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CLIMATE CHANGE, FLOW REGULATION AND LAND-USE EFFECTS ON THE HYDROLOGY OF THE PEACE-ATHABASCA-SLAVE SYSTEM; FINDINGS FROM THE NORTHERN RIVERS ECOSYSTEM INITIATIVE

T. D. PROWSE[1,*], S. BELTAOS[2], J. T. GARDNER[3], J. J. GIBSON[1], R. J. GRANGER[4], R. LECONTE[5], D. L. PETERS[1], A. PIETRONIRO[4], L. A. ROMOLO[6] and B. TOTH[4]

[1]*Water and Climate Impacts Research Centre, National Water Research Institute @ University of Victoria, PO Box 1700, STN CSC, Victoria, BC, Canada;* [2]*National Water Research Institute, Environment Canada, Burlington, ON, Canada;* [3]*Department of Geography, University of Western Ontario, London, ON, Canada;* [4]*National Water Research Institute, Environment Canada, Saskatoon, SK, Canada;* [5]*École de technologie supérieure, Montreal, QC, Canada;* [6]*Southern Regional Climate Center, Louisiana State University, Baton Rouge, LA, USA*

*(*author for correspondence: e-mail: terry.prowse@ec.gc.ca)*

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 Rivers Basin Study (NRBS). This manuscript summarizes the results from a number of reports on hydrologic research conducted on 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, flow regulation and land-use changes. 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 over time; the synoptic weather patterns and atmospheric teleconnections that are responsible for the generation of major snowmelt runoff that drive major floods; the potential effect that climate and land-use changes might have on basin runoff and delta lake levels; 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; remote-sensing methods to document delta flooding and vegetation change; and the dual effect of climate and flow regulation on the water levels of Great Slave Lake and how these may affect other nearshore processes, particularly wind seiches, that influence flooding of the Slave River Delta. A review of the major findings and recommendations for future research concludes the report.

Keywords: climate change, delta, floods, flow regulation, ice jam, land-use changes, northern rivers, synoptic climatology, water balance

1. 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 1970s following regulation of its main headwater river, the Peace River. Further concern following two decades of drying water conditions 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.*, 2002a) 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 an analysis of the hydro-meteorological conditions controlling ice-jam occurrence on the Peace River indicated that declining snowpacks on a major "trigger" tributary (Keller, 1997) played a significant role in reducing the frequency of major ice jams (Prowse and Conly, 1996). Notably, 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 hydrologic research were made by the supporting government agencies (Gummer *et al.*, 2001; NRBS, 1996). In general, these agencies recommended that further investigations be undertaken to assess the effects of climate, flow regulation and land-use on hydro-ecological changes that have occurred within the Peace-Athabasca system, including the PAD, and further downstream, specifically the SRD. This manuscript briefly reviews and integrates the findings from a number of reports of hydrologic studies conducted on these systems that were commissioned by a multi-year research program, the Northern Rivers Ecosystem Initiative (NREI), to address the major research recommendations. Following an overview description of the hydrologic regime, the methods and results of nine major hydrologic studies are presented. For readers seeking more detailed information beyond this summary document, references are made to the original hydrologic reports. Figure 1 conceptualizes the interrelationship of the major hydrologic stressors and study foci. As illustrated, these studies of headwater basins of the Mackenzie are the forerunners to broader-scale studies trying to understand hydroecological impacts further downstream the Mackenzie and into the near-shore marine environment. Moreover, they broaden our understanding of hydrologic regime changes; information that has been identified as being critical to evaluating the role of arctic river flow on global climate and arctic aquatic systems (e.g., Rouse *et al.*, 2003; Walsh *et al.*, 2005; Wrona *et al.*, 2005). A set of summary conclusions draws the various report results together and makes recommendations for future research.

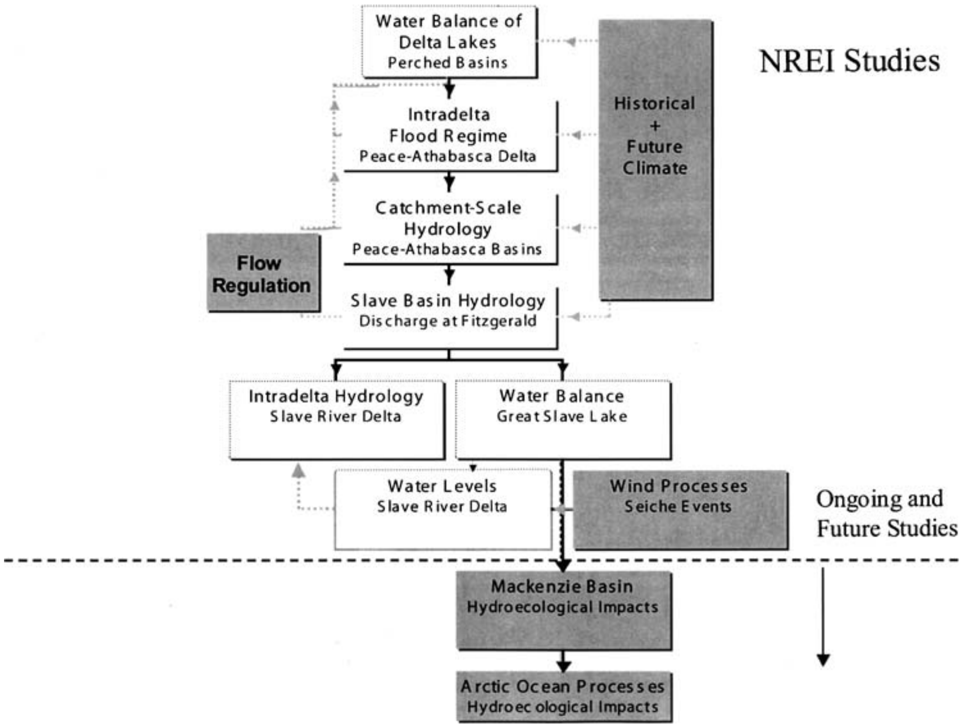


Figure 1. Conceptual figure of integrated hydrologic studies conducted for NREI. Studies described here relate to those above the dashed line. Major stressors evaluated include climate (historical and future), flow regulation and lake wind processes – as denoted by shaded boxes. NREI studies were conducted in the headwater Athabasca, Peace and Slave catchments of the Mackenzie river system and are providing information for other broader scale studies of hydroecological impacts being evaluated in the downstream portions of the Mackenzie River and in the near-shore Arctic Ocean.

2. 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 ($\sim$41 km^3) between 1968 and 1971. At about this point (Hudson Hope hydrometric station), the catchment area is approximately 70×10^3 km^2 and the mean annual discharge is 1100 m^3/s. 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 293×10^3 km^2 (Figure 2) but only doubled its flow

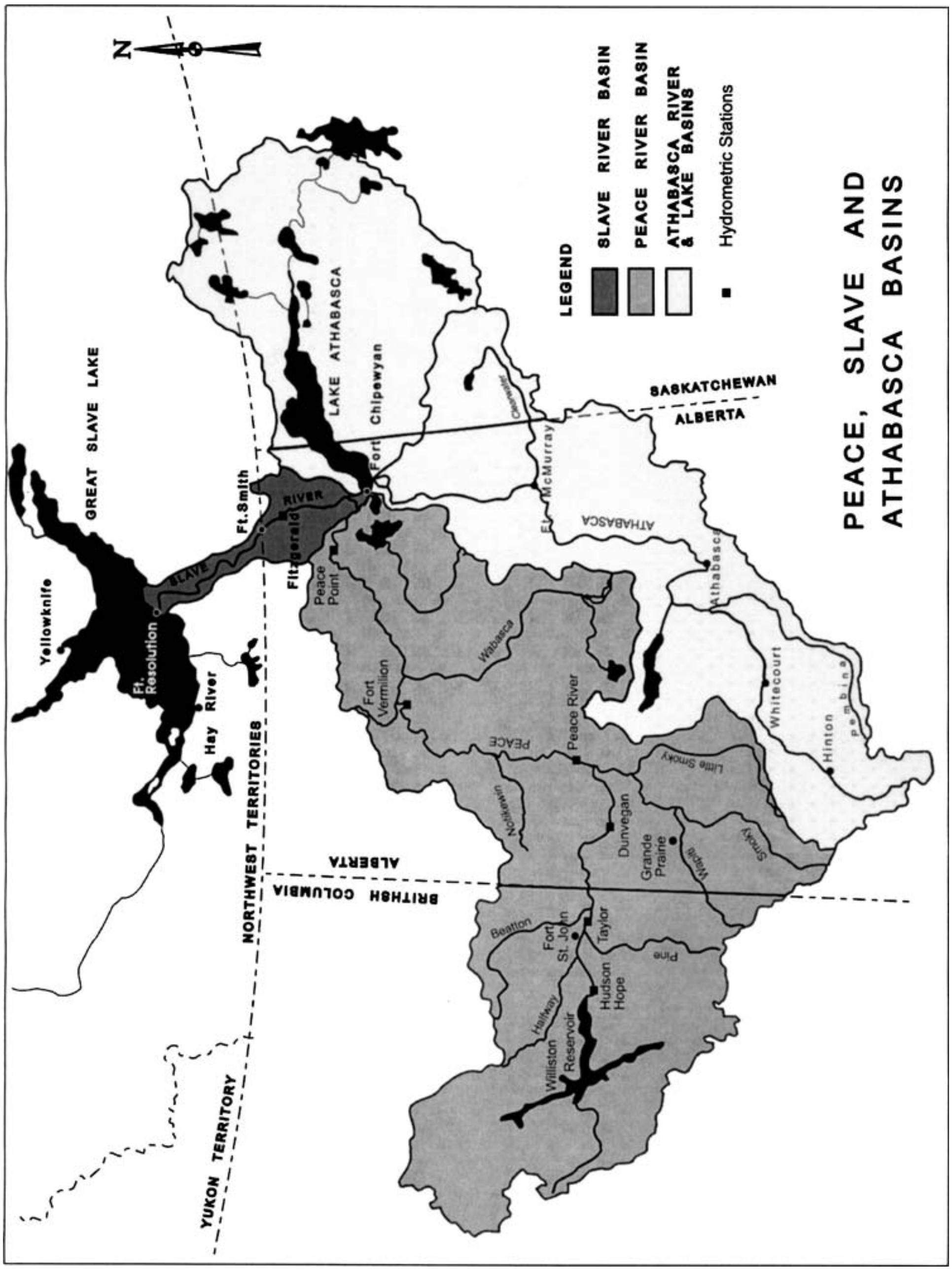


Figure 2. Athabasca, Peace and Slave river and lake basin system.

Figure 3. Typical perched basin and channel network in the Peace River Delta (by T.D. Prowse).

to approximately 2100 m^3/s. Peak discharge typically occurs in late May to early June, driven primarily by snowmelt runoff in the headwaters.

The PAD is formed by the Peace, Athabasca and Birch Rivers at the western end of Lake Athabasca. Flow in this complex network is typically northward but can reverse and flow into the PAD and Lake Athabasca when water levels on the Peace River are higher than those of the more southerly lake and river systems. Surrounding the main lakes are hundreds of shallow ponds (commonly referred to as "perched basins"; Figure 3) 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 (GSL). At this point, an area of approximately 615,000 km^2 (mean annual flow $\sim$3400 m^3/s) 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 outflow 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*. (2002a).

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 GSL, the SRD has become increasingly exposed to the deeper portions of GSL. As a result, progradation rates have decreased leaving an active arcuate front of only 400 km^2, or 5% of the total SRD (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.

3. Methods and Results

The following outlines nine major hydrologic studies conducted for the NREI focused primarily around the flow chart in Figure 1. They first describe research conducted to evaluate the hydrology of the PAD perched-basin and lake systems, then at a large spatial scale the sources and controls (e.g., climate change, flow regulation, land-use effects and atmospheric patterns) of runoff from the Peace-Athabasca catchments, and finally the influence of the contributing flows to the water budget of GSL and potential interactions with the SRD. Since this is only a summary overview of major NREI results, references have been included in each sub-section to literature containing more detailed background, methodology and results.

3.1. Water budget of PAD perched basins

A key interest of the NRBS and subsequent NREI was to determine the relative importance of hydro-climatic components on the water balance of the PAD perched basins and the range in duration of basin floodwaters under contrasting hydro-climatic scenarios (e.g. wet-dry, warm-cold, etc). To this end, an earlier prototype water-balance model produced for the PAD-TS was improved during the NREI to include a more realistic representation of perched basins and tested over a range of hydroclimatic conditions.

3.1.1. *Methods*

The water balance equation for Jemis Lake, a representative perched basin (80 cm deep) adjacent to Mamawi Lake (for details about the lake see Peters *et al.*, 2006a), is described as:

$$Q_F + P_S + P_O - E_O \pm Q_G = ds/dt \qquad (1)$$

where Q_F is overbank flow of channel/lake into or out of the basin; P_S is winter precipitation in the form of accumulating snow on the lake-ice surface; P_O is precipitation onto the surface during the open-water period; E_O is evaporation (from open-water and emergent vegetation) during the open-water period, Q_G is groundwater flow, and ds/dt is the change in water storage per unit time (all in m^3/s).

3.1.2. *Results*

The following highlights the major findings from the NREI perched-basin modeling studies (Peters, 2003; Peters *et al.*, 2006a). Overall, it was found that perched basins are able to retain water for a period of 5 years under cool-dry conditions (e.g., 1920s) and up to 9 years for wet conditions (e.g., 1940s and 1950s). A seasonal drawdown of water occurred in almost every year modeled, due primarily to evaporation being greater than precipitation. Groundwater flow resulted only in a minor loss or gain of water to the basin. Although the prevailing hydro-climatic conditions influenced the duration of water, the primary conclusion of this modeling study was that perched basins are highly dependent on floodwater additions to maintain an aquatic environment.

Water-balance modeling of future climatic conditions (2070–99) was also carried out based on data input from the Canadian General Circulation Model (CGCM1; Prowse *et al.*, 2004). Results showed a 3-week reduction in the ice season compared to the 1961–1990 period (approximately 1 week in the fall, 2 weeks in the spring), which would extend the open-water season and permit greater evaporation. This, combined with warmer air temperatures (approximately +4°C annual air temperature) was forecast to increase total evaporative loss by approximately +35%. Despite projected increases in precipitation (approximately +11%), the enhanced evaporation was projected to produce more rapid drying and thus, an enhanced dependence on flooding to avoid drying of the perched-basins.

3.2. 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 conducted to determine the sources and regional importance of various flood types. A focus was placed on three delta regions (near-delta locations of the Peace and Athabasca rivers, and the intra-delta lakes) and two flood types (open-water and ice-jam). See Peters *et al.* (2006b) for detailed descriptions of the flood regimes.

3.2.1. *Methods*

To assess the complicating effects of flow regulation on the flow to and through the PAD, a one-dimensional 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 Peace River hydrometric station to the PAD. Creation of naturalized flows is especially important because only nine years of hydrometric data exist prior to regulation that would permit pre- and post-regulation comparisons. The river hydraulic model was coupled with an updated One-Dimensional (ONE-D) Hydrodynamic model of the PAD (PAD-IC, 1987; Aitken and Sapach, 1994) to naturalize flow and water levels within the PAD.

3.2.2. *Results*

Full details of the flow-modeling studies are presented in Peters and Prowse (2001; 2005), Peters (2003) and Peters *et al.* (2006b). Results of the historical open-water 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 observed during the summer of 1971, and lesser events in 1982, 1986 and 1995. On the northern perimeter of the PAD (affecting primarily the Peace Delta), high-stage events capable of overtopping the banks have been virtually non-existent along the Peace River mainstem during the open-water season. Analysis showed that the highest 1-day observed flow (12,600 m^3/s) occurred in June 1990 after the river became regulated. It is noted in the flow-modelling reports that this flood peak would likely have been higher without the effect of water impoundment. Similarly, another very high (>12,600, m^3/s) 1-day flood peak (Q_1) would possibly have occurred in 1972, if not for regulation. However, 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. Even if they contain substantial overestimation (e.g., +20%), it was found that they would both still be significantly greater than any other observed flow before or after regulation and be in the range of flows (>14,000 m^3/s) capable of producing direct overbank flooding (without ice jam backwater effects) of the north shore of the PAD (PAD-PG, 1973). Overall, the mean peak flows at Peace Point have been significantly ($\alpha = 0.05$) reduced by ~3,000 m^3/s since regulation. The same is true for the longer term sustained high-flows (30-day high flows), which are associated with major flow reversals into the PAD (see below) and the raising of the large intra-delta lakes to flood levels.

The NREI studies were the first to systematically examine the nature of lateral lake expansion into contiguous perched basins (e.g. Jemis Lake). Using Lake Athabasca water levels as an index of intra-delta lake levels, an historical analysis (1930s onward) revealed that natural hydro-climatic conditions in the contributing basins created at least two years in the pre-regulation period with lake levels below the exceedingly low levels that characterized the filling years (1968–1971) of the Williston reservoir (Figure 4a). The all-time high water level on Lake Athabasca occurred prior to regulation during the summer of 1935. Despite engulfing other large lakes in and around the delta, it was found that this event did not recharge the highly perched, delta basins. The simulation results support the general conclusion of prior studies by the PAD-IC (1987) and NRBS (Aitken and Sapach, 1994) that outflow control structures constructed in the 1970s have partially countered the major effects of upstream flow regulation. Lake levels would probably have been, however, lower in some years and higher in others without such regulation.

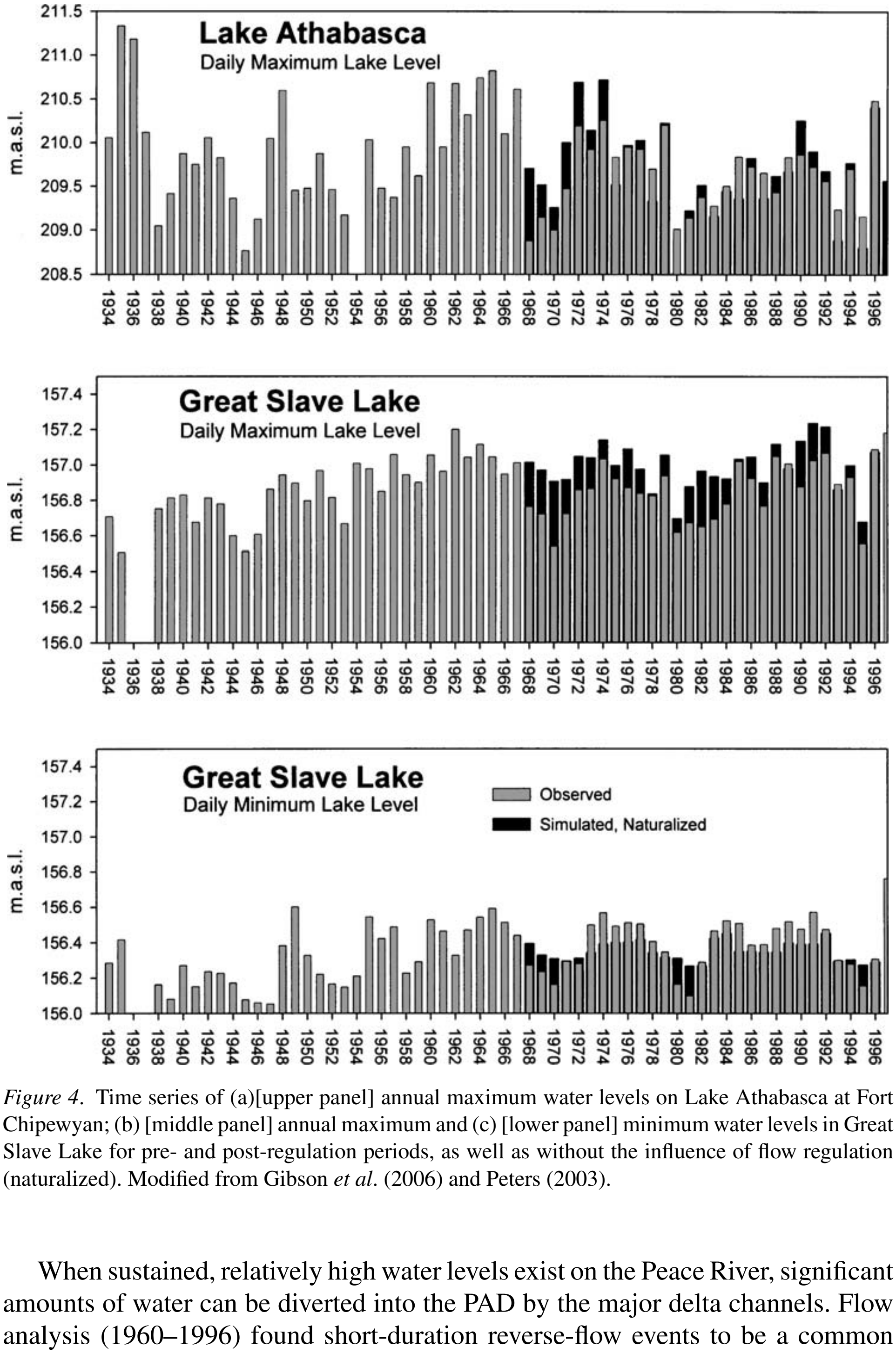


Figure 4. Time series of (a)[upper panel] annual maximum water levels on Lake Athabasca at Fort Chipewyan; (b) [middle panel] annual maximum and (c) [lower panel] minimum water levels in Great Slave Lake for pre- and post-regulation periods, as well as without the influence of flow regulation (naturalized). Modified from Gibson *et al*. (2006) and Peters (2003).

When sustained, relatively high water levels exist on the Peace River, significant amounts of water can be diverted into the PAD by the major delta channels. Flow analysis (1960–1996) found short-duration reverse-flow events to be a common occurrence during the spring, with no significant difference between the mean spring volume of flow that occurred prior to and after regulation. Results showed that the Peace River contributed some reverse flow to the delta lakes each year prior to regulation during the open-water period. By contrast, after regulation, more than half the years were estimated to have not experienced any reversal and those that did were characterized by much smaller events. Overall, based on this 1st-order assessment, the mean annual volume and duration of reverse flow for the regulated open-water period (1972–1996) was significantly lower than for the period (1960–1967) prior to closure of the dam - an estimated mean reduction from approximately 2.6×10^9 to 2.69×10^8 m^3. A major implication of reduced reverse flows is a lowered flood potential from the reduced lateral expansion of the central lakes into contiguous perched basins.

Ice-jam flooding was found to be an important source of delta inundation from both the Peace and Athabasca Rivers. Moreover, supporting earlier NRBS findings for the Peace River, it was found that the generation of such flooding is largely driven by snowmelt runoff from key "trigger" tributaries in the mid- to lower-portions of the basins, such as the Smoky and Wabasca sub-basins in the Peace Basin and the Clearwater and Pembina sub-basins in the Athabasca Basin. Rainfall from these sub-basins and snowmelt runoff from the more elevated upper portions of the basins generate open-water high flows. Contrasting the periods of pre- and post-regulation (1960–1967 and 1972–1996) revealed that, along with climate variability within the basin, the storage of alpine runoff has shifted the generation of peak flows to the downstream portion of the Peace Basin, such as the Smoky River (relative contribution to peak flow increased from 20% to 30%).

3.3. Modeling land-use impacts

In designing hydrologic studies for the NREI, it was also recognized that changes in land-use (e.g., forest clearing and agricultural expansion) might have caused changes to the flow regimes including, for example, modification of flood peaks. Moreover, there was interest in developing a model to be able to assess the potential effects of any future land-use shifts. As a result, the NREI supported research into the advancement of a physically-based Cold Regions Hydrology Model (CRHM). Details are provided in Granger *et al.* (2004). Of particular focus were some cold-climate processes, such as snow accumulation and redistribution, ablation, evapotranspiration and infiltration, which can be significantly different for different land covers and produce markedly different runoff volumes and peaks.

3.3.1. *Methods*

CHRM makes use of a flexible modular framework that draws from a library of physically-based hydrological and energy process algorithms and can therefore be tailored to specific conditions. It was tested using field observations, meteorological and hydrometric measurements from the Upper Paddle River basin, a tributary of the Athabasca River, in Alberta. This basin has already undergone some land use changes, and is under continued pressure from the forestry industry for further modifications. A series of "virtual land use change" scenarios, including forest clear cutting, were applied to the basin, and the model used to determine the impacts on snow accumulation, infiltration and runoff, for wet and dry antecedent conditions (as exemplified by contrasting years 1998 and 1999).

3.3.2. *Results*

Results showed that agricultural, pasture and riparian land surfaces produce much higher runoff than forestlands. Modifying the relative proportions of these land covers within a basin could thus have a significant effect on the total runoff from the basin. "Removal" of part of the forest cover (30% and 50% of the basin area) in the Upper Paddle River Basin had the following impacts: (i) an increase in basin snow water equivalent (due to reduced losses by sublimation in forests) – the 1998 basin snow-water equivalent increased from 138 to 148 mm (156 mm) with a 30% (50%) reduction in forest cover; (ii) a reduction in basin infiltration (agricultural lands have a lower infiltration capacity and available time for infiltration than forests); and (iii) an overall increase in basin runoff. The 1999-spring runoff volume increased from 58 mm to 98 mm (120 mm) for a 30% (50%) reduction in forest cover.

3.4. 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. Building from earlier work by Keller (1997) and an evaluation of synoptic weather-typing procedures, an analysis of historical trends in snowpack accumulation (Romolo *et al.*, 2006a) and spring snowmelt (Romolo *et al.*, 2006b) were conducted for the Smoky River basin, the key "trigger" tributary for spring ice-jam flood events affecting the PAD.

3.4.1. *Methods*

For both of the above-mentioned investigations, an eigenvector-based map pattern classification scheme was employed to create a synoptic catalog 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 adapted from Yarnal (1984), the winter (spring) synoptic types were first divided into precipitating and non-precipitating (high and low energy) patterns and then related to variances in the snowpack (snowmelt) at Grande Prairie, Alberta (climate station representative of conditions controlling the Smoky River).

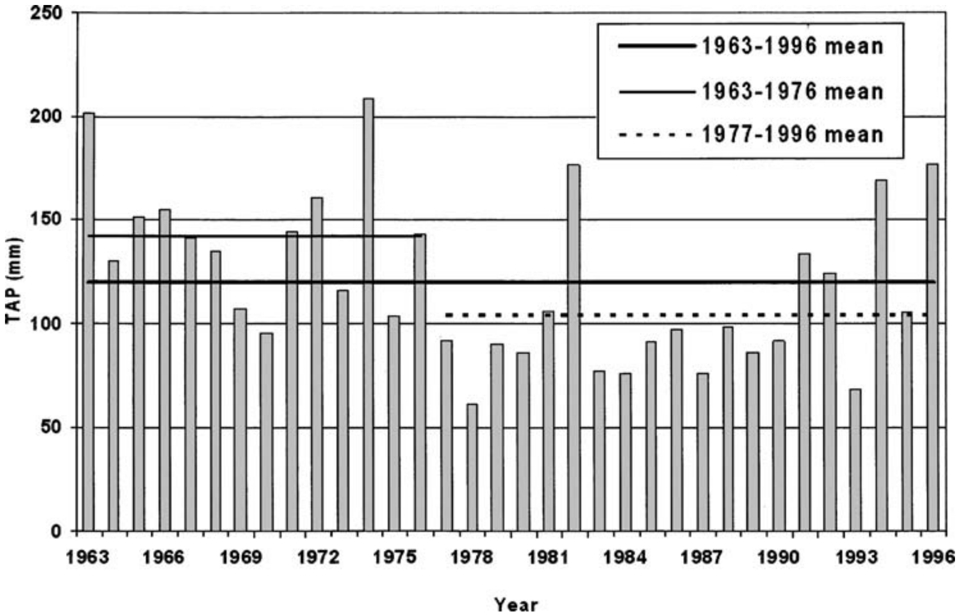


Figure 5. Total Accumulated Precipitation (TAP) at Grande Prairie, AB., from 1963 to 1996. Note shift that occurred in the mid-1970s. From Romolo *et al.* (2006b).

3.4.2. *Results*

As previously noted, snow accumulation in the Smoky River basin experienced an inter-decadal shift to lower values in the mid-1970s (Figure 5), which also corresponded with reduced ice jamming (Prowse and Lalonde, 1996). Using a frequency analysis, Romolo *et al.* (2006a) 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. 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 6). 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). Conversely, dry types dominated under a positive PNA (meridional flow) and negative SOI (El Niño). 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.

A similar study for the same region also demonstrated strong relationship between synoptic circulation and snowmelt (Romolo *et al.*, 2006b). Through the

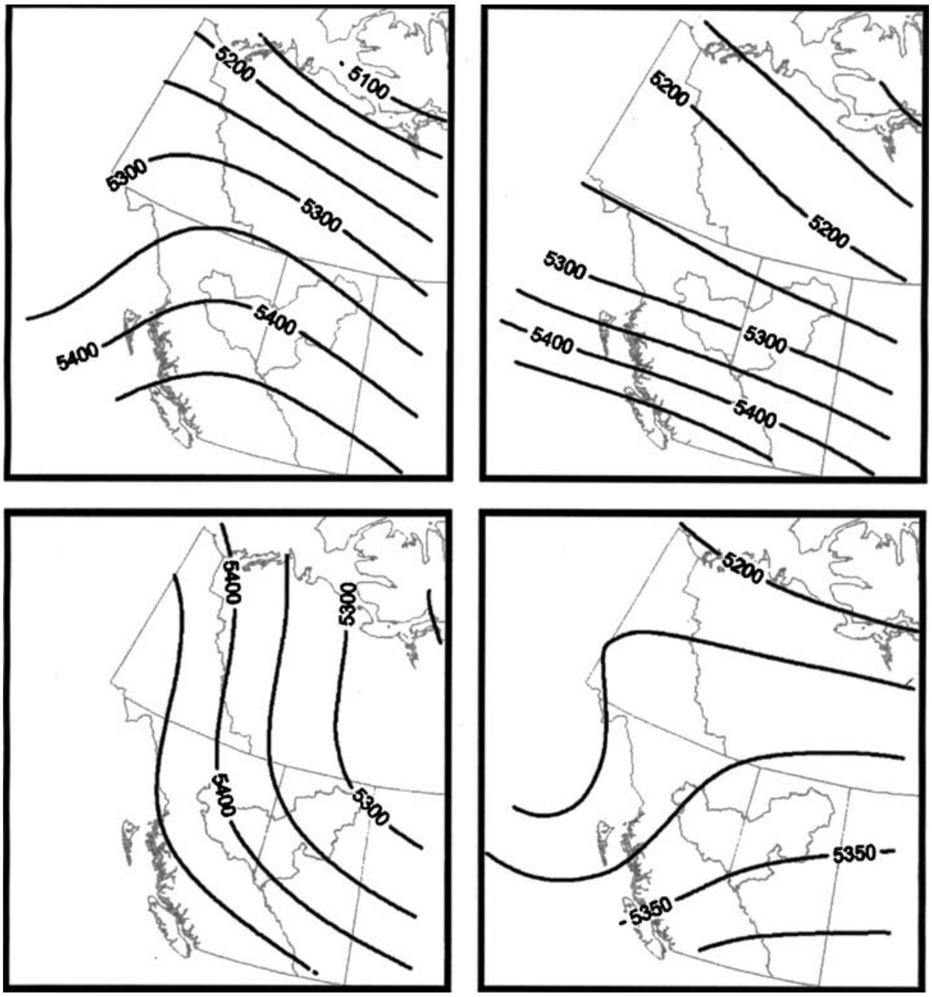


Figure 6. Example of zonal (wet) and ridging (dry) (upper panel), and northerly flow and troughing low-energy yielding synoptic types (lower panel). Ridging pattern is the typical synoptic signature that is associated with high yielding energy during spring. Likewise, troughing (northerly flow) is typical of the synoptic signature associated with wet (dry) conditions during winter. Geopotenial heights are in meters with a 50-m contour interval. From Romolo *et al*. (2006a,b).

use of both a degree-day and energy balance model, spring melt was categorized according to its timing and intensity. Specifically, melt periods were classified as early/late and rapid/protracted. It was discovered that the initiation of spring melt at Grande Prairie, which typically occurs in March, has been occurring progressively earlier over the study period, with early and mid-winter melts (Jan.-Feb.) dominating during the 1980s and early 1990s. This was partially explained by an increasing (decreasing) trend in the March frequency of high (low) energy yielding synoptic types, characterized by ridging (troughing) patterns and a weakened (strengthened) circumpolar vortex (Figure 6). A frequency analysis revealed that early and rapid melt periods were dominated by the high-energy synoptic types, while late and protracted melts were influenced by low-energy synoptic types. Shifting beyond the synoptic scale, further analysis identified that high (low) energy yielding patterns were influenced by the positive (negative) phase of the PNA. Although the SOI was found not to have a significant impact on the occurrence of synoptic types, La Niña events were significantly associated with late melts and a strong March dominance of low-energy types.

3.5. Climate impacts on water availability

Another goal of the NREI was to assess how future climate might affect the flow of the major river catchments feeding the PAD and thereby the delta-lake water levels.

3.5.1. *Methods*

For these purposes, climate-change scenarios (based on a doubling of CO_2 emissions) were downscaled from a set of five Global Circulation Models (GCM) recommended by the Intergovernmental Panel on Climate Change. These included: CGCM1 (CGCM): Canadian General Circulation Model, 1st generation, Canada; CSIRO (CSI): Commonwealth Scientific and Industrial Research Organization model, Australia; ECHAM (ECH): GCM based on ECMWF forecast models, Germany; GFDL (GFD): Geophysical Fluid Dynamics Laboratory model, USA; and HADCM2 (HAD): Hadley Centre Climate Prediction and Research Model, UK (see Pietronrio *et al*., 2004, 2005 for details about model sources). Temperature and precipitation data from these models were input to a distributed hydrologic model "WATFLOOD" with river-routing schemes as described in Kouwen *et al.* (1993) and Toth *et al.* (2005). Resultant flow data were then used as input to the early noted ONE-D hydrodynamic model of the PAD that was further modified during these studies to better derive delta-lake water levels (see Leconte *et al*., 2001, 2006). Changes created by reductions in ice cover due to enhanced warming were also considered. Linkage of the GCM, hydrologic and hydraulic models is further described in Pietroniro *et al*. (2006).

3.5.2. *Results*

All GCM models predicted increased air temperatures over the Peace and Athabasca basins with the average-model values being approximately 2 °C warmer than current climate in summer and 4 °C higher in winter, although some models predicted temperatures to rise to about +5 °C for a number of winter months. All models also forecast annual increases in precipitation although the values varied widely among models and seasons. The largest increases were forecast to occur in spring with the 5-model average being largest in May at approximately +10 mm/month. Notably, the smallest increases were predicted for the summer months, with a number of models even showing decreases and reaching +10 mm/month in late summer. Full details are provided in Pietroniro *et al.* (2004, 2006).

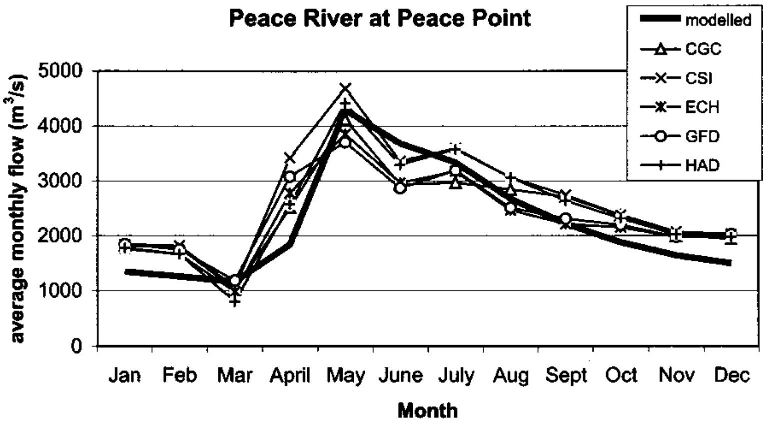
Modeled hydrographs for 14 hydrometric stations were produced by WATFLOOD for a 24 year period (1965–1989) using current climate data, and showed good agreement for volume and timing of flow with observed records. Comparisons with hydrographs driven by the future climate scenarios generally revealed a shift to an earlier melt season and higher winter flows. There was variability in the prediction of the peak spring flows with the CSI and HAD models indicating an increase in flows while the GFD and ECH models predicted lower peak flows under a changing climate – largely reflecting their differences in predictions of spring precipitation. All models forecast total annual volumes to increase but there was some spatial variation. For example, although the upper portions of the Athabasca catchment is forecast to experience a significant increase in runoff of 28% at Hinton (Figure 2), it shrinks gradually downstream to only 7% below Fort McMurray (Figure 2) closer to the PAD. The overall trend is also to increased flow for the larger Peace catchment, albeit less strong, but the negative standard deviation of the 5-model ensemble indicates that flow may even slightly decrease with a doubling of CO_2. Figure 7a shows the monthly hydrograph for the Peace River at Peace Point, the hydrometric station used by previous NRBS studies to evaluate PAD flood conditions.

Similar to the prediction of an earlier freshet on the rivers, spring water levels of the major PAD lakes (Athabasca, Claire and Mamawi) are forecast to rise earlier (Figure 7b). The overall seasonal behavior, however, varies by GCM scenario. For example, on Lake Athabasca during the summer period, the GCM scenarios that show significant precipitation increases result in a 10 (HAD) to 25 cm (CSI) water-level increase. Furthermore, the winter water levels for the same two scenarios stay consistently above the current-climate levels. By contrast, the other scenarios show the peak levels in Lake Athabasca to decrease by 15 cm (CGC), 25 cm (GFD) and 40 cm (ECH) and summer water levels to become lower by 15 (CGC), 25 (GFD) and 30 cm (ECH).

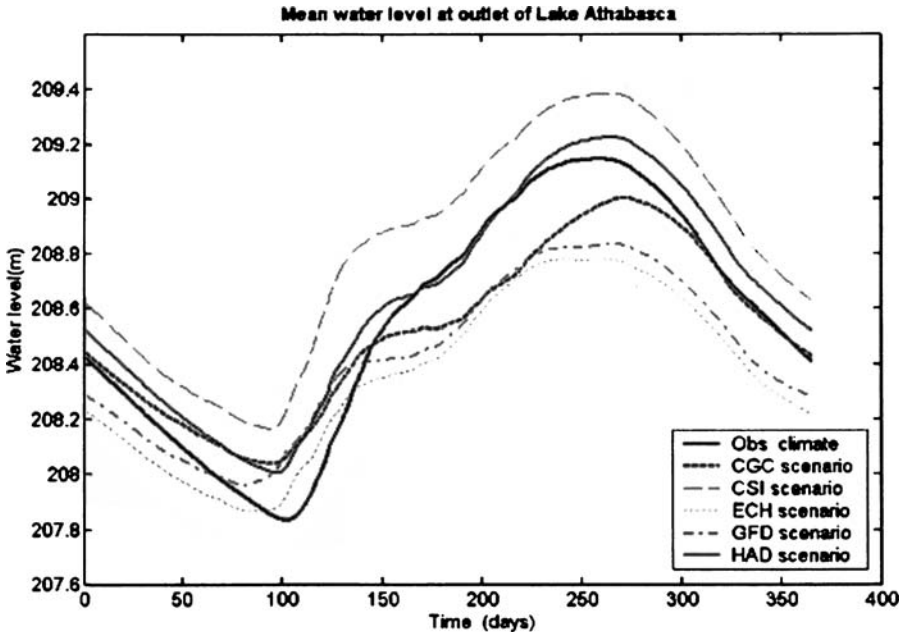
Although the ensemble of models converges towards the same general results on annual time scales, there is variability at the smaller time scales. Further modeling of river and lake levels are recommended, particularly with newer generation atmospheric and hydrologic models that are continually improving spatial and temporal resolutions, and becoming increasingly coupled by design.

3.6. ICE-JAM FLOOD MODELING

Given the importance of particular ice-jam flood sites on the Peace River to flooding of the PAD, an ice-jam modeling study was undertaken to quantify the flow conditions required for significant over-bank flooding and to assess what conditions might exist under a changing climate.



(a)



(b)

Figure 7. (a) Average modelled monthly flows for 24 year (1965–1989) current climate simulation, and the five GCM 2×CO_2 scenarios for the Peace River at Peace Point hydrometric station. Note earlier initiation of melt and higher winter surface flows. (b) Same current-future climate comparison as for 7a but showing mean water surface elevation for Lake Athabasca. From Toth *et al.* (2006).

3.6.1. *Methods*

Detailed field surveys and river-ice breakup observations were conducted on the Peace River to permit the use of the hydraulic model RIVJAM (Beltaos, 1993, 1996). Hydro-climatic records associated with past ice-jam flood events were analyzed to

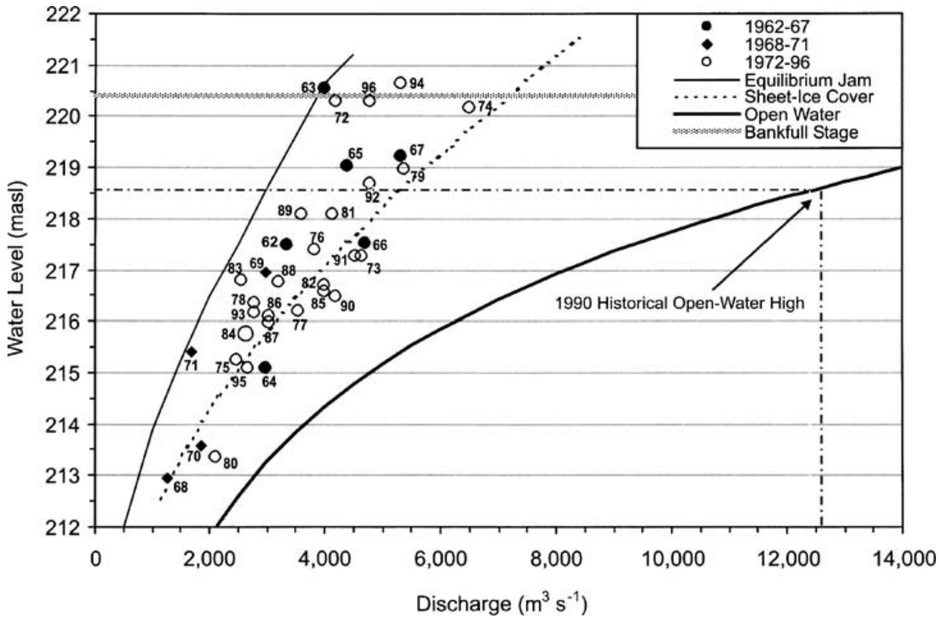


Figure 8. Rating curves for the Peace-Point hydrometric stations showing water level/discharge relationships for different flow conditions and comparison with peak stages recorded during breakup. Upper-most line: calculated maximum stage from an equilibrium ice jam. Intermediate line: sheet ice cover just prior to breakup, assume thickness of 0.6 m and Manning roughness coefficient of 0.03; lowermost line: open-water condition. From Prowse *et al.* (2002b).

characterize the type and severity of ice-jam floods and used to assess the probability of future events under climate change. An assessment of potential climate-change impacts was carried out using air temperature and precipitation output from the CGCM2 for the future-scenario years of 2070–2099.

3.6.2. *Results*

Ice-jam flooding of the PAD (Figure 8) was found to occur when the following conditions are fulfilled: (a) the breakup event is of the "mechanical" type (breakup events are characterised 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 m^3/s. 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, 2003; Beltaos *et al.*, 2006a). Consequently, the scarcity of ice-jam floods (only 4 after 1968) appeared 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). However, it was not possible to quantify the relative significance of these two factors, owing to the brevity of the pre-regulation record.

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. The latter is considered representative of runoff conditions that can generate mechanical breakups at the PAD by indexing conditions in the Smoky River, the major "trigger" tributary. It was found that major floods required a total winter snowpack of at least 150 mm at Grand Prairie and intense spring heating (Beltaos *et al.*, 2002, 2006b) to generate a large ice-jam flood.

Using the above results as a benchmark and the results from the CGCM2, 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. Notably, Romolo *et al.* (2006b) documented that mid-winter melts had already become more frequent even under current climate conditions (especially mid-1980s to early 1990s).

Having established the hydro-climatic conditions leading to ice-jam flooding and with a preliminary indication as to future hydro-climatic impacts, it was possible to examine potential options for enhancing flooding of the PAD. 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 the hydro-electric company operating the reservoir (BC Hydro) followed a recommendation of the NRBS final reports and released an additional flow of 500 m^3/s 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.* (2002b).

3.7. Monitoring water-level restoration

Given the dearth of hydrometric information about the PAD, a remote sensing study was initiated by the NREI to help better understand the extent, frequency and duration of flooding. The remoteness, large size and particularly the low-elevation complex terrain of the PAD posed a particularly difficult challenge (Pietroniro *et al.*, 1999). The objectives of the remote-sensing study were three-fold: (a) delineate the flood extent in the PAD following the major flood of 1996; (b) assess general vegetation characteristics over the delta; and (c) evaluate remote sensing as a tool for ecosystem management.

3.7.1. *Methods*

A time series of Landsat and SPOT satellite data were acquired that were coincident with Radarsat overpasses, providing for both Visible and Infrared (VIR)

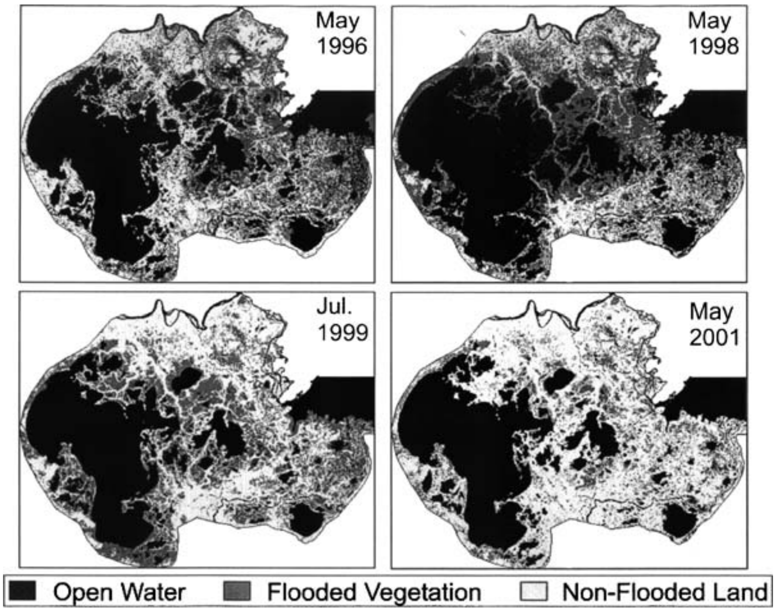


Figure 9. Classified flood maps of the Peace-Athabasca Delta. Note that the 1998 image does not cover the western edge of the study area. Choice of spring-summer months for each year determined by availability of clear images. From Pietroniro and Töyrä (2004).

and Synthetic Aperture Radar (SAR) coverage of the delta. For flood mapping, a combination of SAR and VIR imagery was used. Coincident with the flood monitoring, mapping of general vegetation classes in the central portion of the delta used multi-temporal SPOT-4 imagery. See Pietroniro and Töyrä (2004) for details about the various types of remote sensing imagery employed.

3.7.2. *Results*

Detailed results of advances in using the multi-sensor approach for flood mapping of the PAD are described by Töyrä *et al.* (2001, 2002) and Pietroniro and Töyrä (2004). Overall, the techniques permitted a multi-year time series of percentage areas covered by open water, flooded vegetation and non-flooded land as shown in Figure 9. Notably, declining water levels resulted in much of the open water in May 1998 being replaced by flooded vegetation by July 1998 – approximately two years after the major 1996 delta-wide flooding. After this time, the open-water class remained relatively constant around 40% of total area, while the flooded vegetation class was slowly replaced by non-flooded vegetation.

The derived flood maps provide a useful quantitative estimate of the flooding extent and the subsequent drying of the PAD. When the flood maps are compared, the drainage patterns and the duration of flooding within certain areas can be observed. This information is important for assessing the influence of flooding or absence of

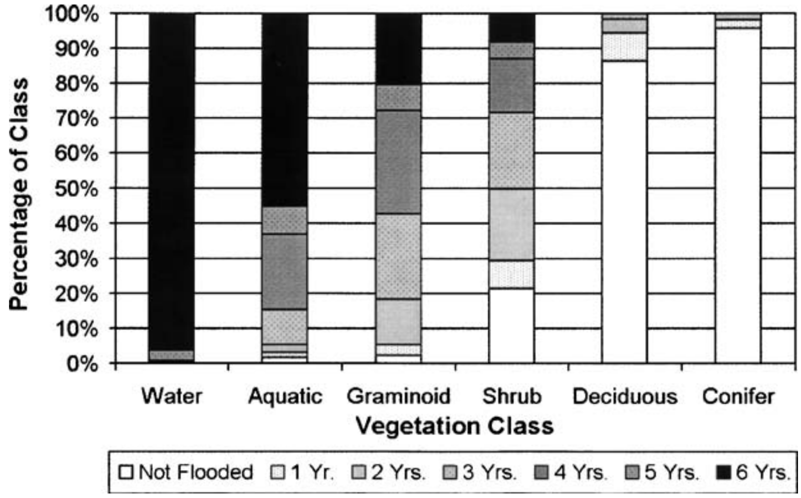


Figure 10. Percentages of area covered by water and different vegetation classes including the duration of flooding between 1996 and 2001. From Pietroniro and Töyrä (2004).

flooding on vegetation and wildlife. It was found that the vegetation patterns within the entire delta could be mapped using either Landsat TM data or a mosaic of SPOT-4 data. These vegetation maps could then be combined with spatial flood duration maps to assess the vegetative response over the long term. Figure 10 illustrates examples of water/vegetation coverage prevailing prior to the 1996 flood and in three subsequent years.

3.8. Water levels of Great Slave Lake

As earlier noted, the NREI investigations extended to evaluating how the hydro-ecology of the SRD could be affected by changes in flow of the Peace-Athabasca-Slave river system and related water levels of GSL. To assess the potential role of the lake, an historical water-balance analysis was conducted for the entire lake catchment for the period 1964–1998. This would permit examination of the potential sensitivity of the system to climate and water-resource impacts over the past 35 years. Water-level records for GSL dating back to 1938 were examined to extend pre- and post-regulation comparisons.

3.8.1. *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:

$$Q_i + P - Q_o - E = dS/dt \pm Q_G \pm error \quad (2)$$

where Q_i is the mean-annual riverine inflow to the lake, P is mean-annual precipitation on the lake surface, Q_o mean-annual riverine outflow, E is mean-annual evaporation, dS/dt is the mean change in lake storage from, and the residual $\pm Q_G$ $\pm error$ includes error in all measurements including the net groundwater exchange (all in m^3/s). A working model was also developed to test the models robustness for predicting daily water-balance and water-level changes. Overall, the measured inflow + precipitation exceeded measured outflow + evaporation by +2% for the 1964–1998 period, which is attributed to minor systematic error in discharge gauging, but also may reflect additional, ungauged groundwater inflows to the lake. Full details of the climatic and hydrometric data employed in the model and necessary calibrations, particularly for evaporation during changing open-water periods, are summarized in Gibson *et al*. (2006).

Estimates of how climate has altered water levels on the lake were also conducted but first required elimination of the effects of upstream flow regulation. To quantify the effects of changing climate on GSL, the water-balance model was used along with naturalized flow simulations from the Peace River (Peters, 2003; Peters and Prowse, 2001) to approximate conditions 1967–1996. The simulations required development of an additional routing module for the lake to estimate outflow. The 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 examine climate versus regulation impacts on GSL water levels.

3.8.2. *Results*

During 1964–1998, it was found that 74% of inflow to GSL originated 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 the years of upstream dam filling. 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 GSL, including the post-regulation period was found to be climate-driven precipitation variability in the Peace-Athabasca basins.

Comparison of pre-regulation (1938–1967) 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, which approximates the conditions during 1972–1996 if the Williston reservoir was not constructed, suggest that climate-driven changes have also occurred. For example, amplitude of water-level fluctuations and maximum water levels would have likely increased rather than decreased in the later period by about 0.08 m and 0.01 m respectively; peak water levels would still have occurred but probably shifted to a lesser degree (late July), and spring mean water levels risen by only 0.08 m due to hydro-climatic 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 Figures 4b and c.

3.9. Lake level-delta channel interactions

Given the potential range of water levels on GSL some exploratory studies were undertaken to assess their possible effect on the SRD. These included assessing the potential for lake-river interactions, changes in morphology of the delta over time, and possible extremes in water levels as produced by lake seiche events (defined as a wind-forced surface water set-up and set-down). Details are provided in Gardner (2002) and Gardner *et al*. (2006).

3.9.1. *Methods*

Since no hydraulic gradient data for the Delta were known to exist, extensive field surveys were conducted to determine how far inland lake water levels could intrude. 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). To assess changes in the delta, 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 (Carter, 1996). The historical frequency and magnitude of seiche events were analyzed from water level records, measured at Yellowknife Bay and Fort Resolution, on the north and south ends of the lake respectively.

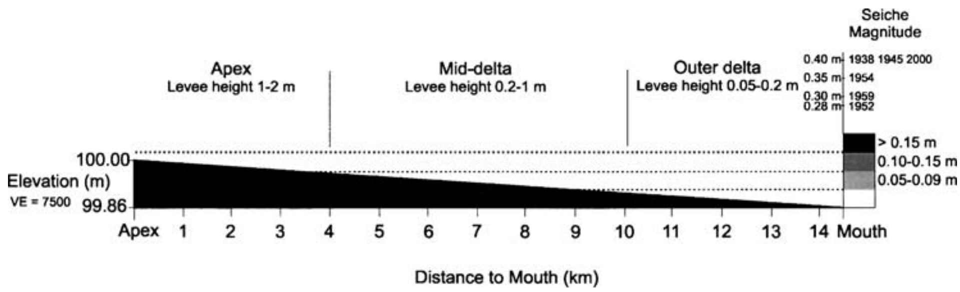


Figure 11. Slope Profile of Old Steamboat Channel, Slave River Delta. The spatial extent of a seiche event of a given magnitude can be determined by comparing the seiche magnitude to the average slope of the delta. Small seiche events affect distributary water levels in the outer delta and mid-delta, large seiche events affect the entire modern delta. From Gardner *et al.* (2006).

3.9.2. *Results*

Results of the channel surveys indicated that a low slope of approximately 0.007–0.0015 m/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 0.1–0.2 m 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 (Figure 11). 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 produced by flow regulation. Hence, both effects have the potential to alter large areas of the main active delta.

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 GSL typically begin in mid-July and continue until freeze-up. Seiches greater than 0.05 m occur approximately 10–15 times per year with most events producing water level increases 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; Gardner *et al.*, 2006). 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).

Given the low slope of the SRD, seiche events can penetrate far upstream 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

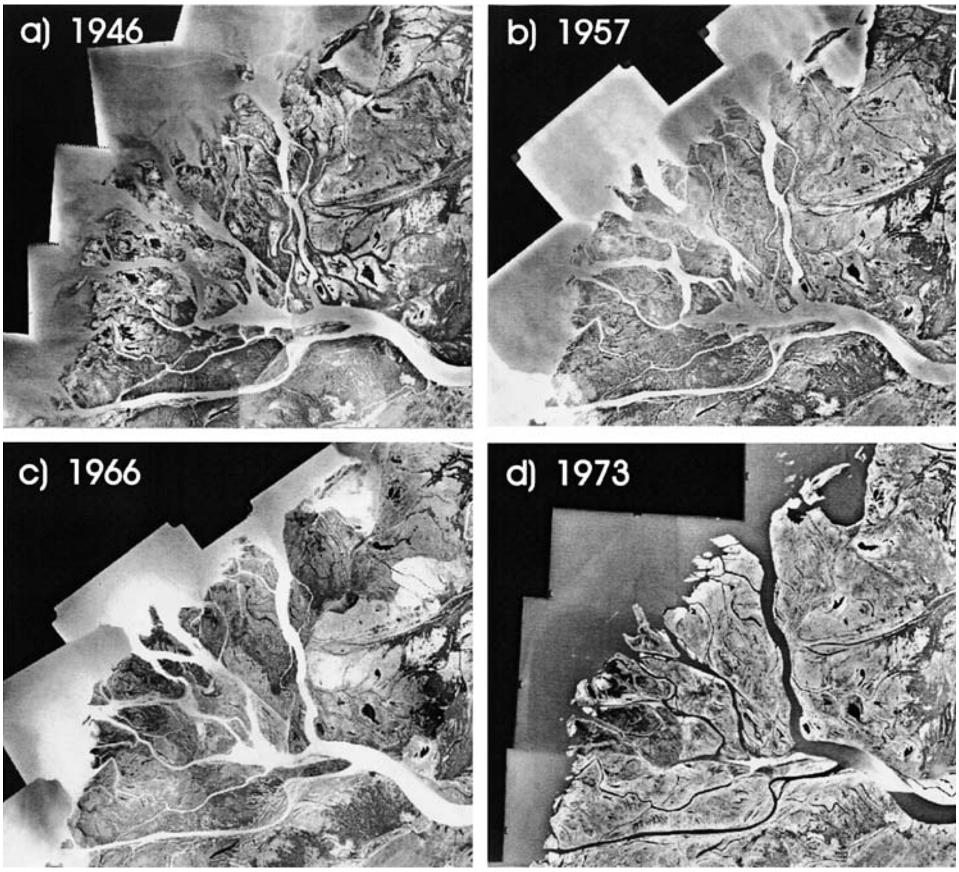


Figure 12. Mosaics of aerial photography of the Slave River Delta (From Carter, 1996). Note the major shift in flow direction to the ResDelta Channel (from centre to northwest) that began in the mid-1960s and was well established by 1973.

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. 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 12 [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. 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 Bennet

Dam. By 1973, however, the shift in flow to the ResDelta channel appears complete leaving only minor flow channels through the western and southern portions of the SRD.

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 0.05 to 0.2 m for individual years and the resultant reduction in effectiveness of lake-generated flood events would likely 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 dependant 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 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.

4. Summary and Research Recommendations

Historical water-balance modelling revealed that a typical shallow PAD perched basin is 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 they will dry out even more rapidly, largely because of higher 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 there was no significant difference between the mean-spring flow-reversal volumes prior to and after regulation, the frequency of reverse-flow events did decrease after regulation. Moreover, analysis of naturalized flows suggests that these changes have resulted from a decrease in major flow events on the Peace River. Although this could affect the potential for flooding of perched basins adjacent to the lakes, it is 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 also occurred in at least two instances (e.g. 1972 and 1990) under open-water conditions without the effect of regulation. Some caution in evaluating the extent 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.

Changes in land use were shown to have significant potential to modify flow volumes and particularly flow peaks that are so important to the hydro-ecology of the PAD. It is recommended that water-management assessments of future hydro-ecological conditions include land-use modeling of hydrologic changes. Large-scale land-use changes even have the potential to outweigh some of the impacts that could result from climate change.

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.

Climate change has the potential to significantly affect the timing and volume of flows in the Peace and Athabasca rivers, as well as lake levels within the PAD. Largely because of increased precipitation, flow is predicted to generally increase although the effect diminishes significantly downstream. Equally likely are earlier melt seasons and higher winter flows. The magnitude and sign of some of the results, however, depended very much on which GCM provided the input data. Further modelling is recommended employing newer version GCMs (see below) and more specifically, data from Regional Climate Models (RCM) that have higher spatial resolution and thus more compatibility with current generation of distributed hydrologic models.

In the case of ice-jam floods, the NREI results reinforce the findings of the earlier NRBS studies, i.e., that such floods are primarily generated by “trigger tributaries” 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 help to quantify the controlling processes. Notably, flows in excess of approximately 4000 m^3/s 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.

Remote sensing of changing flood and vegetation conditions conducted under the NREI demonstrated that a geomatics-based approach to studying such a large ecosystem can provide invaluable data that are otherwise unavailable or impractical to obtain. Remote sensing does not and will never completely replace detailed vegetation and ground surveys, but rather is able to complement *in situ* analyses with a more generalized delta-wide view. Such a comprehensive approach to hydro-ecological monitoring is recommended for all future monitoring strategies for the PAD.

The NREI studies also showed that the effects of regulation are experienced as far downstream as the SRD and GSL, 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 GSL originates from the Slave River to which the Peace is the dominant headwater river. Many of the regulation-related effects on GSL 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 components of these NREI studies included preliminary assessments of projected climate-change impacts and some of these were conducted using the 1st generation Canadian GCM (CGCM1). During the NREI, however, newer versions of a suite of GCMs were evaluated by Bonsal *et al*. (2003) for their ability to replicate the magnitude and spatial variability of current (1961–1990) climate over the study region of the NREI. 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.

Acknowledgements

The authors wish to acknowledge the immense contribution from all the researchers (far too long to list here) that contributed to the various NREI studies on which this overview is based. Most of these are supporting co-authors on the publications cited in the reference list. Funding for this research was primarily provided by the Northern Rivers Ecosystem Initiative but additional resources were contributed by the different authors' universities and/or government agencies noted in the listing of affiliations.

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