Climatic Change (2011) 105:555–576
DOI 10.1007/s10584-010-9890-x

# Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada

**Katharine A. Forbes · Stefan W. Kienzle ·
Craig A. Coburn · James M. Byrne · Joseph Rasmussen**

Received: 30 April 2008 / Accepted: 14 June 2010 / Published online: 17 August 2010

**Abstract** The current body of research in western North America indicates that water resources in southern Alberta are vulnerable to climate change impacts. The objective of this research was to parameterize and verify the ACRU agro-hydrological modeling system for a small watershed in southern Alberta and subsequently simulate the change in future hydrological responses over 30-year simulation periods. The ACRU model successfully simulated monthly streamflow volumes ($r^2 = 0.78$), based on daily simulations over 27 years. The delta downscaling technique was used to perturb the 1961–1990 baseline climate record from a range of global climate model (GCM) projections to provide the input for future hydrological simulations. Five future hydrological regimes were compared to the 1961–1990 baseline conditions to determine the average net effect of change scenarios on the hydrological regime of the Beaver Creek watershed over three 30-year time periods (starting in 2010, 2040 and 2070). The annual projections of a warmer and mostly wetter climate in this region resulted in a shift of the seasonal streamflow distribution with an increase in winter and spring streamflow volumes and a reduction of summer and fall streamflow volumes over all time periods, relative to the baseline conditions (1961–1990), for four of the five scenarios. Simulations of actual evapotranspiration and mean annual runoff showed a slight increase, which was attributed to warmer winters, resulting in more winter runoff and snowmelt events.

---

K. A. Forbes · S. W. Kienzle (✉) · C. A. Coburn · J. M. Byrne
Department of Geography, University of Lethbridge, 4401 University Drive,
Lethbridge, Alberta, Canada T1K 3C6
e-mail: stefan.kienzle@uleth.ca

J. Rasmussen
Department of Biological Sciences,
University of Lethbridge, 4401 University Drive, Lethbridge,
Alberta, Canada T1K 3C6

## 1 Introduction

The availability of water resources in the province of Alberta is of particular concern due to growing water demands by agriculture, industry, and a rapidly increasing population coupled with potential impacts to water resources due to changes in climate. Alberta's government has recently placed an increased emphasized on understanding Alberta's surface and groundwater resources (AENV 2008). Alterations to the natural flow regime of surface water in southern Alberta have been identified in the observed records throughout the last century. Byrne et al. (1999) reported a continuous decline in the annual minimum monthly streamflow in an unregulated tributary of the Oldman Basin since 1949. Rocky Mountain headwater streams that feed the southern Alberta streams and rivers have also shown declining trends in mean annual streamflow over the past century (Rood et al. 2005). Given the projected future changes in climate, Barnett et al. (2005) concluded that regions with snowmelt-dependent water supply, such as Alberta, may experience severe changes to the hydrological regime, potentially requiring equally severe adaptations to ensure a secure and sustainable regional water supply.

Trends in historical climate records indicate that, over the twentieth century, the Canadian Prairies experienced an increasingly warmer and, to a lesser extent, drier climate (Gan 1998). Modeled projections of the future climate in the Canadian Prairie Provinces indicate that the mean annual temperature may further increase between 4°C and 5°C by 2050, relative to conditions of the 1961–1990 period (Wheaton 2001). For the province of Alberta, mean annual temperature is projected to increase between 3 and 5°C by the 2050s (Barrow and Yu 2005).

The projected future changes in precipitation in the Prairie region are variable, synonymous with projections at the global scale (IPCC 2007a, b). In Alberta, mean annual changes in future precipitation are expected to be between −10% and +15% (Barrow and Yu 2005). Based on observed trends and modeled future projections for both temperature and precipitation, Schindler and Donahue (2006) predict that, in the near future, forecasted warming may likely contribute to water scarcity issues in the western Prairies.

Climate scenarios are often derived using output from General Circulation Model (GCM) experiments (Xu 1999a, b; Loukas et al. 2004; Xu 2005). The large spatial scale of GCMs inhibits their direct application in hydrological studies (Cohen 1990; Carter et al. 1994; Xu 1999b). Downscaling techniques exist to resolve the scale disparity between GCMs and the needs of impact modeling, and consist of statistical, dynamic and the delta change techniques. Impact studies that rely on decadal and inter-annual climatic variability cannot be adequately simulated using statistical and dynamic downscaling methods (Hamlet and Lettenmaier 1999). Recent studies demonstrate that the delta method of downscaling successfully modeled change scenarios for hydrological impact assessments of climate change, employing a physically-based hydrological model (Morrison et al. 2002; Miller et al. 2003; Schulze and Perks 2003; Merritt et al. 2006). This method utilizes the relative change in a GCM modeled climate variable and applies it to a local climate record while preserving the local variability of the climate record at the research catchment.

In addition to research carried out in alpine regions, understanding the effects of climate change on the hydrology in hybrid watersheds should not be understated (Loukas and Quick 1996; Loukas et al. 2002). In hybrid watersheds both snowmelt and rainfall events occur, and consequently the watershed behavior is dominated by contrasting hydrological processes, and may respond uniquely to changes in the future climate (Loukas and Quick 1996; Whitfield et al. 2003).

The hydrological response to climate change has been studied through the application of watershed-scale hydrological models driven by GCM-derived scenarios of future climate (Loukas et al. 2002; Morrison et al. 2002; Schulze and Perks 2003; Toth et al. 2006; Nurmohamed et al. 2007). Physically-based, spatially distributed hydrological models are an effective means to assess the impacts of climate change on hydrological response as they are able to capture the spatial variability of hydrological processes throughout complex watersheds (Bathurst et al. 2004). The ACRU agro-hydrological modeling system (Schulze 1995; Smithers and Schulze 1995) was applied in this study as it is a physical-conceptual, distributed hydrological modeling system designed to be responsive to changes in land use and climate (Smithers and Schulze 1995). The ACRU model has been applied in climate change impact studies (Schulze et al. 2004; Schulze and Perks 2003; Schulze 2000) and hydrological assessments (Kienzle and Schmidt 2008; Everson 2001; Kienzle and Schulze 1991; Kienzle et al. 1997).

## 2 Objectives

This research focused on quantifying the impacts of climate change on the hydrology of a relatively undisturbed watershed in southern Alberta. The Beaver Creek watershed is a tributary of the Oldman River, a tributary of the South Saskatchewan River, and is located in the Porcupine Hills in southern Alberta. The objective of this research was to quantify climate change impacts using a physically-based hydrological model and verifying modeled output against observed streamflow, and then simulating the watershed behavior for a range of GCM-derived scenarios. Future impacts on snow pack development and timing of snow melt, actual evapotranspiration, groundwater recharge, and streamflow were evaluated for three future 30-year time periods (starting in 2010, 2040, and 2070), by comparing model output with the verified 1961–1990 baseline conditions.

## 3 Methods

### 3.1 Study area

The Beaver Creek study watershed, centered at 49°44′ N, 113°52′ W, is a tributary of the Oldman River (Fig. 1), a major watershed of the South Saskatchewan River watershed. The Beaver Creek is classified as a hybrid stream. Streamflow is perennial, with a bimodal hydrograph indicating the influence of both snowmelt and rainfall processes (Water Survey of Canada 2007). The creek has two ungauged, ephemeral tributaries (Five Mile Creek and Nine Mile Creek), both originating on the west-facing slopes of the watershed (Fig. 1). The headwaters of Beaver Creek stem from the higher elevation slopes of the Porcupine Hills, east of the Front Range of the Rocky Mountains, Alberta, and are characterized by the rapid spatial transition from montane forest to aspen parkland and prairie grasslands.

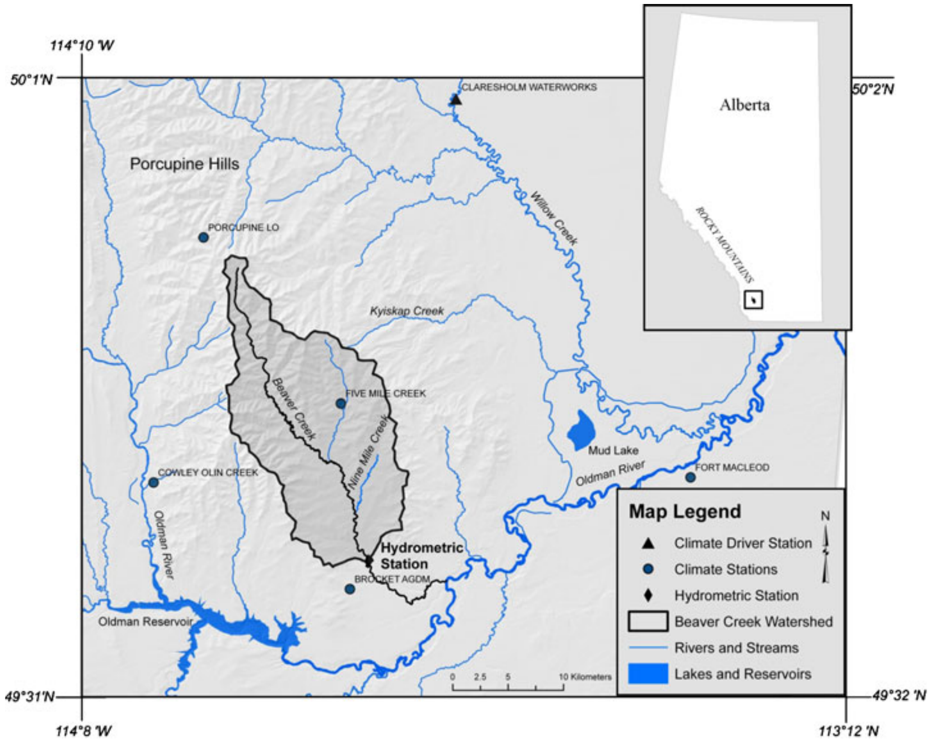


**Fig. 1** Map of the Beaver Creek watershed

The Beaver Creek watershed has a drainage area of 254 km$^2$, defined by the Water Survey of Canada hydrometric station (05AB103) located near the town of Brocket, Alberta. Elevations in the watershed range between 1,100 and 1,500 m, with the general aspect facing south to south-east, and slopes ranging from flat, in the lower elevation rangelands, to 28°, on the south-west and north-east facing slopes.

In the southern Alberta region, winter precipitation events result primarily from frontal air masses, while summer events are typically convective in nature. The proximity to the eastern slopes of the Rocky Mountains exposes the area to the rain shadow effect and regular occurrences of warm foehn winds (Grace 1987), called Chinook winds. Therefore, due to the orographic influences on this area, it is not uncommon for a deficit in the annual moisture budget due to high evapotranspiration relative to precipitation.

## 3.2 Hydrological modeling

### *3.2.1 The ACRU agro-hydrological modeling system*

The ACRU model was developed by the Department of Agricultural Engineering (now the School of Bioresources Engineering and Environmental Hydrology) at the University of KwaZulu-Natal, Pietermaritzburg, South Africa, in the late

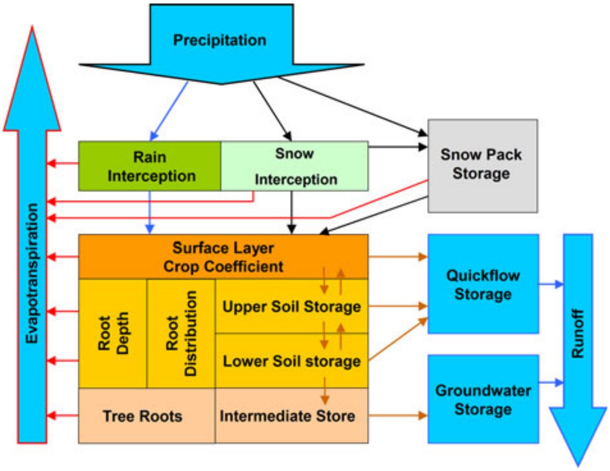


**Fig. 2** Major components of the ACRU agro-hydrological modelling system

1970s and has been continuously refined and updated (Schulze 1995; Smithers and Schulze 1995). The ACRU model is a multi-purpose, multi-level, integrated physical-conceptual model that can simulate total evaporation, soil water and reservoir storages, land cover and abstraction impacts on water resources, and streamflow at a daily time step (Schulze 1995; Smithers and Schulze 1995).

The most recent version of the ACRU model (Fig. 2) includes a new method to separate rain and snow precipitation (Kienzle 2008). The ACRU model simulates the principal hydrological processes of rain and snow interception, infiltration, snowpack accumulation and snowmelt, soil water storages, unsaturated and saturated soil water redistribution, total evaporation (a daily summation of snow sublimation, plant transpiration from the rooting zone and evaporation from the soil surface, as well as interception) and temporally discrete runoff generation. The multi-layer soil water budgeting routine is the central focus of the ACRU model conceptual structure. The total evaporation routine is partitioned between growth-stage specific transpiration and soil water evaporation, making it sensitive to changes in crop phenology and seasonal temperature (Smithers and Schulze 1995).

### *3.2.2 Model parameterization*

*Hydrological response units* The ACRU model was parameterized as a distributed model using spatially distinct units with relatively homogenous hydrological response, i.e. hydrological response units (HRUs). These are parameterized individually for input into the ACRU model. Three major physiographic data types were utilized to delineate the HRUs: a 30 m digital elevation model, generalized land cover (PFRA 2001) (Fig. 3), and plant available water storage capacity, calculated from the Agricultural Region of Alberta Soil Inventory Database version 3 (AGRASID 2005). A GIS overlay analysis was used to delineate five HRUs based on these variables.

The parameterization of all subsequent model input parameters, such as those representing soils and land cover characteristics, were area-weighted to the area of each HRU, constructing the spatially representative input files for the ACRU model. The delineated HRUs are presented in Fig. 4, with the general characterization

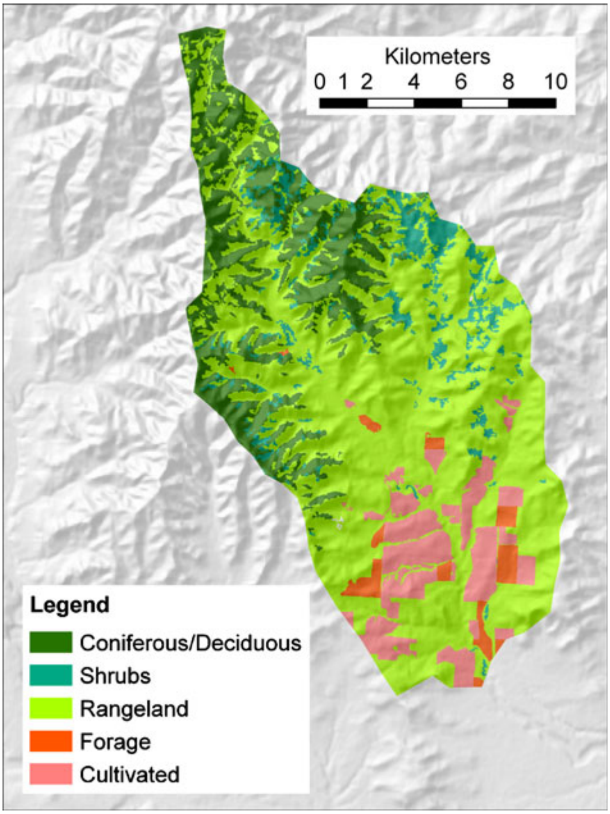


**Fig. 3** Land cover in the Beaver Creek watershed

of each response unit given in Table 1. The delineation of HRU 1 closely follows the 1,500 m-elevation contour and forested land cover. This HRU represented the deepest estimated surface soils with the highest precipitation and highest soil water potential. HRUs 2 and 3 encompass two rangeland response units. Soil water availability in these HRUs was highest in HRU 2, and thus HRU 3 contained a higher proportion of drought tolerant, perennial shrubs and woody vegetation. HRU 3 predominantly spans the headwaters of Five Mile Creek. HRUs 4 and 5 represent the transition from the montane slopes and fescue grasslands of the upper reaches to the agricultural land uses in the lower parts of the Beaver Creek watershed. The separation of these two HRUs follows the division between natural (forage) and cultivated land, as soils and elevation are relatively homogenous for this area. This was necessary, as the canopy interception and plant physiology of perennial (forage) and annual (cultivated) species are simulated differently.

*Precipitation* The Claresholm Waterworks climate station, located approximately 25 km northeast of the Beaver Creek watershed, was chosen to “drive” the hydrological model. The Claresholm Waterworks climate station has a complete 40-year climate record that overlaps the hydrometric observations and is located in an area with similar physiographic characteristics as the Beaver Creek watershed. This station received an average annual precipitation amount of 428 mm (1971–2000),

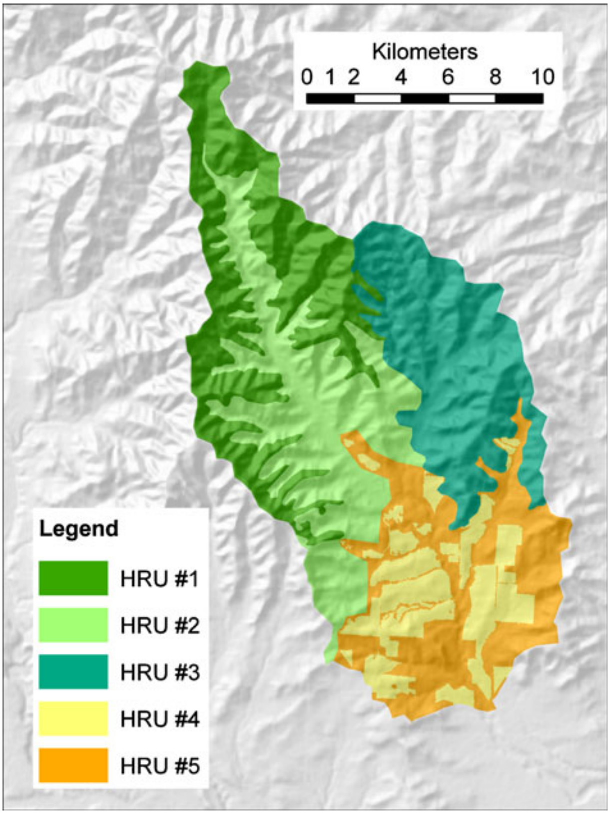


**Fig. 4** Hydrological response units delineated for the Beaver Creek catchment

with ~29% falling as snow (Environment Canada 2007). Mean daily temperature in the summer was 16°C and −6.1°C in the winter.

Monthly correction factors were needed to account for differences between precipitation recorded at the Claresholm Waterworks climate station and precipitation at each of the HRUs in the watershed. Mean monthly precipitation surfaces with a spatial resolution of 100 m were created using the ANUSPLIN 4.3 interpolation software (Hutchinson 2004). ANUSPLIN uses a thin plate spline surfacing technique that uses elevation from a digital elevation model as a covariate to spatially interpolate climate variables. Relationships were established between the estimated precipitation surface within the pre-defined HRUs and the surface value at the

**Table 1** Major physiographic characteristics of hydrological response units including area, percent area of total catchment, mean elevation, dominant soil type and generalized land cover

| HRU | Area (km$^2$) | Area % | Elevation (m) | Soil type | Land cover |
|---|---|---|---|---|---|
| 1 | 60.03 | 23.63 | 1,500 | Clay loam | Mixed forest |
| 2 | 55.88 | 21.99 | 1,400 | Loam | Rangeland |
| 3 | 61.31 | 24.13 | 1,400 | Clay loam | Shrub and rangeland |
| 4 | 46.42 | 18.27 | 1,300 | Clay loam | Forage |
| 5 | 30.43 | 11.98 | 1,200 | Sandy clay loam | Cultivations |

location of the Claresholm Waterworks climate station. This comparative method provided a systematic monthly correction factor for each HRU.

It was unrealistic to assume that the daily precipitation amount received at the climate station was spatially continuous over the entire watershed, particularly for recorded extreme events. The problem of point-to-area rainfall conversion was addressed using depth–area relationships. To derive an estimate for the total watershed area, areal reduction factors are often applied (Asquith and Famiglietti 2000; Veneziano and Langousis 2005). We applied a simple areal reduction factor (Eq. 1) to correct daily precipitation events:

$$P_{corr} = P^{*}(1 - (0.005^{*}P)) \tag{1}$$

where $P_{corr}$ is the corrected daily precipitation depth and P is the original depth recorded at the climate station. This method resulted in a precipitation record for each HRU that conserved the variability of the driver station while avoiding unrealistically high areal precipitation events.

*Reference evaporation* The Penman (1948) method was used to simulate daily reference evaporation and determine the A-PAN equivalent evaporation. Data requirements for the Penman (1948) equation included daily temperatures, monthly values of incoming radiation, relative humidity and wind speed. Monthly values were converted into a daily time step using a Fourier harmonic transformation (Schulze 1995).

Monthly solar radiation data were estimated for each HRU by modeling solar radiation input from the digital elevation model. For each 30 m grid cell of the watershed, hourly energy input data were summed and monthly totals were averaged for each HRU. To account for atmospheric transmittivity, ten years of shortwave radiation observations at the Environment Canada climate station in Stavely, Alberta, approximately 35 km north of the Beaver Creek watershed, were compared with the modeled solar radiation and the monthly radiation surfaces were adjusted accordingly.

Daily mean wind speed (km/h) was derived from the Pincher Creek climate station (Environment Canada), the nearest station with available wind speed data. Monthly means of daily average relative humidity were computed from the Stavely climate station, the nearest data source to the study watershed. Saturated vapor pressure is empirically related to the observed temperature within the ACRU model structure (Schulze 1995).

*Soil information* Soil information in the agricultural regions of Alberta was provided by the AGRASID digital database. For the A- and B-horizons, soil depth, soil water redistribution and retention values were derived by averaging the relevant values for each AGRASID soil polygon. Soil polygons were then area-weighted to the overlying HRU, using a GIS.

*Land cover information* Generalized land cover data were provided by the Prairie Farm Rehabilitation Administration (PFRA 2001). The digital dataset was classified from 30 m Landsat 7 imagery into the dominant land cover classes. These included cultivated cropland, forage, grasslands, shrubs, trees, wetlands, water, and non-agricultural lands. The resulting land cover map was field verified to ensure accuracy across the watershed. Using a GIS overlay analysis, land cover polygons were area-weighted to reflect the proportionality of each land use category within each HRU.

Non-destructive estimates of LAI were collected in situ using an LAI-2000 plant canopy analyzer (Li-Cor Inc., Lincoln, NE). Measurements were collected for forest, shrub, grassland and crop canopies for various periods during the growing seasons of 2006 and 2007. Field measurements considered dual-stage canopies with understory vegetation as well as row crops by taking multiple measurements. These measurements were used as field verification for a monthly LAI dataset provided by Agriculture and Agri-Food Canada.

Monthly crop coefficients were calculated for the dominant vegetation of each land use according to the method outlined in the FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

*Streamflow information* Groundwater recharge was simulated to occur when the soil water storage in the B-horizon is above field capacity. Groundwater outflow is simulated in the ACRU model using an exponential decline function, where the decline variable was based on observed recession curves of the streamflow hydrographs. An overland flow function, which determines the proportion of runoff reaching the watershed outlet on the same day, was also based on hydrograph analysis.

## 3.3 Deriving scenarios of future climate

### *3.3.1 General circulation model data*

The Pacific Climate Impacts Consortium (http://pacificclimate.org/) has made available monthly GCM output from all publicly available SRES model experiments. The GCMs in Table 2 correspond to the selection of models recommended by the IPCC Data Distribution Center Task Group on Data and Scenario Support for Impact and Climate Analysis (IPCC-TGCIA 1999). Thus, the model experiments used for this study were the most recent, advanced, highest resolution, publicly available data for impacts research. The nearest four GCM grid cells to the study watershed were

**Table 2** Models and experiments available from the PCIC

| Modeling center | Country | Model | SRES simulations |
|---|---|---|---|
| Canadian Center for Climate Modeling and Analysis | CAN | CGCM2 | A2, B2 |
| Hadley Centre for Climate Modeling and Research | UK | HadCM3 | A1F1, A2, B1, B2 |
| Max Planck Institute for Meteorology | GER | ECHAM4 | A2, B2 |
| Commonwealth Scientific and Industrial Research Organization | AUS | CSIRO-Mk2 | A1, A2, B1, B2 |
| Geophysical Fluid Dynamics Laboratory | USA | GFDL-R30 | A2, B2 |
| National Centre for Atmospheric Research | USA | NCAR-PCM | A2, B2, A1B |
| Centre for Climate Research Studies | JPN | CCSR/NIES | A1F1, A1T, A1B, A2, B1, B2 |

After Barrow and Yu (2005)

averaged to reduce the influence imposed by using a single, overlying grid cell (Von Storch et al. 1993).

### *3.3.2 Climate change scenario selection*

The selection method consisted of a combination of the hypothetical technique (e.g. Nemec and Schaake 1982; Xu 2000) with projections from all available GCMs, thus facilitating a less-biased sensitivity analysis to the full range of projected regional climates. Five GCM experiments were selected, based on their representation of the range of possible future climates of warmer-wetter, warmer-drier, median, hotter-[1]wetter and hotter-drier. Where the selection was complicated by similarities between the experiment results, the selection was based on the greatest change in precipitation.

The proposed method applied a range of GCM-based climate change scenarios. This resulted in a hypothetical range of the projected alternatives of future climate and constructed an appropriate stimulus for the analysis of future hydrology in the Beaver Creek watershed. This method of climate scenario selection was adapted from Barrow and Yu (2005), who constructed climate scenarios for the province of Alberta.

### *3.3.3 Regional downscaling*

The “delta” method (Arnell 1999; Hay et al. 2000) has been used to downscale GCM output in several regional hydrological impacts studies (Morrison et al. 2002; Schulze and Perks 2003; Andreasson et al. 2004; Loukas et al. 2004; Cohen et al. 2006; Merritt et al. 2006). This method calculates the relative change of a GCM-derived climate variable between the baseline period (1961–1990) and a future time period. The delta method is advantageous in impact sensitivity analyses as the monthly mean of the observations are perturbed, while preserving the variability of the local and regional climate (Leavesley 1994; Hamlet and Lettenmaier 1999; Loukas et al. 2004). The selection of the downscaling technique was made in consideration with the objective of the study, which was to examine the sensitivity of the Beaver Creek catchment to the range of projected future climate scenarios. The delta method applies the climate change signal to the mean of the observed data, however, it does not account for the anticipated changes to the variability of future climate (Wood et al. 1997; Hay et al. 2000). Future temporal scales assessed in this study followed the IPCC-TGCIA (1999) recommended periods of 2010–39, 2040–69, and 2070–99.

This hydrological assessment required monthly changes to be calculated for minimum temperature, maximum temperature and precipitation. Changes in both temperature variables were calculated as the absolute change and changes in precipitation were calculated as a ratio change in the mean of the monthly precipitation. The 12 monthly mean changes were smoothed by a Fourier transformation (Schulze 1995; Morrison et al. 2002) that constructed continuous daily adjustments for minimum and maximum temperature and precipitation. The transformed monthly changes were applied to the observed climate for five scenarios, for each of the

---

[1] “hotter” designates those scenarios which have higher projected temperature increases than the “warmer” designation as the models unanimously predict warmer temperatures in all scenarios at all time steps.

three future time periods. The original station observations were used as the baseline scenario to compare the 15 model runs, and determine the hypothetical change in future hydrological conditions.

### 3.4 Analysis of future hydrological conditions

The analysis of the scenarios was primarily focused on how the changes in temperature and precipitation affect the hydrological regime of the Beaver Creek watershed. The results show how the scenario-derived future projections in temperature and precipitation affected the major water balance components, annual flow volume, and the potential seasonal shift of the hydrological regime. The results were compared over the three recommended time periods, and were analyzed relative to the baseline simulation.

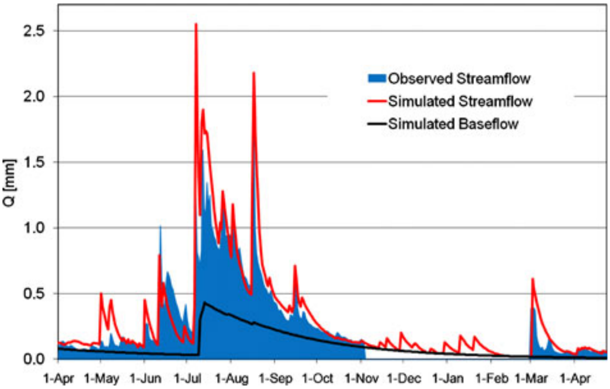
## 4 Results

### 4.1 Verification of ACRU model output

The ACRU model simulated the observed streamflow record in the Beaver Creek with reasonable accuracy over the 27-year verification period. Figure 5 presents a typical simulation for a 12 month period. The simulated and observed hydrographs demonstrate characteristic problems in hydrological simulations, where the timing, and often the magnitude, of simulated and observed hydrographs may differ significantly. This is the result of differences of precipitation events observed at the climate station, and those occurring within the watershed boundaries. What matters for climate change impact studies is not the exact duplication of runoff events, but a realistic representation of the hydrological behavior of seasonal changes, water yield, and the magnitude and frequency of extreme events such as floods and low-flow periods.

A comparison of simulated and observed hydrographs in Fig. 5 showed that the magnitudes of floods and low-flows were very similar. The seasonal timing was well simulated, and that the recession of the hydrographs was captured. Observed streamflows were not available for November to March due to freezing of Beaver

**Fig. 5** Simulated and observed hydrograph for the period April, 1993, to April, 1994



Creek. The baseflow hydrograph is shown to demonstrate how streamflows in the winter depend almost entirely on baseflow, except during short rainfall or snowmelt events.

The overall quality of the simulation is demonstrated by the reasonable fit between simulated and observed monthly flows as indicated by a coefficient of efficiency of 0.77, a coefficient of determination ($r^2$) of 0.78, a slope of the regression line of 0.9, and an average annual over-simulation of 3.5%. A 2.1% difference in standard deviation between simulated and observed monthly streamflows shows that both high and low flow months were simulated accurately. It was concluded that the accuracy of the ACRU model over the verification period was sufficient for simulating the mean response to climate change scenarios, and that inherent errors would be consistent and allow the proper evaluation of climate change impacts on this watershed.

## 4.2 Climate scenario selection

The distribution of annual GCM projections in Fig. 6 illustrates that the models were not in uniform agreement in the direction or magnitude of changes for the 2010–39 time period. However, there was unanimous agreement among the models of an increase in mean annual temperature.

The monthly changes of minimum and maximum temperatures, as well as precipitation from each of the five scenarios, were used to perturb the 1961–1990 observed baseline climate record at the Claresholm Waterworks climate station. This provided

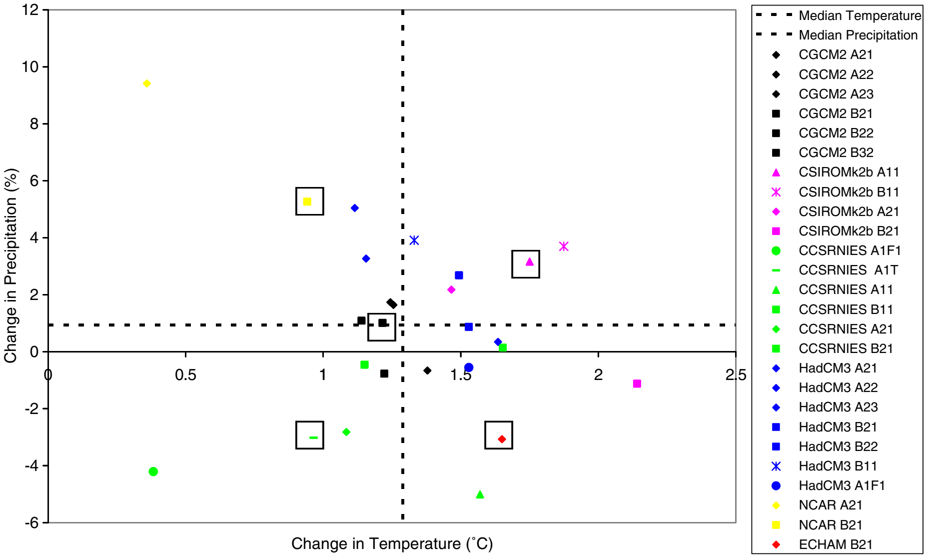


**Fig. 6** Mean annual projections of all publicly available GCM experiments for change in mean annual temperature (°C) and the mean annual change in precipitation (%) for the period 2010–2039 over the Beaver Creek watershed. *Colors* denote different models while *symbols* reflect different SRES emissions scenarios. *Dashed black lines* represent the median of all available scenarios, and *boxed* scenarios represent the five selected scenarios

**Table 3** Models and experiments used in this study

| Scenario | GCM | Emissions Scenario | Resolution (°) |
|---|---|---|---|
| HD | ECHAM4 | B2 (1) | 2.8 × 2.8 |
| HW | CSIRO-Mk2 | A1 (1) | 5.6 × 3.2 |
| MD | CGCM2 | B2 (1) | 3.75 × 3.75 |
| WD | CCSR | A1T | 5.62 × 5.62 |
| WW | NCAR-PCM | B2 (1) | 2.8 × 2.8 |

After Barrow and Yu (2005)

the input to the ACRU model for future hydrological scenarios. Five scenarios of future climate were selected based on their predictions for annual temperature and precipitation changes for the 2010–39 period of warmer wetter (WW), warmer drier (WD), median (MD), hotter wetter (HW) and hotter drier (HD) climates. The resulting five scenarios consisted of a range of GCMs and SRES emissions scenarios (Table 3).

The mean annual changes in temperature and precipitation, as well as the mean seasonal changes in temperature and precipitation for the five representative scenarios, are presented in Table 4. It is important to note that since the selection of the representative scenarios was based on the relative performance of the GCMs over the 2010–39 period, the five representative scenarios in the 2040–69 and 2070–99 periods do not necessarily reflect the same relative distributions. Thus, the interpretation of the results must be directly related to the individual scenario changes in temperature and precipitation as illustrated in Table 4. The scenarios in which this occurs are denoted by an asterisk (*).

**Table 4** Mean annual and seasonal GCM projections of temperature and precipitation for 2010–39, 2040–69 and 2070–99 periods

| Scenario | Mean annual GCM projections | | | Mean seasonal GCM projections | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Period | Temp (°C) | Precip (%) | Winter | | Spring | | Summer | | Fall | |
| | | | | T (°C) | P (%) | T (°C) | P (%) | T (°C) | P (%) | T (°C) | P (%) |
| HD | 2010–39 | 1.7 | −3.1 | 1.4 | 4.9 | 1.0 | −2.8 | 2.5 | −15.5 | 1.8 | 1.1 |
| HW | 2010–39 | 1.8 | 3.2 | 2.6 | 16.5 | 1.3 | 4.3 | 1.6 | −5.3 | 1.6 | −2.9 |
| MD | 2010–39 | 1.2 | 1.0 | 1.6 | 10.0 | 1.6 | 2.8 | 1.6 | −5.6 | 0.7 | −3.2 |
| WD | 2010–39 | 0.9 | −3.0 | −0.2 | −5.5 | 1.8 | 1.7 | 1.2 | −3.5 | 0.9 | −4.8 |
| WW | 2010–39 | 0.9 | 5.3 | 1.7 | 0 | 0.7 | 12.4 | 1.1 | 10.2 | 1.2 | −1.5 |
| HD* | 2040–69 | 2.8 | 1.6 | 1.8 | 9.1 | 1.8 | 6.7 | 1.9 | −10.4 | 1.8 | 0.8 |
| HW | 2040–69 | 3.5 | 2.6 | 3.9 | 19.4 | 2.8 | 19.0 | 3.5 | −15.5 | 3.8 | −12.4 |
| MD* | 2040–69 | 2.4 | 2.3 | 2.6 | 8.9 | 3.2 | 4.4 | 2.2 | −5.7 | 1.6 | 1.4 |
| WD* | 2040–69 | 4.3 | 2.5 | 4.5 | 9.4 | 4.4 | 9.9 | 4.3 | −3.5 | 4.1 | −5.8 |
| WW | 2040–69 | 1.5 | 6.0 | 1.3 | 1.3 | 1.3 | 7.4 | 2.0 | 5.2 | 1.6 | 10.2 |
| HD* | 2070–99 | 4.0 | −0.2 | 3.7 | 12.3 | 2.8 | 7.2 | 5.2 | −17.9 | 4.1 | −2.4 |
| HW | 2070–99 | 5.1 | 9.3 | 6.4 | 33.0 | 3.8 | 27.4 | 5.0 | −15.2 | 5.2 | −7.8 |
| MD* | 2070–99 | 3.2 | 3.7 | 3.5 | 8.1 | 4.5 | 13.1 | 2.9 | −9.7 | 2 | 3.4 |
| WD* | 2070–99 | 6.4 | 8.4 | 6.9 | 13.8 | 6.4 | 19.8 | 6.3 | −2.1 | 5.8 | 2.1 |
| WW | 2070–99 | 2.0 | 15.3 | 2.2 | 11.2 | 1.6 | 20.5 | 2.3 | 17.1 | 2 | 12.5 |

Temperature is expressed as mean change in degrees Celsius relative to the 1961–1990 baseline, and precipitation is expressed as the percentage change in mean precipitation relative to the 1961–1990 baseline. The seasonal periods are defined as Winter (DJF), Spring (MAM), Summer (JJA) and Fall (SON)

**Table 5** Mean annual water balance components simulated by the ACRU model for the baseline, 2010–39, 2040–69 and 2070–99 time periods

| | Period | Rain (mm) | Snow (mm) | Mixed (mm) | Total P (mm) | APAN (mm) | AET (mm) | Q (mm) | WB (mm) |
|---|---|---|---|---|---|---|---|---|---|
| Baseline | 1961–90 | 218 | 209 | 33 | 460 | 959 | 431 | 25 | 4 |
| HD | 2010–39 | 228 | 176 | 30 | 435 | 1,111 | 411 | 20 | 4 |
| HW | 2010–39 | 245 | 186 | 36 | 466 | 1,106 | 435 | 28 | 3 |
| MD | 2010–39 | 250 | 181 | 30 | 462 | 1,089 | 433 | 25 | 4 |
| WD | 2010–39 | 245 | 171 | 32 | 448 | 1,089 | 422 | 22 | 4 |
| WW | 2010–39 | 282 | 179 | 33 | 494 | 1,085 | 461 | 29 | 4 |
| HD | 2040–69 | 252 | 179 | 29 | 459 | 1,156 | 430 | 26 | 3 |
| HW | 2040–69 | 242 | 179 | 39 | 460 | 1,180 | 423 | 34 | 3 |
| MD | 2040–69 | 266 | 169 | 33 | 468 | 1,141 | 440 | 25 | 3 |
| WD | 2040–69 | 269 | 162 | 35 | 467 | 1,216 | 436 | 28 | 3 |
| WW | 2040–69 | 281 | 177 | 32 | 490 | 1,106 | 460 | 27 | 3 |
| HD | 2070–99 | 240 | 173 | 30 | 443 | 1,208 | 415 | 26 | 2 |
| HW | 2070–99 | 267 | 182 | 38 | 487 | 1,245 | 444 | 40 | 3 |
| MD | 2070–99 | 280 | 161 | 34 | 475 | 1,179 | 445 | 28 | 2 |
| WD | 2070–99 | 310 | 148 | 40 | 497 | 1,302 | 463 | 32 | 2 |
| WW | 2070–99 | 303 | 194 | 37 | 534 | 1,116 | 493 | 38 | 3 |

Total precipitation (summation of rain and snow), APAN (Potential evapotranspiration), AET (Actual evapotranspiration from all storages, including interception) and Q (Total streamflow) are expressed in millimeters. The WB (water balance) reflects the combined storage changes in the soil moisture, groundwater reservoir, snowpack and interception

### 4.3 Simulated mean annual water balance components

The simulated changes in the mean annual water balance components are presented in Table 5. Annual precipitation volume increased in the majority of scenarios, except in those scenarios which projected a decrease in annual precipitation (HD in the 2010 and 2070 scenarios, WD in the 2010 scenario). In all scenarios, a greater volume of the rainfall was simulated, while concurrently snowfall was simulated to be reduced. The proportion of snowfall to total precipitation falls from the historical (1961–1990) 48.9% to an average of 41.7% for 2010–2039, an average of 39.8% for 2040–2069, and an average of 38.1% for 2070–2099.

The median scenario (2020s) simulated no change in annual streamflow volume, however, the trend of decreased precipitation as snow and increased rain persisted. Similarly in the 2050 period, the median scenario simulated no change in annual streamflow volume despite increases in temperature and precipitation. As is presented in Table 5, the increase of precipitation when higher temperatures are simulated resulted in a compensation due to an increase in simulated actual evapotranspiration.

In all scenarios, A-pan equivalent potential evapotranspiration increased beyond the baseline simulation (Table 5), which can be attributed to the increase in mean annual temperatures across the scenarios (Table 4). Potential evapotranspiration increased throughout the time periods, with the greatest increases of A-pan potential evapotranspiration projected for the 2070–99 period.

The simulated changes in actual evapotranspiration (AET) reflected the changes in available moisture throughout the scenarios. In all scenarios, the changes in

AET are related to the changes in precipitation (Table 4). This is an interesting result, as it indicates that in this semi-arid, water limited region future changes in AET depend more on precipitation changes than on temperature changes. In this environment, actual evapotranspiration is limited by available soil moisture rather than atmospheric demand.

The simulated changes in mean annual streamflow (Q), relative to the baseline, showed an increase for all simulations with the exception of the HD, MD and WD 2010–2039 and the MD 2040–2069 scenarios (Table 5). This is due to an increase in precipitation with a concurrent lesser increase in actual evapotranspiration. The explanation becomes clear when seasonal water balances are investigated.

### *4.3.1 Mean seasonal flow volumes*

The seasonal contributions to mean annual streamflow were calculated for the baseline and each scenario over the three time periods and are presented in Table 6. The baseline period received the greatest contribution to annual streamflow in the spring (March, April and May), followed by summer (June, July, August), winter (December, January, February) and fall (September, October, November). This inter-annual behavior was maintained in all scenarios in the 2010–39 simulations. However, in the 2040–69 time period the HW and WD scenarios simulated a seasonal shift, where the winter volume became larger than the summer flow. Similarly, in the 2070–99 period, this shift also occurred in the HD, HW and WD scenarios.

The simulations indicate an increase in the winter flow volume in nearly all scenarios (WD 2020 excluded) with a near doubling of the baseline volume in the HW scenario over the 2020 period (from 6.81 to 13.03 $m^3s^{-1}$). Spring volumes are better conserved throughout the simulations where the greatest increase occurred in the HW scenario and the most conservative simulations in the HD and MD scenarios. The projected summer and fall climate resulted in a reduction of summer and fall seasonal volumes below the simulated baseline for all future scenarios, except the WW scenarios, where mean summer and fall volumes were consistently greater

**Table 6** Mean changes in seasonal streamflow for 2010–39, 2040–69 and 2070–99 periods in $m^3/s$ of streamflow from 1961–1990 baseline

| | Winter ($m^3s^{-1}$) | Spring ($m^3s^{-1}$) | Summer ($m^3s^{-1}$) | Fall ($m^3s^{-1}$) |
|---|---|---|---|---|
| Baseline | 6.81 | 40.86 | 20.43 | 5.33 |
| HD2010–39 | 9.18 | 35.83 | 11.84 | 3.26 |
| HW2010–39 | 13.03 | 52.12 | 14.81 | 3.85 |
| MD2010–39 | 11.25 | 42.94 | 17.17 | 3.26 |
| WD2010–39 | 6.22 | 39.98 | 15.69 | 3.85 |
| WW2010–39 | 8.88 | 44.12 | 26.95 | 5.63 |
| HD2040–69 | 11.55 | 47.67 | 13.92 | 4.74 |
| HW2040–69 | 17.47 | 65.44 | 16.58 | 1.18 |
| MD2040–69 | 12.14 | 42.64 | 16.58 | 4.15 |
| WD2040–69 | 15.10 | 50.04 | 14.51 | 3.26 |
| WW2040–69 | 9.18 | 41.75 | 23.99 | 6.22 |
| HD2070–99 | 13.62 | 48.56 | 11.84 | 2.07 |
| HW2070–99 | 25.47 | 76.69 | 15.69 | 1.78 |
| MD2070–99 | 13.92 | 47.97 | 15.99 | 4.15 |
| WD2070–99 | 18.95 | 55.67 | 16.29 | 5.03 |
| WW2070–99 | 13.62 | 56.85 | 33.76 | 7.70 |

due to the only forecasted increases in summer precipitation across the three time periods. With a few exceptions, the overall future streamflow regime is simulated to change towards much increased streamflow in winter, a smaller increase in spring, a decline in summer, and a potentially severe decline in fall.

The choice of the downscaling method also impacted the scenario simulations. Akinremi and McGinn (1999) found that, while annual precipitation in the Prairies increased in recent decades, the total precipitation volume was attributed to a higher frequency of low-intensity events. Applying the mean monthly change between the baseline climate and future climates (i.e. the delta method) assumed that the variability observed in the baseline period would persist in the future. This method does not account for changes in the behavior of future meteorological variables, particularly important for projections of precipitation. The importance of groundwater recharge in the Beaver Creek watershed suggests that both the frequency and intensity of future precipitation may impact annual interception amounts, soil water storages and groundwater recharge rates. Methods such as statistical downscaling, which use daily GCM output rather than mean change, may prove to be beneficial in addressing these research questions.

## 5 Discussion

The simulations of streamflow in the Beaver Creek watershed revealed a shift in the seasonal streamflow distribution beyond the 2010–39 time period. In each season, the majority of scenarios were in agreement that winter and spring flow volumes will increase, while summer and fall flow volumes will decrease relative to the baseline simulation. Byrne et al. (1999) estimated that spring runoff volumes in the Oldman River watershed would increase in a $2 \times CO_2$ climate. Leith and Whitfield (1998) also found that warmer temperatures resulted in higher winter flows and reductions in summer and fall streamflow volumes in south-central British Columbia. In the semi-arid Okanagan watershed, Cohen et al. (2006) and Merritt et al. (2006) found that future scenarios projected reductions of summer flow volumes. Annual streamflow volumes were simulated to increase in the future due to warmer and wetter winter and spring seasons. This is expected, because the partial replacement of snowfall by rainfall during months when the potential evpotranspiration rates are low will result in increased runoff or groundwater recharge during that time.

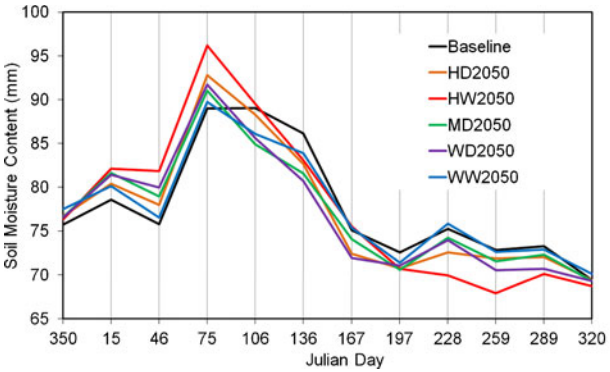
Simulation results indicated an overall drying and associated lower streamflows for the majority of summer and fall seasons beyond the 2010–39 period. The seasonal results indicated that water supply will be dramatically reduced in the summer and fall seasons. As the late summer and fall streamflows are maintained by groundwater outflow, it is important to try to gain a better perspective on the main factors that contribute to groundwater recharge and the subsequent maintenance of baseflow volumes in the Beaver Creek watershed. The relationship between seasonal precipitation and late season streamflow was investigated, based on available climate and hydrological observations. A number of predictors, such as seasonal precipitation, rainfall and snowfall volumes, were tested for their ability to establish a linear relationship with mean volumes of streamflow in the late summer/early fall period. Of all possible combinations of months, seasons and forms of precipitation, the only significant relationship that emerged in a stepwise multiple linear regression was predicted by spring (MAM) rainfall ($R^2 = 0.37$, $n = 39$). Seasonal snow volume and summer rainfall made no contribution to the linear regression model.

These results indicate that it is plausible that groundwater recharge in the spring melt period may have the greatest effect on baseflow production in the summer and fall months. Likewise, Rock and Mayer (2006) concluded through isotope analysis that groundwater is a principal contributor to peak streamflow in the Oldman River watershed. Beaver Creek is a perennial stream, yet the majority of precipitation is received in the months of May, June and July. Therefore, a significant portion of perennial flow is maintained by groundwater. Understanding how the projected changes in annual temperature and precipitation will manifest in groundwater recharge, and thus baseflow volumes (Fig. 5), is essential to estimating the full range of impacts on the hydrological regime of the Beaver Creek watershed.

Based on simulated climate change projections for the Beaver Creek watershed (WD 2010–39 excluded) it was estimated that a higher proportion of liquid water will be available in the winter season. A partial replacement of snowfall for rainfall, at times when the atmospheric water demand is low, results in low potential and actual evapotranspiration rates, and, subsequently, in higher soil moisture content, and groundwater recharge. However, despite the presence of warmer and wetter winters, four of the five scenarios projected decreases in the fall streamflow volume.

A closer examination of the 2040–69 simulations was carried out to investigate the impact of the changes in temperature and precipitation on the simulated storages, and, thus, water available for baseflows in the fall season. Soil moisture storages are simulated to increase above baseline conditions beginning in the early winter and continuing through early spring (Fig. 7). However, after Julian day 106 (mid April), this storage will fall below the baseline condition until Julian day 320 (mid November). Figure 8 shows that actual evapotranspiration will respond to the higher potential evapotranspiration, and will exceed the baseline in the winter months (Julian days 350–46). This response will proceed until around Julian day 115 (end of April), when several of the scenarios will fall below baseline actual evapotranspiration, which indicates that soil moisture will be limiting actual evapotranspiration at this point. This will have consequences for both dryland and irrigated agriculture. Dryland farming will produce likely lower yields, and will be more exposed to

**Fig. 7** Simulated mean monthly change in soil moisture content for the 2040 to 2069 period



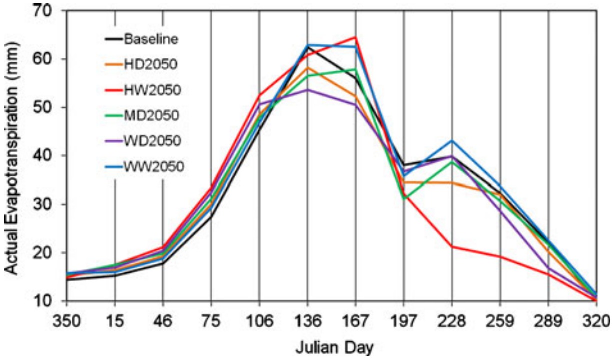


**Fig. 8** Simulated mean monthly change in actual evapotranspiration for the 2040 to 2069 period

drought risk, while the water demand for irrigated agriculture will increase due to lower natural soil water conditions.

In the ACRU model, groundwater storages are recharged when soil moisture levels exceed the field capacity of the subsurface soil horizon, and water is redistributed to the groundwater storage. Therefore, a reduction of soil moisture below baseline conditions resulted in a reduced number of events of soil moisture exceeding the field capacity. Consequently, this resulted in a reduction of the total volume of groundwater recharge, and groundwater storage (Fig. 8). The warmer and drier summer conditions resulted in an earlier recession of the groundwater store relative to the baseline period. Around November, the groundwater storage did not contain the volume required to sustain baseflow contributions of the baseline period. In addition to the reductions of precipitation, reduced groundwater flows may have contributed to the declining flows simulated by four of the five scenarios in this period.

The interpretation of the simulations presented here is limited due to the assumptions and uncertainties in both data and methods. The validity of the hydrological model over the verification period has a significant influence on the bias of the results as the best parameterization resulted in a 3.5% mean monthly under-simulation of streamflow. The simulations of future hydrological responses also assume that the parameterization for the 1965–2005 period will be applicable to future climates. Further, due to the lack of detailed hydrogeological information, the Beaver Creek watershed was assumed to receive no groundwater contribution from outside the watershed, and release all groundwater upstream of the watershed outlet area.

## 6 Conclusion

This paper examined the impact of climate change on the hydrological regime of the Beaver Creek watershed. Previous research in the Oldman River watershed had not explicitly focused on climate change impacts in a hybrid watershed, or impacts on soil moisture, groundwater recharge, or seasonal streamflow changes. This research was focused on examining the effects of the range of projected regional climate changes on the hydrological response of the Beaver Creek watershed. The simulations of the potential future hydrology in the Beaver Creek watershed illustrated the sensitivity of hydrological processes to changes in temperature and precipitation. This provided important information on the future of water availability in the Beaver Creek watershed based on changes in climate presently forecast by GCMs for this region.

In the verification assessment, the ACRU model simulations explained 78% of the variation in the monthly streamflow observations (27 year sample), while under-simulating the monthly volume by an average of 3.3% per month. Statistical results show a reasonable fit of simulated and observed monthly streamflows, where annual magnitude, as well as low and flood flows, were well simulated. The mean monthly volumes were well simulated, particularly in the late summer and fall baseflow periods.

The GCM projections for future regional climate change were within the range reported for North America and the province of Alberta. All scenarios of future climate change were in agreement on the increase of mean annual temperature. Projections of future regional precipitation were less certain in the direction of change, however, the majority of models projected slightly increased annual volumes, particularly in later time periods.

Hydrological simulations of these projections have shown that, while the majority of scenarios projected an increase in annual precipitation, the seasonal availability of streamflow, particularly in the summer and fall months, was affected by the seasonal projections of temperature and precipitation. The majority of scenarios projected increased winter and spring precipitation, while summer and fall precipitation decreased below the baseline volume. As a result, the majority of hydrological simulations (i.e. four of five scenarios) indicated an increase in winter and spring streamflows and a decrease in summer and fall streamflow volumes. The simulated soil water storages illustrated the importance of groundwater in the hydrology of the Beaver Creek watershed and its potential vulnerability to climate change, despite projections of warmer and wetter winters in the future. The consequences are less available soil water, with potential negative impacts for agriculture, and also increased stresses for the natural vegetation, lower streamflows in late summer and fall, with potentially adverse impacts on the aquatic ecosystem and anyone who withdraws water from the river.

The Beaver Creek responds similarly to a typical prairie watershed, having a low runoff coefficient of just over 5%. Results from this study show the sensitivity and vulnerability of such rivers to climate change due to the impacts of the changes in the hydrological regime. The overall water yield likely remains the same or even slightly increases, the summer and fall soil moisture will decline, and low streamflows will become more frequent.

This research provided an initial indication of the impacts of climate change on hydrological processes in a southern Alberta watershed. Future research needs to compare these results to simulations driven by other methods of downscaling, particularly those which incorporate changes in precipitation variability such as statistical downscaling. Recognizing that only changes to precipitation and temperature were made in these simulations, future work should also include changes in other meteorological variables as well as land cover changes associated with climate change.

**Acknowledgements** This research was funded by the Alberta Ingenuity Center for Water Research (Grant # 42321) and the University of Lethbridge.

## References

AGRASID version 3 Retrieved October, 2005 from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag5173?opendocument

Akinremi OO, McGinn SM (1999) Precipitation trends on the Canadian prairies. J Climate 12(10):2996–3003

Alberta Environment (AENV) (2008) Water for life. Alberta's strategy for sustainability. Government of Alberta

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper (FAO) No 56, FAO, Rome (Italy), p 300

Andreasson J, Lindstrom G, Grahn G, Johansson B (2004) Runoff in Sweden-mapping of climate change impacts on hydrology. Nord Hydrol Programme 48(2):625–632

Arnell NW (1999) Climate change and global water resources. Glob Environ Change 9:31–49

Asquith WH, Famiglietti JS (2000) Precipitation areal-reduction factor estimation using an annual-maxima centered approach. J Hydrol 230(1–2):55–69

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of warming on water availability in snow dominated regions. Nature 438:303–309

Barrow E, Yu G (2005) Climate scenarios for Alberta a report prepared for the prairie adaptation research collaborative (PARC) in co-operation with Alberta environment. Alberta Environment, Regina, Saskatchewan

Bathurst JC, Ewen J, Parkin G, O'Connell PE, Cooper JD (2004) Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. J Hydrol 287(1–4):74–94

Byrne JM, Berg A, Townshend I (1999) Linking observed and general circulation model upper air circulation patterns to current and future snow runoff for the Rocky Mountains. Water Resour Res 35:3793–3802

Carter TR, Parry ML, Harasawa H, Nishioka S (1994) IPCC technical guidelines for assessing climate change impacts and adaptations. Department of Geography, University College London, London

Cohen SJ (1990) Bringing the global warming issue closer to home. The challenge of regional impact studies. Bull Am Meteorol Soc 71:520–526

Cohen SJ, Neilsen D, Smith S, Neale T, Taylor B, Barton M, Merritt W, Alila Y, Shepherd P, McNeill R, Tansey J, Carmichael J, Langsdale S (2006) Learning with local help: expanding the dialogue on climate change and water management in the Okanagan Region, British Columbia, Canada. Clim Change 75:331–358

Environment Canada (n.d.) Retrieved October, 2007 from: http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html

Everson CS (2001) The water balance of a first order catchment in the montane grasslands of South Africa. J Hydrol 241:110–123

Gan TY (1998) Hydroclimatic trends and possible climatic warming in the Canadian prairies. Water Resour Res 34(11):3009–3015

Grace BW (1987) Chinooks. Chinook 9:52–56

Hamlet AF, Lettenmaier DP (1999) Effects of climate change on hydrology and water resources in the Columbia river basin. J Am Water Resour Assoc 35(6):1597–1623

Hay LE, Wilby RL, Leavesley GH (2000) A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. J Am Water Resour Assoc 36(2):387–397

Hutchinson MF (2004) ANUSPLIN version 4.0 user guide. Centre for Resources and Environmental Studies, Australian National University, Canberra

IPCC (2007a) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, p 996

IPCC (2007b) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 7–22

IPCC-TGCIA (1999) Guidelines on the use of scenario data for climate impact and adaptation assessment. Version 1. In: Carter TR, Hulme M, Lal M (eds) Intergovernmental panel on climate change, task group on scenarios for climate impact assessment, p 69

Kienzle SW (2008) A new temperature based method to separate rain and snow. Hydrol Process 22:5067–5085

Kienzle SW, Schmidt J (2008) Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. J Hydrol N Z 47(2):67–84

Kienzle SW, Schulze RE (1991) The simulation of the effect of afforestation on shallow ground water in deep sandy soils. Water SA 18(4):265–272

Kienzle SW, Lorenz SA, Schulze RE (1997) Hydrology and water quality of the Mgeni catchment. Report TT87/97, Water Research Commission, Pretoria, pp 1–88

Leavesley GH (1994) Modelling the effects of climate changes on water resources- a review. Clim Change 28:159–179

Leith RMM, Whitfield PH (1998) Evidence of climate change effects on the hydrology of streams in south-central BC. Can Water Resour J 23(3):219–230

Loukas A, Quick MC (1996) Effect of climate change on hydrologic regime of two climatically different watersheds. J Hydrol Eng 1(2):77–87

Loukas A, Vasiliades L, Dalezios NR (2002) Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. J Hydrol 259:163–188

Loukas A, Vasiliades L, Dalezios NR (2004) Climate change implications on flood response of a mountainous watershed. Water, Air & Soil Pollution: Focus 4:331–347

Merritt WS, Alila Y, Barton M, Taylor B, Cohen S, Neilsen D (2006) Hydrological response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. J Hydrol 326:79–108

Miller NL, Bashford KE, Strem E (2003) Potential impacts of climate change on California hydrology. J Am Water Resour Assoc (JAWRA) 39(4):771–784

Morrison J, Quick MC, Foreman MGG (2002) Climate change in the Fraser River watershed: flow and temperature projections. J Hydrol 263:230–244

Nemec J, Schaake J (1982) Sensitivity of water resource systems to climate variation. Hydrol Sci J 27(3):327–343

Nurmohamed R, Naipal S, De Smedt F (2007) Modeling hydrological response of the Upper Suiname river basin to climate change. J Spat Hydro 7(1):1–22

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc Lond, A Math Phys Sci 193(1032):120–145

PFRA Generalized Landcover for the Canadian Prairies, Retrieved October 2006 from: http://www.agr.gc.ca/pfra/gis/lcv_e.htm

Rock L, Mayer B (2006) Isotope hydrology of the Oldman River basin, southern Alberta, Canada. Hydrol Process 21(24):3301–3315

Rood SB, Samuelson GM, Weber JK, Wywrot KA (2005) Twentieth-century decline in streamflows from the hydrographic apex of North America. J Hydrol 306(1–4):215–233

Schindler DW, Donahue WF (2006) An impending water crisis in Canada's western prairie provinces. PNAS 103(19):7210–7216

Schulze RE (1995) Hydrology and Agrohydrology: a text to accompany the ACRU 3.00 agrohydrological modelling system. Report TT69/95, Water Research Commission, Pretoria, RSA

Schulze RE (2000) Modelling hydrological responses to land use and climate change: a southern African perspective. R Swed Acad Sci 29(1):12–22

Schulze RE, Perks LA (2003) The potential threat of significant changes to hydrological responses in southern Africa as a result of climate change: a threshold analysis on when these could occur, and where the vulnerable areas are. In: Schulze RE (ed) Modelling as a tool in integrated water resources management: conceptual issues and case study applications. WRC Report 749/1/02, Water Research Commission, Pretoria, RSA, Chapter 14, pp 250–258

Schulze RE, Lorentz S, Kienzle SW, Perks L (2004) Modelling the impacts of land-use and climate change on hydrological responses in the mixed underdeveloped/developed Mgeni catchment, South Africa. In: Kabat P et al (eds) Vegetation, water, humans and the climate a new perspective on an interactive system. Springer, New York, p 17

Smithers J, Schulze RE (1995) ACRU agrohydrological modelling system user manual. WRC Report TT 70/95, Water Research Commission, Pretoria

Toth B, Pietroniro A, Malcolm Conly F, Kouwen N (2006) Modelling climate change impacts in the Peace and Athabasca catchment and delta: I-hydrological model application. Hydrol Process 20:4197–4214

Veneziano D, Langousis A (2005) The areal reduction factor: a multifractal analysis. Water Resour Res 41:W07008. doi:10.1029/2004WR003765

Von Storch H, Zorita E, Cubasch U (1993) Downscaling of global climate change estimates to regions scales: an application to Iberian winter rainfall. J Climate 6:1161–1171

Wheaton E (2001) Limited report. Changing climates: exploring possible future climates of the Canadian Prairie Provinces. SRC Publication No 11341–3E01, Government of Canada

Whitfield PH, Fraser D, Cohen S (2003) Climate change impacts on water in Georgia Basin/Puget Sound–special issue. Can Water Resour J 28(4):523–529

Wood AW, Lettenmaier DP, Palmer RN (1997) Assessing climate change implications for water resources planning. Clim Change 37:203–228

Xu CY (1999a) Climate change and hydrologic models: a review of existing gaps and recent research developments. Water Resour Manag 13:369–382

Xu CY (1999b) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Prog Phys Geogr 23(2):229–249

Xu CY (2000) Modelling the effects of climate change on water resources in Central Sweden. Water Resour Manag 14:177–189

Xu CY (2005) Modelling hydrological consequences of climate change–progress and challenges. Adv Atmos Sci 22(6):789–797