Hydro-climatic Impacts Affecting the Peace-Athabasca-Slave Catchments and Deltas


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ABSTRACT

The Northern Rivers Ecosystem Initiative (NREI) was established in the late 1990s to address important science questions resulting from previous studies undertaken by the Northern River Basins Study (NRBS). This manuscript reports on a number of integrated hydro-climatic studies of the Peace-Athabasca-Slave river and lake systems. Specific concerns expressed by the NRBS and subsequent NREI focused on how these systems were being affected by climate change and flow regulation. Issues addressed in this report include: the fate of aquatic perched basins within the Peace-Athabasca Delta under historical and future climate trends; the sources of major floods that replenish these basins and how the frequency, magnitude and source areas of such events have changed with time (climate variability) and from the effects of regulation; the specific hydro-climatic conditions required to produce major ice-jam floods on the Peace River and how these may be altered by climate change; the synoptic weather patterns and atmospheric teleconnections that are responsible for the generation of major snowmelt runoff that drive the ice-jam floods; and the dual effect of climate and flow regulation on the water levels of Great Slave Lake and how these may affect other near-shore processes, such as wind seiches and ice jamming, that influence flooding of the Slave River Delta. A review of the major findings and recommendations for future research concludes the report.

Keywords: hydrology, climatology, climate change, flow regulation, modeling, Athabasca River, Peace River, Slave River, delta.

* This report may be cited as:
INTRODUCTION

The Peace-Athabasca Delta (PAD) and Slave River Delta (SRD) are two major river deltas located in the upper drainage network of the Mackenzie River in northern Canada. Concern developed over the ecological health of this river system in the early 1970’s following regulation of its main headwater river, the Peace River. Further concern following two decades of drying lasting into the 1990s prompted a series of major hydro-ecological assessments as part of the Northern River Basins Study (NRBS; Prowse and Conly, 2002; Prowse et al., 2002) and the Peace-Athabasca Delta Technical Studies (PAD-TS, 1996). Although the Peace-Athabasca-Slave system was found to be influenced by the effects of flow regulation, the results indicated that climate variability over the past several decades has also been an environmental stressor on the region’s hydrology (Prowse and Conly, 2001). One of the most important stresses on the riparian ecology of the deltas was found to be periodic droughts that specifically affected the high-elevation perched basins of the PAD. Retention of water in such basins was shown to be highly dependent on the occurrence of ice-jam floods along the Peace River (Prowse and Lalonde, 1996; Prowse et al., 1996). Results from a 1st-order analysis of the hydro-meteorological conditions controlling ice-jam occurrence indicated that changes in the magnitude of alpine snowpacks on a major “trigger” tributary (Keller, 1997) played an important role in reducing the frequency of major ice jams (Prowse and Conly, 1996; 1998). Importantly, this tributary was located downstream of the point of regulation and was shown to be historically important, even before regulation, in the generation of downstream ice jams.

Based on the results of these studies, a number of recommendations for future hydro-climatic research were made by the supporting government agencies (Gummer et al., 2001; Northern River Basins Study, 1996). In general, these agencies recommended that further investigations be undertaken to assess the effects of climate and flow regulation on hydro-ecological changes that have occurred within the Peace-Athabasca system, including the PAD, and further downstream, specifically the SRD. This manuscript reports on two studies focused on the PAD and SRD that were commissioned by the NREI to address the research recommendations. The results described below outline the major hydro-climatic effects on the Peace-Athabasca and Slave river/delta systems over the available historical record and, with the use of future climate-change scenarios, illustrate how such effects may be altered in the future. Results are reported in six sections each dealing with separate scientific foci but successively building on one another to provide an integrated evaluation of the hydro-climatic impacts as conceptualized in Figure 1.

Section 1 of this report focuses on the water balance of the perched basins of the PAD, one of the original concerns that initiated the hydrologic studies of the NRBS. For the NREI, the water-balance modelling approach was improved by including field studies within a representative test
basin that were used to test the validity of the model for a decadal period incorporating significant wetting and drying cycles. The validated model was then used to evaluate drying times based on historical records of contrasting climatic conditions. Future climate scenarios were also utilized to estimate the potential effects of climate change on the intra-basinal water balance.

**Figure 1.** Conceptual figure of integrated studies conducted for NREI.

In Section 2, discussion shifts to identification of other hydro-climatic processes affecting the basin water balance, including extra-basinal controls. These include local factors such as inter-delta flow and water-level regimes and regional factors such as the flow and flood regime of the major contributing rivers, evaluations of both open-water and ice-jam flood conditions, and the role of climate and regulation on lake water levels and flow reversals.

Section 3 describes a detailed model applied within the NREI to describe the requisite hydro-climatic conditions for ice jamming, given the established dominance of ice-jam floods to the PAD. The model was employed to determine the magnitude of Peace River flows required to produce an ice jam capable of overtopping the banks and flooding the PAD. Additionally, the upstream hydro-climatic conditions associated with major ice-jam floods were quantified and an assessment made of their future occurrence under a changing climate.
In Section 4, atmospheric conditions responsible for the observed trends in winter snowpack accumulation and spring melt are examined. Given that large snowmelt floods have historically been responsible for driving ice-jam floods, this section describes some of the prevailing synoptic weather patterns and large-scale teleconnections associated with their development.

Further downstream of the PAD, investigations focused on how hydro-climatic conditions had changed on the SRD, as described in Section 5. Water-level conditions in the outermost delta are the most dynamic and arguably, the most productive portions of the SRD. These areas are also strongly influenced by Great Slave Lake. Hence, it was necessary to also evaluate how flow and climate conditions had affected water levels on the lake. Section 5 describes a complete water budget model assembled for Great Slave Lake, which is subsequently used to evaluate historical fluctuations in water levels to partition the effects of natural climate variability and flow regulation.

Additional NREI work focused directly on the SRD. Section 6 describes the results of field studies to assess the relationship of lake water levels and their penetration into the delta, including the effects of major wind-generated seiche events. Changes in the overall channel network of the SRD over the last six decades, including a description of conditions before and after flow regulation, are also reviewed.

The report is intended to provide a general description of methodology used in the analysis, a summary of significant results, and provides references to published manuscripts that contain further detailed information. Discussion of the major results and recommendations for future research are also included.

**Hydro-Ecological Setting**

The Peace River, the major tributary of the Slave River, has its headwaters within the Rocky Mountains of British Columbia (Figure 2). Most of the alpine runoff from this headwater region is captured by the Williston Reservoir, which was constructed and filled (~ 41 km$^3$) between 1968 and 1971. At about this point (Hudson Hope hydrometric station), the catchment area is approximately $70 \times 10^3$ km$^2$ and the mean annual discharge 1100 m$^3$ s$^{-1}$. Below the reservoir, the incised river proceeds northeasterly to the town of Peace River where it is joined by its major tributary, the Smoky River, which is also fed by flow from the eastern slopes of the Rocky Mountains. Approximately 1100 km downstream of the reservoir, the Peace River reaches the northern edge of the 3900-km$^2$ PAD, having more than quadrupled its drainage area to 293,000 km$^2$ (Figure 2) but only doubled its flow to approximately 2100 m$^3$ s$^{-1}$. Peak discharge typically occurs in late May to early June, driven primarily by snowmelt runoff in the headwaters. Large rainstorm events during most years produce additional more-spiked summer flood peaks.
Figure 2.  Athabasca, Peace and Slave river and lake basin system.

The upper portion of the basin generally has higher annual precipitation than the middle or lower reaches, partly explaining its higher runoff-precipitation ratio. Average annual precipitation declines from west to east, ranging from 468 mm at Fort St. John to 388 mm at the town of Peace River and only 352 mm at Fort Smith on the Slave River.

The PAD is formed by the Peace, Athabasca and Birch Rivers at the western end of Lake Athabasca, and dominated by three major shallow lakes that are interconnected by a variety of active and inactive channels. Flow in this complex network is typically northward but can reverse and flow into the PAD when water levels on the Peace River are higher than those of the PAD. Surrounding the main lakes are hundreds of shallow ponds that are to varying degrees isolated from the main flow system. The biological productivity and diversity of this extensive riparian landscape depends on periodic flooding and drying cycles. Details of the delta flora and fauna are summarized in Prowse and Conly (2002).
The Peace River then joins with other north flowing rivers draining the PAD to form the Slave River, and ultimately discharges via the SRD into Great Slave Lake. At this point, an area of approximately 615,000 km$^2$ (mean annual flow ~3400 m$^3$ s$^{-1}$) has been drained by the combined Slave River, Peace River, Athabasca River, PAD, and Lake Athabasca systems, with the Peace River playing the major influence on flood events and the seasonality of the hydrograph. Highest Slave River flows typically occur in June and July with the subsequent recession being augmented by flow from the PAD/Lake Athabasca system. Further details about the hydrology and effects of flow regulation on the Peace-Athabasca-Slave system are provided in Prowse et al. (2002).

Although the SRD carries and is subject to variations of, the combined flow of the various southern Mackenzie River tributaries, it is also strongly affected by water levels, waves and ice from the lake into which it enters. Prograding into the south arm of glacial Great Slave Lake (Craig, 1965) since 8070 BP at approximately 20 m/yr (Vanderburgh and Smith, 1988), the SRD has become increasingly exposed to the deeper portions of Great Slave Lake. As a result, progradation rates have decreased leaving an active arcuate front of only 400 km$^2$, or 5% of the total SRD (English, 1984; English et al., 1996). Similar to the PAD, biological productivity of the SRD is dependent on its flood regime and related deposition of alluvial material. Based on botanical and geomorphical differences, the SRD can be subdivided into three distinct zones as influenced by flood frequency: the outer delta, the mid-delta, and the apex, the former being the most water-dominated landscape and the latter, the driest. Further details about these zones and how they can be affected by river and lake levels can be found in Prowse et al. (2002).

**METHODS AND RESULTS**

1. **Water Budget of PAD Perched Basins**

To explain the origin, fate and persistence of water held in the myriad of perched basins within the Peace-Athabasca Delta, a water-balance study was initiated for the PAD-Technical Studies (PAD-TS, 1996). This earlier prototype model was improved during the NREI to include a more realistic representation of basins (the modelling was conducted using a typical basin in close proximity to the large delta lakes; Jemis Lake) and updated/extended historical hydroclimatic data. The objective of the NREI study was to determine the relative importance of hydroclimatic components on the water balance and the range in duration of floodwaters for contrasting hydroclimatic scenarios (e.g. wet-dry, warm-cold, etc). Refer to Peters (2003) for more details.
Methods

The water balance equation for Jemis Lake, a representative perched basin located adjacent to Mamawi Lake was described as (Peters, 2003):

\[ Q_F + P_S + P_O + E_O + Q_G = \frac{\Delta S}{\Delta t} \]  

where \( Q_F \) is overbank flow of channel/lake into or out of the basin, \( P_O \) is precipitation onto the surface during ice-free period, \( E_O \) is evaporation (open water and emergent vegetation) during the ice-free period, \( Q_G \) is groundwater flow, and \( \Delta S/\Delta t \) is the change in ponded water storage per unit time. Values are positive when water is added to and negative when removed from the wetland. Changes are expressed in mm d\(^{-1}\) or m\(^3\) d\(^{-1}\) derived with hypsometric relationships of volume (m\(^3\)) with area (m\(^2\)) and elevation (m) based on a detailed basin survey (Carter, 1996). Data required to drive the water-balance model were obtained from Environment Canada’s (1998a) climate archive for nearby Fort Chipewyan and from hydrometric records (Environment Canada, 1998b) for the delta lakes. Groundwater characteristics were defined with field measurements (Peters, 2003). The model was verified on a 1974-1984 time series using remote-sensing data (Pietroniro et al., 1999) and air photos of Jemis Lake (Peters, 2003).

Results

It was found that perched basins (test value set at a stereotypical 0.80 m depth) are able to retain water for a period of 5 years under cool-dry conditions, such as experienced during the 1920s, and up to 9 years for the wet period of the 1940s and 1950s (Figure 3; Peters, 2003). A seasonal drawdown of water occurred in almost every year modelled and was primarily due to evaporation being greater than precipitation. Groundwater flow resulted in only a minor loss or gain of water. Although the prevailing hydroclimatic conditions influenced the duration of water, the crucial conclusion of this modelling study was that perched basins are dependent on floodwater additions to maintain an aquatic environment (Peters, 2003).

Water-balance modelling of future climatic conditions (2070-2099) was also carried out based on data input from the Canadian General Circulation Model (CGCM1) (Peters et al., 2001) and a stereotypical perched basin. Results showed a 3-week reduction in the ice season (approximately 1 week in the fall, 2 weeks in the spring) relative to the 1961-90 period, which would extend the open-water season and permit greater evaporation (Figure 4). This, combined with warmer air temperatures (approximately +4°C annual air temperature near Fort Chipewyan) was forecast to increase total evaporative loss by approximately +35%. Despite projected increases in precipitation (approximately +11%), the enhanced evaporation will lead to more rapid drying and thus, an increased dependence on flooding to avoid drying of the perched-basin environment.
Figure 3. Duration of water modelled for Jemis Lake for contrasting sets of hydro-climatic conditions a) 1920s, b) 1940-50s, and c) 1970-80s (Peters, 2003).
Figure 4. Comparison of winter and summer water balance components of Jemis Lake for a present (1961-90) and future (2070-99) set of hydro-climatic conditions.
2. PAD Flood Regimes

Given the importance of flooding to the perched basins throughout the PAD and their anticipated greater importance in the future, a multi-component flood-regime analysis was included in the NREI studies. The focus was placed on three identified (Peters, 2003) flood areas (near-delta locations of the Peace and Athabasca rivers, and the intra-delta lakes) and two flood types (open-water and ice-jam). Previous studies for the NRBS (Prowse and Lalonde, 1996; Prowse and Conly, 1996) assessed the hydrometeorological conditions controlling ice-jam floods on the Peace River near the Peace-Athabasca Delta and the magnitude of open-water flood flows on this river to the delta. The major unknowns regarding flooding of the perched basins were the ice-jam and open-water events on the Athabasca Delta and the expansion of the delta lakes into the inland areas of the PAD.

Methods

To assess the natural hydroclimate influence on flows to and through the PAD without the complicating effects of hydroelectric production, a first-generation hydraulic flow model of the Peace River produced for the NRBS (Hicks and MacKay, 1996) was employed to simulate naturalized flows (i.e. no Bennett Dam) at Peace Point, the nearest flow station to the delta. Details of the modelling study are presented in Peters and Prowse (2001). The model was calibrated (Manning’s $n$ adjustments) to best replicate a high (1990) and low (1981) flow year. Flow modelling accuracy had an average RMS error of $\pm 5\%$. To close the annual water balance at Peace Point for both the observed and naturalized flow simulations, it was necessary to include runoff from ungauged/omitted tributaries (24% of total area) not considered in the original model version. Inflows from these areas, mostly located in the zone below the town of Peace River, were estimated as the difference between the observed and simulated hydrographs at Peace Point. By coupling the Peace River hydraulic model with the updated (lake cross-sections, Manning’s $n$ channel calibrations, inflow data, and measured ice thickness) One-Dimensional (ONE-D) Hydrodynamic model of the PAD [Figure 5; previously used for Peace-Athabasca Delta Implementation Committee (PAD-IC-1987) and Northern River Basins Study (Aitken and Sapach, 1994)], Peters (2003) evaluated the flow conditions that have produced intra-delta channel and lake levels without the influence of regulation (i.e. no Bennett Dam and no weirs) from 1968 to 1996 (generally reproduced to an average of $\pm 0.20$ m). The ONE-D model was calibrated/tested using the same years specified above. It was difficult to assess the error in the naturalized flows/levels because of the complex river and lake hydrology; nevertheless, the error was believed to be similar as found in replicating the observed hydrology, except for extreme events that were beyond the range of model calibration. Producing a model designed for extreme flow events and complexities of riparian flows and storage is noted as a future research priority. Such additional research is required to more accurately model extreme flow conditions beyond that possible with the first-generation one-dimensional models.
The magnitude and duration of reverse flow to delta lakes was evaluated by comparing the lagged-hydrograph of the Peace River at Peace Point to that of the Slave River at Fitzgerald. When flow at Peace Point was greater than at Fitzgerald, the difference in the hydrographs was assumed to be routed south into the delta lakes. To assess the relative flow contributions to Peace Point on the Peace River and Fort McMurray on the Athabasca River to peak break-up backwater levels ($Q_B$) and annual high flows (1-day and 30-day mean; $Q_1$ & $Q_{30}$), sub-basin flows were lagged according to flow travel times estimated by Peters (2003).

Results

Results of the historical flow analysis showed that high-stage events (capable of flooding the adjacent landscape) have been, and remain relatively common in the southern perimeter of the PAD within the Athabasca Delta, including for example, the all-time high flood flow of 4,700 m$^3$ s$^{-1}$ observed during the summer of 1971, and lesser events in 1982, 1986 and 1995 (Peters, 2003). On the northern perimeter of the PAD, the Peace Delta, high-stage events capable of overtopping the banks have been virtually non-existent along the Peace River mainstem (as identified in the earlier NRBS study by Prowse and Conly (1996). The results showed that the highest 1-day observed flow (12,600 m$^3$ s$^{-1}$) occurred in 1990 after the river became regulated. This flood peak, however, was simulated to have been even higher without the effect of water impoundment (Peters and Prowse, 2001). Similarly, another very high (>12,600 m$^3$ s$^{-1}$) 1-day
flood peak ($Q_1$) would probably have occurred in 1972, if not for regulation. Similar modelling results were found by PAD-IC, (1987), Aitken and Sapach (1994), Taggart (1995), and Hicks and McKay (1996). Given that these peaks exceed the flow range over which the hydraulic model was calibrated and verified, they may be less accurate than other naturalized flow values. If the modeled results were overestimated by, for example, even 20%, both naturalized flow events would still be greater than any other observed flow before or after regulation. Moreover, they would be in the range of flows (>14,000 m$^3$ s$^{-1}$) that have been previously noted to be capable of producing direct overbank flooding of the north shore of the PAD (PAD-PG, 1973), an area that otherwise can only be flooded via backwater from ice jams (Prowse and Lalonde, 1996; Peters, 2003). Overall, it is estimated that the mean peak flows at Peace Point have been significantly ($\alpha=0.05$) reduced by ~3,000 m$^3$ s$^{-1}$ since regulation. The same is true for the longer term sustained high-flow events (i.e., 30-day high flows; $Q_{30}$). A monthly flow analysis tabulated by Choles et al. (1996) in an NRBS report, which was based on observed and naturalized (Streamflow Synthesis and Reservoir Regulation Model) flows, supports this conclusion. Sustained flows are associated with major flow reversals into the PAD (see below) and the raising of the large intra-delta lakes (Claire and Mamawi) to flood levels.

Although anecdotal information exists about the flooding of perched basins as result of the lateral expansion of the large delta lake during periods of high water levels, the NREI studies were the first study to systematically examine the nature of such flooding (Peters, 2003). Using Lake Athabasca water levels as an index of intra-delta lake levels, a historical analysis (1930s onward) revealed that natural hydroclimatic conditions in the contributing basins created at least one year in the pre-regulation period with lake water levels below the exceedingly low levels that characterized the filling years of the Williston reservoir (Figure 6). Hence, the natural hydroclimatology was capable of producing extremely low, as well as, high lake levels. The all-time high of 211.33 masl on Lake Athabasca occurred prior to regulation during the summer of 1935. Based on a digital elevation model (DEM) of the PAD, it was estimated that Lake Athabasca engulfed Lakes Richardson, Mamawi, Baril and Claire, creating one large continuous lake (Figure 7a). Despite the large magnitude of the 1935 event, the DEM analysis revealed that lake expansion did not recharge the highly perched basins located in the perimeters of the Peace and Athabasca Deltas. This would have required lake water levels to be significantly higher, such as those produced by the 1974 and 1996 ice-jam floods, both of which occurred after the introduction of flow regulation (Figure 7b) (Peters, 2003).

A comparison of the observed to the naturalized regime on Lake Athabasca showed that Lake Athabasca water levels (and on the related delta lakes) have been both higher and lower under the regulated regime than those which would have occurred under unregulated hydroclimatic conditions, although simulations indicated that there probably have been fewer higher peak years.
Overall, the year-to-year pattern of the regulated water-level record was found to be similar to that of the modelled naturalized record. A high correlation ($r = 0.80$) between regulated and naturalized peak-water levels suggests that hydroclimatic conditions within the unregulated portions of the contributing basins had a strong control on summer lake levels. For example, above average flood levels ($>209.55$ masl) were attained in the 1970s and below-average levels occurred in the early 1980s regardless of flow regulation. Overall, the naturalized annual-peak levels ($209.60$ masl; 1976-96 mean) on Lake Athabasca were not significantly ($\alpha = 0.50$) greater ($\sim 0.06$; close to the accuracy of the One-Dimensional modelling) than those observed under the regulated regime ($209.54$ masl; 1976-96 mean) (Peters, 2003). The simulation efforts of this study support the general conclusion of prior studies by the PAD-IC (1987; Farley and Cheng, 1986) and NRBS (Aitken and Sapach, 1994) that the outflow control structures have partially countered the effects of flow regulation. The outflow control structures, however, have had no influence on the hydrology of the perched basins situated above the level of the weirs (PAD-IC, 1987). The result of Peters (2003), also show that without the influence of regulation, lake levels would have probably been higher in wet years and lower in dry years (Figure 6) and thus reservoir operation has probably reduced the maximum potential of inland flooding from lake expansion, such as Jemis Lake, during particular years.

![Graph](image)

**Figure 6.** Annual peak water level on Lake Athabasca at Fort Chipewyan for pre- and post-regulation, as well as without the influence of flow regulation (naturalized) (Peters, 2003).
Figure 7. Estimated extent of inland delta flooding (dark grey areas) as a result of:
a) enlargement of the main delta lakes in the summer of 1935 and
b) ice jamming in the spring of 1974 (Peters, 2003).
When sustained, relatively high water levels exist on the Peace River and significant amounts of water can be diverted into the PAD by the major delta channels, thereby raising the lake levels, sometimes to flood levels that could inundate the surrounding riparian landscape (e.g. 1990; see Figure 6). As found in the flow analysis (Peters, 2003), short-duration reverse flow events during the spring breakup were estimated to be a common occurrence. Unfortunately, it was not possible to determine how regulation of the Peace River flows and introduction of delta weirs have affected this type of event because the ONE-D hydraulic model used in the analysis is not capable of modelling transient ice effects. Nevertheless, Peters (2003) showed that there was no significant ($\alpha = 0.05$) difference between the mean magnitude of all spring events that occurred before (1960-67) and after regulation (1972-96). For the open-water period after spring breakup, the Peace River was found to contribute some reverse flow to the delta lakes each year prior to regulation. By contrast, after closure of the dam, more than half the years were estimated to not have experienced any reversal, and those that did were characterized by much smaller events (Peters, 2003). Even the extreme discharge event in June 1990 was estimated to not have lead to an abnormally large amount of river reversal (total of 15,220 m$^3$ s$^{-1}$ over 10 days) to the inner delta. Notably, however, analysis of naturalized flow conditions suggested that the magnitude of this reversal event would have been greater without the effects of regulation. Overall, the mean volume (m$^3$ s$^{-1}$) and duration (days) of reverse flow for the regulated period (1972-96) was estimated to be significantly lower than for the period prior to closure of the dam (1960-67) - a mean reduction in event total from approximately 22,000 to 3,000 m$^3$ s$^{-1}$ (Peters, 2003). On average, the mean volume and duration of the reversals estimated under the regulated regime (1972-96) were significantly ($\alpha =0.05$) less than those under a naturalized scenario (1972-96) (Peters, 2003). The major implication of less reverse flow contribution from the Peace River to the delta lakes was a lowered flood potential (e.g., 1990) from the lateral expansion of the central lakes into contiguous perched basins, such as Jemis Lake (Peters, 2003). This supports the comment of Farley and Cheng (1986), arrived at based on a previous ONE-D modelling effort for the PAD-IC, that the perched basins were not replenished as often under the modified regime, event with the weirs in place.

In the case of ice-jam flooding, an assembly of hydroclimatic data near the Athabasca Delta (Figure 8a) has revealed that ice jamming is an important and continuing source of overbank flooding (Peters, 2003). Extending the hydroclimatic analysis of ice-jam flooding from the Peace River (conducted for the NRBS) has verified the earlier result that such flooding is naturally dependent on tributary flow downstream of the dam. Moreover, large events (e.g. 1974 ice-jam flood in Figure 7b) are associated with large snowpack on “trigger tributaries”, such as the Smoky River in the Peace Basin and the Clearwater and Pembina sub-basins in the Athabasca Basin. Importantly, the trend after 1976 to lower snowpacks was disrupted in the mid-1990s. The relative importance of upstream sub-catchments responsible for the production of downstream
peak discharge and water levels at the delta perimeter (i.e., as represented by Peace Point on the Peace River and Fort McMurray on the Athabasca River), and flow reversals that feed water to the intra-delta lakes are briefly discussed below. Full details are provided in Peters (2003).

Figure 8. Annual peak water level vs. discharge under break-up conditions: a) the Athabasca River just below Fort McMurray and b) Peace River at Peace Point (Peters, 2003).
Figure 9: Flow contributions: a) from mainstem stations and b) major tributaries to peak break-up levels ($Q_B$) on the Peace River at Peace Point (Peters, 2003).

Considering ice-jam floods on the Peace River (Figure 8b), this extended analysis confirms the earlier results of Prowse and Lalonde (1996) and Prowse et al. (1996) regarding the relative importance of catchments upstream and downstream of the point of regulation to the generation of $Q_B$ near the PAD. Firstly, more than half (~65%) of $Q_B$ (for both the unregulated and regulated flow periods) was found to originate from the plain-foothill-mountain areas located...
>700 km upstream of the PAD (Peters, 2003: Figure 9). In a natural system, the alpine headwaters upstream of the dam (Hudson Hope) contribute little snowmelt runoff to $Q_B$ but following regulation, flow contributions above the dam to $Q_B$ nearly doubled (~31%). The most important supplier of runoff from areas below the dam was confirmed to be the Smoky River (26% and 15%, respectively, for the pre- and post-regulation eras). This sub-basin, which drains mostly plains and foothills areas, has been identified as the “trigger” to large ice-jam floods within the Peace Delta.

After the spring breakup, floods of the PAD depend on open-water flow extremes to either overtop the banks at the delta boundaries or to produce large flow reversals into the delta and flood the riparian zones surrounding the large lakes. Although the alpine zone above the dam comprises one quarter of the drainage basin area, it was found to produce on average over half (54%) of the peak flow measured near the delta prior to regulation, and this value has decreased to 17% after 1972 (Peters, 2003). Analysis of the naturalized flows revealed that without storage of the alpine runoff, the average relative flow contributions from above Hudson Hope would have been an estimated 48% (Peters, 2003). With storage of significant amounts of alpine runoff, the Smoky River has subsequently become the main producer of peak runoff on the Peace River near the PAD (increased from 20% to 30% of $Q_1$; Figure 10) (Peters, 2003). Similar findings were found for the longer-term flow index (30-day mean flow; $Q_{30}$) that is important in flow reversal to and raising of the delta lakes. The regulation of flow from the alpine headwaters of the Peace River, along with climate variability within the entire basin, has therefore altered the relative importance of the upstream and downstream sub-catchments responsible for generations of peak break-up backwaters and open-water flows near the delta (Peter, 2003).

In the unregulated Athabasca basin, the bulk of the flow (>75%) to $Q_B$ was found to originate from the plains and foothills regions (Peters, 2003: Figure 11) whereas runoff from the more elevated mountain areas (e.g., above Windfall) contributed less than 14%. The most important sub-basins involved in generating water to $Q_B$ were the Clearwater River (25%), the largest and closest sub-basin to the delta, followed by the smaller rivers draining the plain-foothill areas (e.g., Pembina 13% and Lesser Slave 9%) (Peters, 2003). During the summer period there was a shift in relative contributions from the plains to the foothill-mountain regions (Figure 12). For instance, the Clearwater River, characterized by a spring freshet flow regime typical of the plains, was not the predominant generator of runoff to summer high flows ($Q_1$ and $Q_{30}$) (Peters, 2003). Delayed snowmelt runoff from the elevated mountain areas and rainfall runoff (orographic precipitation) from the foothills (e.g., 4 to 11% from the Pembina, Lesser Slave, Berland, and McLeod Rivers) played an increased role in generating the 1-day peak and sustained high flows near the delta, as compared to the spring period (Peters, 2003).
Figure 10: Flow contributions to Peace River at Peace Point at the time of annual 1-day maximum flow ($Q_1$) from: a) selected mainstem stations and b) major tributaries (Peters, 2003).
Figure 11: Flow contributions: a) from mainstem stations and b) major tributaries to peak break-up levels ($Q_B$) on the Athabasca River just below Fort McMurray (Peters, 2003).
Figure 12: Flow contributions to Athabasca River below Fort McMurray at the time of annual 1-day maximum flow ($Q_1$) from: a) selected mainstem stations and b) major tributaries (Peters, 2003).
3. Ice-Jam Flood Modelling

Given the importance of particular ice-jam flood sites on the Peace River that were recognized from the earlier work of the NRBS/PAD-Technical Studies and reinforced in the more recent extended analysis noted above, research continued under the NREI to focus more specifically on the ice-jamming process during the spring breakup of the ice cover. It comprised four main components:

a. Continuation and expansion of previous analysis of historical hydrometric-station records at Peace Point, a gauge site located some 50 km upstream of the 60-km long, Delta reach of Peace River (~Sweetgrass Landing to Peace River mouth). This component includes development of methods to identify those breakup events that have the potential for ice-jam flooding and relate this potential to antecedent and prevailing flow and weather conditions. Implicit here is the assumption that the main features of any one ice season within the Delta reach are similar to those occurring in the vicinity of the Peace Point gauge, which is the only source of historical hydrometric data in the lower portion of Peace River. Though plausible, this assumption was initially a mere working hypothesis. Its validity and limitations are continuously being assessed on the basis of in situ observations and measurements, as outlined next.

b. Field observations and measurements to document important ice processes pertaining to ice-jam formation and magnitude in the last 150 km of Peace River, a reach that extends some 40 km above Peace Point. In addition to winter and spring programs, river bathymetry and slope are surveyed in selected reaches in order to characterize channel hydraulics and obtain requisite input data for numerical modelling.

c. Application of physically-based equations and numerical modelling to quantify the hydro-climatic conditions that lead to ice-jam flooding, including extensive use of the model RIVJAM (Beltaos, 1993; 1996). This component relies heavily on results obtained under components 1 and 2, respectively furnishing the historical depth and the in situ understanding of local ice processes.

d. Climate impacts on the breakup and jamming processes of rivers, in general, are also being examined in order to establish the necessary background for the present study.

Results

Ice-jam flooding of the PAD occurs when the following conditions are fulfilled: (a) the breakup event is of the “mechanical” type (breakup events are characterized as “mechanical” or “thermal”, depending on whether the winter ice cover is dislodged and broken up while still retaining significant mechanical strength); (b) a major ice jam forms within the main delta reach;
and (c) the river flow exceeds $4000 \text{ m}^3 \text{ s}^{-1}$. The flow threshold was determined by the RIVJAM model, following calibration against high water marks attained during the 1996 and 1997 ice-jam flood events (Figure 13; Beltaos, 2002a). It was further shown that the occurrence of a mechanical event is promoted by low freeze-up stage and high spring flow, and vice versa (Beltaos, 2002b; Beltaos et al. 2003). Consequently, the scarcity of ice-jam floods (only 4 after 1968) appears to result from two factors: increased freeze-up stage (effect of regulation) and reduced spring flow (effect of changing climate, as manifested in reduced snowpack). It is not possible at present to quantify the relative significance of these two factors, owing to the brevity of the pre-regulation record.

![Diagram of River distance (m) vs Elevation (m)](image)

**Figure 13.** RIVJAM prediction for April 27, 1996 and comparison with observed 1996 high water marks (squares). Continuous lines: predicted water surface (uppermost), bottom of jam (intermediate), channel thalweg (lowermost); dashed line: approximate elevation of south (right) bank.

To assess climate-change impacts on ice-jam flood frequency, an empirical methodology was developed, utilizing climatic indices as surrogates for the controlling hydroclimatic variables. These indices included end-of-winter snowpack, air temperature, and rate of accumulation of degree-days of thaw at the Grande Prairie meteorological station. The latter is considered representative of runoff conditions that can generate mechanical breakups at the PAD by indexing conditions in the Smoky River, a “trigger” tributary identified in the NRBS studies. It was found that major floods required a total winter snowpack of at least 150 mm and intense spring heating (Beltaos and Prowse, 2001; Beltaos et al., 2002) to generate a large ice-jam flood.
An assessment of potential climate-change impacts was carried out using air temperature and precipitation output from the CGCM1 (Canadian General Circulation Model Version 1). The model output was manipulated to derive daily values of T and P for the future-scenario years of 2070-2099. Using this information, and the above described results, it was determined that the frequency of ice-jam floods would be further reduced in the future, mainly because of reduced snowpack. The latter effect results from the advent of mid-winter thaws under a new climate that is characterized by higher temperatures, especially during the winter months. To calculate future snowpack, it was simply assumed that winter precipitation changes from snow to rain on days with mean daily temperature above 0°C. No attempt was made in this first phase, whose main results are summarized in Beltaos and Prowse (2001) and Beltaos et al. (2002), to calculate snowpack reductions due to mid-winter melt.

Having established the hydro-climatic conditions leading to ice-jam flooding, and with a preliminary indication as to future hydro-climatic impacts, it is possible to examine potential options for restoring water to the Delta. One such option is to augment spring flow in years when other factors (e.g. snowpack) appear promising for a mechanical breakup event. This was actually tried during the 1996 breakup event, when BC Hydro followed a recommendation of the NRBS final reports and released an additional flow of 500 m$^3$ s$^{-1}$ to the Peace River. Detailed analysis of the event using the calibrated RIVJAM model revealed that the flow addition increased the flood level at the PAD by some 0.27 m at its peak effect. Proposal of this method as an adaptation strategy for dealing with the effects of climate change is described in Prowse et al. (2002).

General assessments of climate impacts on river ice processes and breakup jamming have also been carried out, in parallel with the site-specific investigations described in the preceding paragraphs (Beltaos and Prowse, 2001; Prowse and Beltaos, 2002; Beltaos and Burrell, 2003). The high sensitivity of ice processes to climatic inputs has been demonstrated, and a variety of probable future hydro-ecological effects outlined. Of particular relevance to the PAD study is the predicted occurrence of mid-winter thaws in parts of Canada that do not presently experience such events. This can have significant repercussions to the ice regime of rivers, and is primarily responsible for the expected reduction in ice-jam flooding frequency of the PAD.

4. Upstream Hydro-climatic Conditions

Having established the importance of alpine snowmelt events to ice-jamming and to the flow reversals that affect flooding of the PAD, additional research concentrated on defining the climatological reasons for the historical variations in the magnitude of these events. Earlier research by Keller (1997) had attempted to quantify the changes in synoptic weather patterns that could explain reductions in winter snow accumulation and ice jamming noted by Prowse and
Lalonde (1996) to have occurred in the mid-1970s. This earlier work employed the Kirchhofer technique (Kirchhofer, 1973) to classify synoptic patterns. Recent work, however, identified errors within the Kirchhofer algorithm that cast substantial doubt on its usability (Blair, 1998). After a comparison of techniques Romolo et al. (2002), it was decided to employ an eigenvector-based procedure. Using this procedure, the snowpack accumulation trends were re-examined Romolo et al. (2002) and a new analysis conducted of snowmelt events (Romolo et al. 2003).

Methods

For both of the above-mentioned investigations, the eigenvector-based map pattern classification scheme (as outlined in Yarnal, 1993) was employed to create a synoptic analog of western Canada at the 500-mb level over the period 1963-1996. The synoptic window ranged from 140° to 105° W longitude and from 50° to 70° N latitude. To investigate the atmospheric controls on snowpack accumulation, all days from November 1 to March 31 were classified, while for snowmelt, the spring months (March 1 to May 15) were used. Using an efficiency index developed by Yarnal (1984), the winter (spring) synoptic types were first divided into precipitating and non-precipitating (high and low energy) patterns and were then related to variances in the snowpack (snowmelt) at Grande Prairie, Alberta.

Results

As earlier noted by Keller (1997), snow accumulation in the ice-jam trigger tributary, the Smoky River (Grande Prairie), exhibits an inter-decadal shift in the mid-1970s to reduced values (Figure 14). Using a frequency analysis (Romolo et al. 2002) demonstrated that variances in the occurrence of synoptic patterns were significantly related to both inter-annual and inter-decadal variances in the magnitude of the snowpack at Grande Prairie. Specifically, it was determined that years of high (low) snowpack were dominated by the occurrence of precipitating zonal flow/troughing (non-precipitating meridional/northerly flow) patterns (Figure 15). The interval 1963-1976, characterized by enhanced snowpacks, was particularly dominated by these same precipitating synoptic types. Opposite conditions were observed after 1976. Further analysis revealed that variances in the Pacific/North American (PNA) pattern and the Southern Oscillation Index (SOI) influenced the local synoptic regime with the winter months dominated by wet types under the negative phase of the PNA (zonal flow) and the positive phase of the SOI (La Niña) (Table 1). Conversely, dry types dominated under a positive PNA (meridional flow) and negative SOI (El Niño) (Table 1). A storm track analysis identified that the PNA, which governs the local synoptic regime, is a dominant broad-scale control on the magnitude and direction of surface lows in and about the Peace River Basin, and Western Canada (Romolo et al., 2002).
Figure 14. Total Accumulated Precipitation (TAP) at Grande Prairie, AB., from 1963 to 1996.

Figure 15. a) A sample of the non-precipitating (dry) synoptic types. Geopotential heights are in metres with a 50-m contour interval. b) A sample of the precipitating (wet) synoptic types. Geopotential heights are in metres with a 50-m contour interval.
Table 1. Contingency Tables for chi-square analysis (percentages shown in parentheses) of wet/dry type frequency and select teleconnection patterns. Asterisk denotes significance at the 95% level of confidence.

<table>
<thead>
<tr>
<th></th>
<th>- PNA</th>
<th>+ PNA</th>
<th></th>
<th>- SOI</th>
<th>+ SOI</th>
<th></th>
<th>- AO</th>
<th>+ AO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>36 (71)</td>
<td>15 (29)</td>
<td>Wet</td>
<td>20 (39)</td>
<td>31 (61)</td>
<td>Wet</td>
<td>19 (37)</td>
<td>32 (63)</td>
</tr>
<tr>
<td>Dry</td>
<td>40 (35)</td>
<td>75 (65)</td>
<td>Dry</td>
<td>71 (61)</td>
<td>45 (39)</td>
<td>Dry</td>
<td>62 (53)</td>
<td>54 (47)</td>
</tr>
</tbody>
</table>

A similar study for the same region also demonstrated strong relationships between synoptic circulation and snowmelt (Romolo et al., 2003). Through the use of both a degree-day and energy balance model, spring melt was categorized based on the timing and intensity of melt. Specifically, melt periods were classified as early/late and rapid/protracted. A frequency analysis revealed that early and rapid melt periods were dominated by high energy yielding synoptic types characterized by ridging patterns and a weakened circumpolar vortex (Figure 16a). In contrast, late and protracted melts were influenced by low energy yielding synoptic types characterized by troughing patterns and a strengthened circumpolar vortex (Figure 16b). Shifting beyond the synoptic scale, further analysis identified that high (low) energy yielding patterns were influenced by the positive (negative) phase of the PNA (Table 2) (Romolo et al., 2003).

**Figure 16.** a) A sample of the high-energy yielding synoptic types. Geopotential heights are in metres with a 50-m contour interval. b) A sample of the low-energy yielding synoptic types. Geopotential heights are in metres with a 50-m contour interval.
Table 2. Contingency Tables for chi-square analysis (percentages shown in parentheses) of high/low energy type frequency and select teleconnection patterns. Asterisk denotes significance at the 95% level of confidence.

<table>
<thead>
<tr>
<th></th>
<th>- PNA</th>
<th>+ PNA</th>
<th></th>
<th>- SOI</th>
<th>+ SOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy</td>
<td>13 (33)</td>
<td>26 (67)</td>
<td>High Energy</td>
<td>24 (59)</td>
<td>17 (41)</td>
</tr>
<tr>
<td>Low Energy</td>
<td>20 (74)</td>
<td>7 (26)</td>
<td>Low Energy</td>
<td>12 (48)</td>
<td>13 (52)</td>
</tr>
</tbody>
</table>

5. Water Levels of Great Slave Lake

As earlier noted, hydro-ecological conditions of the SRD were believed to be affected by changes in flow of the Peace-Athabasca-Slave river system and relatedly water levels of Great Slave Lake (e.g., Figure 17). To assess the potential role of the lake, an historical water-balance analysis was conducted for the entire lake catchment for the period 1964-98 (Gibson et al., 2003). This would permit examination of the potential sensitivity of the system to climate and water resources impacts over the past 35 years, including the influence of Peace River flow regulation. Water level records for Great Slave Lake (GSL) dating back to 1938 were also examined to extend pre- and post-regulation comparisons. This work extends a previous water

![Figure 17. Schematic of interaction between lake and river levels controlling flow and sediment processes affecting the Slave River Delta.](image)
balance analysis (Kerr, 1997) by 15 years, including the period of initial filling of the Williston reservoir, and includes two additional climate-driven drying cycles. In addition, this analysis benefits from knowledge gained through recent ice phenology and evaporation process studies by Menard et al. (2002) and Blanken et al. (2000), respectively to constrain the evaporation component of the water cycle. Importantly, this reduces uncertainty in characterization of annual variability in the water balance terms and enhances the ability to examine the underlying causes (hydroclimatic versus regulation) of water balance and water level variability of GSL.

Methods

The lake water balance calculations relied on estimation of total inflow as the sum of riverine inflows and precipitation directly on the lake surface, and estimation of total outflow as the sum of riverine discharge and evaporation from the lake surface, using water level records to characterize storage changes. The annual water balance was computed for calendar years (January 1 to December 31) based on the relationship:

\[ I + P - Q - E = \frac{dS}{dt} \pm G \pm \text{error} \]  \hspace{1cm} [2]

where \( I \) is the mean annual riverine inflow to the lake, \( P \) is mean annual precipitation on the lake surface, \( Q \) is mean annual riverine outflow, \( E \) is mean annual evaporation, \( \frac{dS}{dt} \) is the mean change in lake storage from, and the residual \( \pm G \pm \text{error} \) includes error in all measurements including the net groundwater exchange (all in m³ s⁻¹). A working model was also developed to test the models robustness for predicting daily water balance and water level changes.

Precipitation data from Environment Canada weather stations in the vicinity of Great Slave Lake were used to estimate the precipitation falling directly on the lake surface. The lake surface (28,568 km²) was divided into sub-regions using a Theissen polygon approach (see Dingman, 2002, p. 121) so that whole lake precipitation was weighted according to the fraction of sub-basin situated closest to each individual precipitation station. Several combinations were assessed to test the sensitivity of the results to elimination of one, two, or three stations, although all available station data were used in the analysis. The following precipitation station weightings were calculated from the Theissen polygon analysis and used to estimate the precipitation over the lake: Yellowknife (17.4%), Hay River (25.2%), Fort Reliance (14.2%), Fort Resolution (41.3%) and Snare Rapids (2%). For running the operational daily water balance model, snow and rain were accounted for separately to allow snow accumulation to occur on lake ice from the time of freeze-up until May 1. Snow was then melted and added to the lake storage over a period of 15 days, intended to roughly simulate the melt cycle.
Evaporation for the entire ice-free periods of 1997 and 1998, the last two years of the water balance period used in this analysis was taken directly from eddy covariance measurements by Blanken et al. (2000). Blanken et al. (2000) also demonstrated that cumulative evaporation was similar in both years between mid-August and mid-November, and that higher totals for 1998-99 were mainly due to a protracted ice-free season associated with the 1997-98 El Nino. Annual evaporation totals were also shown to be less sensitive to the date of break-up than freeze-up due to higher rates of evaporation during the later months. Although evaporation estimates were not available for 1964-96, an evaporation algorithm was developed to account for variations in annual evaporation due to length of the ice-free period, assuming similar monthly evaporation rates in each year. For the calculations, the ice-free period was characterized from historical records of freeze-up and break-up dates measured on Back Bay near Yellowknife (Lenormand et al., 2002) and adjusted to match the systematic offset we note between the Back Bay record and whole lake estimates predicted using SSM/I 85 GHz passive microwave imagery (Menard et al., 2002, their Figure 11). The algorithm assumes an evaporation function based on monthly values estimated from Blanken et al. (2000), combined with data on the shifting ice-free period to estimate annual evaporation. The reconstructed estimates of evaporation for the 1964-96 period are found to range from 275 to 410 mm/yr with a mean of 336 mm (Gibson et al., 2003). E/P ratios are also within a reasonable range of 0.96 to 1.86 with a mean of 1.5, which is consistent with values cited in the Hydrological Atlas of Canada (denHartog and Ferguson, 1978).

Riverine inflows were taken from HYDAT for WSC gauging stations. On average 86% of the contributing area was gauged during 1964-98. Representative flow records for ungauged areas/years were reconstructed for approximately 95% of the basin through comparison with hydrographs from basins with similar observed hydrologic responses. Approximately 5% of the basin had no representative gauging records, and these areas were assigned values of the average runoff. Outflow from the lake after 1991 was estimated from the gauging records for Mackenzie River at Strong Point, subtracting inflows from upstream tributaries such as the Trout River. Outflow from the lake before 1991 was estimated from records at Fort Simpson and subtracting upstream tributaries and the Liard River. Lake water level records, compiled by averaging records from Yellowknife, Fort Resolution, Hay River, and Lutselke were used to calibrate the model, which required adjustments in inflow of between 0 and 10% for annual periods. Overall, the measured inflow+precipitation exceeded measured outflow+evaporation by +2% for the 1964-98 period, which is attributed to minor systematic error in gauging, but also may reflect additional ungauged groundwater inflows to the lake. The study area, watershed boundaries and key hydrometric stations are shown in Figure 18.
Figure 18. Maps of a) the Mackenzie Basin showing major sub-basins and large lakes, b) Great Slave Lake and water level and precipitation monitoring sites, c) catchments tributary to Great Slave Lake. “ug” denotes ungauged catchment.
Results

A functional daily water balance model of the lake was developed that is capable of predicting the amplitude and frequency of annual water level fluctuations in Great Slave Lake (Gibson et al., 2003). The authors also applied the water balance model to estimate water levels in GSL using simulated, naturalized flow record developed by Peters (2003) and Peters and Prowse (2001). During 1964-1998 it was found that 74% of inflow to Great Slave Lake originates from the Peace-Athabasca catchments that enter the lake via the Slave River. Approximately 21% of the water originates from catchments bordering GSL, whereas 5% is derived from precipitation on the lake surface. A strong relationship was observed between daily to annual inflow, outflow and lake water levels suggesting that water balance was the over-riding control on long-term water levels in GSL. Lake levels during 1964 to 1998 fluctuated within a range of about 1.1 m, with lowest water levels observed during periods of dry conditions (1980, 1981, 1995) in the Peace-Athabasca catchments. Similar lows were observed during dam filling in the 1968-1972 period. Lake levels fluctuated by 0.5 m or so during typical yearly cycles although such changes could be more rapid, as observed during November 1995 to August 1996 when lake levels rose by over 1 m in response to wet climate conditions and additional water releases from the Williston reservoir. Generally wet conditions and increasing water levels were also observed during much of the 1980s. The primary driving force behind water level fluctuations in Great Slave Lake, including the post-regulation period was found to be climate-driven precipitation variability in the Peace-Athabasca basins.

Naturalized flow simulations

To differentiate the effects of regulation versus climate on the water balance and water-level variations in Great Slave Lake, the water-balance model was used along with naturalized flow simulations [as described earlier; results based on first-order hydraulic models of the Peace River and Delta flow systems (Peters, 2003)] to approximate conditions during 1968-1996. The simulations required development of an additional routing module for the lake to estimate outflow. The routing module was comprised of three simple regression models to estimate outflow from lake level under ice-covered (Jan-April), transitional (Nov.-Dec., May-June) and open-water periods (July-Oct.), and was tested preliminarily against observed data with acceptable reproducibility ($r^2=0.80$). Direct comparisons of pre- and post-regulation water levels, along with the resulting naturalized flow simulations were then analyzed to estimate climate versus regulation effects on Great Slave Lake water levels.

Comparison of pre-regulation (1938-67) and post-regulation periods (1972-1996) suggests that the amplitude of water level variations has been reduced by 0.11 m, from 0.56 to 0.45 m. Mean maximum water levels have also declined by about 0.12 m, and peaks have tended to be earlier
in the season, typically late June, during the post-regulation period, as opposed to early August during the pre-regulation period. By contrast, mean spring water levels (April-May) have increased on average by approximately 0.28 m.

Comparison of pre-regulated and naturalized simulations suggests that climate-driven changes have also occurred. For example, amplitude of water level fluctuations and maximum water levels would have probably increased rather than decreased in the later period by about 0.08 m and 0.01 m respectively; peak water levels would still have likely occurred but shifted to a lesser degree (late July), and spring mean water levels probably risen by only 0.08 m due to hydroclimatic changes. Climatic and regulation impacts have generally counter-balanced changes in amplitude of water level fluctuations and magnitude of peak levels but have cumulatively contributed to a shift toward earlier peak water levels in the lake. A comparison of observed annual water level maxima and minima and simulated naturalized conditions are shown in Figure 19.

Figure 19: Time-series of annual maximum and minimum water levels in Great Slave Lake based on observed and estimated naturalized flow conditions.
6. Lake Level –Delta Channel Interactions

To evaluate the potential effect of inter-annual and inter-seasonal changes in water levels of Great Slave Lake, it was necessary to establish how far inland such water levels could intrude into the Slave River Delta. Since no gradient data for the Delta was known to exist, extensive field surveys along a western tributary of the Delta were conducted. Ideally, slope surveys of all major delta distributaries were desired but limited resources precluded comprehensive surveys. The western delta region was selected because it was largely unaffected by the major eastern shift in channel migration found to occur in the mid-1960s (see below regarding changes in channel patterns). Results of the surveys indicated that a very low slope of approximately 7-15 mm/km characterized the zone from the outer delta to 14 km upstream, approximately at the first major bifurcation of the Slave River. Hence, a lake level rise of 10-20 cm is sufficient to affect the flow and related fluvial processes (e.g., sediment transport and deposition) up to the main entry point of the river. Notably, such increases are smaller than the inter-annual differences in lake levels produced by varying hydro-climatic conditions (i.e., between wet and dry years) and less than the seasonal changes in water level probably produced by flow regulation. Hence, both effects may have the potential to alter large areas of the main active delta.

To evaluate the effects of wind-driven events on the SRD, the NREI studies also included a historical analysis and field evaluation of the effects of wind seiches. Full details of the program are described in Gardner (2002). A seiche event was defined as a wind-forced surface water set-up and set-down. Data were analyzed to define the historical frequency and magnitude of seiches on the lake, measured at Yellowknife Bay and Fort Resolution. Water level data from the delta were collected and compared with historical trends, and hydraulic conditions within the delta during seiches were assessed.

Lake water-level variability was found to be greatest during the autumn, indicating seiches have a seasonal character. The onset of seiches is related to the duration of ice cover on the lake and diminishing Slave River flows in mid- to late-summer. Seiches (on a north-south axis) on Great Slave Lake typically begin in mid-July (July 10 at Fort Resolution and July 23 at Yellowknife Bay on average) and continue until freeze-up. Seiches greater than 0.05 m occur approximately 10-15 times per year with most events producing water level ranges near the SRD perimeter of 0.05 – 0.09 m. However, larger seiches do occur each year, with magnitudes as great as 0.4 m. Seiche set-up events at the delta are typically caused by northwesterly winds (85% of all studied events), whereas southeastern winds force seiche set-down events (68% of all studied events) (Gardner, 2002). Wind direction driving the seiche events can produce a variable response in the water slopes of distributary channels. For example, it was observed that strong North winds created a backwater seiche that was detectable at least as far as the bifurcation between the
ResDelta Channel (North flowing) and Old Steamboat Channel (West flowing). Figure 20a shows the water level recorded at the Mouth (Lake) and at the Apex (bifurcation) on Old Steamboat Channel plus related wind roses of daily direction and speed over late August 2001. As illustrated in Figure 20b, a WNW 15km/hr mean wind speed had a negligible effect on the water surface slope while a later NNW 23km/hr mean wind speed increased the slope on Old Steamboat Channel from 0.6 cm/km to 1.2 cm/km in less than one day (Gardner, 2002).

**Figure 20.** Wind seiche events recorded on Great Slave Lake at the Slave River Delta during the summer of 2000 (Gardner, 2002): a) water levels recorded at two delta channels and discharge of the Slave River. Wind roses are given for 5-day and 1-day periods with mean wind speed (km/h); origin at centre of wind rose indicating wind direction. 1-day wind rose indicates wind conditions for each event. b) water levels at an apex and outer delta location, plus the river slope prevailing between the two sites.
Given the low slope of the SRD, seiche events can penetrate far upstream (Figure 21) and alter significantly deposition and erosion processes, such as in the formation of instream shoals and bars, and growth of the subaerial outer delta. In general, the main sediment deposition zones would move upstream as the penetrating lake levels cause the river to lose sediment carrying capacity. Similarly, large magnitude events would be capable of inundating most of the outer portions of the SRD and flood areas further inland with relatively low levees. Notably, however, an NREI assessment of changes in flow channels and riparian zones of the SRD revealed that the system has not been stable over the last half-century. A time series of delta mosaics was constructed using 880 airphotos for the years 1999, 1997, 1994, 1991, 1979, 1977, 1973, 1972, 1970, 1966, 1960, 1957, 1954, 1946, and 1930. Inspection of the mosaic time series revealed that the overall flow pattern (channels) from 1946 to 1960 appeared relatively static with the main flow path through the central delta (Figure 22a and 22b [1957 illustrated instead of 1960 because of image clarity although conditions were similar]). In 1966, a period of lower flows and decreasing lake levels, there appeared to be a major shift eastward to the ResDelta channel (Figure 22c). Importantly, this shift occurred prior to the system being regulated and is interpreted as being the result of natural processes. Unfortunately, hydrologic interpretation of the next mosaic (1970) is complicated by the effects of flow impoundment at the Bennett Dam. By 1973, however, the shift in flow to the ResDelta (East) channel appears complete leaving only minor flow channels through the western and southern portions of the SRD (Figure 22d).

**Figure 21.** Slope Profile of Old Steamboat Channel, Slave River Delta. The spatial extent of a seiche event of a given magnitude can be determined by comparing the seiche magnitude to the average slope of the delta. Small seiche events affect distributary water levels in the Outer delta and Mid-delta, large seiche events affect the entire modern delta. Delta zones and levee heights indicate threshold levels above which flooding occurs. Seiche magnitudes and extreme historical seiche events given on right axis (Gardner, 2002).
Overall, the degree to which such wind-driven events can affect the SRD has been altered because of the combined effects of channel migration, flow regulation and climate variability. In the case of lake levels, however, the pre- and post-regulation/ naturalization analysis does provide considerable insight into the potential for modifying some in-delta processes. For example, a general reduction in peak-annual water levels by 5 to 20 cm for individual years and the resultant reduction in effectiveness of lake-generated flood events would logically lead to a long-term enhancement of delta progradation and subsequent shifts or drying in pre-existing lake and wetland regimes. Notably, however, climatic factors have generally been acting in the
opposite direction to increase peak water levels and thereby limiting delta progradation. In the
case of delta flooding, it is expected to remain highly dependent on the co-incidence of high
water levels and wind seiche events. However, contrasting the observed seasonal shift in peak
water levels to earlier in the summer with a greater water-level variability and seiche frequency
in the late summer, it would appear that conditions may have become less favourable to delta
flooding. Although an ice-jam study of the SRD was not part of this research program, ice-jam
flooding is known to be a regular occurrence at river-lake confluences (e.g., Beltaos, 1995). The
substantial rise in spring lake levels is likely to affect the location and possibly the severity of
river-ice jamming and thus have further implications for SRD flooding.

CONCLUSIONS AND FUTURE RESEARCH

Historical modelling of the in situ water balance of the PAD perched basins revealed that these
systems were able to retain water for a maximum of 9 years under a wet cycle and as little as 5
years when exposed to relatively steady cool-dry conditions. Future climate scenarios suggest
that the basins will dry out even more rapidly, largely because of higher intensity of open-water
evaporation and longer duration of the open-water season. Hence, their current and future
viability as aquatic systems depends on periodic inundation by overbank floodwaters.

Many perched basins located adjacent to the large intra-delta lakes can be flooded during periods
of high lake levels and lateral lake expansion. This can occur in response to significant inflow
from the Athabasca systems, particularly when large volumes of water are diverted southward
from the Peace River during flow reversals. Although this study could not evaluate spring
reversals, analysis of the open-water events did reveal some systematic changes in the frequency
of these events, particularly after the mid-1970s. Moreover, analysis of naturalized flows
suggests that a decrease in the volume and duration of reversals has resulted from the decrease in
major flow events on the Peace River. As noted earlier and below, however, improved hydraulic
models of the Peace, Slave and PAD flow system are required to more accurately quantify flow
reversal and resultant near-lake flooding.

Although flow reversals could affect the potential for flooding of perched basins adjacent to
the lakes, they are unlikely to have had any effect on the higher elevation basins in the delta
perimeters since even large-magnitude events (e.g. 1935) were shown to be unable to recharge
these systems. One major finding of this study is that large-scale overbank flooding from the
major rivers is primarily responsible for filling the higher elevation basins. As noted in the
earlier NRBS studies, this is most likely to occur under ice-jam conditions but, as concluded
from these NREI studies, it might have occurred in two instances (e.g. 1972 and 1990) under
open-water conditions without the effect of regulation. Some caution in evaluating the extent

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of this flood potential is required, however, because the event flows during these periods exceeded the calibration range of the models used to assess the peaks. Given this, more research is suggested to:

a. evaluate the ability of the current first-order hydraulic model of the Peace River, or
b. produce a two-dimensional hydraulic model based on actual river cross-sections;

to better simulate extreme flows and to account for potential overbank storage in the riparian zone.

The effects of regulation also appear to have had some effect on the relative importance of the upstream and downstream sub-catchments in the generation of these flood peaks. In general, storage of alpine runoff in the Williston reservoir has placed an increased dependence on downstream tributaries in the system, such as the Smoky River, to produce the major flows events that are also responsible for flow reversals into the PAD.

In the case of ice-jam floods, this study reinforces the findings of the earlier NRBS studies, i.e., that such floods are primarily generated by “trigger tributaries” (the Smoky River in the Peace Basin and the Clearwater and Pembina sub-basins in the Athabasca Basin) located in the downstream portions of the catchments. Although the importance of ice-jam events in the Peace River to the recharge of high-elevation perched basins in the PAD was previously established, further work conducted within the NREI has helped to quantify the controlling processes. Notably, flows in excess of approximately 4000 m$^3$ s$^{-1}$ are required to produce overbank flooding, and major ice-jam floods require intense heating of a snowpack of at least 150 mm water equivalent located in the trigger tributary. Analysis of a future climate-change scenario also suggests that the frequency of ice-jam floods will be reduced, largely because of an expected smaller alpine snowpack. There is also the possibility that mid-winter breakup events might develop as the climate warms. Although a full analysis of this possibility remains to be completed, the unpredictable nature of such events and their associated large socio-economic damage potential suggests that this should be a research priority.

Calibration of an ice-jam flood model for the PAD also permitted a detailed evaluation of the effectiveness of an adaptation strategy recommended from the results of the NRBS. Analysis showed that augmenting flow during the spring breakup period through an enhanced flow release substantially contributed to recharge flooding of the PAD in the spring of 1996. This raises further hope that similar strategies might be used in the future to combat the negative effects of climate change on this aquatic system.
Climatologic analysis of weather systems controlling snow accumulation and melt within the trigger basin on the Peace River showed that variations in both of these controlling factors are strongly related to the Pacific/North American (PNA) pattern and the Southern Oscillation Index (SOI). The results suggest that during both winter and spring, the position and intensity of the Aleutian Low pressure system plays an important role in controlling the local synoptic regime over the Peace River basin. The degree to which these teleconnection patterns and principal atmospheric features may be altered by climate change is recommended for further study.

This study showed that some effects of regulation are experienced as far downstream as the Slave River Delta and Great Slave Lake, although natural climate variability increasingly obscures the effects. Part of the reason for the large effect on the Slave systems is that almost three quarters of the inflow to Great Slave Lake originates from the Slave River to which the Peace is the dominant headwater river. Many of the regulation-related effects on Great Slave Lake water levels, including changes in the timing and magnitude of peak levels have been affected by climate variability. Most importantly, climatic and regulation impacts have generally counter-balanced changes in amplitude of water level fluctuations and magnitude of peak levels but have cumulatively contributed to a shift toward earlier peak water levels in the lake. Primarily because of the low slope of the water surface in the SRD, such lake-level changes have the potential of modifying other important natural processes that control delta development and flooding. In terms of the latter, the effectiveness of late-summer wind seiches and spring ice-jams could be significantly affected by shifts in the timing of water levels. Further research on the latter events is recommended since they were not part of this NREI study but are known to be an especially important to the riparian hydrology of many cold-regions delta systems.

Some of the components of this NREI study included analyses of projected climate-change impacts (e.g., perched-basin water balances, winter snow conditions, and ice-jam events). These preliminary assessments were conducted using data from the first generation Canadian GCM (CGCM1). During the NREI, however, newer versions of the GCMs were evaluated to provide up-to-date assessments of the climate-change impacts on the various hydrologic events and processes. Specifically, several international GCMs (recommended by the Intergovernmental Panel on Climate Change; IPCC) were evaluated in their ability to replicate the magnitude and spatial variability of current (1961-90) climate over western regions of Canada that formed the focus for these NREI studies. A summary of the model inter-comparison can be found in Bonsal et al. (2003). It is therefore recommended that further assessments of climate change on hydrologic processes in the Peace-Athabasca-Slave system be conducted using the inter-comparison results as a guide. It is further recommended that GCM output from a range of greenhouse gas emission scenarios be used to provide the full scope of the potential impacts.
REFERENCES


