Modelling climate change impacts in the Peace and Athabasca catchment and delta: III—integrated model assessment

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Abstract:

This study utilized the hydrodynamic model, ONE-D, coupled to the distributed hydrological model WATFLOOD, to evaluate the potential effects of a shift in climate on the hydrological regimes of three large lakes (Athabasca, Claire, and Mamawi), and two important sources of inflow (the Peace and Athabasca rivers) in the Peace-Athabasca Delta (PAD). The coupled WATFLOOD/ONE-D system was forced by current climatology and downscaled climate change scenarios from five selected general circulation models (GCMs).

Under the selected climate change scenarios, water levels in Lakes Athabasca, Claire, and Mamawi peaked, on average, 40–50 days earlier than at present. Some GCM scenarios predicted an increase in peak lake levels while others predicted suppressed lake levels. Inter-annual water level variability was also sensitive to predicted changes in precipitation and temperature, increasing in winter and decreasing in summer.

Water level fluctuations in the major input rivers of the PAD were found to be more variable under the climate change simulations. Moreover, spring freshet peaks were estimated to occur earlier (20–30 days) and to be considerably reduced (up to 1-0 m reductions).

Although the simulations converged towards the same general results in seasonality shift, flow level amplitude was GCM-dependent. Simple downscaling methods may well be too coarse to adequately address the important spatial variations that can occur in the long-term climate signal. It is therefore important to understand the sensitivity of this regime to local climatic influences to produce more reliable, quantitative results. An ensemble of approaches that provide meaningfully downscaled results should be considered to confirm the results presented. Copyright © 2006 Crown in the right of Canada, and John Wiley & Sons, Ltd.

KEY WORDS Peace-Athabasca Delta; hydrology; hydrological modelling; ONE-D; WATFLOOD; model coupling; climate shift; hydrological regimes

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INTRODUCTION

The Peace-Athabasca Delta (PAD) is located at the western end of Lake Athabasca in northern Alberta, Canada. The Peace River is the largest river flowing into the PAD and its headwaters are located in the Rocky Mountains of northern British Columbia. Since 1968, the Peace River has been regulated by a reservoir located in the headwaters. The PAD relies on periodic flooding, predominantly by spring ice jams (Prowse and Conly,
1998), from both the Peace and Athabasca rivers. However, a combination of hydroclimatic changes and flow regulation has influenced the formation of ice jams and may have resulted in an overall drying trend in the delta (Prowse et al., 1996). With the expected occurrence of a change in climate over the next 50 years, the impacts on the hydrodynamics of the delta may very well be significant, and quantitative estimates of such impacts should be made. Although any future scenarios derived from atmospheric-hydrological and hydraulic model projections are fraught with uncertainty, it is important to establish a modelling framework to examine possible scenarios and their potential impacts, as well as establish general trends and possible sensitivities in the modelling framework to better quantify any future research assessing these impacts. There is recognition within the water resources and ecological community that methods to understand potential future climate impacts are required. This is highlighted for the PAD in the conclusions of the Northern River Basins Study (NRBS, 1997), which recommend that further research is needed to better understand the climate–hydrology interactions within this ecologically important region.

Hydrological and hydrodynamic models are tools that can be utilized to assess the effects of a shift in climate on the hydraulic behaviour of river systems. In a companion paper (Toth et al., 2006), the hydrological regimes of the Peace and Athabasca watersheds were studied under conditions of climate change by forcing climate scenarios from five well-known general circulation models (GCM) in the WATFLOOD hydrological model. Results from the climate change scenarios showed a shift in the timing of peak flows and small changes in the volume of flows. Since climatically variable freshwater ice regimes are known to significantly affect flows and water levels within the PAD, a sensitivity analysis was conducted using Environment Canada’s ONE-D hydrodynamic model. The duration of the ice-cover period was varied in the simulation. Results, which appear in a second companion paper (Leconte et al., 2006), revealed that while the winter severity effect was of relatively short duration in the rivers, the subsequent reduction in large lake levels extended throughout the summer. In this paper, the ONE-D hydrodynamic model was forced at the boundaries with simulated flows from the WATFLOOD hydrological model to assess the magnitude of the change in the flow regime of the PAD for different climate change scenarios. The coupled WATFLOOD/ONE-D runs also accounted for the reduction in the ice-cover season resulting from the anticipated global warming.

SITE DESCRIPTION

The Peace and Athabasca rivers meet at the western end of Lake Athabasca, Alberta (Figure 1). This confluence forms one of the largest and most biologically productive freshwater deltas of the world. It provides habitat and/or breeding ground for a variety of small and large mammals and migratory birds. The delta also contains spawning sites for many fish species, large populations of which migrate between the delta lakes and rivers (PADPG, 1973).

The PAD landscape is dominated by three large lakes: Claire, Mamawi, and Baril. Each lake is 1–3 m deep and is connected to Lake Athabasca by countless active and inactive channels. Although delta waters normally flow north, if water levels in the Peace River exceed those in Lake Athabasca (as can occur during the spring break-up period), flow direction may reverse. More complete descriptions of the PAD can be found in Leconte et al. (2006), Peters (2003) and Peters et al. (2006). As previously stated, the largest river flowing into the PAD is the Peace River, which has a total drainage area of 293,000 km², referenced to the Peace Point hydrometric station. The second most important river feeding the PAD is the Athabasca. It flows in northeasterly from its headwaters in west-central Alberta. Its drainage area, measured at Fort McMurray, is 133,000 km². Regulation of this system is largely limited to the Peace River, which was first regulated in 1968 with the filling and operation of Williston reservoir, located approximately 1200 km upstream of the PAD. Roughly, 24% of the Peace River drainage area is now captured by the reservoir. Regulation has dampened the natural flow of this system, thereby increasing the flow during the fall/winter seasons, while reducing the spring/summer peak flow in the river (Peters and Prowse, 2001). Outflow control structures were added on two channels in 1975/1976 to counter decreased peak lake levels associated with storage of alpine run-off.
Figure 1. Study site
These changes in the flow regime have also been influenced by noted variations in climate, confounding to some degree the understanding of the influence of regulation on the hydrological regime of this system (Prowse and Conly, 2001).

METHODS

The potential effects of climate change on the flows and water levels within the PAD have been assessed by establishing downscaled meteorological climate change scenarios that are used as input into a hydrological modelling system, WATFLOOD (Kouwen et al., 1993). The resulting streamflow simulations are then linked to a one-dimensional hydrodynamic model, ONE-D (Environment Canada and BC Environment, 1995). At its core, WATFLOOD is a conceptual, distributed hydrological model capable of simulating river flows in continuous simulation mode over periods of many years. Thus it is well suited for climate change studies. WATFLOOD uses the Grouped Response Unit (GRU) concept to model large watersheds, by which all similarly vegetated areas in a sub-watershed or element are grouped together as a hydrologically significant land cover type, or GRU. Complete descriptions of the WATFLOOD system are presented in Kouwen (1988), Kouwen et al. (1993) and in Toth et al. (2006). ONE-D is Environment Canada’s one-dimensional hydrodynamic model capable of simulating open channel hydraulics in complex river systems (Aitken and Sapach, 1994). It employs a finite difference, fully implicit, numerical scheme to solve the St-Venant equations for water levels and discharge. The model also allows for simulating river systems under partial and full ice-cover conditions. A more extensive description of ONE-D and its functionalities can be found in Leconte et al. (1999, 2006).

To assess potential climate impacts, our climate change scenarios were based on the latest available IPCC-GCM scenario data at the initiation of the project. These represent the first series of IPCC results, and do not include the most recent Special Report on Emissions Scenarios (SRES), which have been constructed to explore future developments in the global environment, with special reference to the production of greenhouse gases and aerosol precursor emissions. (IPCC, 2003) While climate change scenarios are not a predictor of future climate, they are an important tool used to provide data for impact assessment studies and to aid in strategic planning. The choice of climate change scenarios is significant because it determines the outcome of the climate change impacts analysis. The selection of climate change scenarios should meet three conditions. They should cover the broad range and the variability of global warming projections, they should be physically plausible, and the scenarios should estimate a sufficient number of variables on both temporal and spatial scales to allow for impact assessment (Smith and Hulme, 1998).

Given that climate change scenarios are not explicit predictors of future climate, their output cannot be used directly, and an evaluation must be performed on scenario output before they can be effectively utilized in a climate change impact assessment. Climate change scenarios resulting from five GCMs have been investigated and used to represent potential climatic variability. The selected GCMs are as follows:

1. Canadian General Circulation Model (CGCM1);
2. Commonwealth Scientific and Industrial Research Organisation model (CSIRO);
3. GCM based on ECMWF forecast models, modified and extended in Hamburg (ECHAM);
4. Geophysical Fluid Dynamic Laboratory model (GFDL); and
5. Hadley Centre Climate Prediction and Research Model (HADCM2).

The monthly 1961–1990 and 2040–2069 precipitation and temperature data for each of the five GCMs were retrieved and used to calculate monthly spatially distributed \( \Delta T \) and \( \Delta P/P \) values. These were then applied to observed gridded precipitation and temperature fields to construct anticipated future climate (2 × CO\(_2\)), temperature and precipitation series. The range of temperature increases by the selected GCMs fell primarily within the 1–4.5°C interval, which is generally accepted as the potential increase in temperature which
results from a doubling of CO₂ concentrations (IPCC, 1990), with the highest temperature changes occurring during the winter months (i.e. December–March) and the lowest changes occurring in the summer months (June–August). With respect to precipitation, all the models showed an increase for all months with the exception of June–August. For June–August, the GCM projections are rather inconsistent with some models demonstrating an increase in precipitation, while others project a decrease. Overall, the increases typically varied from 5 to 15 mm per month, with the largest increases during the February–May period. Details of the scenario development and results are presented in Toth et al. (2006). Given that the watershed areas are of the same order of magnitude as the GCMs resolution from which the scenarios were developed, the approach renders rather crude scenarios. Moreover, the downscaling technique used to construct regional climate scenarios from the GCMs assumes that only temperature averages are altered due to climate change, while spatial variability around the mean remains unchanged. Although the climate scenarios used in the analysis could be refined using either Regional Climate Model outputs (if available), more sophisticated statistical downscaling techniques, or by accounting for temporal variability of precipitation and temperature, the approach followed in this study nonetheless constitutes a useful tool in providing information for impact assessment studies and in strategic planning.

Using the WATFLOOD hydrological system, a total of six hydrological regime scenarios were generated for further incorporation as boundary conditions for the ONE-D model. WATFLOOD was first calibrated and validated on the Peace, Athabasca, and Birch rivers using observed temperature and precipitation for the years 1966–1989 (24 years). The resulting hydrographs formed the baseline scenario. For modelling purposes, the watershed is divided into square-shaped cells of an appropriately sized area, and for this study 45 km grids were employed. Simulated hydrographs for five climate change scenarios, each derived from monthly GCM scenarios, were then generated using the calibrated WATFLOOD system. Details and results of the modelling procedure can be found in Toth et al. (2006).

The WATFLOOD output hydrographs were used as flow rate boundary conditions for the ONE-D hydrodynamic model. The boundary nodes for the One-D model are listed in Table I. In addition to input hydrographs, a ONE-D run also requires calculated precipitation and evaporation (P-E) values over the larger lakes (Athabasca, Claire, Mamawi) as well as ice-cover freeze-up and break-up dates. These were generated as follows:

**P-E over the larger lakes**

Lake evaporation was computed from observed and synthesized temperature time series data using the Penman equation adjusted for lakes. Parameters of the equation were adjusted so that annual evaporation matched the observations obtained during the Mackenzie GEWEX studies over Great Slave Lake (Rouse et al., 2003). Because large lakes such as the Athabasca can store tremendous quantities of heat, most evaporation equations do not provide reliable results on a daily, or even monthly, basis. For that reason, seasonal values of evaporation were calculated from monthly averages of temperature data, and a constant P-E was used in ONE-D for the entire summer season.

<table>
<thead>
<tr>
<th>Location</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peace River at Peace Point</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Athabasca River at Fort McMurray</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Birch River at Alice Creek</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Slave River at Fitzgerald</td>
<td>Stage-discharge curve</td>
</tr>
<tr>
<td>Lake Athabasca at Fond du Lac</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Lakes Athabasca, Claire, and Mamawi</td>
<td>Lateral flows (P-E)</td>
</tr>
</tbody>
</table>
Ice-cover freeze-up and break-up dates

The dates were estimated from the HYDAT database for the observed scenario runs. For the climate change scenario runs, freeze-up and break-up dates were adjusted according to a $0.2 \degree \text{C day}^{-1}$ rate (Prowse and Beltaos, 2002) of change in autumn (October and November) and spring (March and April) air temperatures. For example, if the mean March–April air temperature of the CGCM model were $2 \degree \text{C}$ higher than the observed air temperature, then the ice break-up date would occur $2 / 0.2 = 10$ days earlier than for the observed scenario run. Ice thickness was not incorporated in the future climate modelling scheme, and ice jams were not simulated.

Finally, the ONE-D model was also calibrated and validated by adjusting the Manning’s roughness coefficients of river reaches until simulated water levels in the PAD matched the observed levels as closely as possible. Water levels measured between years 1968 and 1990 were used for the calibration-validation process. A stage-dependent Manning coefficient was used for the large rivers that control the drainage of the PAD. Details of the calibration procedure can be found in Peters (2003).

WATFLOOD simulated flow hydrographs, P-E values and ice-cover freeze-up and break-up dates were then incorporated into the calibrated ONE-D model to generate current and future climate-derived water levels and discharge values for the various channels and lakes that constitute the PAD hydrodynamic system. The ONE-D model was run in continuous mode over a 24-year period (January 1966–September 1989) for each of the six scenario runs.

RESULTS AND DISCUSSION

Hydrological modelling

The results of the WATFLOOD simulation runs for the Athabasca River below Fort McMurray and for the Peace River at Peace Point (Figure 1) are given in Figure 2. The 24 years of simulated flows (1966–1989) for the current and future climate scenarios were averaged for each month. The figure reveals that an increase in winter flow volumes and a significant shift in seasonality with earlier melt onset are predicted by all climate change scenarios. The predictions of change in the annual spring melt volumes are not consistent: the CSI and HAD models predict an increase in spring melt volumes while the GFD and ECH models predict a decrease. However, all scenarios estimate an increase in annual volumes. There is a spatial pattern to the uniform temperature and precipitation pattern. The wetland and lower elevations of the Athabasca basin will be significantly wetter whereas the predominantly forested environments and higher elevations of the Peace River basin will experience a compensating increase in evaporative flux and will not realize as significant an increase in streamflow. The inflows to the Williston Reservoir will also be subjected to an increase in winter flows and a shift in seasonality, but the spring freshet and subsequent summer flow input will be reduced under climate change. This may have a significant effect in the early autumn months as the Peace struggles to refill the reservoir before the higher winter flows accumulate the necessary recharge volume.

Hydraulic modelling

The output hydrographs from the WATFLOOD simulations were used as input data for the current climatology (January 1966–September 1989) and for the five selected GCMs for (January 2046–September 2069). It should be noted that a few of the Peace River hydrographs, as simulated by WATFLOOD for the baseline scenario, necessitated slight modification because unrealistically high and low ONE-D input flow values caused the model to become numerically unstable. For example, simulated peak flow for year 1974 reached 16 000 m$^3 \text{s}^{-1}$, which is well above the maximum observed flows of 12 600 m$^3 \text{s}^{-1}$ recorded at Peace Point, in June 1990. Simulated low flows around 80–100 m$^3 \text{s}^{-1}$, which are well under the 350 m$^3 \text{s}^{-1}$ minimum recorded in 1968, were also obtained. These extreme flows resulted in either exceeding the maximum water elevation imposed by the channels geometry in ONE-D, or in drying-up of sensitive reaches, such as
the Claire River next to its confluence with the Peace River. These modifications have not significantly altered the overall ONE-D simulation results, mainly because the volumes of flow are still reasonably well simulated with WATFLOOD, despite the fact that peak flows during the calibration period were often over-estimated (Toth et al., 2006).

The hydrodynamic regimes of Lakes Athabasca, Clair, and Mamawi are strongly dependent upon the flows in the Peace and Athabasca rivers. Lake levels will be affected by an eventual climate change, resulting in either an overall increase or a decrease, depending on which GCM scenario is employed. All GCM scenarios predict generally higher winter levels in the rivers, which cause elevated pre-melt spring levels in the lakes of the PAD. Spring melt is accelerated under perturbed climate.

The magnitude of flow and water level fluctuations due to climate change varies with the GCMs selected for analysis. On the basis of computed averages over the entire simulation period (i.e. 24 years), the CSI simulation produced the highest water levels in the lakes (Athabasca, Claire, Mamawi, see Figure 3) and major rivers (Peace and Athabasca, see Figure 4) followed by the HAD, CGC, GFD, and ECH simulation scenarios. For the lakes, the CSI run produced average water levels that were systematically (i.e. all seasons) higher than the observed scenario run. The HAD model produced similar water levels during the summer season and higher levels during winter and the CGC, GFD, and ECH runs produced lower water levels during the summer and winter seasons. For the rivers, the CSI and HAD model runs predicted higher spring water levels, lower late spring/early summer levels and higher levels starting again in July and August. The CGC,
Figure 3. Simulated mean water surface elevation for Lakes Athabasca, Claire, and Mamawi under current and future climate scenarios.
GFD, and ECH global circulation models produced lower flows in spring and summer and similar or higher flows starting in September or later.

Although these effects are obviously tied to both temperature and precipitation changes, it is difficult, at this point, to clearly identify the relative importance of each climatic variable to the overall response observed. For example, the smallest predicted monthly $\Delta P/P$ values were produced by the ECH and the HAD models. However, the reduction in water elevation during the summer and winter months was most significant with the ECH scenario run, while the HAD run produced only minor changes. This suggests that precipitation may not be the most important variable affecting the hydrodynamic regime of the PAD. Conversely, the CSI model produced the highest $\Delta P/P$ values, with a corresponding significant increase in water level changes all year long. In this case, precipitation changes appear to affect the flows more than temperature changes. This is important because precipitation is simulated with less accuracy than air temperature by global climate models. Since the models/runs do not converge towards the same general results (some predict an increase in water levels, while other predict the opposite), there is a need to use more accurate scenario runs to produce more reliable quantitative results. These scenarios could either come from Regional Climate Models, or from statistical approaches, as with stochastic weather generators (Richardson, 1981; Wilby et al., 2002).
Lake responses to climate change

While in general the spring peak elevation occurs earlier under changed climate for each of the lakes, the overall behaviour of Lake Athabasca is highly dependent on the GCM scenario considered. During the summer period, GCM scenarios that show significant precipitation increases (i.e. the CSI and HAD), result in a 10 (HAD) to 25 cm (CSI) increase in the water levels of Lake Athabasca (see Figure 3). In addition, the mean water level at the lake outlet derived from the CSI and HAD scenarios stays above the ‘observed’ water levels during winter. Conversely, the CGC, ECH, and GFD scenarios show the peak levels in Lake Athabasca decreasing by 15 cm (CGC), 25 cm (GFD), and 40 cm (ECH), and summer water levels remaining lower; 15 (CGC) to 25 (GFD) to 30 cm (ECH) over the summer as compared with the actual climate scenario. Note that the lower water levels estimated by the CGC, GFD, and ECH models are consistent with the ice-cover analysis (Leconte et al., 2006), i.e. a shorter ice season due to earlier melt lowers lake levels.

The ONE-D modelling exercise resulted in very large quantities of output data, since every node in the finite difference mesh contains a predicted water level. Results for ‘hydrologically representative’ years, i.e. corresponding to low, average, and high year flows (years 1968, 1979, and 1972, respectively) are presented here. Inter-annual variability is illustrated by the response of the lake under low, average, and high flows. Table II indicates a very significant time shift occurring in the peak levels for low (1968) and high (1972) water years. The rise in levels, which is the result of significant flow reversal episodes, occurs earlier under climate change. The trend observed for the year 1968 is that of flow reversal and peak flows are accelerated by approximately 65 days. The CSI model predicts an increase in peak lake levels, the HAD model predicts very little change and the remainder of the models forecast a reduction in spring peak lake levels. Early melt and flow reversal also occurs during the year 1972, a high water year. Again, the rise in lake level occurs 60 days earlier and, depending on the magnitude and the timing of the flow reversal episodes compared to that of the actual climate, the lake level would peak at higher (CSI scenario) or lower (HAD, CGC, ECH, GFD) values. The hydrodynamic behaviour of the lake is, however, different for the year 1979, an average flow year. Although lake levels are still affected by a changed climate, the time to peak remains virtually unchanged. This is because an important summer flood in the Athabasca River (day 200) was simulated by WATFLOOD (in particular for the CSI and HAD scenarios), spilling large amounts of water into the PAD, further elevating lake levels beyond those attained with the advent of the spring flood.

The responses of Lake Claire and Lake Mamawi to the river flows that feed them are consistent with that of Lake Athabasca. In general, the CSI scenario results in a lake level increase of approximately 25 cm for most of the year, while all other scenarios show a general decrease of up to 40 cm in water levels depending upon the scenario considered. Again, the hydrodynamic conditions under climate change during the low flow year (1968) are unusual. Namely, very significant spring replenishment occurs approximately 65 days earlier than normal. This results in a sharp rise in the simulated water levels (see Figure 5), over those obtained under the current climate scenario levels. Care must be exercised, however, in the quantitative interpretation of the modelled water level increase, as it is affected by the presence of an ice-cover whose period of decay has been empirically estimated and may be occurring too late.

Table II. Lake Athabasca difference in peak elevation and time to peak between baseline and changed climate. Negative values mean lower peak levels and earlier time to peak under a changed climate.

<table>
<thead>
<tr>
<th>GCM</th>
<th>1968—low water year</th>
<th>1972—high water year</th>
<th>1979—average water year</th>
<th>Average (all years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGC</td>
<td>−0.21 m (−65 days)</td>
<td>−0.50 (−55)</td>
<td>−0.42 (−25)</td>
<td>−0.13 (−48)</td>
</tr>
<tr>
<td>CSI</td>
<td>+0.20 m (−55 days)</td>
<td>+0.18 (−55)</td>
<td>+0.21 (−25)</td>
<td>+0.25 (−45)</td>
</tr>
<tr>
<td>ECH</td>
<td>−0.27 m (−70 days)</td>
<td>−0.55 (−60)</td>
<td>−0.45 (−25)</td>
<td>−0.40 (−52)</td>
</tr>
<tr>
<td>GFD</td>
<td>−0.23 m (−75 days)</td>
<td>−0.25 (−70)</td>
<td>−0.42 (−15)</td>
<td>−0.29 (−53)</td>
</tr>
<tr>
<td>HAD</td>
<td>+0.04 m (−65 days)</td>
<td>−0.13 (−50)</td>
<td>−0.01 (−10)</td>
<td>+0.07 (−42)</td>
</tr>
</tbody>
</table>
Water levels in Lake Athabasca and in the larger lakes within the PAD fluctuate from year-to-year as a consequence of climatic variability and are also affected by Williston Reservoir releases (Prowse and Conly, 1998). Such fluctuations would still occur under a changed climate. However, with snowmelt occurring earlier, snow accumulation would be less. And with more frequent winter thaws occurring under a warmer climate, year-to-year fluctuations in water levels would be affected. Figure 6 illustrates the time series of standard deviations of Lake Athabasca water levels under current and projected climates. The current climatology curve is typical of large lakes experiencing alternating summer and winter seasons. There is little winter variability in the absence of significant snowmelt input, but more significant variability during the summer months as the spring snow melt replenishes the lakes, sustaining high water levels for most of the summer season. Although all the curves display a similar shape, the effect of a climate change on Lake Athabasca water regime variability would be, as expected, to increase winter variability because of higher flows and levels.
Increased air temperature (winter thaw events and earlier spring melt) and increased precipitation (winter rain on snow events) explain the increase in standard deviation. Year-to-year variability under future climate is also evident in Table II.

**River responses to climate change**

The Peace and Athabasca rivers exhibit a general trend that is manifest by a reduction in spring peak water levels and an earlier time to peak, and is presented in the average annual stage hydrograph produced by the 24 years of simulation. Figure 4 clearly shows that the water levels encountered during the spring run-off season are reduced by 0.0–1.0 m (depending on the GCM output used), and that the time to peak occurs 20–30 days earlier than for the baseline scenario. Average peak elevations, calculated from the annual peak water levels, show that peak levels typically vary from 0.0–1.0 m, depending on the GCM scenarios utilized.

Inter-annual variability is more significant. Table III summarizes the results for the Peace River. In the low flow year (1968), a dramatic change in the winter regime takes place and the peak surface elevation occurs approximately 2 months earlier than under the current climate scenario, with all scenarios estimating higher peak levels. The high flow year (1972) results in higher levels from the CSI runs while the GFD, CGC, ECH, and HAD runs result in slightly lower levels, with the peak occurring 20–30 days earlier. The average flow year (1979) predicts generally lower spring peaks occurring 10–20 days earlier. This apparent lack of sensitivity must be interpreted with caution, as the presence of an ice-cover, for which the dates of appearance and disappearance were empirically estimated, does affect the results. Nevertheless, such changes are expected to have non-negligible effects on the replenishment of the PAD, in particular the perched lakes, through a modification of the frequency and severity of ice jams. These results further exemplify the uncertainty regarding the magnitude of the anticipated changes, and the need to conduct further studies using many GCMs, as well as to develop regional scale scenarios.

Just as important as the decrease in frequency and earlier occurrence of the spring flood is the decrease in water levels in both the Peace and the Athabasca Rivers during the summer period. Depending upon the scenario examined, up to 1.6 and 0.6 m reductions are noticed in the major rivers supplying flow to the
Table III. Peace River difference in peak elevation and time to peak between baseline and changed climate. Negative values mean lower peak levels and earlier time to peak under a changed climate

<table>
<thead>
<tr>
<th>GCM</th>
<th>1968—low water year</th>
<th>1972—high water year</th>
<th>1979—average water year</th>
<th>Average difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGC</td>
<td>+0.05 m (-65 days)</td>
<td>-0.9 (-21)</td>
<td>-0.5 (-15)</td>
<td>-0.53 (-30)</td>
</tr>
<tr>
<td>CSI</td>
<td>+0.9 m (-35 days)</td>
<td>+0.3 (-24)</td>
<td>+1.1 (-20)</td>
<td>+0.12 (-20)</td>
</tr>
<tr>
<td>ECH</td>
<td>+0.28 m (-60 days)</td>
<td>-0.7 (-23)</td>
<td>+0.14 (-18)</td>
<td>-0.57 (-30)</td>
</tr>
<tr>
<td>GFD</td>
<td>+0.7 m (-60 days)</td>
<td>-0.3 (-35)</td>
<td>-0.4 (-25)</td>
<td>-0.57 (-20)</td>
</tr>
<tr>
<td>HAD</td>
<td>+0.64 m (-35 days)</td>
<td>-0.2 (-19)</td>
<td>-0.3 (-10)</td>
<td>-0.15 (-30)</td>
</tr>
</tbody>
</table>

PAD, the Peace, and the Athabasca Rivers, respectively (see Table IV and Table V). This occurs during a significant number of the 24 years of simulation. Similar variations are encountered in other rivers within the delta environment. This can be of substantial importance because transportation on and recreational utility of the rivers may be jeopardized if water levels drop too low. The fact that the results differ significantly depending on the GCM scenario used, further emphasize the need to carefully develop and refine credible climate change scenarios. Note that the summer flow and water level decrease occurs more frequently in the Peace River than in the Athabasca River. This may be related to flow regulation in the Peace River, and illustrates the need to update the Williston reservoir operating rules to better address the potentially adverse effects of climate change.

CONCLUSIONS

Hydrological and hydraulic models are tools that can be utilized to assess the effects of a shift in climate on the hydrodynamic behaviour of the Peace–Athabasca drainage basin and the delta region. In this study, the WATFLOOD hydrologic model was driven by current climatology and climate change scenario temperature

Table IV. Peace River difference in average summer water level between baseline and changed climate. Negative values mean lower levels under a changed climate. The analysis was carried out over a 24-year period

<table>
<thead>
<tr>
<th>Average difference (m)</th>
<th>Maximum difference (m)</th>
<th>No. of years with decrease</th>
<th>Average over years with decrease (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGC</td>
<td>-0.21</td>
<td>-1.08</td>
<td>15</td>
</tr>
<tr>
<td>CSI</td>
<td>+0.13</td>
<td>-0.96</td>
<td>10</td>
</tr>
<tr>
<td>ECH</td>
<td>-0.41</td>
<td>-1.56</td>
<td>18</td>
</tr>
<tr>
<td>GFD</td>
<td>-0.38</td>
<td>-1.61</td>
<td>17</td>
</tr>
<tr>
<td>HAD</td>
<td>+0.03</td>
<td>-0.92</td>
<td>14</td>
</tr>
</tbody>
</table>

Table V. Athabasca River difference in average summer water level between baseline and changed climate. Negative values mean lower levels under a changed climate. The analysis was carried out over a 24-year period

<table>
<thead>
<tr>
<th>Average difference (m)</th>
<th>Maximum difference (m)</th>
<th>No. of years with decrease</th>
<th>Average over years with decrease (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGC</td>
<td>-0.05</td>
<td>-0.48</td>
<td>15</td>
</tr>
<tr>
<td>CSI</td>
<td>+0.34</td>
<td>-0.14</td>
<td>1</td>
</tr>
<tr>
<td>ECH</td>
<td>-0.28</td>
<td>-0.57</td>
<td>22</td>
</tr>
<tr>
<td>GFD</td>
<td>-0.23</td>
<td>-0.53</td>
<td>20</td>
</tr>
<tr>
<td>HAD</td>
<td>+0.17</td>
<td>-0.07</td>
<td>4</td>
</tr>
</tbody>
</table>

and precipitation data from five selected GCMs to produce estimates of hydrographs of historic and future streamflow for the Peace–Athabasca drainage basin. The estimated future streamflow for the five GCMs was further used with the hydrodynamic model, ONE-D, to evaluate the magnitude and direction of changes in the flow regime in the Peace–Athabasca Delta area, one of the largest and most biologically productive freshwater deltas in the world. The coupled WATFLOOD/ONE-D model simulations accounted for the reduction of the ice-covered season caused by global warming and the hydraulic complexities of this wetland/lake complex.

Consistent with the hydrological analysis, all GCM scenarios predict generally higher winter levels in the PAD system, which cause elevated pre-melt spring levels in the lakes of the PAD. Increased temperature, which increases winter melt events, reduces the snow pack and accelerates the spring melt, is a significant factor explaining this response. Corresponding spring peak water levels in the rivers will be lower by up to 1-0 m and occur 20–30 days earlier. Average annual peak elevations will vary from +0-1 to 0-6 m, depending on the GCM scenario. Of particular concern is the occurrence of lower summer levels in the Peace and Athabasca rivers with decreases averaging 0.5 m and 0.2 m, respectively, in 19 (Peace River) and 12 years (Athabasca River) of the 24-year simulations. This is significant as the rivers are often used for navigation and other purposes, these utilities can be jeopardized if river levels get too low.

The lake response signal to anticipated climate change is not as clear. The time to peak for the lakes is consistently earlier. However, depending on which GCM model output is used, the change in peak lake levels varies. The CSI and HAD models predict an increase (0.25 and 0.1 m, respectively) in spring levels for Lake Athabasca while the ECH, GFD, and CGC models predict a spring level decrease (−0.4 m, −0.25 m, and −0.15 m). These water levels are predicted to remain relatively constant over the summer months. The lower water levels estimated by the CGC, GFD, and ECH models are consistent with the ice-cover analysis of Leconte et al. (2006), which shows that a shorter ice season due to an earlier melt suppresses lake levels. The variability of water levels under climate change increases during the winter months, due to increased precipitation inputs and increased temperatures that result in winter thaw events.

The results for the hydrodynamic analysis further the hydrological analysis presented by Toth et al. (2006). The complex interaction between connected channels, and the possibility of flow reversal and overbank storage necessitates hydraulic analysis. This study demonstrates an end-to-end analysis of GCM forcing to a hydrological model and finally to a hydraulic model, all previously calibrated to this region. This study also presents a first attempt to quantify potential climate impacts on this highly sensitive ecosystem using such a sequence of models. Clearly, future work will require further analysis. Future downscaling methods, dynamic or statistical, should provide a new range of meteorological outcomes, which can be used as the upper boundary to the system described. Improvements to our understanding of the hydrology in this system, and our understanding of the complex interactions of lakes and channels within the PAD can only strengthen and clarify our knowledge of potential climate impacts in this region.

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REFERENCES


