Modelling climate change impacts in the Peace and Athabasca catchment and delta: I—hydrological model application

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Abstract:
The Peace–Athabasca Delta (PAD) is an extensive freshwater delta fed by the confluence of the Peace and Athabasca rivers. The Peace River, with regulation at the W.A.C. Bennett Dam, has a direct influence on the hydrology and eco-hydrology of the PAD. To investigate the relative roles of climate variability and flow regulation, the Peace and Athabasca watershed and delta were simulated using a distributed hydrologic model, WATFLOOD. The model was forced using historical, station-observed data as well as climate change scenario temperature and precipitation data. The modelled hydrographs over the 24-year simulation period were compared with measured values at the 14 streamflow stations with generally good agreement for volume and timing of flow, monthly estimates having a Nash–Sutcliffe ($R^2$) of 0.76 and 0.72 for the Peace and Athabasca Rivers, respectively. However, the total of the monthly runoff estimates were positively biased by 19% and 29%, respectively (Peace River at Peace Point, $D_v$ = 19%, Athabasca River at Ft. McMurray $D_v$ = 29%). A comparison between estimated current and future climate scenarios revealed a significant shift towards an earlier melt season as well as elevated winter flows for both river systems. The uniform application of temperature and precipitation change yields a non-uniform response. The lower elevations of the Athabasca system show trends towards increased streamflow volumes; however, the higher elevations of the Peace River system may experience increased evaporative flux which will more fully compensate for higher precipitation resulting in only slightly increased streamflow under changed climate. The degree and direction of estimated change in streamflow are heavily dependant on the climate change scenario. Copyright © 2006 Crown in the right of Canada, and John Wiley & Sons, Ltd.

KEY WORDS Peace–Athabasca Delta; hydrology; hydrologic modelling; hydraulic model; model forcing; climate variability; flow regulation

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INTRODUCTION AND SITE DESCRIPTION

The Peace and Athabasca catchment is located in east-central British Columbia, northern Alberta and northwestern Saskatchewan (Figure 1). The headwaters of the Peace and Athabasca Rivers originate in the eastern slopes of the Rocky Mountains and are supplemented from various lowland environments in Alberta. Additional contribution originates from the Fond du Lac system in Saskatchewan, which flows west into Lake Athabasca. The Peace and Athabasca Rivers normally experience peak flows during the spring breakup period, (late April to early May) and approximately a month later during a period of sustained high flow produced by snowpack runoff from the Rocky Mountains.

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Since 1968, the Peace River flows have been harnessed by the W.A.C. Bennett Dam at the Williston Lake reservoir. The flow releases from the reservoir are governed by power demand, with the greatest requirements occurring from October through April. This regulation has resulted in significantly altered discharges directly below the dam, with notable effects as far downstream as Peace River at Peace Point as well as in the Slave River (Prowse et al., 2002).

Researchers involved in the Northern River Basins Study (NRBS) (Prowse and Conly, 2000; Prowse et al., 2002; Peters, 2003) noted that, in addition to direct regulation effects, climate change may be a factor in moderating the hydrologic regime of the Peace River, the alluvial wetland habitat of the Peace and Athabasca Delta (PAD, also in Figure 1) as well as areas as far downstream as the Slave River Delta. A complex dynamic exists between natural tributary inputs, which are subject to atmospheric circulation and synoptic climatic variations, and the regulated flow from the Bennett Dam (Prowse and Conly, 1998). NRBS (1997) recommended that further research would be necessary to understand and adapt to these climate–hydrology interactions. This may be particularly relevant to the hydrologically sensitive PAD, where the development of adaptation strategies for managing the flooding regime could be considered (Prowse and Demuth, 1996; Prowse and Conly, 2002).

Climate change estimates of streamflow have been accomplished at scales ranging from global to regional. For example, Nijssen et al. (2002) used a variable infiltration capacity macroscale hydrological model (MHM) to calculate changes in hydrological fluxes under four GCMs at the global scale. Results from this approach uncovered that the largest changes in the hydrological cycle are predicted to occur in cold regions and snow-dominated basins at higher latitudes. In the coldest, snow-dominated basins the response to warming is forecast to be an increase in the spring streamflow freshet. In the basins dominated by a transitional snowpack the spring runoff is predicted to decrease, while winter streamflow increases. Arora and Boer (2001) used the
Canadian Centre for Climate Modelling and Analysis (CCCma) coupled global climate model (CGCM) and forecast that the middle and high latitude rivers will show marked changes in the amplitude and phase of the hydrologic cycle resulting from a decrease in snowfall and earlier spring melt.

Arora (2001) refined his global study for the Mackenzie River basin and modelled an increase in mean annual runoff (+20%) with an earlier phase and damped amplitude (−17%) for the spring melt portion of the hydrograph due to less snow storage in the basin despite an overall increase in precipitation for the annual timescale. Chin and Assaf (1994) also found an increase in annual flow of 6% for the Mackenzie basin using the Canadian Climate Centre (CCC) 2 × CO₂ GCM coupled with the University of British Columbia (UBC) Watershed model (Quick and Pipes, 1977). However, Soulis et al. (1994) utilized the WATFLOOD hydrologic model and forecast that the basin will be drier under climate change for the CCC scenario and the 2 × CO₂ scenario from the Geophysical Fluid Dynamics Laboratory (GFDL); total runoff would decrease by −3.7% and −7.1%, respectively.

A study in the neighbouring Columbia basin (Payne et al., 2003) showed very small changes in annual runoff (−3% to +5%) but noted the same shift to an earlier spring melt as well as higher winter flows. This work also examined reservoir capacity on a seasonal basis and concluded that projected hydrologic changes have the greatest effect between spring and autumn, when the reservoir system refills. Lower summer flows and increased withdrawals to meet instream flow needs result in decreased storage at the end of the summer; this would reduce the ability of the system to meet power production targets for the fall and early winter period before reservoir storage is restored by winter precipitation. The objective of the study is to examine the relative roles of climatic variability at the local (intra-delta or PAD area) and regional (contributing catchment) scales in the context of the historical operating regime of the W.A.C. Bennett Dam. Climate change scenarios resulting from selected 2 × CO₂ Global Circulation Models (GCMs) have been investigated and used to represent potential climatic variability. Hydrologic modelling of the Peace–Athabasca basin, utilizing both historic climatology and climate change scenarios will be presented.

METHODS

Modelling of the Peace and Athabasca catchment was accomplished with WATFLOOD, a distributed hydrologic model (Kouwen, 1988). The hydrologic processes of precipitation, interception, evaporation and infiltration are quantified as a distribution over the landscape and routed utilizing a grouped response unit (GRU). The GRU approach aggregates all similarly vegetated areas in a sub-watershed or element as a hydrologically significant landcover type (Kouwen et al., 1993). The model can accommodate sub-grid routing; within a single grid there may be multiple flow paths that progress in differing directions. For example, WATFLOOD can apportion 20% of grid flow in a northward flow while directing the remaining 80% of flow to the east by allowing a portion of one grid to be assigned to surrounding grids. In continuous simulation mode, WATFLOOD is capable of simulating river flows over periods of many years, and thus is well suited for application in climate change studies.

A wetland module was developed and utilized for the Peace Athabasca basin study. In previous versions of WATFLOOD, wetlands were treated as a separate landclass, however, the routing of water through a wetland was completed as channel routing. The new wetland module within WATFLOOD utilized two routing schemes, the channel routing and a wetland routing scheme that more accurately modelled wetlands as a storage device that deliver runoff to the channel network at a dampened release rate. The interaction between the wetland and the channel is governed by the Dupuis–Forchheimer discharge formula (Stadnyk, 2001; Bear, 1979).

WATFLOOD requires operationalization from topography and landcover data. Calibration is best accomplished using the fine temporal resolution data; the model is particularly sensitive to precipitation data. The forcing data required is distributed temperature and precipitation fields. Validation is performed by comparing observed streamflow to estimated flows. The estimation of future flows was realized with the use of downscaled climate change scenario temperature and precipitation data.
Hydrological modelling—operationalization of WATFLOOD

Basin topography realized from a digital elevation model (DEM) derived data includes watershed area, channel elevation, sub-basin drainage area and direction. Additional operational parameters include landcover characteristics, and reservoir and channel properties. The model is initialized on the recessional arm of the observed hydrograph and is forced with the hydrometric variables of precipitation and temperature. For modelling purposes, the watershed is divided into a grid. Once physiographic and landcover data acquisition are complete, a WATFLOOD map file is created that synthesizes the information in a matrix (in this case 32 by 25 grid of 45 by 45 km cells) that covers the watershed. A more complete description of operationalizing WATFLOOD may be found in Shaw (2003).

Digital elevation model. A DEM was produced for the Peace and Athabasca river basins using a distance transform interpolation algorithm (Zhao, 1997; Töyrä, 2003). This method uses contour lines or elevation points as a 3D source data and 2D layers as additional constraints for the interpolation (a valley vector was used to indicate a local minimum, while a ridge vector was used to indicate a local maximum). For this study, the main data source was National Topographic Database (NTDB) 1:250 000 digital data. In total, 73 1:250 000 digital map sheets were needed to cover both river basins. Each digital map sheet contained contour lines, outlines of rivers and streams (arcs) and outlines of water bodies (polygons). The contour lines were used as 3D source data and the stream and river outlines were used as 2D valley vectors. The contour lines from each of the 73 map sheets were imported into an image analysis software package (PCI) and merged into one continuous vector segment. The same procedure was repeated for the river and stream outlines and the water body outlines.

Due to the considerable width of the Peace and Athabasca rivers, they were represented as polygon features in the water body vector layer. To achieve a local minimum along these major river valleys, a line was digitized along the centre of the Peace and Athabasca rivers. The digitizing was accomplished using the polygons in the water body layer as guidelines. There were no contour lines at the 1:250 000 scale within the PAD region and additional elevation data were necessary to ensure that the water would flow in the correct direction through the confluence. Contour lines from 1:50 000 digital map sheets, survey points and lake outlines with associated elevation values were used as an additional 3D data source for this area. In addition, outlines of the major lakes across the watersheds were assigned elevation values and used as complementary contour lines. A greyscale image of the resulting DEM is presented in Figure 2.

Watershed analysis, topography and landcover. WATFLOOD requires the topography of the watershed be outlined and the internal physiographic features such as contour density, drainage direction, channel elevations and densities along with river classifications, are parameterized for each grid. These physiographic parameters are key to describing the horizontal transfer (routing) of water in the model, required for each of the 45 × 45 km grid elements.

The determinations of contour density, channel elevations, drainage direction and area for each of the grids are fairly objective procedures and have been described extensively (WATFLOOD User’s Manual, 2005; Shaw, 2003). The definitions of river classifications, however, are subject to the hydrologist’s judgement and experience in the region. The river class identifications determined for the Peace Athabasca basin are represented in Figure 2. WATFLOOD subsequently uses these classification values to assign a roughness coefficient for each grid.

Landcover classification is based on the Canadian Centre for Remote Sensing (CCRS) landcover map of Canada. The landcover map represents AVHRR NOAA data at a 1-km resolution. This data was used to extract the percent landcover of differing classes within each 45 × 45 km WATFLOOD element. It was necessary to aggregate the original 32 distinct landcover types found in the CCRS data into nine simplified landcover categories.
Meteorological and hydrometric data. Fourteen gauging stations were chosen for comparison between observed flow and model output (Figure 2). Observed flows assist in hydrologic model calibration as well as serving to validate the current climatology model runs, and as a benchmark for estimated future flow comparisons.

WATFLOOD was driven using current climatology in the form of station-observed temperature and precipitation data. Station-observed data is available in both an hourly and daily format. At some stations, the daily data is the sum of the hourly data; however, other stations only record total precipitation and maximum/minimum temperatures for the day. Because most of the basin is described by daily data, the current climatology data was based on a continuous 30-year record of daily temperature and precipitation. As hourly data should be used to maximize the utility of WATFLOOD, script programs were written to extract the Canadian Meteorological Centre (CMC, as the source of station-observed data) flat file, ASCII matrix to the distributed hourly product required by WATFLOOD.

The temperature extraction process used the elevations from the DEM combined with an assumed lapse rate provided corrected, diurnally varying hourly temperatures. To distribute precipitation hourly, a daily hourly
disaggregation technique was developed. The available hourly data for the basin were used to determine the average hourly variation of precipitation over a day to provide a daily to hourly index to yield hourly precipitation. This index varied monthly.

In addition to temporal considerations, there are also spatial precipitation distributions, primarily due to the range of elevation in the basin. Because of the remoteness of the mountainous terrain, most of the climate data is recorded at lower elevations. This is particularly true in the winter months, when the few high terrain stations are closed. The vertical precipitation gradient was examined by correlating monthly precipitation values to station elevation. Summer precipitation shows considerable dispersion and the elevation-precipitation correlation for the Peace–Athabasca basin is weak (Bullas, 1999). This is likely because much of the summer convective precipitation occurs in a south-westerly flow, which produces a rain-shadow effect in the immediate lee of the mountains while precipitation is enhanced on the south-facing slopes of the hills. Thus the maximum precipitation occurs at approximately 1500 m. The average summer precipitation gradient was estimated to be a multiplier of 1.2 to 1500 m and then no gradient was assumed. Snowfall is more highly correlated and the gradient multiplier applied for snowfall was 2.0.

There are seven stations in the basin with records of temperature and precipitation for the period 1961–1990 (Figure 2). Initial runs with these data illustrated the need for additional temperature and precipitation data for calibration as well as supplemental precipitation observations for better model performance. An hourly data set from 1987, with over 1512 temperature and precipitation observations, was used to calibrate conditions such as channel roughness, lower zone discharge functions, base melt temperatures and melt rates, interception and evaporation parameters (WATFLOOD User’s Manual, 2005).

Once model calibration was complete, additional precipitation records were extracted to augment the data input to WATFLOOD for the 1961–1990 period as high resolution spatial precipitation gauging enhances accuracy when modelling channel output (Kouwen, 1988). There are 307 climate stations that have daily precipitation records for more than 5 years during the 30-year period. The potential climate change relative to current climatology was established as offsets to temperature and multipliers of precipitation; the offsets and multipliers were used during the script programming of the station-observed data to gridding process, resulting in anticipated future climate temperature and precipitation.

Climate change scenarios

To assess the influence of climate change within the Peace and Athabasca watershed, IPCC (Intergovernmental Panel on Climate Change) publicly available, doubled CO₂ emission, climate change scenarios were used and they are as follows:

- CGCM (CGC): Canadian Global Climate Model, first generation, Canada
- CSIRO (CSI): Commonwealth Scientific and Industrial Research Organization model, Australia
- ECHAM (ECH): GCM based on ECMWF forecast models, modified and extended in Hamburg, Germany
- GFDL (GFD): Geophysical Fluid Dynamics Laboratory model, USA
- HADCM2 (HAD): Hadley Centre Climate Prediction and Research Model, UK
- NCAR: USA National Centre of Atmospheric Research
- CCSR: Japanese Centre for Climate Research Studies

Table I provides the model generation and spatial resolution for each of these scenarios. The models were evaluated on their performance for current climatology. Future temperature and precipitation fields were then extracted from those climate scenarios showing good agreement with observed data.

GCMs should be evaluated based on their ability to replicate past-observed climate data (Kundzewicz and Somlyody, 1997). A continuous record of recent climate data containing wet, dry, warm and cool periods and is therefore widely used for describing the regional climate (Rosenzweig and Parry, 1994). The 30-year ‘normal’ period, as defined by the World Meteorological Organization (WMO), is recommended by the IPCC for use as a baseline period (Carter et al., 1994).
Table I. Publicly available Global Climate Models (also called General Circulation Models or GCMs) at the initiation of the Peace Athabasca study—all assume a doubling of CO₂ concentrations

<table>
<thead>
<tr>
<th>GCM</th>
<th>Modelling centre</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGC (M1)</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>~3.7° x 3.75°</td>
</tr>
<tr>
<td>CSIRO (MK2b)</td>
<td>Australian Commonwealth Scientific and Industrial Research Org.</td>
<td>~3.2° x 5.625°</td>
</tr>
<tr>
<td>ECHAM (4)</td>
<td>Geophysical Research Centre</td>
<td>~2.8° x 2.8125°</td>
</tr>
<tr>
<td>GFDL (R15)</td>
<td>Geophysical Fluid Dynamics Laboratory</td>
<td>~4.4° x 7.5°</td>
</tr>
<tr>
<td>HAD (CM2)</td>
<td>Hadley Centre for Climate Prediction and Research</td>
<td>~2.5° x 3.75°</td>
</tr>
<tr>
<td>NCAR (DOE)</td>
<td>USA National Centre for Atmospheric Research</td>
<td>~4.4° x 7.5°</td>
</tr>
<tr>
<td>CCSR (NIES)</td>
<td>Japanese Centre for Climate Research Studies</td>
<td>~5.62° x 5.625°</td>
</tr>
</tbody>
</table>

The monthly 1961–1990 precipitation and temperature data, the monthly 2040–2069 precipitation and temperature data, the grid centre information, and the land/sea mask for each GCM were downloaded from the IPCC website. The grid centre information consists of the longitude and latitude of each grid cell centre. According to the longitude and latitude co-ordinates, the actual grid centre spacing varied in north–south direction for some of the models. The average grid centre spacing was calculated for Canada and used to create the GCM grids. Figure 3 illustrates an example of the generated grid centres, graticule lines and grid cell polygons for the Canadian Global Climate Model (CGCM).

The land/sea mask attributes were associated with the grid centre co-ordinates and joined spatially to the grid cells. All grid cells covering the ocean and the USA were deleted. The monthly 1961–1990 and 2040–2069 change in precipitation and temperature data were associated with the grid centre co-ordinates and joined spatially to the grid cells so that each grid cell obtained a precipitation and a temperature value for each month and for each climate scenario.
RESULTS AND DISCUSSION

Climate change scenario evaluation

The GCM data was compared to a gridded dataset of observed 1961–1990 data. The observed data set is based on an interpolated 50 km grid derived by the University of Waterloo, using historic climatological records available from Environment Canada. This gridded (CANGRID) dataset represents the monthly mean average climatology and matches the period of record for the GCM comparison. The 1961–1990 GCM estimates were compared to the CANGRID dataset provided the basis of evaluation of the GCMs; those scenarios replicated the baseline climatology within the Peace and Athabasca basin were used to provide an estimate of future climate.

Figure 4 provides a comparison of the observed data within the Peace–Athabasca basin to the various GCM predictions. Table II and Table III highlight the absolute differences among the monthly current climatologies of each of the respective GCMs. The tables indicate that the HAD, ECH, and CSI models appear to simulate the 1961–1990 precipitation climatology reasonably well while temperature climatology is better represented by CCSR, GFD, and CSI. It should be noted that the 2040–2069 precipitation estimates by all future climate scenarios show a clear positive bias.

Basin-wide estimates of potential climate change to the basin, as predicted for 2040–2069 were derived for those GCMs that performed well under current climatology, namely, CGC, CSI, ECH, GFD, and HAD. The predicted changes with respect to temperature and precipitation based on the five selected GCMs are shown in Figure 5. Note the range of temperature increase predicted by these GCMs primarily falls within the desired 1 to 4.5 °C, a generally accepted interval for a potential increase in temperature resulting from a doubling of CO₂ concentrations (IPCC, 1990).

Figure 4. Temperature and precipitation for the Peace–Athabasca derived from observed climatology (WAT) and each of the GCMs for the normal period of 1961–1990
Table II. Precipitation comparison and rank of the GCM estimates compared to 1961–1990 climatology. (differences are expressed in mm month$^{-1}$)

<table>
<thead>
<tr>
<th>GCM</th>
<th>Average absolute difference</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>HADCM2</td>
<td>15.54</td>
<td>1</td>
</tr>
<tr>
<td>ECHAM</td>
<td>17.24</td>
<td>2</td>
</tr>
<tr>
<td>CSIRO</td>
<td>23.88</td>
<td>3</td>
</tr>
<tr>
<td>CCSR</td>
<td>24.71</td>
<td>4</td>
</tr>
<tr>
<td>GFDL</td>
<td>26.84</td>
<td>5</td>
</tr>
<tr>
<td>CGCM</td>
<td>38.99</td>
<td>6</td>
</tr>
<tr>
<td>NCAR</td>
<td>44.95</td>
<td>7</td>
</tr>
</tbody>
</table>

Table III. Temperature comparison and rank of the GCM estimates compared to 1961–1990 climatology (differences are expressed in degree celsius)

<table>
<thead>
<tr>
<th>GCM</th>
<th>Average absolute difference</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSR</td>
<td>1.55</td>
<td>1</td>
</tr>
<tr>
<td>GFDL</td>
<td>1.98</td>
<td>2</td>
</tr>
<tr>
<td>CSIRO</td>
<td>2.02</td>
<td>3</td>
</tr>
<tr>
<td>ECHAM</td>
<td>2.05</td>
<td>4</td>
</tr>
<tr>
<td>HADCM2</td>
<td>3.52</td>
<td>5</td>
</tr>
<tr>
<td>CGCM</td>
<td>4.04</td>
<td>6</td>
</tr>
<tr>
<td>NCAR</td>
<td>6.67</td>
<td>7</td>
</tr>
</tbody>
</table>

The potential climate changes for monthly temperature and precipitation were expressed as offsets and normalized multipliers respectively (i.e. $\Delta T$ and $\Delta P/P$). These were utilized to generate a gridded hourly product based on observed climatology, with the future climate adjustments applied.

**Hydrologic modelling**

Using station-observed meteorological data, the estimated flows at selected stations over the watershed were compared to measured flows and the comparison is presented in Figure 6. Good agreement in timing of peak flows and total volume of flows is achieved for 24 years of flow (1965–1989) with a monthly Nash–Sutcliffe coefficient, $R^2$ (ASCE Task Committee, 1993) of 0.76 and 0.72 for the daily Peace River at Peace Point and Athabasca River flows. Total runoff on the two major rivers was overestimated by 19% and 29% (Peace River at Peace Point, $D_v = 19\%$, Athabasca River at Ft. McMurray $D_v 29\%$). The coefficient of gain from the monthly means is 0.84 for the Peace River and 0.82 for the Athabasca River.

Modelling challenges are presented by the uncertainty of some of the input data and the process of calibration. Historical reservoir releases for Williston reservoir are shown in Figure 7. The mean release averages about 1075 m$^3$ s$^{-1}$, over the period from 1 January, 1968 (dam completion) to 30 September 1989; however, the modelled inflows for current climatology average 660 m$^3$ s$^{-1}$ over the same period. These errors in estimation are a function of the modelling exercise, which was completed with the objective of minimizing the deviation from observed flows for the entire basin with particular emphasis on the PAD. Additionally, the errors in estimation are a function of uncertainties in the input data, particularly in the lack of precipitation data over the mountainous headwater regions of the Peace River. Thus the modelling errors are considerably decreased as the quality of the input data increases downstream and the modelled flows at Peace River overestimate the observed flow ($D_v$) by 11% with a monthly Nash–Sutcliffe ($R^2$) of 0.79.
Additional modelling challenges for the monthly estimated flows occur during the critical spring melt season. While monthly estimates of streamflow agree closely with measured flows for the winter and most of the summer months, there are noteworthy estimation issues related to predicting streamflow during spring melt (Figure 8). This is due in part to the inherent difficulties of mesoscale hydrologic modelling of the complex physical processes surrounding snow accumulation, redistribution, interception and snowmelt; issues such as snow interception/sublimation, snow blown between basins, the timing of melt due to slope orientation and snowmelt infiltration into seasonally frozen soils are not well defined. (Pomeroy et al., 1998; Gray et al., 2001). However, other issues relating to the estimation of spring melt streamflow are addressed by the use of the hydrodynamic model study presented in companion papers in this issue, which concentrate on the dynamics of flow depth related to varying winter severity (Leconte et al., 2006) and flow regimes under perturbed climate (Pietroniro et al., 2006).

The 24 years of simulated flows (1 October 1965–30 September 1989 in current climatology, 2040–2069 for future scenarios) were averaged for each month. For both the Athabasca and Peace Rivers, the onset of spring melt is earlier under all future climate scenarios. The peak volumes for the spring freshet are predicted to increase with the CSI and HAD models while the GFD, and ECH models predict a decrease in peak volumes (Figure 9). The second peak of sustained high flows attributed to runoff originating in the Rocky Mountains is also predicted to increase by the HAD and CSI models, while the remainder of the models predict a lower peak and a decrease in runoff from the mountains. Total annual volume of flow is predicted to increase under the increased temperature and precipitation of future climate for all models on the Peace River and by all except the ECH model on the Athabasca River. The Peace River shows a potential flow increase, by all models, for the recession period January through February of the annual hydrograph. The ensemble of

Figure 5. Potential change (modelled) for 2040–2069 in temperature and precipitation for each of the climate change scenarios
Figure 6. Measured streamflow compared to estimated flows across the Peace and Athabasca watershed showing good agreement in timing and volume of flow.
models predicts the same increase in recessional flows for the Athabasca River, although the magnitude is not as pronounced.

Although the forecast changes of temperature and precipitation are uniformly over the basin, the resultant change in flows under perturbed climate varies with predominant landcover type and elevation (Figure 10). The increase in predicted runoff is more pronounced on the lower elevation and wetland dominated sub-basins of the Athabasca River, with the increase in flows gradually decreasing in magnitude towards the northern extent of the basin. The higher elevation and mountainous and/or forested basins contributing to the Peace River show a modest increase in flows, which also decline towards the outlet. The standard deviation in forecast percentage change in flows is noted and for the Peace River shows that flows may potentially decrease. Thus, in the higher elevations the increased temperature of future climate scenarios, and the resultant increase in evaporative flux, will more fully compensate for the increase in precipitation. In fact, for some models the increase in evaporation exceeds the increase in precipitation. For the lower elevations and wetland regions, the precipitation increase overshadows the potential increase in evaporation. It should be noted that landcover is presumed to be unchanged. This is not likely to be the case as vegetation and land management decisions will respond to changes in climate; however, it was beyond the scope of this project to extrapolate a change in landcover.

It should be noted that the management of the W.A.C. Bennett Dam on the Peace River is not altered under future climate. There is a lack of an objective physical basis on which to surmise future dam management and the change in management is likely to have a socio-economic base such as increased power or irrigation demands on the reservoir capacity; thus the modelled flows are forced by historic releases at the reservoir. Therefore, the assumed climate change flows for the Peace River at Peace Point are normalized at the dam.
and are altered by temperature and precipitation only for the downstream portion of the basin. The climate change flows downstream of the reservoir should be viewed in this context.

A comparison of future scenario inflows to modelled current climatology inflows provides an index of the possible effect of altered runoff into the Williston Lake reservoir (see Figure 11). Modelled inflows under current climatology for the 24-year simulation period total a volume of $4.2 \times 10^{11}$ m$^3$. The modelled total inflows under future climate scenarios show significant variability between $4.0$ and $4.9 \times 10^{11}$ m$^3$ with the lower inflows predicted by the ECH and GFD models and the higher flows again predicted by the CSI and HAD models.

While the estimates of total inflow into the Williston reservoir show considerable variability, the timing of inflows predictions showed a consistent increase of inflows from October to April, with a significant increase in magnitude due to an earlier spring melt for the months of March and April (Figure 12). The entire set of future scenarios predicts lower inflows for the months of May through July.
CONCLUSIONS

The WATFLOOD hydrologic model was successfully operationalized and calibrated for the Peace and Athabasca watershed based on current landcover characteristics, historic climate and streamflow data, along with several physiographic parameters necessary in defining the basins. This model was subsequently forced with climate change scenario temperature and precipitation data from five selected GCMs to produce estimates of hydrographs of future streamflows for the Peace–Athabasca drainage basin. Results from these future climate scenarios were compared and contrasted to the observed and estimated historic streamflow.

The 24-year WATFLOOD simulation, using current climatology, produced hydrographs for the 14 streamflow measurement stations and demonstrated relatively good agreement for volume and timing of flow; the Nash–Sutcliffe ($R^2$) coefficient for the Peace and Athabasca rivers is 0.76 and 0.72, respectively. The total runoff was overestimated by $D_v = 19\%$ and $D_v = 29\%$, respectively. The coefficient of gain from the monthly means is 0.84 for the Peace River and 0.82 for the Athabasca River.
Figure 10. Modelled runoff averages for all future scenarios compared to modelled current climatology runoff. The mean change is presented along with one standard deviation of the range of predicted change in flow.

Figure 11. Modelled inflows into Lake Williston for current climate and future climate scenarios.
The performance of the selected GCMs was evaluated and ranked. The GFD and CSI provided the most accurate estimates of 1961–1990 temperature and were thus ranked as the best predictors of future temperature. Future temperature estimates were consistent with the 1 to 4.5 °C increase accepted by the IPCC as the potential result of a doubling of CO₂ concentrations. All selected models provide estimates of increasing future precipitation, although precipitation estimates are generally accorded less confidence due to their reduced ability to accurately predict temperature for the 1961–1990 timeframe. The HAD and ECH models were ranked as the best estimators of precipitation under perturbed climate.

A comparison of estimated current and future climate scenarios generally exhibits an earlier melt season and higher winter flows. There is 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 predict lower peak flows under perturbed climate. Total annual volume of flow is predicted to increase under the increased temperature and precipitation of future climate for all models on the Peace River and by all except the ECH model on the Athabasca River. The Athabasca River system initially experiences a significant increase in runoff at its headwaters (28% increase at Hinton), which gradually dissipates to a 7% increase at Athabasca River below Ft. McMurray. In the Peace River system the trend is also an increase in flow, but to a lesser degree with the standard deviation of the ensemble of estimates indicating that flow may slightly decrease with a doubling of CO₂. Thus while temperature and precipitation increases were applied uniformly across the basin (as is consistent with the scale of GCM predictions) the runoff response varies with elevation and landuse. In the lower elevations and wetland dominated regions of the Athabasca portion of the basin the increased evaporative effect due to an increase in temperature does not offset the increase in precipitation and channel flow increases, while for the higher elevations of the Peace River area evaporative flux more fully compensates and may indeed exceed the increase in precipitation.

The ECH and GFD models predict lower inflows to the Williston Reservoir, while the HAD and CSI models indicate an increase in inflows to the reservoir. However, there is a consistent seasonality shift in the flows with an earlier melt, as well as an increase in winter flows, and a reduction in the peak flows which continues through the summer months. These factors contribute to a decreased ability of the system to replenish during the spring melt which is further exacerbated by lower summer streamflows, affecting the ability of the reservoir to meet power demands in the early winter months before the higher winter flows fully recharge the reservoir.

The results of this hydrologic modelling exercise illustrate some of the current challenges facing mesoscale modelling and climate change assessments. Uncertainties in input data, the calibration of gauged basins, the imperfect representations of physical processes, particularly those involving snow and phase change; these
issues all point to future needs in the modelling of our water resources. The variability in the forecasts produced by the ensemble of hydrologic modelling forced with climate change scenario data highlight the need for better regional climate and downscaling assessments in atmospheric and hydrological scenarios. The errors in these assessments need to be quantified to assist in ranking threats to our future water availability.

However, utilizing the best available climate change data coupled with a distributed hydrologic model, this effort provides an estimate of the effect of climate change on water resources in the Peace and Athabasca basin. The results from this study are also utilized in additional analysis concerned with the effect of varying winter severity on the water levels and flow in the PAD (Leconte et al., 2006) and further linked to coupled hydrologic–hydraulic (WATFLOOD/ONE-D) study that performed an integrated watershed assessment of both the catchment and the delta (Pietroniro et al., 2006).

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