USING ICE TO FLOOD THE PEACE–ATHABASCA DELTA, CANADA

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ABSTRACT

Flooding of deltas on large, northern rivers is usually the result of spring ice-jam events, as opposed to high flows during the open-water season. Some of the most sensitive components of such ecosystems are the perched basins: small ponds and lakes that are hydraulically isolated from the main flow system. The biological structure and productivity of these basins are highly dependent on flooding and flushing associated with high stage events. Major flooding of the Peace–Athabasca Delta, one of the world’s largest and most productive deltas, has not occurred since 1974, the time of the last major ice-jam event. Prior to this, the Delta also experienced an extensive drying period, from 1968–1971, as one of its main rivers became regulated. As a result, extensive changes have occurred in the vegetation regime and associated wildlife habitat. Recognizing the historical role of ice-jam flooding, attempts are being made to induce flooding through regulation of the natural flow system using ice. The changing hydroecology of this flood-dependent ecosystem, common approaches related to regulation effects and river ice covers, and the unique strategies used to construct artificial ice dams and/or initiate ice jams, are all reviewed.

KEY WORDS: climate variability; delta ecology; flooding; ice jams; remedial measures; river ice; river regulation; water balance

INTRODUCTION

Ice is an integral component of the hydrology of cold region rivers and streams and creates many of the annual hydrological extremes. These can vary from the production of high magnitude floods, which regularly surpass those experienced under open-water conditions (Gerard and Karpuk, 1979), to annual low flows, which occur at autumn freeze-up instead of late winter when landscape runoff is normally at a minimum (Gray and Prowse, 1993). Historically, most attention has been placed on river ice because of its flood potential during both autumn freeze-up and spring break-up. The magnitude of economic losses resulting from ice-flood processes has been significant enough to stimulate extensive science and engineering research into the development of methods and structures to prevent or mitigate ice related hazards.

More recently, however, river ice has been recognized as having important ecological significance (Prowse and Gridley, 1993; Prowse, 1994). In particular, the immense disturbance created by break-up ice scour and flooding is now considered as a strong biological set-point for many river ecosystems (Scrimgeour et al., 1994). Nowhere has the importance of break-up, ice-jam flooding to river ecology become more evident than in the perched basin environments of northern rivers and deltas (Prowse and Gridley, 1993). This paper focuses on the Peace–Athabasca Delta (PAD), which has experienced serious periods of drying over the last three decades. The earliest period of drying began in the late 1960s associated with the filling of a large hydroelectric reservoir, some 1200 km upstream. Notably, however, two major floods inundated the PAD in the early 1970s after regulation. None has occurred since, and a second drying trend has ensued. Prowse and Lalonde (1996) have revealed that this decline is related to a decreased frequency of spring ice-jam flooding. An analysis of hydrometeorological factors controlling ice-jam occurrence identified both flow regulation and climatic variations affecting spring snowmelt in downstream tributaries as important in the decline. Establishing the relative significance of each factor is currently the focus of additional research. Early suggestions that ice jams could have played a role in flooding of the PAD, and more recent scientific confirmation of such, had led to attempts to recreate such flooding through construction of artificial ice dams and jams. The aim of this paper is to examine the various approaches that have been used to construct such
ice accumulations. As a background, we review the common reasons and standard approaches for modifying ice/spring flow regimes, then analyse the unique physical design and hydrological significance of the methods used in the PAD. Descriptions of the PAD study site and the hydroecological changes that have occurred as a result of reduced flooding and associated drying are also included.

STUDY: PEACE–ATHABASCA DELTA

Study site description

The Peace–Athabasca Delta, covering some 3900 km², is one of the world’s largest, inland, freshwater deltas. It has evolved from alluvial deposits from three separate flow systems, the Peace, Athabasca and Birch Rivers (Figure 1). The PAD and the adjacent Lake Athabasca are hydraulically connected to the northward flowing Slave River via three, large shallow lakes (Claire, Mamawi and Baril; < 1 to 3 m deep) and a myriad of channels (approximately > 100 m side and up to 10 m or more deep), primarily including the Rivière des Rochers, Chenal des Quatre Fourches and Revillon Coupé (Figure 2). Channel discharge is proportional to

![Map of Peace, Athabasca, Lake Athabasca and Slave River catchments](image)

Figure 1. Peace, Athabasca, Lake Athabasca and Slave River catchments in the provinces of Saskatchewan, Alberta and British Columbia, and the Northwest Territories. Inset shows location within Canada.
the difference in water levels of the lakes and the Peace River, both of which can vary significantly between winter and summer. The dominant flow direction is northward but can reverse when the Peace River water levels are higher than those of the lakes. Peak water levels occur on the Peace and Athabasca rivers during spring break-up (late April–early May) and a few weeks later (June) from snowmelt in the Rocky Mountain headwaters. It is during these two periods that high water levels on the Peace River can obstruct the northward flow of water. As a result, lake water levels are typically highest in the Delta and on Lake Athabasca during the spring and summer, but then recede during fall and winter when the outflow to the Slave River is greater than inflow to the Delta.

Surrounding the main lake and channel system are some 1200 km$^2$ of sedge meadows and grasslands. Hundreds of shallow basins are distributed around this landscape and, when filled with water, create some additional 19 000 km of shoreline (Townsend, 1984). Filling of these basins depends on the efficiency of the hydraulic connection to the main flow system. Three types have been classified from previous hydrological studies (PADPG, 1973; Figure 2). In the 'open drainage' type, water levels fluctuate in direct accordance with adjacent lakes and channels. Some form of hydraulic restriction characterizes the 'restricted drainage' type, causing a temporary lag in water level relative to the primary flow paths. 'Isolated' basins are those in which significant infilling can be achieved only through overbank flooding, and decreases in water level are almost exclusively controlled by evapotranspiration. Although some deep groundwater recharge and flow through the levees occurs, the low hydraulic conductivity of the silty clay material dictates that rates are negligible (Nielsen, 1973) compared with the other water balance terms. Annual precipitation averages 381 mm yr$^{-1}$ (Atmospheric Environment Service, 1993) and small pond evaporation equals 450 mm yr$^{-1}$ for this region (Fisheries and Environment Canada, 1978), resulting in an annual water deficit of approximately 70 mm yr$^{-1}$. Hence, periodic overbank flooding is critical to retaining a significant depth
of water in these basins. Such flooding, especially in the northern parts of the Delta, is believed to be related to the formation of spring ice jams on the Peace River (Prowse and Lalonde, 1996).

Periodic flooding and drying are also essential to maintaining a high level of biological productivity within the perched basins. Important local species, such as muskrat and bison, thrive on early successional forms of emergent and submergent vegetation that can only be produced within shallow marsh environments. Since the elevational range of most delta plant communities is quite small, only minor changes in water levels can lead to the advance or retreat of plant succession over large areas. Determining how vegetation succession has responded to historic drying and flooding periods is the focus of additional PAD studies.

**Hydroecological changes**

Changes to the ecology of the PAD are related to two hydrological events: the original filling of the Williston Reservoir between 1968 and 1971, and the decrease in ice-jam flooding that has occurred since 1974. Over the four-year filling period, some $41 \times 10^9$ m$^3$ of water was held back from the Peace River (Muzik, 1985) reducing flows by as much as 5600 m$^3$ s$^{-1}$ and river water levels near the PAD by as much as 3–4 m. The impact on the PAD was dramatic: the shoreline was reduced by 36% and the water surface by 38%, exposing some 500 km$^2$ of mudflats (Townsend, 1975). After initial filling of Williston Reservoir, there was a general displacement of flow volume from the summer to the winter months. Despite the existence of a number of large tributaries between the reservoir and the PAD, the downstream seasonal changes on the hydrograph were still quite pronounced (Figure 3). As a result of the initial drying a rapid decline in the muskrat population ensued (Townsend, 1975, 1984), and productive sedge-meadow vegetation was replaced by more invasive woody forms, such as willow and poplar.

Early impacts on the Delta associated with reservoir filling resulted in the creation of a major federal–provincial programme, the Peace–Athabasca Delta Project Group (PADPG), which included major hydrological and ecological assessments of this poorly understood, remote environment (PADPG, 1972, 1973). To mitigate lowered lake and channel levels in the PAD, one of the PADPG recommendations was to construct rock-filled weirs and to conduct a preliminary investigation of using ice in a regulating structure (discussed later). The first rock-filled weir, established on the west arm of the Quatre Fourches, was successful in raising lake water levels during a large spring runoff event in 1972, but the crest of the weir was damaged by an ice push. Since the weir was believed to pose an impediment to the migration of fish between the large lakes, it was ultimately decommissioned by removing the top few metres of strata. New rock weirs, including a fish passageway, were subsequently constructed on the Revillon Coupé and the Rivière des Rochers (Figure 2).

![Figure 3. Pre- and post-regulation hydrographs for Peace River at Peace Point (based on monthly mean flows)](image-url)
ICE FLOODING OF THE PEACE-ATHABASCA DELTA

Since the mid 1970s, a one-dimensional flow model has been developed and used to assess the performance of the rock weirs (Peace–Athabasca Delta Implementation Committee; PADIC, 1987). Overall, the weirs have proven to be relatively successful in restoring water levels on the delta lakes and channels to their pre-regulation state (PADIC, 1987; Prowse et al., 1996). Within many perched basins, however, a serious drying trend developed following the last major overbank flood in the spring of 1974.

In 1990, the Peace River experienced an open water discharge event surpassing any on record, including the previous high recorded prior to regulation in 1964 (Prowse and Lalonde, 1996). Although such flow events significantly raised the water levels in the large lakes and perched basins, characterized by low elevation connections to the main flow system, they were ineffective in flooding the isolated or high elevation perched basins. In response to the protracted drying of the PAD, another federal–provincial study (Peace–Athabasca Delta Technical Studies, PADTS) was initiated that included the participation of local native bands and the British Columbia Hydro and Power Authority—operators of the upstream reservoir. Recognizing that the rock-filled weirs were never going to be effective in flooding such zones, this group placed a renewed emphasis on developing unique ice-based control structures. These are described following a review of traditional ice regulation methodologies.

METHODS FOR ICE CONTROL IN LARGE RIVERS

Traditionally, strategies developed to modify river ice regimes have been formulated with the objective of optimizing the operation of hydroelectric plants (Wigle et al., 1989) or reducing ice-jam floods (Beltaos, 1995). Most intervention strategies have involved in-channel structures and/or flow regulation schemes to control freeze-up or break-up. Structures include temporary booms, frazil screens and fences placed across a channel or permanent pilings or piers. All have the same general design purpose: to act as a surrogate ice edge for initiating and/or retaining an accumulating ice cover.

Flow regulation, usually involving dams or weirs, is often used in combination with ice control structures. In the case of freeze-up, a common objective of regulation is to create the flow conditions most conducive to formation of a stable ice cover, thereby preventing the massive ice production that often occurs through frazil ice generation in the more turbulent reaches. The most common approach simply involves a lowering of the flow (and hence velocity) to permit juxtapositioning and freeze-up of ice floes into a solid cover. This can minimize the potential for freeze-up floods resulting from large, thick accumulations of ice, or minimize operational problems associated with the generation of frazil upstream of hydropower facilities. Quite a different flow regulation strategy, however, may be adopted for controlling freeze-up conditions downstream of a hydropower plant. In this case, flow can be temporarily increased to permit the downstream ice cover to develop and stabilize at an elevated stage. This reduces the possibility of premature, mid-winter break-up induced by hydropower operations.

Flow regulation procedures also exist for controlling break-up through attenuating runoff and preventing sudden stage increases (IAHR, 1986). The overall objective is to avoid situations where an ice cover begins breaking in an upstream reach and is driven into more competent ice downstream, where it could jam and induce flooding. Minimizing the potential for break-up flooding is best achieved when break-up proceeds upstream and at a rate at which the downstream channel can safely pass the ice without it lodging and accumulating into a jam. It is, however, often impossible or impractical to ensure that break-up proceeds in an upstream direction, and other procedures have been used to ensure that the downstream cover does not pose a critical blockage to the passage of upstream ice. For example, the dusting of an ice cover to decrease its mechanical strength; cutting, blasting and removal of ice cover at key locations, and ice-breaking vessels have been used. Hence, the usual objective of break-up control is to prevent flooding. The PAD situation is unique in that ice management is intended to increase the probability of ice-jam flooding.

METHODS OF ICE CONTROL IN THE PAD

Part of the reason for employing ice is its temporary nature: an important consideration given that 80% of the PAD lies within Wood Buffalo National Park. The ice-based control structures designed in the early
1970s and the early 1990s employed two contrasting strategies that operate on different scales and under different hydraulic conditions. The first, termed an artificial ice dam, involves construction of a very thick in-channel obstruction that will lead to significant backwater flooding under subsequent high flow conditions (Figure 4a). In contrast, an artificial ice jam involves creating a less thick, well-grounded structure (bank and/or bed attachments) that can act as a stable collector of inflowing ice. The accumulation is intended to build into a configuration similar to that of a natural ice jam (Figure 4b; see Beltaos, 1995). Extensive backwater can only be achieved during the main break-up period unless artificial means (e.g. blasting) are used to add upstream ice to the accumulation. An ice dam can obstruct flow at any time as long as it remains intact. It should be stressed that enormous amounts of ice are required to cover major channel cross-sections because of their large width (100 m or more) and depth (up to 10 m or more). Moreover, to achieve hydraulic stability, the accumulations generally have to be larger in the stream-wise direction than the river width and require varying degrees of freeboard over the grounded portions of the structure. To construct such a massive accumulation within a subarctic climate poses a considerable scientific and engineering challenge.

Phase I—immediate post-regulation. As part of the original set of remedial measures to control flow within the Delta, an attempt was made to construct an ice-based impoundment on the Rivière des Rochers (Nuttall et al., 1973). The basic principle was to block the channel completely with ice until the early spring to midsummer, when it would act as an obstruction to large open-water flows attempting to exit the PAD into the northward flowing Peace and Slave Rivers. Notably, at this time, the full significance of the role of natural ice jams in flooding was not appreciated and the focus of remedial measures was only on replicating summer flood peaks.

The original design of the Rivière des Rochers ice structure was to use aspects of both artificial ice-jam and -jam strategies. It was to be initiated with the construction of ice berms or wings using surface flooding and water sprinklers. These were to be built outwards from the shore immediately downstream of a rapids section where a hanging dam (localized deep accumulation of frazil ice; see Figure 5) forms naturally. Growth of this accumulation depended on cryopiles (thermal syphons) and additions of ice produced by blasting of the upstream cover. These would subsequently be forced into the interstitial spaces of the cryopile-based accumulation by high velocities from the rapids. The dam was to be approximately 150 m long, up to 20 m thick and able to withstand a 6.5 m difference in head from upstream to downstream. The cryopiles were to ensure the dam remained frozen to the bed during the summer months and a thick (0.6–0.9 m) cover of earth and/or sawdust was to minimize surface ablation. Unfortunately, although the separate components of this multifaceted approach were field tested, problems such as ineffective blasting and cryopile ice generation negated
an integrated, full-scale testing of the strategy. It appears that insufficient resources and the closure of many of the original studies precluded the pursuit of this approach. Although considerable ice hydraulic knowledge was gained from this study, subsequent findings about the dominant importance of spring ice jamming demonstrated that the focus on retaining an ice-structure until well after the spring period was unnecessary.

Phase II—1990s. By the time new scientific studies were initiated in the early 1990s, some of the perched basins near the Peace River had not been flooded for almost two decades. Decisions made by the PADTS group shifted the focus of the previous PADGP and PADIC groups from methods to induce summer floods, to the historical role of spring ice-jam floods and how to replicate them. Although, historically, major ice-jam events that produced wide-scale flooding of the PAD formed on the Peace and Slave Rivers, attention again focused on modifying the ice regime on smaller channels within the PAD. An environmental impact assessment of a potential artificial ice structure on the larger Peace River was also initiated by the PADTS.

Chenal des Quatre Fourches. As in the earlier Rivière des Rochers experiment, a field site for artificial ice-jam construction was selected on a major channel, the Chenal des Quatre Fourches. Although this is a low-slope channel, there was some historical evidence of ice jams forming at a specific sharp bend adjacent to some large perched basins. In the late winter of 1993 a short-term testing of surface flooding and spray ice approaches was conducted (Prowse et al., 1993). One of the objectives was to evaluate whether the spray ice approach (previously used in constructing Arctic sea ice floating platforms and grounded islands, and in ice road construction) could be used to construct large accumulations of ice within narrow (aerodynamically confined) river channels, especially under the subarctic climatic conditions experienced in the PAD. A comparison between initial field experiments using surface flood-freeze and spray ice methodologies in the PAD is presented in Prowse et al. (1996). Spray ice proved to be a far superior method for producing the large quantities of ice necessary to block the large, deep channels. Unfortunately, mild spring melt and runoff conditions precluded formation of a significant ice run in the channel, and no jamming resulted.

Quatre Fourches—west arm. In the winter of 1994/1995 a decision was made by the PADTS to employ again the spray ice methodology, to build an ice dam over the remnants of the original rock-filled weir on

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Figure 5. Early multi-faceted ice dam design for the Rivière des Rochers based on a description from Nuttall et al. (1973)
the west arm of the Quatre Fourches (Figure 2). This site is a critical hydraulic node in the PAD because all water from the catchment areas of the large delta lakes (e.g. Birch River) must pass through it before entering the main northward flowing channels (Figure 2). Its hydraulic significance was enhanced in the early 1980s by the rapid growth of a breakthrough channel (Cree Creek) which now permits the direct entry of spring flow from the Athabasca River into the interior of the PAD, instead of the total flow being fed into Lake Athabasca.

Remnants of the rock weir would also provide stability to the ice dam and reduce the volume of spray ice required to block completely the channel cross-section. Over the winter of 1994/1995, approximately 60,000 m$^3$ of ice was sprayed into the channel. This grounded the natural ice cover and created a structure 100 m long, spanning two channels, 50 m and 100 m wide, either side of a prominent island. Average deposition amounted to 3.5 m at a mean elevation of 209 m (a.m.s.l.). Several reference elevations for typical perched basins, levees, open water weir ranges and the 1974 ice-jam flood are depicted in Figure 6.

Unfortunately, above-normal winter temperatures and a pronounced mid-winter decline in water levels due to upstream regulation (e.g. see Peace River discharge data, Figure 6) complicated the ice production and prevented the establishment of the design freeboard (212 m a.m.s.l.). Notably, the mid-winter local decline in water levels (see Mamawi Lake water level data, Figure 6) was considered unprecedented by many local inhabitants.

The efficiency of the structure was further complicated by abnormally low spring runoff (see flow for Athabasca and Birch Rivers, Figure 7) which severely limited the amount of water available for storage behind the dam. As a result, the ice structure gradually decayed over the early spring period, lost its grounding and finally disintegrated into large pieces as it was forced downstream by the impounded
water. Despite the less than favourable hydrometeorological conditions, the structure still managed to store a significant amount of water. This is evidenced by the rapid recession of water levels following dam release (2 May) and an associated, observed surge in flow velocities (Figure 6). A post-study analysis suggests that with more constant winter water levels and average spring runoff conditions, localized flooding of some of the perched basins could be achieved with an ice structure in the west arm of the Quatre Fourches.

SUMMARY

Traditionally, regulating the ice regime of cold streams and rivers has involved the construction of structures or the operation of specific flow schemes designed to minimize flood effects and/or optimize hydroelectric production. The example of the Peace–Athabasca Delta heralds a new era in ice research; one that is based on a recent recognition of the ecological significance of river ice to natural systems. Despite over twenty years of hydroecological research conducted in the PAD, only recently has it been acknowledged that ice-jam floods are the principle method by which essential floodwater could replenish a vast area of this valuable ecosystem.
Compared with the vast research and resources expended on methods to minimize ice-jam floods, the PAD efforts are relatively small. Despite the lack of flooding success to date, significant advances have been made in designing ice-based, remedial regulation strategies and integrating them properly within the natural flow regime. Thus, the best opportunity for achieving successful ice-effected flooding is to construct ice-dams, using spray ice systems, at critical hydraulic nodes for operation during the spring runoff period. Based on such an approach, the site in the west arm of the Quatre Fourches has a good probability of achieving localized flooding of restricted and isolated perched basins near the large delta lakes, if spring runoff conditions comply. Similar success might be achieved in other localized areas of the PAD using a combination of the ice-dam and ice-jam strategies. Restoration of macro-scale flooding of the PAD, however, is possible only through disrupting flow on the large Peace or Slave Rivers. While not physically impossible, the design of such a large structure requires, by federal legislation, an environmental assessment of related impacts, especially those that could result from a major downstream surge when the jam releases.

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