USE OF DOWNSCALED GCM DATA FOR MODELING GROUNDWATER RECHARGE, BASIN RUNOFF, AND GROUNDWATER LEVELS

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ABSTRACT

Climate data from the Canadian Global Coupled Model 1 (CGCM1) for current and future time periods are downscaled and used to predict changes in aquifer recharge, basin runoff and groundwater levels in a small unconfined aquifer in south central British Columbia, Canada. The change factors predicted from Statistical DownScaling Model (SDSM) are extracted and applied in the LARS-WG stochastic weather generator, and then input to the one-dimensional HELP hydrologic model, which is used to model groundwater recharge. Using a GIS in combination with HELP, recharge is modeled spatially, accounting for soil distribution, vadose zone depth and hydraulic conductivity, extent of impermeable areas, surficial geology, and vadose zone thickness. CGCM1 downscaling is also used to predict basin-scale runoff for a 26 km long river that meanders through the unconfined valley aquifer and exerts strong control on the groundwater levels in the aquifer. Stage-discharge relations for river segments were calculated using USGS BRANCH and calibrated to observed historical data. River schedules of high temporal resolution (1 to 5 days) were imported into a transient three-dimensional groundwater flow model, implemented in MODFLOW, for each climate scenario. The calibrated model is then used to simulate four climate scenarios in 1-year runs (1961-1999 present, 2010-2039, 2040-2069, 2070-2099) and to compare groundwater levels to present. By the 2050’s the largest increase in recharge relative to present occurs in late spring, by a factor of three or more, a 50% increase in summer months in most areas of the aquifer, a 10 to 25% increase in autumn, and a reduction in recharge in winter. Future climate predictions suggest a shift in the hydrograph peak to an earlier date, although the peak flow remains the same, and baseflow level is lower and of longer duration. Consequently, groundwater levels near the river floodplain are predicted to be higher earlier in the year due to an earlier onset of peak flow, but considerably lower during the summer months. Away from rivers, groundwater levels increase slightly due to the predicted increase in recharge.

1. INTRODUCTION

This paper summarizes the methodology and describes the results of a climate change impacts study of an unconfined aquifer that is strongly influenced by surface water. We present a case study of a small regional unconfined aquifer (34 km^2), contained within the mountainous valley of the Kettle River near the City of Grand Forks in south-central British Columbia (BC), Canada (Fig. 1). The aquifer consists of glaciofluvial sediments overlying glaciolacustrine sediments, which partially infill steep and variable bedrock topography. The climate is semi-arid and most precipitation occurs in summer months during convective activity. Groundwater is used extensively for irrigation and domestic use (Wei et al., 1994). Within the Grand Forks valley, the Kettle River is a meandering gravel-bed river incised into glacial outwash sediments, and previous studies (Allen et al., 2004a) demonstrated that the aquifer water levels are highly sensitive to water levels in the Kettle River. Thus, consideration of impacts of climate change must necessarily consider both surface water and groundwater.

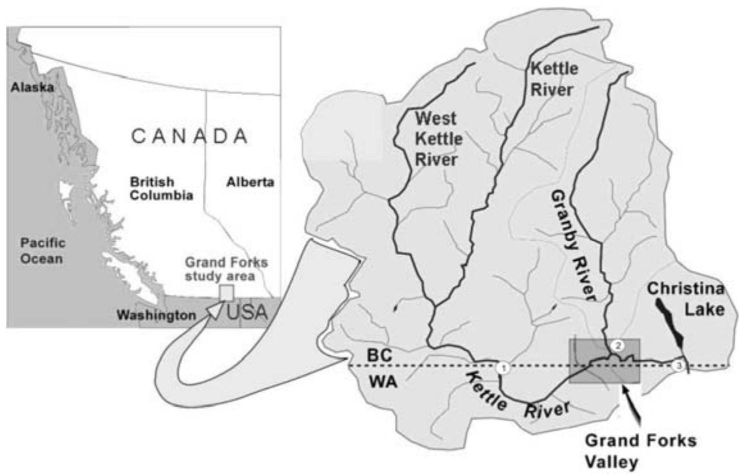

FIGURE 1. Kettle and Granby River drainage areas with inset map of the study area in British Columbia, Canada. (1) Kettle River at Ferry (2) Granby River at Grand Forks, and (3) Kettle River at Laurier represent the locations for daily discharge calculations for the Kettle River.

2. CLIMATE PREDICTIONS

1.1 Climate Scenarios.

Climate scenarios for modelled present and future conditions were taken from the Canadian Global Coupled Model (CGCM1) (Flato et al., 2000) for the IPCC IS92a greenhouse gas plus aerosol (GHG+A1) transient simulation. CGCM1 predictions are valid for Canada and fall in the average of other global climate models (GCMs). Five data sets were obtained from the Canadian Institute for Climate Studies (CCIS, 2004) for a grid location nearest to Grand Forks (Y=11 Latitude: 50.09°N and X=16 Longitude: 120°W – Grand Forks is at 49.1N and 118.2W). Four were CGCM1 scenarios, each with data for a number of potential predictor variables. The "current climate" scenario was generated for the period 1961-2000. The subsequent "future climate" experiments were for 2020s, 2050s and 2070s. The fifth data set was a calibration data set, which contains observed daily data for 1961-2000, derived from the NCEP (National Centre for Environmental Prediction) re-analysis data set (Kalnay et al., 1996) for the period 1961-2000. Most climate modelling experiments in North America use the NCEP datasets for calibration of downscaling models.

1.2 Downscaling.

Downscaling of CGCM1 results for use in recharge modeling was accomplished using Statistical Downscaling Model (SDSM) software (Wilby et al., 2002). NCEP daily data for the period 1961-2000 were used for calibration of SDSM. The SDSM model was well-calibrated for monthly precipitation means, and calibration bias from the NCEP dataset to observed data was less than a 10% difference for most months. Downscaled precipitation time series were analyzed for: mean monthly precipitation, standard deviation in daily precipitation, % wet days, dry series length, and wet series length. CGCM1 underestimated precipitation up to 40% compared to observed in the summer months (Fig. 2) due to the inability of the GCM to model local convective precipitation and rain shadow effects. Daily temperature time series were analyzed for: mean temperature and standard deviation. The calibration bias for temperature to NCEP dataset was very small (less than 1%), and the model bias of downscaled CGCM1 to observed was less than 10% for most months (Fig. 2).

Despite the model bias, an important assumption is made that the GCM can predict absolute changes in temperature and relative changes in precipitation (Fig. 3), which then can be used to perturb current weather to arrive at future weather conditions. A second important assumption is that the downscaling method is able to link GCM variables to local climate observations, and thus predict climate changes. Thus, four climate scenarios were generated using each calibrated downscaled model: current climate (1960-1999), 2020's climate (2010-2039), 2050's climate (2040-2069), and 2080's climate (2070-2099). The current climate statistics are based on 40 years of record, while the future climate scenarios represent three steps, each step representing an average of a 30 year period.

Summer precipitation is predicted to increase in July and August (Fig. 3), but in other months there are either no changes or there are predicted decreases. The % of wet days in the summer months (not shown) is predicted to increase under future climate scenarios. Temperatures are predicted to increase in all months from present to future at a rate of about $1^{o}C$ per 30 years (Fig. 3). It was not possible to downscale solar radiation for Grand Forks due to the lack of observed mean daily incident solar radiation at this location. Data were extracted from monthly Canadian Regional Climate Model (CRCM) outputs for grid cells representing Grand Forks and imported from the CCIS website. The CRCM solar radiation values were not downscaled. Absolute changes of solar radiation, by month, for current climate and future climates suggest that changes are relatively small, with no clear seasonal patterns (results not shown).

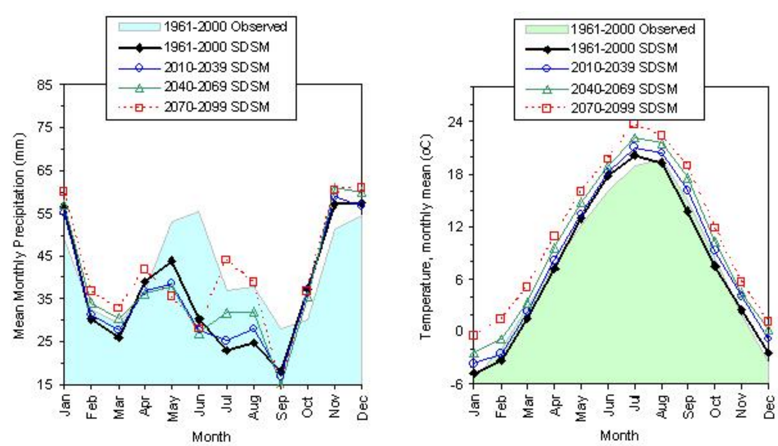

FIGURE 2. Observed and SDSM downscaled mean monthly precipitation and mean monthly temperature at Grand Forks, BC for current and future climate scenarios.

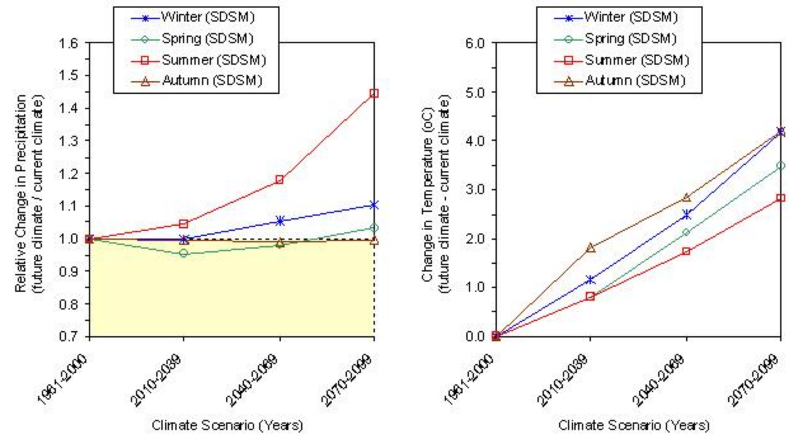

FIGURE 3. Relative change in seasonal precipitation and absolute change in seasonal temperature as predicted by downscaled CGCM1 model runs.

For hydrologic modeling, downscaling was accomplished using principal component analysis (PCA) and was undertaken by Environment Canada. A k-nearest neighbour analog model (Zorita and von Storch, 1999) was used to link principal component scores (explained variance > 90%) of the climate fields with the maximum temperature, minimum temperature, and precipitation series (of the NCEP dataset). The PCA linked the climate fields over BC and the eastern Pacific Ocean with daily discharge values for Kettle and Granby Rivers. The end product is sets of daily discharge data for three local hydrometric stations for the simulated 1962-2100 period: Kettle River at Ferry (WA), Granby River at Grand Forks (BC), and Kettle River at Laurier (WA) (Fig. 1). The somewhat poor fit between the downscaled and observed hydrograph for 1971-2000, shown for the Kettle River at Laurier station (Fig. 4), can mostly be attributed to biases existing between the GCM simulated climate fields and the observed climate fields from the NCEP data, which result in the onset of freshet begin delayed. The model bias is similar for all three hydrometric stations.

In the future climate scenarios (Fig. 5) the hydrograph peak is shifted to an earlier date, although the peak flow remains the same. There is also a significant increase in winter discharge in the future climate scenarios, most likely caused by an increase in rain and snowmelt volumes during the winter under warmer climate scenarios. Changes to the river hydrograph are predicted to be much larger for the 2040-2069 scenario than for the 2010-2039 scenario, compared to the modeled 1971-1999 period. The Kettle River and the Granby River had very similar responses to climate change.

The discharge data set for present climate scenario was truncated to 1971-1999 period (30 years) to make it the same length as the modeled river discharge for future climate scenarios. Thus, there is a slight discrepancy in the time periods used for modeling the groundwater response to climate change. In the groundwater flow model, the base case (present climate) river hydrograph is the mean hydrograph for the 1971-2000 period, while the downscaled climate for generating recharge to the aquifer in the groundwater flow model is based on GCM climate scenario output for 1960-2000 period.

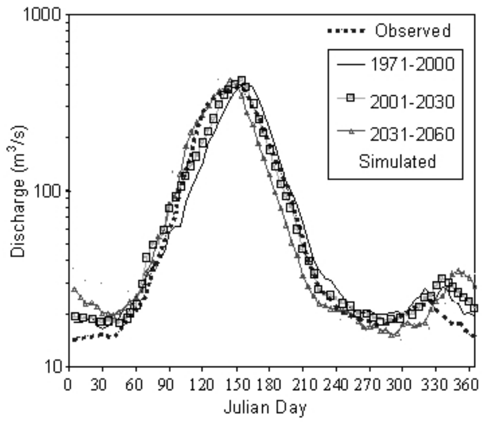

FIGURE 4. Predicted discharge in the Kettle River at Laurier, WA, modeled using statistical downscaling model and comparing to observed discharge in last 30 years (Environment Canada, 2002).

3. RECHARGE MODELING

3.1 Stochastic Weather Generation.

The downscaled daily data already contain a stochastic component from SDSM downscaling, but the poor downscaling results for precipitation did not allow us to use these data directly in a recharge model. Our approach was to compute change factors (relative for precipitation and absolute for temperature), and redistribute them to daily time series with a stochastic series weather generator, LARS-WG (Semenov et al., 1998) (Fig. 3). LARS-WG utilizes semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation, and compares favourably to other weather generators according to Wilks and Wilby (1999).

The base case is defined as the average of the entire historical period, assuming that it is representative of pre-climate change conditions. Then, climate change scenarios are generated by perturbing the generated weather using the change factors to modify the base case. Each scenario consists of 100 years of generated weather, noting that although generated weather runs of 1000 years converge better to specified “normals”, there are diminishing returns of performance after 100 years. The length of generated weather time series is not meant to model actual changing climate year-to-year, but rather to model climate change step-wise for each scenario, and to generate a long enough weather time series to preserve and properly represent statistical properties for the site and the specified climate for the scenario.

3.2 Methodology

Recharge was modeled using a GIS linked to the one-dimensional software HELP (US EPA Hydrologic Evaluation of Landfill Performance model) (Schroeder et al., 1994). Inputs consist of a representative sediment column with defined soil and sediment properties, surface slope, meteorological conditions, and evaporation controls. The approach consisted of defining recharge zones, defined by unique combinations of vertical saturated hydraulic conductivity of the vadose zone, vadose zone thickness, and irrigation return flow, at high (20m) spatial resolution. In total, 161 recharge zones (with unique transient recharge schedules) were created. The temporal inputs to HELP were derived from the LARS-WG stochastic weather generator, with parameters derived from downscaled GCM predictions. Details concerning the distributed recharge modelling are provided in Allen et al. (2004b).

3.3 Recharge Results.

Recharge was modelled for present climate and two future climate scenarios (2010-2039, 2040-2069). Monthly average recharge was computed and used in the groundwater flow model. Mean annual recharge varies considerably across the 64 recharge zones, ranging from near 30 to 120 mm/year or between 10% and 30% of mean annual precipitation. The western and the northwestern portions of the aquifer receive the lowest recharge, while the highest recharge is received in the central and eastern portions of the aquifer. Most of the recharge is received in spring and summer seasons, while in winter the ground is frozen and snow melt does not occur. The autumn season is relatively dry. In spring time, by monthly value, the aquifer receives 40% to 80% recharge from precipitation, depending on soil properties and aquifer media properties; in summer the values are 30% to 50%. During late summer the aquifer receives 60% to 90% of precipitation, but overall recharge amount is small because rainstorms are infrequent. Irrigation return flow contributes 10 to 20% of recharge.

Recharge as percentage of precipitation increases in future climates (Fig. 5). The 2010-2039 climate scenario shows a 2 to 7 % increase (spatially-variable) from present mean annual recharge. The 2040-2069 climate scenario shows a 11 to 25 % increase from present mean annual recharge. Overall, the largest predicted increase due to climate change is in late spring, which suggests a factor of three or more increase from present levels. Predictions suggest 50% increase in recharge in summer months, and 10 to 25% increase in autumn.

4. RIVER MODELING

River modeling was accomplished using the USGS BRANCH model (Schaffranek et al., 1981). The model was applied to 26 km length of the Kettle River, including a small section of the Granby River (about 1 km). Boundary conditions were specified at three external nodes, and river stage was computed at 67 channel cross-sections. Stage and discharge (rating curves) were calculated for all river cross-sections at 1-minute time intervals over 10,000 time steps. The shapes of these curves were compared to historical rating curves from local hydrometric stations. Modeled discharge hydrographs were converted to river stage hydrographs at each of the 123 river segments, roughly 200 to 250 m in length, and interpolated between known river channel cross-sections with known stage-discharge curves.

5. GROUNDWATER MODELLING

Details concerning the construction of the groundwater flow model can be found in Allen et al. (2004b). In summary, the hydrostratigraphy for the groundwater flow model was interpreted from selected high-quality well lithology logs, with layering constrained by the Quaternary depositional history of the valley sediments. Hydrostratigraphic units were modeled in three-dimensions from standardized, reclassified, and interpreted well borehole lithology logs. Solid models were constructed using GMS software (v. 4.0) (Brigham Young University, 2002), converted to a five layer system underlain by solid bedrock, and imported into Visual MODFLOW. Representative homogeneous and isotropic hydraulic properties were assigned to each layer, based on values determined from pump test data. The rivers were represented as specified head boundaries, and river stage schedules along the 26 km long meandering channels were imported at varying, temporal resolution (1 to 5 days) for every cell location independently. The model was calibrated to replicate the observed variation in groundwater levels in the floodplain of the Kettle River at Grand Forks (RMS error was 8%).

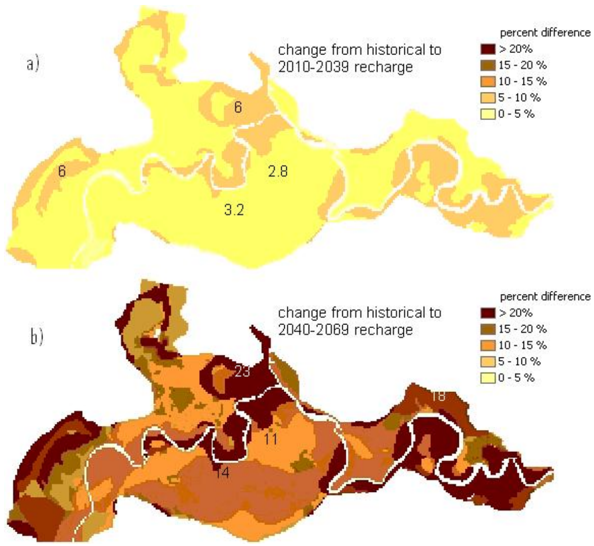

FIGURE 5. Percent change in mean annual recharge to the Grand Forks aquifer modeled in HELP and assigned to recharge zones: between (a) 2010-2039 and historical, (b) 2040-2069 and historical. Historical climate scenario (1961-1999).

6. IMPACTS OF CLIMATE CHANGE ON GROUNDWATER LEVELS

Future climate scenarios for the Grand Forks aquifer indicate temporal shifts in river hydrographs, although the overall hydrograph shape remains the same. These shifts cause changes in aquifer water levels compared to present, when compared on the same day of the year. Modeled water level differences are less than 0.5 m away from floodplain, but can be greater than 0.5 m near the river. As the river peak flow shifts to an earlier date in a year, the aquifer water levels shift by the same interval. Impacts are smallest in zones least connected to the river (away from the river and at higher elevation). The hydrograph shift for the 2040-2069 climate is larger than for the 2010-2039 climate scenario, therefore the computed differences in water levels for future scenarios compared to historical are similarly larger. The maximum water levels associated with the peak hydrograph are very similar to present climate because the peak discharge is not predicted to change, only the timing of the peak.

Groundwater elevation (water table) profiles were constructed for different areas in the aquifer, and illustrate both the transient behaviour of the aquifer and the resulting climate change impacts relative to current conditions. Figure 6 shows a profile extending away from the Kettle River. Both pumping and non-pumping conditions are represented in “Site A” along the profile close to pumping wells in a major irrigation district. “Site B” is at the far end of the profile, at a point furthest away from the river, and is not significantly influenced by drawdown due to pumping. Note that vertical scale is different for both “sites” and that actual groundwater elevation was used. The climate change effect at both sites without pumping effect is different because of different distance to river of each site. As the river hydrograph shifts to earlier peak day in future climates, the groundwater levels follow. This figure shows that climate change effects (river + recharge) are much smaller in magnitude than typical seasonal variation, but are significant.

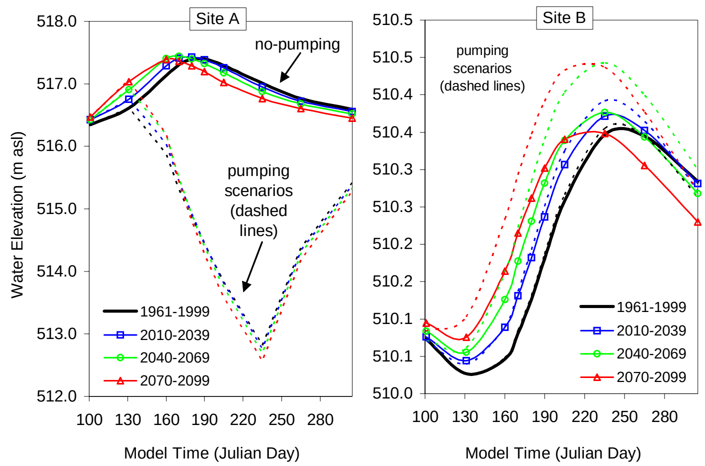

FIGURE 6. Effect of climate change under pumping and non-pumping conditions on groundwater elevations: Site A (close to pumping wells), Site B (away from pumping wells).

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