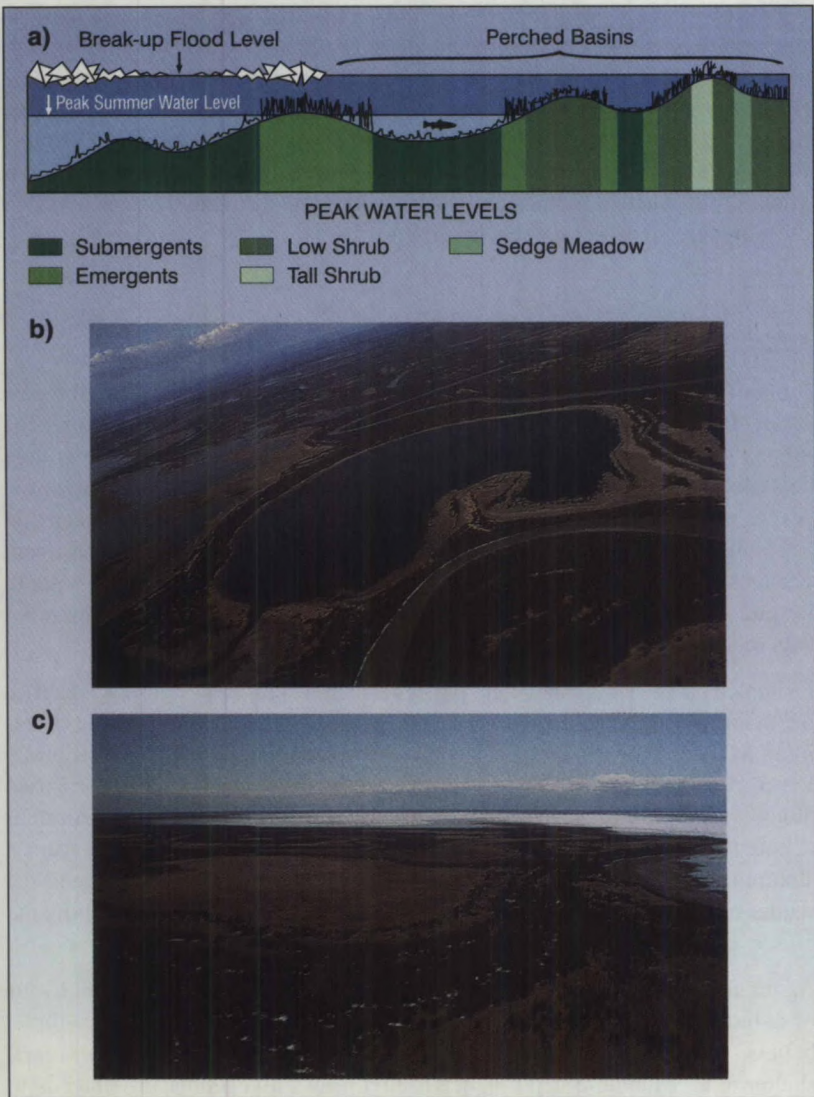


Figure 14: (a) Vegetation composition of water level in perched basin and maximum water levels achieved under open-water and ice break-up conditions (Peace-Athabasca Delta, AB, Canada). (b) Typical perched basin fed by overbank flooding produced by ice-jam backwater. (Peace-Athabasca Delta, AB, Canada; photograph: T.D. Prowse) (c) Perched basin that has dried over multiple years without ice-jam flooding. Note encroachment of woody vegetation at basin perimeters. (Peace-Athabasca Delta, AB, Canada; photograph: T.D. Prowse).

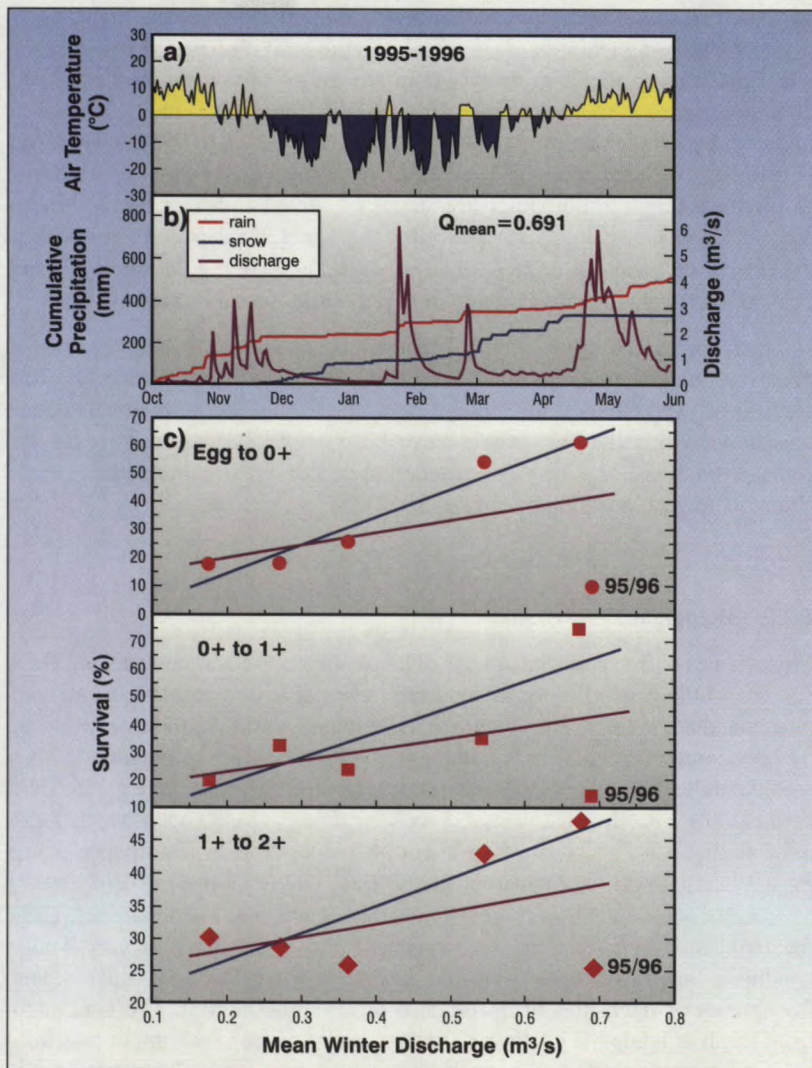


Figure 15: Ice break-up conditions leading to low survival rate of Atlantic salmon, Catamaran Brook, NB, Canada (after Cunjak et al., 1998). (a) Mid-winter warming accompanied with (b) a rain-on-snow event produced a mid-winter peak in discharge and break-up of the ice cover that normally occurs in early spring. (c) Normally the stream exhibits a strong correlation between survival rate of various life stages, especially eggs, and mean winter discharge. Very low survival occurred in 1995/96 despite relatively high mean discharge. The low % survival was attributed to scouring effects of the mid-winter event, especially for the younger age classes.

various life-stage development of biota. Although river ice break-up is primarily a spring event in areas of cold continental climates, it can occur at any time during the winter season in the more temperate and maritime climatic regions, and is usually initiated by rapid snowmelt such as is induced by rain-on-snow events (e.g., Lawford *et al.*, 1995). Given this variability in seasonal timing, river-ice break-up poses a potential disturbance threat to all winter life-stages of stream and river biota, the less mobile stages being the most susceptible to impact. Furthermore, any shift in the timing of break-up induced by, for example, flow regulation or climate change, could also mean a change in the potential biotic impact.

Apart from direct physical disturbance, ice break-up is also known to produce undesirable habitat conditions by modifying general flow conditions. Specifically, the storage of water behind ice jams or its sudden drawdown when the jam breaks have both been cited as reasons for the suffocation of fish that become stranded in dewatered stream reaches or side channels (e.g., Needham and Jones, 1959):

5.2.3 Biological Disturbance

Most studies of the biological effects of break-up are site or time-specific. There has been little research into its long-term effects. It is reasonable to assume, however, that the time-series nature of these would be similar to those produced by open-water floods. That is, although possibly varying by magnitude, they would parallel the open-water response to degree of disturbance (e.g., see Resh *et al.*, 1988). Specifically, measured ecological responses to open-water floods indicate that it is the intermediate event or middle class of disturbance that is most beneficial to biological diversity (i.e., the *intermediate disturbance hypothesis*; see Connell, 1978 for original theory and, Ward and Stanford, 1983, for application to open-water lotic regimes). Physically harsh or very benign conditions are characterized by the lowest diversity whereas intermediate frequencies or intensities of disturbance produce the highest. The continuum from harsh to benign is analogous, in the context of ice break-up, to that from *pre-mature* or *dynamic* to *over-mature* or *thermal* (e.g., see Gray and Prowse, 1993). Advancing this line of reasoning one step further, it is to be expected then that any alteration to the regime of break-up intensity of a river, such as produced by climate or flow regulation, would also have a direct effect on in-channel and riparian biological productivity. If, for example, dynamic break-ups are virtually eliminated and thermal events dominate - a regime that might seem desirable for protection of developed areas - the result could be lower overall biological diversity and productivity. To avoid such negative ecological impacts, it would therefore seem prudent in regulated systems to ensure that dynamic break-up events remain at least a limited part of the regular regime.

5.2.4 Water Chemistry

Water quality during break-up is dominated often by high sediment concentrations and, from an aquatic ecology perspective, these can have both positive and negative effects. The latter generally relates to reductions in species diversity and abundance brought about by, for example, reductions in the quantity and quality of available habitat, difficulties in feeding and filtering, reduced primary production, etc. Elwood and Waters (1969) note that winter and spring floods can have an immediate disturbance impact on invertebrate populations but also a lagged impact on fish populations because of habitat destruction induced by the deposition of sand and debris in pool and riffle areas (Figure 16a). By contrast, however, the transport and deposition of sediment material can also mean improved productivity because of inputs of organic material and nutrients. Lotic food webs are powered by the supply of organic matter, which for many rivers is supplied to the channel by seasonal floods that flush the riparian zone. Given that the magnitude and recurrence interval of water levels produced by ice jams often exceed those for open-water conditions, break-up is probably the main supplier of allocthonous organic material on cold-regions rivers (Figure 16b). In the same manner, break-up probably serves as an indirect

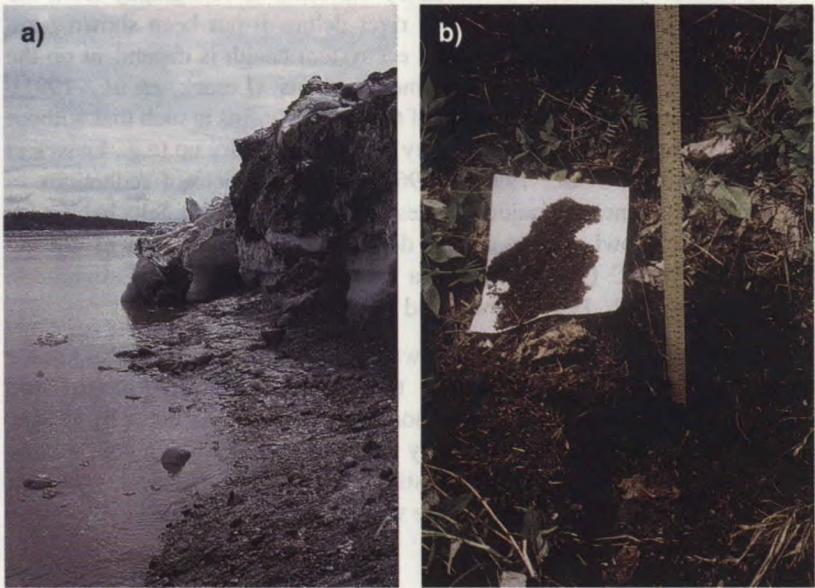


Figure 16: (a) Thick veneer of sediment coating the cobble bed material after break-up. (Liard River, NWT, Canada; photograph: T.D. Prowse). (b) Deep layer of organic material deposited on floodplain from a break-up ice jam. (Little Southwest Miramichi River, NB, Canada; photograph: T.D. Prowse).

driver of primary and secondary productivity through the supply of nutrients - a common limiting factor to productivity in cold-regions rivers. The dissolved and particulate organic matter flushed into the river from shorelines and floodplains is likely to contain significant amounts of important nutrients, such as nitrogen and phosphorus (e.g., Scrimgeour *et al.*, 1994; Harper, 1981).

Despite the increasing recognition of break-up flooding as a dominant flood mechanism on cold-regions rivers, its ecological significance has not yet been incorporated into river-ecology models, such as the fundamental *river continuum concept* (Vannote *et al.*, 1980; Minshall *et al.*, 1985) that describes a streamwise dependence of ecosystem-level processes on a downstream integrating series of physical gradients and associated biotic adjustments. Moreover, break-up flooding has been ignored when the basic ecological theory has evolved to consider the importance of flood pulses, including their significance in distributing material to riparian zones and floodplains (e.g., Power *et al.*, 1995; Junk *et al.*, 1989). This is most likely because research in temperate and open-water systems has provided most of the data on which river-ecology theory is based. The role of ice-jam floods in supplying organic material and nutrients to floodplain areas, however, is reasonably well documented. The best examples are provided by "perched" basins (those hydraulically removed by elevation or topography from the main open-water channel system) in river deltas. It has been shown for a number of major northern deltas that ecosystem health is dependent on the spring input of water, sediment and nutrients (Lesack *et al.*, 1991). Moreover, the annual water balance of these delta basins is such that without the input of break-up floodwaters, they would simply dry up (e.g., Lesack *et al.*, 1991; Prowse *et al.*, 1996a; 1996b). Direct impacts of reductions in ice-jam flooding include major declines in the availability of delta habitat for migrating waterfowl, and in similar declines of the population of aquatic mammals (PADIC (Peace-Athabasca Delta Implementation Committee), 1987; Beltaos *et al.*, 1993; Prowse and Conly, 1996).

The final export of break-up ice and water to marine systems is also known to be an important modifier of the morphologic, hydrologic and oceanographic development of nearshore environments. As noted by Walker (1974), the sudden influx of relatively warm fresh water into a cold marine ice-covered system can produce drastic changes in the physical, chemical and biological nature of the nearshore waters.

5.3 CLIMATIC INFLUENCES

Break-up-induced flooding of delta systems can be extensive enough to produce meso-scale climatic influences. This results from a rapid change in surface temperature and albedo. Particularly during dynamic (or mechanical) break-ups characterized by a sequential downstream clearance of ice, there is commonly a rapid increase in water temperature at the ice-water break-up interface (Prowse and Marsh, 1989). This large hydrothermal flux can rapidly melt ice contained within the delta channels and ponds and cause a rise in the air temperature. At the same time, melting of the highly-reflective snow and ice cover and injection of dark sediment cause a dramatic reduction in surface albedo. Much greater radiative warming can then occur within the lower boundary layer of the atmosphere. On the Mackenzie River Delta, for example, conditions typical of a dynamic break-up have led to almost complete inundation of the entire delta landscape, and a rapid increase in air temperature by as much as 5°C. In contrast, a thermal break-up produced only 30 - 60% flooding and had little effect on air temperature (Hirst, 1984). Even moderate increases in air temperature near 0°C at this time of year can be biologically important, such as in stimulating budding and early-spring plant growth (e.g., Gill, 1974).

For many decades, the study of river ice has focussed primarily on hydraulic issues. Only in the past ten years has there developed a significant interest in the broader field of environmental aspects of river ice. Although this is a nascent science, river ice has been shown to affect numerous environmental processes and create unique ecological conditions at all scales of riverine systems, from brooks to major rivers and deltas. Incorporating information about river ice into the ecological understanding of lotic systems, however, will be most difficult for the larger scales. This is primarily because there is no clear theoretical basis for the functioning of large-river ecology even under open-water conditions (e.g., Johnson *et al.*, 1995). Hence, achieving a greater understanding of the environmental aspects of river ice will not only require further advances in the physical sciences but in the field of aquatic ecology as well. The most efficient method to achieve this is to conduct, whenever possible, multi-disciplinary studies of river ice. From a more general river-management perspective, it would also seem prudent to begin expending resources to a degree that more closely reflects the proportion of the year that rivers are affected by ice. For many hydrologic regimes of the world, streams and rivers are ice-covered for a majority of the year, yet minimal research is conducted during this period compared to the more 'researcher-friendly' open-water period. Without doubt, scientific progress is hampered by the logistical difficulties and high costs associated with conducting 'winter' research. Such obstacles, however, can no longer be deterrents if a comprehensive understanding of lotic systems is to be achieved.

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